STUDIES ON PERFORMANCE ENHANCEMENT BY RECURING OF THERMALLY DETERIORATED CONCRETE AND APPRAISAL OF PLASTER COMPOSITIONS AS HEAT SHEILDS

Thesis

Submitted in partial fulfilment of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

by

SHREE LAXMI PRASHANTH

DEPARTMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,

SURATHKAL, MANGALORE - 575025

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DECLARATION

by the Ph.D. Research Scholar

I hereby declare that the Research Thesis entitled **"Studies on Performance Enhancement by Recuring of Thermally Deteriorated Concrete and Appraisal of Plaster Compositions as Heat Sheilds"** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfilment of the requirements for the award of the Degree of **Doctor of Philosophy** in **Civil Engineering** is *a bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

SHREE LAXMI PRASHANTH

Register No. - **CV07F01,**

Department of Civil Engineering

Place: NITK-Surathkal

Date:

C E R T I F I C A T E

This is to *certify* that the Research Thesis entitled **“Studies on Performance Enhancement by Recuring of Thermally Deteriorated Concrete and Appraisal of Plaster Compositions as Heat Sheilds”** submitted by **Shree Laxmi Prashanth** (Register Number: **CV07F01**) as the record of the research work carried out by her, is *accepted as the Research Thesis submission* in partial fulfilment of the requirements for the award of degree of **Doctor of Philosophy**.

Prof. Subhash C. Yaragal
Department of Civil Engineering,
(Research Supervisor)

Prof. K. S. Babu Narayan
Department of Civil Engineering,
(Research Supervisor)

Prof. K N Lokesh
Department of Civil Engineering
Chairman – DRPC

Dedicated to

My loving mother

Late Mrs. Gayatri (Meera)

(13/5/1961 – 25/9/2013)

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Shree Laxmi Prashant

Place: NITK

Date:

ABSTRACT

Concrete is the most versatile construction material which finds its applications in all the civil engineering structures. The properties of the concrete deteriorate when it is subjected to elevated temperatures. Compressive strength being the most desired property of concrete, it is essential to study the strength retention characteristics of concrete at various elevated temperature levels in order to evaluate the usefulness of concrete.

Residual strength of concrete subjected to elevated temperatures depends on the temperature to which it is exposed and the duration for which it is exposed. The first objective is to evaluate quantitative evaluation of effects of exposure duration, temperature and the soaking periods at those designated temperatures. Exposure durations of ½, 1, 1½ 2, 3 and 4hr for elevated temperature levels ranging from 200°C to 800°C at 100°C interval have been considered for the study. Two heating rates (slow and fast) and cooling methods (furnace cooling and water quenching) have been adopted and investigated for their influence on strength characteristics.

Concrete residual strength has been found to be affected by the temperature levels especially for the temperatures above 600°C. At each of the temperatures studied concrete retains lower strength for higher exposure duration. Slower heating signifies presence of heat for larger duration resulting into larger deterioration of strength. Cooling of concrete by quenching in water results in higher deterioration of strength owing to thermal shock.

Thermally deteriorated concrete when comes in contact with moisture, rehydrates, thereby resulting into partial recovery of strength. The second objective of the study was to study the efficacy of Recuring as a means of strength recovery. To facilitate rehydration thermally deteriorated concrete specimen were subjected to water curing till 56 days and recovery in strength has been noted after 7, 14, 28 and 56 days.

Encouraging results were obtained for concrete exposed to temperatures upto 600°C, for higher temperatures however recuring did not result into substantial recovery. The effectiveness of recuring depends on the rehydration capacity of the dehydrated cement paste, which decreases with the increase in exposure temperatures. Partial recovery of strength after recuring suggests that if situation permits, recuring can be a potential technique that helps reduce restoration costs.

Plastering of concrete elements is an usual practice in order to render a smooth finish and to enhance architectural features. The mortar used for plaster, if made with materials that can resist high temperatures, can protect the structural element. Objective of the research was also to study the effectiveness of mortar as heat shield. Experimental investigations on efficacy of use of vermiculite aggregates in mortar for plastering to enhance fire endurance characteristics have been detailed.

The thesis presents strength deterioration of concrete at elevated temperatures with emphasis on exposure levels, duration and rate of heating and cooling. Potential benefits of recuring in strength recovery have been appraised. Efficacy of vermiculite aggregates in mortar for plaster as heat shield has been evaluated.

Key words: Elevated temperatures, Residual strength, exposure durations, heating rate, cooling method, recuring, vermiculite aggregates.

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Chapter 1

Introduction

1.1 GENERAL

Concrete is a very popular building material because of its unique properties of mouldability and high compressive strength, therefore finds its applications in all civil engineering structures. Concrete is a heterogeneous mixture of aggregates and cement paste which can be mixed in fluid state and can be poured in any form. The strength properties of concrete depend largely on the bond between cement paste and the aggregates. Use of graded aggregates, with proper mixing of concrete ingredients ensures proper bond between aggregates and cement paste.

Extensive research is being carried out in the field of concrete technology to improve the strength and durability properties of concrete so that concrete performs well in various hostile conditions as well. Concrete is considered to be the most durable material as compared to various other building materials such as wood, steel, etc. Concrete neither rusts like steel nor is combustible material like wood. Concrete therefore finds its application in most of the industrial and commercial buildings.

Concrete needs to withstand elevated temperatures when it is used in the vicinity of reactors and furnaces as a functional requirement hence refractory concrete or concrete is used in such cases. Normal structures are also subjected to elevated temperatures during accidental events such as a fire.

For structures such as commercial or domestic buildings, the concrete is not designed to withstand elevated temperatures. Moreover these structures are subjected to accidental events very rarely and designing these structures for fire resistance is rather uneconomical. For such structures it is expected that concrete even though undergoes cracking should not spall off and expose the reinforcement, since steel loses its strength more rapidly compared to concrete when subjected to elevated temperatures.

The study of degradation of concrete strength after elevated temperature exposure is essential to estimate the extent of damage that has occurred and plan the repair strategies in order to restore the lost strength of concrete. Concrete is a non-combustible and inflammable material. It neither burns nor does it emit poisonous gases when subjected to fire. It has a very low thermal conductivity. Because of these properties the concrete is considered to be the best building material for heat resistance. However past experiences during fire events have shown concrete to lose significant amount of strength and integrity and suffer heavy deterioration in form of spalling and cracking. Research on elevated temperature behavoir of concrete has been carried out from the past four to five decades, however significant research is taking since the last decade, popularly known as post 9/11 era.

1.2 GENERAL BEHAVIOUR OF CONCRETE AT ELEVATED TEMPERATURES

The behaviour of concrete at elevated temperatures is different from those at ambient conditions. The mechanical properties such as strength, modulus of elasticity and volume stability of concrete are found to reduce during these exposures. Degradation of` structural concrete results into reduced load carrying capacity, hence may result in undesirable structural failures. Elevated temperature exposure may result into spalling of concrete, hence loss of cover to reinforcement. Therefore, the residual properties of concrete retained after elevated temperature exposure, are of vital importance for determining the load carrying capacity and for reinstating the damaged structural members.

As it is well known that the properties of concrete prepared from same mix may vary in properties. These variations of concrete are because of changes in the moisture condition of the concrete constituents and the progressive deterioration of the cement paste-aggregate bond. The behaviour of concrete depends on thermal expansion values for the cement paste and aggregate. Since at elevated temperatures cement paste has the tendency to shrink and aggregates expand there can be loss of bond between cement paste and aggregates. The bond region is also affected by the surface roughness of the aggregate and its chemical/physical interactions at elevated temperatures.

Concrete being a multiphase material made of materials that differ in thermal properties, determining the residual properties of concrete after thermal deterioration is very complicated even if the properties of constituent materials are known. This is because concrete properties and its behaviour under elevated temperature conditions depend on moisture content and porosity at the time of temperature exposure. Studies on performances of Normal Strength Concrete (NSC) and High Strength Concrete (HSC) after fire have been researched exhaustively.

Many experimental studies have been conducted to quantify the extent of deterioration caused and properties by of residual strength of concrete after elevated temperature exposure, however it is very difficult to correlate the laboratory experiments to real life structural concrete. This is mainly because most of the experimental research is carried out on small scale specimen, while in the real life structures considerable restraint is provided to the structural element subjected to elevated temperature by the cooler structural members. Kulkarni KS (2014) carried out experimental study on performance of High Performance Concrete subjected to elevated temperatures and developed provide useful analytical tools for strength prediction.

Various experimental techniques are adopted by the researchers in order to determine the residual strength of concrete after elevated temperature exposure. In a real fire event the concrete is subjected to flames, while most of the research is carried out by heating the concrete specimen in the furnace or oven. However maximum temperature reached is of interest since most of the reactions are temperature dependent. These experimental studies therefore give an idea on extent of damage occurred. The intensity of a building fire depends on the amount of combustible material present in the room and its calorific value. Even though standard fire curves are proposed by the ASTM E119 and ISO 834 fire curves they are not followed in most of experimental research.

To determine the resistance of concrete samples exposed to high temperature, three test methods are employed for finding the residual compressive strength of concrete at elevated temperatures. These are stressed test, unstressed test and unstressed residual strength test. In the stressed test, specimens are restrained by a preload, prior to and throughout the heating process. In the unstressed test, the specimens are heated without restraint.

The first two types of the tests are suitable for assessing the strength of concrete during high temperatures, while the latter is used for finding the residual properties after the high temperature exposure and it gives the least values. Both stressed and unstressed specimens are loaded to failure under uniaxial compression when the steady-state temperature is reached at the target temperature.

1.3 Factors affecting Thermal Performance of Structural Concrete

Concrete has low thermal conductivity and is a non–combustible material. These properties make concrete a good high temperature resistant material. However the properties such as thermal conductivity depends on moisture content. At elevated temperatures the concrete undergoes colour changes, cracking and spalling. Moreover for reinforced concrete structural members, concrete cracking and spalling can adversely affect its performance, since cracking allows for heat to penetrate to the core and spalling of reinforcement cover can expose the reinforcement to heating. Fig 1.1 shows the spalling of concrete from slab and exposing the reinforcement to high temperatures.

Fig. 1.1 Spalling of concrete from slab [Folic et.al. (2002)]

In some cases the concrete does not appear to be spalled or undergone cracking on the surface. Still the concrete experiences deterioration in strength, this is because the concrete would have undergone internal cracking thereby increasing the porosity. Heavy cracking in the vicinity of aggregates deteriorates the bond between aggregates and cement paste. Whatever be the cause of strength deterioration, it is very crucial to estimate the residual strength of concrete in order to predict the stability of the thermally damaged structure or the structural element. Mechanisms responsible for deterioration of strength of concrete subjected to various elevated temperatures are discussed elaborately in chapter 2.

Concrete near to the heating source is subjected to the maximum temperature, and the temperature to which the adjoining structural concrete is subjected will be somewhere between the maximum temperatures reached during the fire event and the room temperature. Hence it is essential to estimate the strength deterioration when for exposure temperatures upto 800°C, since this temperature is normally encountered in a building fire.

During a fire event, duration for which the structural member is subjected to elevated temperatures depends on the fuel available for the fire to sustain. A typical building fire has four phases as shown in figure 1.2. In the first phase the fire ignites, builds up and grows in second phase, third one is the fully developed stage and fourth is the decay phase.

In the first phase the fire is triggered by some source and it starts developing in the second phase. Its development depends on the amount of combustible material. Then it reaches to fully developed phase and it continues for some duration of time. When the combustible material starts getting consumed by the fire, the decay phase starts and it continues till all the combustible material is consumed.

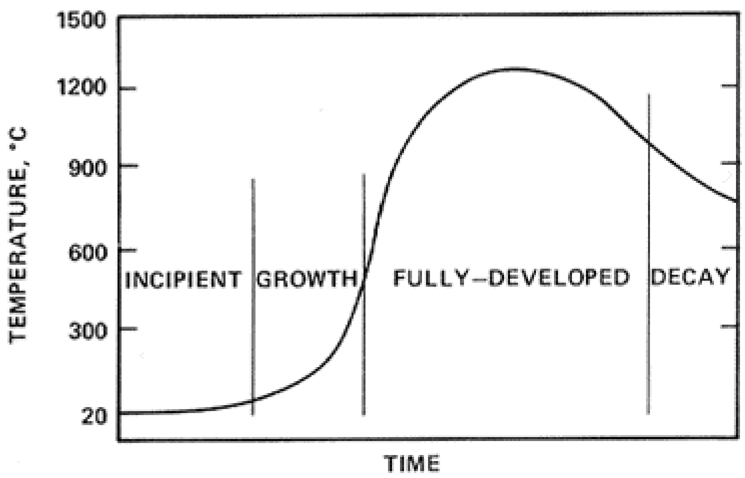


Fig. 1.2 Typical fire build-up curve

Approximate temperatures reached during the fire can be estimated through visual inspections and non-destructive tests. The residual strength of concrete after a fire event is very essential, in order to plan the repair and rehabilitation strategy. Strength of concrete at elevated temperature is sensitive to the temperature level, heating rate, thermal cycling, and temperature duration. Behaviour of concrete at high temperature depends on exposure conditions (i.e., temperature-moisture-load-time regime).

Response of constituent materials of concrete viz., the hardened cement paste and aggregates to high temperatures is different because of differences in their individual thermal properties. Therefore, the effects of high temperatures are visible in the form of surface cracking and spalling. Some changes in surface colour occur during the exposure. The alterations produced by high temperatures are more evident when the temperature surpasses 500°C. Most changes experienced by concrete at this temperature level are considered irreversible. The calcium silicate hydrates (CSH) gel, which is the strength giving compound of cement paste, decomposes further above 600°C. As a result, severe micro-structural changes are induced and concrete loses its strength.

Chemical interaction relates to the chemical reactions between the aggregate and cement paste that can be either beneficial or detrimental. Shrinkage may also start due to the decomposition of $CaCO_3$ into CO_2 and CaO with volume changes causing destructions. Physical interaction relates to dimensional compatibility between aggregate materials and cement paste.

In the present experimental research effect of various heating and cooling regimes on strength retention characteristics of concrete are studied. The major influencing factors on which strength deterioration of concrete subjected to elevated temperatures depend are heating rate, exposure duration, and cooling rate. Extent of Influence of these factors on strength retention is studied at various elevated temperature from 200° C to 800°C.

Thermally deteriorated cement paste, that has undergone dehydration because of elevated temperature exposure, has some self-healing properties. Since loss of moisture from cement paste is the major deteriorating mechanism, if sufficient moisture could be supplied to the same the process is reversed.

The structural concrete is usually covered with plaster in order to provide a smooth finish and improve the aesthetics. This can also serve the purpose of thermal barrier in case of fire event. Since mortar used for plaster is usually made of fine aggregates and cement, both of them being thermally inert, can act as thermal barrier.

The thermal insulation of the existing structural member can be enhanced by providing a coating of a mortar that can resist high temperatures. For this the constituent material of the mortar must be such a material that does not change its properties when subjected to temperatures that are usually encountered. Vermiculite is one such material, which is a light weight material and it exfoliates on heating and act as thermal barrier. Vermiculite can be used a plaster material in order to provide acoustic and thermal insulation in buildings.

1.4 Organisation of the thesis

The aim of this research work is to study and quantify the strength deterioration of ordinary Portland cement concrete when subjected to elevated temperature. Various factors that influence the strength deterioration such as exposure temperature, exposure time and heating rate are studied. The thesis is divided into 7 chapters.

Chapter 1 consists of introduction in which the general behaviour of concrete structures under thermal loads are discussed. The extent of dependence of structural behaviour on concrete properties during and after elevated temperature exposure are discussed. The need of present research is highlighted.

In chapter 2 a detailed state of the art literature on response of concrete during exposure to elevated temperatures and the residual properties after elevated temperature exposure is presented. From past few decades studies are being carried out to quantify the residual properties after exposure to various elevated temperatures normally encountered in building fires. Behaviour of various concretes such as normal strength concrete, high strength concrete, self-compacting concrete, etc is studied. Few researchers have studied the effect of various environmental and material factors responsible for residual properties of concrete.

In chapter 3, detailed information on experimental investigation carried out is given. It includes the preliminary tests on materials used, then followed by the mix design. The procedure of the test carried out is elaborated.

Chapter 4 deals with the study of thermal deterioration of strength of OPC concrete. Effect of exposure temperature, exposure duration and rate of heating on residual strength of OPC concrete are discussed. The concrete strength is tested by destructive testing and the results are presented in this chapter. Exposure temperatures studied are 200°C to 800°C at an increment of 100°C. For each exposure temperature the effect of exposure duration and rate of heating on strength retention are reported. Moreover the rate of cooling also has an impact on the strength retention characteristics of concrete. At each of the exposure temperature and exposure duration two rates of cooling are studied namely furnace cooling and sudden cooling.

The thermally deteriorated concrete is later subjected to recuring in order to enable the concrete to rehydrate and recover the lost strength. The results of the effect of recuring on strength of thermally deteriorated concrete are reported in chapter 5. The effect of recuring on strength regain is tested on concrete cubes after 7, 14, 28 and 56 days of recuring. Prior to recuring the concrete cubes are subjected to elevated temperatures of 200°C to 800°C and six exposure temperatures from ½hr to 4hr.

Chapter 6 reports the strength performance of concrete coated with various mortars made with river sand and vermiculite aggregates. The concrete cube specimen are coated with six mortars made of river sand and vermiculite aggregates

Lastly the conclusions drawn from the experimental investigation are listed out in chapter 7.

1.5 CLOSURE

Behavoir of concrete after exposure to elevated temperatures is discussed and the need for study of deterioration of concrete strength is highlighted. Factors affecting the thermal performance of concrete are discussed. Organisation of thesis is also elaborated.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Concrete is a composite material of hardened cement paste and aggregates along with an intermediate zone known as Interfacial Transition Zone (ITZ) (Olliver et.al 1995). The properties and performance of concrete depends largely on the properties of ITZ (Mehta 2006). Many researchers have reported strength deterioration with the increase in exposure temperatures. The strength degradation due to elevated temperature exposure depends on type of aggregates used, the heating and cooling regime, the presence of pozolanas, fibers, etc.

This chapter presents the mechanisms involved in deterioration of concrete properties in general and strength in particular due to exposure to elevated temperatures. The influence of constituent materials and environmental factors on strength degradation are discussed. Later the literature pertaining to cementitious properties of degraded cement paste and its capacity to rehydrate and recover the lost strength are also discussed.

2.2 DETERIORATING MECHANISM CAUSING STRENGTH DETERIORATION AT ELEVATED TEMPERATURE

Major deteriorating mechanism responsible for strength reduction of concrete subjected to elevated temperatures is the dehydration of cement paste, the differential expansion of cement paste and aggregates and build-up of pore pressure. Studies on mechanisms that are responsible for strength reduction of concrete subjected to elevated temperatures are reported in this section.

Deterioration of concrete properties is due to physical and chemical changes that take place in the hardened cement paste (HCP) [Allen & Desai (1967)] and breakdown of bond between aggregates and the HCP.

According to Chandra S et.al (1980) the thermal incompatibilities between aggregates and hardened cement paste produces internal stresses and microcracks. Internal stresses are found to develop partly due to non-uniform temperature distribution and partly due to vapor pressure (developed during vaporization) resulting in reduction of mechanical strength.

Bazant (1983) has studied the mechanism taking place in the concrete, in order to model the thermal shrinkage and creep occurring at elevated temperature. Creep of concrete increases as a result of simultaneous changes taking place in the moisture content, thermal volume change as well as volume change caused by drying or thermal shrinkage and pore pressure produced by heating.

Chan et.al (1999), has found that moisture content and the initial strength are the determining factors for thermal behavior of concrete. Concrete with high moisture content is found to undergo explosive spalling because of buildup of high vapour pressure. Moreover, it has also been found that, if the strength of concrete is below 60MPa, generally no spalling occurs, even at a high moisture content level. When the concrete strength exceeds 60 MPa, the higher the moisture content, the greater the probability of spalling.

Chan et.al (2000a) has studied mechanical properties and pore structure of thermally deteriorated concrete exposed to 800°C and concluded that pore structure coarsening as a result of elevated temperature exposure, is responsible for mechanical strength deterioration.

According to Odelson (2007) damage of pore structure during rapid escape of moisture from heated concrete coupled with decomposition of CSH is responsible for deterioration of concrete properties.

The performance of concrete at elevated temperatures has been found to depend on the moisture content, since the thermal conductivity of concrete increases with increase in moisture content [Sanak et.al (2008)].

According to Vadacan et.al (2009) rapidly escaping liquid (water vapour) is a dominant mechanism that results in deterioration of strength and the temperature gradient created in the concrete body creates even greater driving force for the water to evaporate out of the concrete.

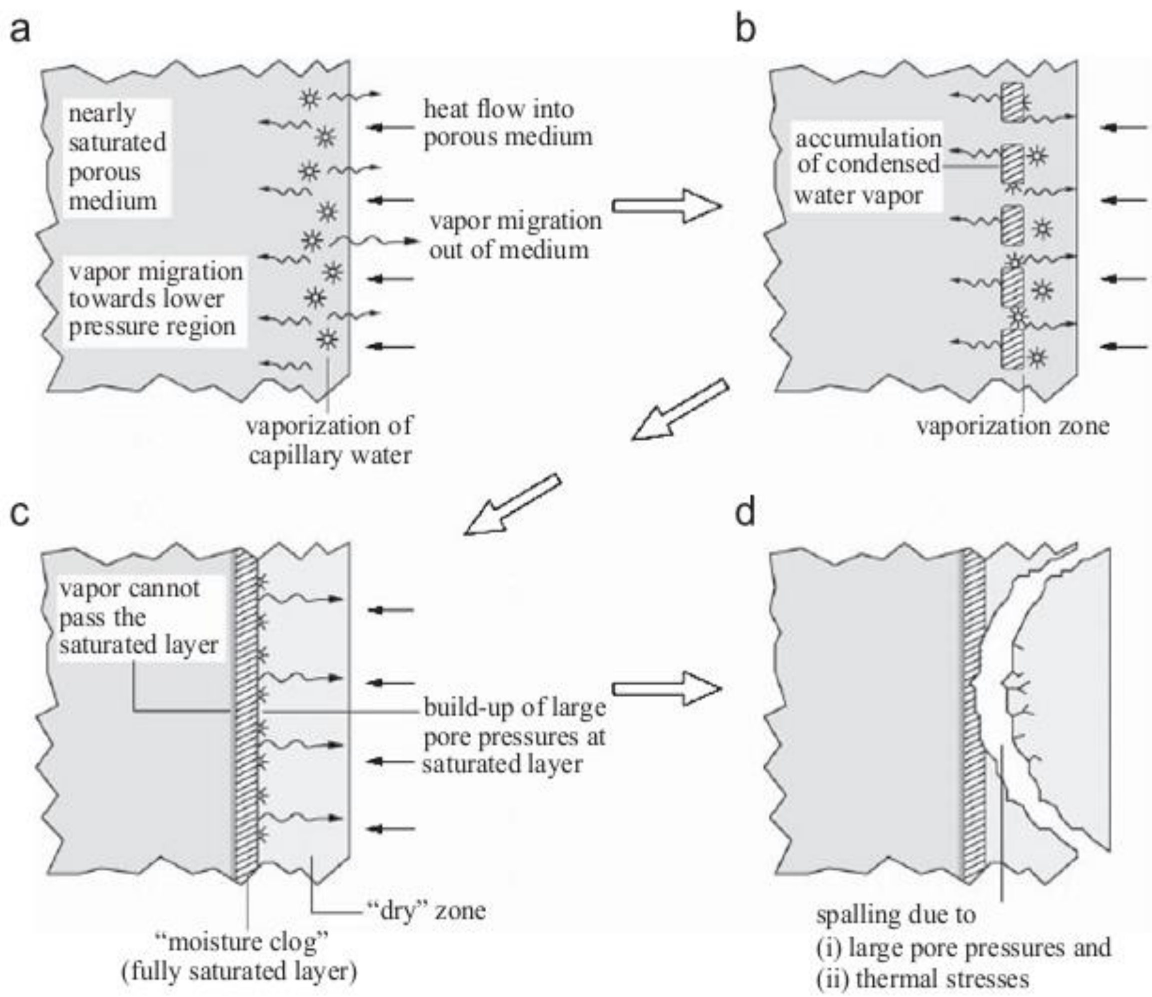


Fig 2.1 Moisture movement in the concrete surface (Behnood et.al 2009)

Behnood et.al (2009) has explained the moisture transport phenomenon occurring in the concrete at elevated temperatures as shown in figure 2.1. Moisture transport is responsible for the deterioration of concrete properties. Concrete is a porous medium and allows for moisture migration within the concrete. When a concrete surface is heated, some of the moisture will evaporate and escape out through the connected pores (fig 2.1a). When the concrete is continuously exposed to heat the moisture cannot escape, since the outside temperature is continuously rising. Hence the moisture will move towards the cooler interior and will form a moisture clog at some distance from the heated surface, where it is unable to move further. Due to this large pore pressure will build up, and the point when it exceeds the tensile strength of concrete, that portion of concrete spalls off.

Differential expansion and contraction due to thermal incompatabilities between HCP and aggregates is responsible for strength deterioration as stated by Ikponwosa et.al (2010).

Concrete made with low w/c ratio has been found to create more stable aggregate bonding by improving the interfacial transition zone, hence performs better under elevated temperature conditions [Culfik et.al (2010)].

According to Henry et.al (2011) thermally damaged concrete is found to be more susceptible to carbonation through reaction of atmospheric CO_2 with calcium oxide produced by dehydration of calcium hydroxide. This may contribute to a slight strength increase through reduction in porosity. However, it can lead to spalling of concrete cover in case of reinforced concrete due to carbonation induced corrosion.

2.3 STRENGTH DETERIORATION OF CONCRETE

Strength is the most desired property of structural concrete. Residual strength estimation is very important in order to predict the stability of concrete structure after elevated temperature exposure. The effect of elevated temperature exposure on strength deterioration with increase in temperature and methods of estimation of the extent of damage occurred is presented in this section.

According to Khoury et.al (1988) the concrete is normally found to preserve strength upto 400°C-500°C. However the effect of strength deterioration is found to be significant for exposure temperatures of 500°C and above. Concrete heated under compressive loading retains larger amount of strength compared to unloaded concrete. The usefulness of concrete is found to normally maintain till 550-600°, beyond this temperature, concrete loses substantial amount of strength and a marked increase in creep is also observed.

Handoo et.al (2002) has found gradual reduction in the compressive strength of concrete exposed to 500°C and rapid reduction in strength is observed for temperatures beyond 500°C. Complete decomposition of portlandite beyond 700°C at the surface and beyond 900°C towards the core samples is observed. Concrete exposed to 900°C experienced total deterioration of strength.

Phan LT (2002) has described three kinds of tests to determine the residual strength of concrete after elevated temperature exposure. These are named as stressed, unstressed and unstressed residual strength tests. In stressed tests, a preload (20–40%) of the ambient compressive strength) is applied to the specimen prior to heating and is sustained during the heating period. In the unstressed test, the specimen is heated, without preload, at a constant rate to the target temperature, which is maintained until a thermal steady state is achieved. In unstressed residual strength test, the specimen is heated without preload at a prescribed rate to the target temperature, which is maintained until a thermal steady state is reached within the specimen. Unstressed residual strength test gives the lowest values. According to Morsy et.al (2009) residual strength test leads the lowest results and therefore more suitable for getting limiting values for the residual strength.

According to Li et al. (2004) the compressive strength of concrete drops with temperature starting from 200 °C. The compressive strength values are found to drop sharply to 21.3% of the strength at ambient conditions, compared to that of specimens unfired after 1000°C firing.

Vodak (2004) has studied the strength porosity relationship for concrete subjected to elevated temperatures and found that the strength porosity relationship of thermally deteriorated concrete depends on the mechanism that has taken at elevated temperatures, which in turn depends on the age of concrete at which the concrete is exposed to elevated temperatures and the degree of hydration. At age of 28 days the concrete contains considerable amount of unhydrated cement. When such a concrete is exposed to temperatures of 100°C to 300°C steam curing effect is produced in the concrete resulting into increase in strength. At age of 90 days when the hydration process is practically terminated, the strength retained after elevated temperature exposure is governed by microcracking and deterioration of pore structure.

Janotka et.al (2005) has found an increase in prism compressive strength up to 100°C also differences were observed in compressive strength of concrete cured at 100 and 200°C and control specimens kept only at the ambient temperature.

Arioz (2007) has observed a gradual reduction in residual strength upto 600°C (residual strength 90% for carbonate aggregates and 50% for river gravel) and sharp reduction in relative strength beyond that point.

Arioz (2009) has studied the effect of elevated temperatures on concrete cube specimen of sizes 100mm, 150mm and 200mm. The effect of specimen size on the retained compressive strength was not pronounced. The specimen size played an important role on the retained splitting tensile strength of concrete when the specimens were heated up to 400°C. However, the tensile behaviour of different sized specimens was found to be almost similar beyond the temperature of 600°C.

According to Behnood (2009) irrespective of the material and environmental factors, the concrete is certainly found to lose strength for exposure temperatures exceeding 400°C.

Damirel et.al (2010) investigated the effect of elevated temperature on the mechanical and physical properties of concrete specimens prepared by substituting cement with finely ground pumice at proportions of 5%, 10%, 15% and 20% by weight. Considerable reduction in strength (about 25%) has been observed for concrete exposed to 600°C because all the hydrated phases including C-S-H and $Ca(OH)_2$ were transformed into amorphous structures at this temperature instead of their characteristic crystal structures.

2.4 FACTORS AFFECTING RESIDUAL STRENGTH

Even though it is clear that whatever be the environmental and material factors the concrete certainly loses strength when subjected to temperatures above 400°C. However the extent of strength loss depends on the constituent materials. It is understood that if the constituent materials can withstand elevated temperatures then the concrete made such materials will naturally withstand elevated temperatures. Researchers have tried to quantify the extent of influence of these factors on residual strength of concrete after elevated temperature exposure. A brief account of the same is presented in this section.

2.4.1 Material Properties

The properties of concrete and its behavior after being subjected to elevated temperatures depends on the thermal properties of the constituent materials used.

Aggregates

Properties of concrete to a great extent depends on properties of aggregates, since aggregates constitute nearly three quarters of the concrete volume (Neville 1997). Hence the performance of concrete at elevated temperatures depends largely on the thermal properties of aggregates.

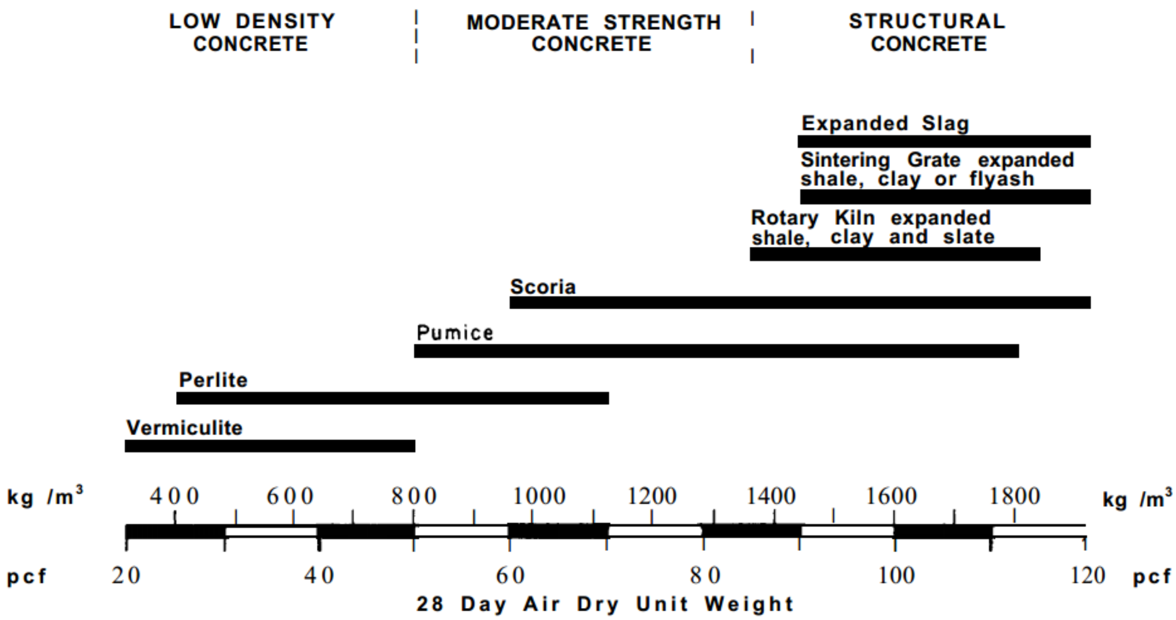


Fig 2.2 Approximate unit weight and use classification of lightweight aggregate concretes

(ACI 213 report)

Steiger et.al (1978) has highlighted the thermal insulation properties of concretes made with light weight aggregates such as perlite, vermiculite and expanded polysterene pellets. Vermiculite is a soft, laminated, mica-like material in its raw form. When heated at temperatures of 1800 to 2000°F, the water molecules trapped in the flakes of vermiculite turn to steam and force the micaceous plates of the material to expand or exfoliate and becomes a lightweight aggregate of great value for fill and insulating concrete.

Use of vermiculite and perlite aggregates gives excellent insulating properties because of the spaces created during exfoliation, however they have a very low compressive strength. While the aggregates prepared by calcining, sintering, or expanding such products as slag, clay, fly ash, shale or slate; also made with aggregates processed from natural materials such as scoria, pumice, or tuff can be used as for structural concrete alongwith some thermal insulation properties.

Figure 2.2 shows the full spectrum of lightweight concretes. Low density mixes (shaded band at left) offer best insulating properties.

Forrest (1980) reviewed the then available literature on performance of concrete made with light weight aggregates under fire conditions and found that structural elements fabricated with light weight concrete perform better under fire conditions.

According to A.H Gustaferro et.al (1986) carbonate aggregates are found to perform well at elevated temperatures as compared to siliceous aggregates. Siliceous aggregates begin to expand abruptly at 570˚C and disintegrate. Since calcining requires heat, the reaction absorbs some of the fire's heat.

Xu et.al (2003) has commented on the influence of aggregates as crack arrestors that the presence of aggregates act as barriers that restrain the propagation of cracking. An appropriate grading of aggregates in concrete is an effective method for improving its resistance to cracking after exposure to high temperatures.

Kodur et.al (2003) has studied the thermal properties of plain and fiber reinforced concrete made with silicate and carbonate aggregates and found that the thermal conductivity of siliceous aggregate is generally higher than that of carbonate aggregate. Generally, the carbonate aggregate concrete has higher specific heat in the temperature range of 600– 850°C. The thermal expansion of siliceous aggregate HSC is higher than that of carbonate aggregate concrete in the 20– 800°C temperature range.

Superior performance of carbonate aggregates as compare to siliceous aggregates was confirmed from the experimental research carried out by Arioz (2007). Limestone aggregates preserved almost 90% of ambient temperature strength after 600°C exposure while river gravel, which were of siliceous origin preserved only 50%. Limestone, dolomite and limerock are termed as "carbonate" aggregates because they consist of calcium or carbonate or combinations of the two. During exposure to fire, these aggregates calcine [carbon dioxide is driven off and calcium (or magnesium) oxide remains].

Laterised concrete is a concrete in which the sand content is replaced partially or completely with laterite fines. Ikponwosa et.al (2010) studied the effect of elevated temperatures on laterised concrete. It was found that laterised concrete can withstand elevated temperatures upto 500°C without any deterioration in strength, while the strength of normal concrete deteriorated for exposure temperatures above 200°C.

A detailed study on influence of different kinds of aggregates on thermal behavior of concrete is carried out by Zing et.al (2011). It was found that the initial moisture state of aggregates plays a very important role in thermal behavior of concrete. Explosive spalling was found to occur in the range of temperature between 150°C and 450°C for the concrete prepared with saturated aggregates. The low porosity of flint aggregates leads to a build-up of vapour pressure. The permeability of aggregates plays an important role in the thermal stability of concrete. With a similar siliceous nature, quartzite and flints are found to have a completely different behavior, oven-dry flint aggregates have shown significant damages after 450°C (cracks, bursting into fragments) while quartzite aggregates have presented lower values of mass loss and of porosity increase.

Pozolanas

Pozolanas have been used in concrete because of their beneficial role played in terms of reduction of calcium hydroxide content as a result of pozolanic reaction. Calcium hydroxide is one of the products of hydration of cement, with no cementitious properties. Pozolanas also provide a better filling effect producing a denser concrete. Effect of presence of these pozolanas on performance of concrete subjected to elevated temperatures are studied by few researchers and a brief account of it is presented here.

Phan L T (2002) has concluded through his experiments that silica fume in the concrete densifies the pore structure resulting in lower permeability and therefore gives rise to increased vapour pressure, resulting into a sharp reduction in strength as the exposure temperature increases.

Xu et al., (2003) have investigated the impact of high temperature on **P**ulverized **F**ly **A**sh (PFA) concrete. At the temperature of about 250°C, the concrete has shown no reduction in compressive strength but, a gain of 8-9% for concrete made with OPC only, while PFA concrete gained about 10-15%.

According to Poon et al. (2003) the use of Metakaolin at a replacement level of 20% of cement has resulted in higher compressive strength than the use of Silica Fume at the level of 10%, but more brittle post-peak stress–strain responses.

2.4.2 Heating Rate and Exposure Duration

Culfik et.al (2002) has studied the effect of exposure durations of 1 hr to 10 hr on extent of deterioration of mechanical properties of high performance mortar and found that deterioration increases with duration of exposure. The concrete heated at faster rate is found to retain larger strength .It also presents data on the effect of two methods of cooling, in air and in water, on the measured strength. Water cooling is found to deteriorate the concrete properties to a larger extent.

According to Hager et.al (2006) higher temperature gradient is produced when concrete is heated at a higher rate and the gradient is independent of the specimen size.

2.4.3 Cooling Rate

In building fires, usually the fire is extinguished by spraying water. This will cause the heated concrete to cool suddenly as against slow cooling in case of laboratory studies. Few researchers have studied the effect of cooling by immersing the heated concrete samples in water at room temperature.

Chan et.al (2000b) has shown that cooling regime has a minor effect on the residual compressive strength and sudden cooling caused slightly higher deterioration of strength for lower temperatures upto 500°C. However, it causes significantly higher deterioration at higher temperatures. It is also noted that effect of cooling rate was less pronounced for concrete exposed to higher peak temperatures.

According to Janotka et.al (2005) rapid cooling of hot concrete surfaces exposed to 100 and 200°C or more, are for structural quality deterioration, equally dangerous as temperature elevations. This is because, the phenomenon of rapid cooling is connected with extreme shrinkage of the specimens and crack propagation, leading to the final effect of strength losses.

Husem (2006) has conducted experiments on heating and cooling effect on HPC and normal concrete. It is concluded that water cooling caused loss of strength in high percentages in normal strength concrete as well as High performance concrete after being exposed to high temperature. Studies have shown that experimental samples damaged to a great extent and they lost their compressive strengths, for high-performance concrete cooled in water after being exposed to the temperature of 800°C, and ordinary concrete is cooled in water after being exposed to the temperature of 600°C.

Lee et.al. (2008) has conducted experiments to investigate effect of different cooling regimes (slow cooling, natural cooling, rapid cooling) on concrete heated to target temperatures of 200, 400, 600 and 800°C. It was found that water cooling has caused severe deterioration of compressive and flexural strengths, while slow cooling has shown lower deterioration of strength.

Experimental investigation on the effect of thermal shock during cooling on residual mechanical properties of fiber concrete exposed to elevated temperatures from 200 to 800°C has been carried out by Peng et.al (2008). It was found that presence of hybrid fiber (steel fiber and PP fiber) enhances both residual strength and fracture energy of concrete subjected to thermal shock induced by rapid cooling from elevated temperature up to 800°C. Concretes with Pozzolanas as partial replacement of cement enhances the strength performance of concrete when subjected to elevated temperature and also resistance against thermal shock due to cooling. Water spraying for duration of 30 minutes or more is in consistency with quenching in water.

2.5 RECURING OF THERMALLY DETERIORATED CEMENT CONCRETE

The deterioration of concrete strength is governed by deterioration of cement paste due to physical and chemical changes taking place in the cement paste, hence it is very essential to study the phase changes taking place in cement with the increase in elevated temperature. There are a few research publications reporting the residual cementitious properties of the dehydrated cement paste.

Alonso et.al (2004) studied the compositional changes in the HCP at elevated temperatures and its subsequent rehydration due to contact of moisture. Ettringite loses its crystalline form around 80°C, the crystalline phases of CSH, as tobermorite, transforms around 400° C. Physically bound water from the cement paste is released upto 200°C. The heating process induces a continuous dehydration of CSH gel with the increasing of temperature. The maximum transformation occurs at 450°C. The rehydration of a heated cement paste shows that the process is reversible and new formation of a CSH gel from the new nesosilicate is confirmed with a CaO/SiO_2 ratio close to the initial CSH gel and recovering its initial stoichiometry. Also crystalline phases, which were transformed to lime at 750°C, are newly formed such as portlandite and calcite from carbonation. Ettringite is rehydrated and anhydrous cement remains practically unaltered.

Decomposition of CH, at elevated temperatures of about 400°C, results into release of Calcium Oxide (CaO). When it comes in contact with moisture, rehydration occurs, which is detrimental to strength and other properties of concrete according to Mendes et.al (2011).

Recently Zhang et.al (2012) carried out phase analysis with the help of XRD in order to quantify the changes taking place in the composition of hardened cement paste. The hydration products of cement, CH and CSH are found to undergo dehydration and decomposition in the range of temperatures of 105°C to 1000°C as shown in fig 2.2.

Both CH and CSH are dehydrated upto 400°C, no phase changes occur in CSH, however the interlayer water is lost. The CH is decomposed into calcium oxide and water at about 420°C, which can explain the rapid mass loss and CH is totally decomposed upto 500°C. From 500°C to 1000°C the CSH loses its bound water and the chain like structure is completely destroyed upto 1000°C. Moreover the existing alite is transformed into belite at elevated temperatures.

$$(CaO)_3SiO_2 \rightarrow (CaO)_2SiO_2 + CaO$$

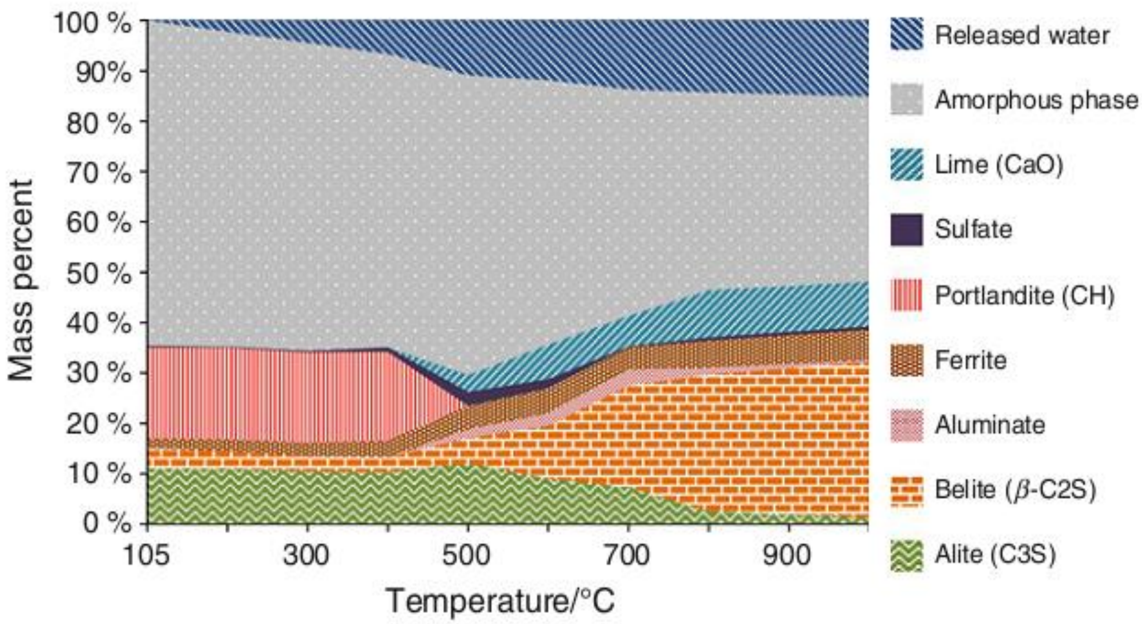


Fig. 2.3 Phase distribution of cement paste subjected to various temperatures

2.6 LITERATURE SUMMARY AND PROBLEM FORMULATION

Based on the, detailed review of available literature, following broad comments can be made regarding state-of-art about our understanding on the behavior of concrete subjected to elevated temperature.

2.6.1 Behavior of Concrete at Elevated Temperatures

Concrete being a multiphase material, its performance is found to depend on the bond between the aggregate and the hardened cement paste. This in turn depends on the binding ability of the cement paste. Cement paste gets its binding ability as a result of the hydration reaction between water and the anhydrous cement. Reaction products of anhydrous cement and water are portlandite and the CSH gel. Reactions that take place in the hardened cement paste at elevated temperature cause dehydration thereby the paste lose its binding property. This causes loss of bond between hardened cement paste and the aggregates.

The aggregates and hardened cement differ largely in their thermal properties. This creates thermal incompatibility between the two phases. This also initializes the cracking and that begins in the interfacial transition zone, which is the weakest phase of concrete. Because of high temperature exposure and concrete being non conducting material, high thermal gradient is produced at the concrete surface. This gives rise to surface cracking. The surface cracking increases with the increase in exposure temperature. With increase in the exposure duration the surface cracks penetrate deep into the concrete layers. This causes severe deterioration of concrete properties.

Performance of concrete subjected to elevated temperatures has been found to reduce due to various physical and chemical transformations taking place in the hardened cement paste at elevated temperatures. The deterioration at any given temperature also depends on the heating rate since all the reactions that cause deterioration are not instantaneous and for slower heating the presence of heat is for longer duration. However larger temperature gradient is produced during faster heating. It is not clear from the literature whether deteriorating effect of faster heating is more severe or the slower heating.

Concrete begins to lose its strength gradually up to 400°C and sharp reduction in strength above 600°C. At this temperature the CSH begins to decompose as a result of which the cement paste lose its binding property, leading to bond deterioration between cement paste and aggregate. The concrete residual strength after elevated temperature is affected by the exposure duration and rate of heating.

Concrete strength has been found to deteriorate by combined effect of high temperature gradients and development of pore pressure because of presence of moisture. Whenever the concrete is subjected to heat for longer duration, the deterioration experienced is larger for any exposure duration, since peak pore pressure increases with prolonged exposure duration, and shifts from the surface towards the centre of the concrete.

The literature reports deterioration of strength with increase in exposure temperature, heating rate, cooling rate. However the extent influence of each of these factors on concrete subjected to a elevated temperatures is not clear. This is because various researchers have used various heating rates, exposure durations and cooling regimes, hence the results cannot be correlated.

The effect of recuring on strength recovery of thermally deteriorated concrete depends on extent of deterioration that has occurred. Very few authors have studied the effect of recuring on concrete subjected to various elevated temperatures. However the rehydration capacity of deteriorated cement paste depends on the physical and chemical changes that have occurred in the cement paste during the elevated temperature exposure. These reactions are not instantaneous. Hence the influence of exposure duration on recuring capacity of thermally deteriorated cement paste is not very clear from the literature.

2.6.2 Towards Problem Formulation

Performance of concrete subjected to elevated temperatures has been found to depend on various environmental factors. Strength retention characteristics of concrete after elevated temperature exposure depends on heating rate, cooling regime and holding time. However the influence of each of these factors is not clear. The present research is aimed at quantifying the influence of two heating rates, two cooling regimes and six exposure durations of ½hr, 1hr, 1½hr, 2hr, 3hr and 4hr for concrete subjected to elevated temperatures of 200°C to 800°C at an increment of 100°C.

Concrete strength begins to deteriorate for exposure temperatures above 200°C. Concrete loses more than 75-80% of the ambient strength for temperatures above 800°C. Hence 200°C and 800°C are chosen as limiting values for the study.

The severity of deterioration depends on exposure temperature and exposure duration. The lost strength can be recovered by the mechanism of recuring. Recuring is provision of continuous supply of moisture to the thermally deteriorated concrete to encourage rehydration of the dehydrated cement paste. The new products formed by rehydration will partially fill the cracks and capillary pores formed due to elevated temperature exposure, thereby regaining the lost strength partially. This however depends on the rehydration capacity of the dehydrated cement paste.

Plastering of concrete elements in a structure is an usual practice. Structural concrete is mostly coated with mortar, with an intention of giving a smooth finish to the structural element and enhance the architectural features. It does not carry any structural load. The mortar is usually a mixture of sand and cement. If the mortar is made of a material that could withstand high temperature and not let the heat to penetrate to the structural member, then the structural member would be protected during an accidental event such as fire. This will be economical compared to constructing the structural element of heat resisting concrete. Moreover this method can be used to strengthen the existing structures made with conventional concrete against the possible thermal damage.

Vermiculite is one such material, which is light in weight and can withstand the temperatures that normally occur in a building fire. The presence of pozzolanas such as fly ash and the ground granulated blast furnace slag are found to play a beneficial role in minimizing the deterioration caused by the elevated temperature exposure. This is because of the pozolanic reaction that minimizes the calcium hydroxide content in the hardened cement paste and thereby contributing to enhanced resistance against elevated temperature exposure, when used as partial replacement of cement.

2.7 OBJECTIVES OF THE RESEARCH

In the light of need outlined and possible means, modes and methods discussed, the following objectives have been proposed for the research.

1. To investigate the qualitative aspects of strength deterioration of concrete at elevated temperatures
2. Performance appraisal of recuring as a technique for strength restoration.
3. To investigate efficacy of plaster compositions as heat shield.

2.8 RESEARCH METHODOLOGY

Detailed methodology adopted to accomplish the objectives has been presented in this section. Methodology involves casting and curing of concrete cubes, exposure to elevated temperatures, finding out residual strength by destructive testing.

1. *Casting of concrete specimen*.

   The concrete cubes of 100mm were cast by mixing ingredients in the concrete mixer and pouring in to the moulds and compacting then by table vibrator. The cubes were demoulded after 24 hours of casting. After that the cubes are water cured for 28 days. After 28 days they were removed from the curing tank and kept exposed to ambient conditions till they were surface dry before testing.

2. *Exposure to elevated temperature*

   Concrete cubes were arranged in the furnace and exposed to designated elevated temperatures from 200°C to 800°C at an increment of 100°C in two furnaces. The concrete is retained at designated temperature for a period of ½ hr, 1 hr, 1½ hr, 2hr, 3hr and 4 hr. After that the furnace is switched off. For sudden cooling the cubes were removed from furnace-1 and immediately plunged into small tank containing water at room temperature and allowed to cool in water till room temperature is reached. For furnace cooling the heated concrete cubes were allowed to cool in the furnace till room temperature is reached.

3. *Testing for residual compressive strength*

   Residual strength in each case was determined by destructive testing as per IS 516- 1959 and was compared with the initial strength of concrete cubes before exposure.

4. *Recuring*

   The remaining specimen after exposure were once again cured in curing tank for 7, 14, 28 and 56 days. The strength after recuring is found by destructive testing and has been compared with initial strength.

5. *Casting of mortar coating*

   The ingredients of the mortar (cement and sand/ vermiculite) was mixed by hand and is coated on the surface of the concrete cube with the help of plywood moulds. They were cured under water for 28 days. These are then exposed to elevated temperatures and later tested for residual strength.

2.9 CLOSURE

Available research publications on concrete performance at elevated temperatures were reviewed and are presented in brief here. State of the art on knowhow of mechanisms responsible for deterioration of concrete strength at elevated temperatures and the extent of influence of factors such as constituent material properties, heating rate, duration and cooling regimes on strength retention of concrete subjected to elevated temperatures are elaborated. The chapter concludes with problem formulation and brief objectives and methodology of the research.

CHAPTER 3

EXPERIMENTAL INVESTIGATION

3.1 GENERAL

Objectives mentioned in the previous chapter have been accomplished with simple experimental techniques. Entire experimental program was carried out on concrete cube specimen of size 100mm.

Details of the materials used for the research and their properties are provided in the following sections. This is followed by the details of the concrete mix used and the casting and curing procedures. Later, the detail of the methodology adopted to accomplish the research objectives is elaborated in this chapter.

3.2 MATERIALS

Physical and chemical properties of all the ingredients used for the entire experimental work are discussed in this section.

3.2.1 Cement

A popular commercial brand of Ordinary Portland Cement (OPC) 43 grade was used. The chemical composition of the cement is given in table 3.1. The cement was tested for its conformation to IS codal provisions. Physical tests such as fineness, soundness, normal consistency and setting times were conducted on cement sample and the results are tabulated in Table 3.2. Fineness test was conducted by Blaine's permeability method as per IS 4031(Part 2):1999. Soundness of the cement sample was found by following the procedure mentioned in IS 4031(Part 3):1988. Normal consistency and setting times of the cement was found according to IS 4031(Part 4):1988 and IS 4031(Part 5):1988 respectively. A sample of cement to be used for the research was tested for compressive strength as per the procedure mentioned in IS 4031(Part 6):1988. It was found that the cement used met the codal provisions.

Table 3.1 Chemical composition of cement

Soluble silica (%)	21.6
Alumina (%)	5
Iron Oxide (%)	3.7
Lime (%)	63.1
Magnesium (%)	0.8
Insoluble residue (%)	1.8
Sulphur (sulphur trioxide) (%)	2.1
Loss on ignition (%)	2
Chloride content (%)	0.01

Table 3.2 Physical Tests on Cement

<table>
<tr><th>sl.no</th><th>Test conducted</th><th colspan="3">Results obtained</th><th colspan="3">Requirements as per I.S</th><th>Remarks</th></tr>
<tr><td>1</td><td>Specific gravity</td><td colspan="3">3.12</td><td colspan="3">--</td><td rowspan="2"></td></tr>
<tr><td>2</td><td>Normal consistency</td><td colspan="3">29%</td><td colspan="3">--</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">Setting times (min)</td><td colspan="3">Initial 65</td><td colspan="3">Not less than 30 min</td><td rowspan="7">Satisfies codal requirements</td></tr>
<tr><td colspan="3">Final 270</td><td colspan="3">Not more than 600 min</td></tr>
<tr><td>4</td><td>Fineness, m^2/kg</td><td colspan="3">330</td><td colspan="3">Not less than 300 m^2/kg</td></tr>
<tr><td>5</td><td>Soundness, mm</td><td colspan="3">Expansion: 2.50</td><td colspan="3">Not more than 10 mm</td></tr>
<tr><td rowspan="2">6</td><td rowspan="2">Compressive strength MPa</td><td>3 days</td><td>7 days</td><td>28 days</td><td>3 days</td><td>7 days</td><td>28 days</td></tr>
<tr><td>34</td><td>51</td><td>61</td><td>23</td><td>33</td><td>43</td></tr>
</table>

3.2.2 Fine Aggregates

The physical properties of fine aggregates were determined and the results are tabulated in table 3.3. River sand conforming to zone III (I.S 383-1970 grading requirements) with specific gravity 2.65 was used. For the casting of concrete the sand passing through 4.75mm IS sieve is used. For mortar preparation sand passing through 2.36mm IS sieve was made use of.

Table 3.3 Properties of fine aggregate

<table>
<tr><th>Sl. No</th><th colspan="2">Property</th><th></th></tr>
<tr><td>1</td><td colspan="2">Specific gravity</td><td>2.65</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">Bulk density</td><td>Loose</td><td>1463kg/m^3</td></tr>
<tr><td>Compact</td><td>1661kg/m^3</td></tr>
<tr><td>3</td><td colspan="2">Moisture content</td><td>Nil</td></tr>
</table>

Table 3.4 Sieve analysis of fine aggregate

<table>
<tr><th rowspan="2">I.S sieve size</th><th rowspan="2">Percentage passing</th><th colspan="4">I.S 383-1970 grading requirements</th><th rowspan="2">Remarks</th></tr>
<tr><th>Zone 1</th><th>Zone 2</th><th>Zone 3</th><th>Zone 4</th></tr>
<tr><td>10 mm</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td rowspan="7">Satisfies zone 3 grading requirements</td></tr>
<tr><td>4.75 mm</td><td>93.9</td><td>90-100</td><td>90-100</td><td>90-100</td><td>95-100</td></tr>
<tr><td>2.36 mm</td><td>90.7</td><td>60-95</td><td>75-100</td><td>85-100</td><td>95-100</td></tr>
<tr><td>1.18 mm</td><td>80.3</td><td>30-70</td><td>55-90</td><td>75-100</td><td>90-100</td></tr>
<tr><td>600 µ</td><td>61.3</td><td>15-34</td><td>35-59</td><td>60-79</td><td>80-100</td></tr>
<tr><td>300 μ</td><td>16.3</td><td>5-20</td><td>8-30</td><td>12-40</td><td>15-50</td></tr>
<tr><td>150 μ</td><td>1.9</td><td>0-10</td><td>0-10</td><td>0-10</td><td>0-10</td></tr>
</table>

3.2.3 Coarse Aggregates

The Physical tests on coarse aggregates were conducted to evaluate the properties such as specific gravity, bulk density and gradation. The results are tabulated in Table 3.5 and Table 3.6.

Table 3.5 Properties of coarse aggregate

Sl.no	Property		
1	Specific gravity		2.77
2	Bulk density	Loose	1360 kg/m^3
		Compact	1527 kg/m^3
3	Moisture content		Nil

Table 3.6 Sieve analysis of coarse aggregate

I.S sieve size	Percentage passing	I.S 383-1970 grading requirements		Remarks
		Percentage passing for single sized aggregate	Percentage passing for graded aggregate	
40 mm	100	100	100	Satisfies graded sized aggregate requirements
20 mm	99.4	85-100	95-100	
10 mm	49.7	0-20	25-55	
4.75 mm	3.1	0-5	0-10	

3.2.4 Vermiculite Aggregates

Fig. 3.1 Vermiculite aggregates

Table 3.7 Physical and chemical properties of vermiculite

Colour	Light to dark brown
Shape	Accordion-shaped granule
Bulk density	64-160 kg/cu m
Moisture loss @ 110 °C (230 °F)	4-10%
pH (in water)	6-9
Combustibility	Non-combustible
MOH Hardness	1-2
Sintering temperature	1150-1250 °C
Fusion	1200-1320 °C
Cation exchange capacity	50-150 me/100g
Specific heat	0.84-1.08 kJ/kgK
Water holding capacity	220-325% by wt 20-50% by vol

Figure 3.1 shows the vermiculite aggregates used in the study conforming to the specifications of ASTM C35. Its specific gravity is 0.63. It is in the form of brown coloured flakes passing through 4.75mm sieve. The properties of the vermiculite aggregates used are given in Table 3.7.

3.2.5 Flyash

Flyash used was procured from state-owned M/s Raichur Thermal Power Station, Karnataka. The comparison of results of chemical analysis on this fly ash (Table 3.8) with the BIS standards (IS 3812-2003) shows that the material is siliceous based. As the quality of fly ash may vary with the source and time of supply of the raw material (coal), entire material required for the investigation is collected in a single batch to avoid any inconsistencies in chemical composition. Specific gravity of flyash is 2.18. The physical and chemical properties of flyash is given in Table 3.8.

Table 3.8 Physical properties and chemical composition of flyash and GGBS (% mass)

Oxide	Fly ash	GGBS
CaO	1.79	40
SiO_2	58.87	35
Al_2O_3	32.17	12
FeO	2.93	0.2
K_2O	1.14	-
Na_2O	0.37	-
Na_2O_{eq}	1.12	-
MgO	0.92	10
P_2O_5	0.56	-
SO_3	0.49	-
TiO_2	0.76	-

3.2.6 Ground Granulated Blast Furnace Slag

Commercially available GGBS with fineness of 410 m^2/kg and specific gravity of 2.9 was used. The chemical composition of GGBS is presented in the above Table 3.8.

3.2.7 Bonding Agent

Commercially available Latex based bonding agent with brand name Algibond Latex has been used to ensure proper bond between the mortar and the concrete surface. Physical and chemical properties of the bonding agent are shown in Table 3.9.

Table 3.9 Physical and chemical properties of bonding chemical

Sl. No	Properties	Description
1	Type	SBR Latex
1	Colour	White
2	State	Liquid
3	Specific Gravity	1.01±.0.01
4	P^H	Neutral

3.2.8 Concrete Mix Design

Concrete Mix is prepared using Ordinary Portland Cement (OPC – 43 Grade), crushed granite aggregates (10 mm down and 20 mm down) and river sand. Mix design of concrete is based on the guidelines given in IS10262-1982. The mix proportion adopted for the present investigation is as shown in Table 3.10.

Table 3.10 Mix proportion

<table>
<tr><th rowspan="2">Water/Cement Ratio</th><th rowspan="2">Cement</th><th rowspan="2">Fine aggregate</th><th colspan="2">Coarse aggregate</th></tr>
<tr></tr>
<tr><td rowspan="2">0.45</td><td rowspan="2">1</td><td rowspan="2">1.198</td><td colspan="2">2.923</td></tr>
<tr><td>30 % 10mm= 0.877</td><td>70% 20mm= 2.046</td></tr>
</table>

3.2.9 Casting of Specimen

100 x 100 x 100mm sized specimen were used for the entire experimental investigation. The concrete is mixed in the mixer and poured in the moulds of size 100 x 100 x 100mm. The first phase of the experiment was conducted to evaluate the strength deterioration when the concrete is subjected to various elevated temperatures for various exposure durations and cooled either slowly or suddenly. Three heating and cooling regimes were studied. Details of the regimes are presented in table 3.11. Table 3.12 shows the number of cubes cast for each regime.

Table 3.11 Heating and Cooling Regimes studied.

Regime Category	Heating	Cooling
1	Fast heating	Furnace cooling
2	Fast heating	Sudden cooling
3	Slow heating	Furnace cooling

Table 3.12 Test matrix for study of strength retention characteristics of concrete after elevated temperature exposure

Exposure Temperature (°C)	Exposure Duration (hr)					
	4	3	2	1½	1	½
200	3	3	3	3	3	3
300	3	3	3	3	3	3
400	3	3	3	3	3	3
500	3	3	3	3	3	3
600	3	3	3	3	3	3
700	3	3	3	3	3	3
800	3	3	3	3	3	3

The second phase of experimental investigation is to study the effect of recuring on strength recovery of thermally deteriorated concrete. Recuring of thermally deteriorated concrete is carried out for 7, 14, 28 and 56 days. Table 3.13 shows the number of cubes cast for the recuring phase of experimental investigation for one exposure duration. As shown in table 3.13, 84 cube specimen were required for one exposure duration. It is planned to study the effect of recuring on strength recovery of concrete subjected to elevated temperatures for six exposure durations as stipulated in IS-456 2000. Hence for six exposure durations 6 x 84 = 504 cubes were required. In all 600 cubes were cast to cater for repeating some experiments if need be.

Table 3.13 Test matrix for studying effect of recuring on thermally deteriorated concrete

Sl. No	Exposure Temperature (°C)	Recuring (Days)			
		7	14	28	56
1	200	3	3	3	3
2	300	3	3	3	3
3	400	3	3	3	3
4	500	3	3	3	3
5	600	3	3	3	3
6	700	3	3	3	3
7	800	3	3	3	3

Third phase of experimentation involved studying the efficacy of various plaster combinations as heat shields. Six plaster combinations and number of test cubes are shown in Table 3.14.

Table 3.14 Test matrix for effectiveness of plaster combinations as heat shields

Mix id	Exposure Temperature (°C)					
	200	300	400	500	600	700
SC	3	3	3	3	3	3
SCG	3	3	3	3	3	3
SCF	3	3	3	3	3	3
VC	3	3	3	3	3	3
VCG	3	3	3	3	3	3
VCF	3	3	3	3	3	3

SC – Cement + Sand

SCG – Cement +Sand + GGBS (Ground Granulated Blast furnace Slag)

SCF – Cement +Sand + FA (Flyash)

VC – Cement + Vermiculite

VCG – Cement + Vermiculite + GGBS

VCF – Cement + Vermiculite + FA

Mix proportions of ingredients of the mortar have been given in Table 3.15

Table 3.15. Mortar mix proportions

	Cement (gms)	Bonding agent (ml)	Water (ml)	GGBS (gms)	Flyash (gms)	River sand (gms)	Vermiculite (gms)
SC	400	40	120	-	-	1200	-
SCG	200	40	120	200	-	1200	-
SCF	200	40	120	-	200	1200	-
VC	400	40	525	-	-	-	214
VCG	200	40	525	200	-	-	214
VCF	200	40	525	-	200	-	214

3.3 TEST PROCEDURE

Experimental procedures followed related to three phases of experimental investigation are detailed in the following section. Experiment procedures broadly involved exposure of cubes to elevated temperatures and cooling them. Various heating and cooling regimes studied are tabulated in table 3.11. Later the residual strengths after cooling was found. In the next phase the thermally deteriorated concrete were recured and its effect on strength recovery is studied. Concrete cubes were coated with various mortars in order to test the efficacy of mortar in form of plaster to function as heat shield and protect the concrete core. Step by step procedure is elaborated.

Fast heating and slow heating was carried in two different furnaces and its rate of heating is represented in figure 3.2.

3.3.1 Determination of strength retention characteristics after elevated temperature exposure

This involves subjecting of concrete cube specimen to elevated temperatures and allowing them to cool. After cooling down to room temperatures concrete specimen were subjected to strength test to determine the residual strength. The detailed procedure is elaborated in this section.

Exposure to elevated temperatures

Figure 3.2 shows the time temperature build up curves for furnace 1 and furnace 2. Table 3.16 shows the time taken to reach the target temperatures studied. Three concrete cubes were subjected to elevated temperature in an electric furnace 1 for regime 1 and regime 2 shown in figure 3.3. For regime 3 at each time 15 cubes were subjected to heating as shown in figure 3.4 in furnace 2. Each of the concrete cubes were allowed to get exposed to heat from all six sides and to ensure that small pieces of ceramic tiles were placed below the specimen for flow of heat.

Temperature range studied is from 200°C to 800°C at an interval of 100°C. After the target temperature is reached the specimen were maintained at that temperature for duration of ½ hr, 1 hr, 1½hrs, 2 hrs, 3 hrs and 4 hrs.

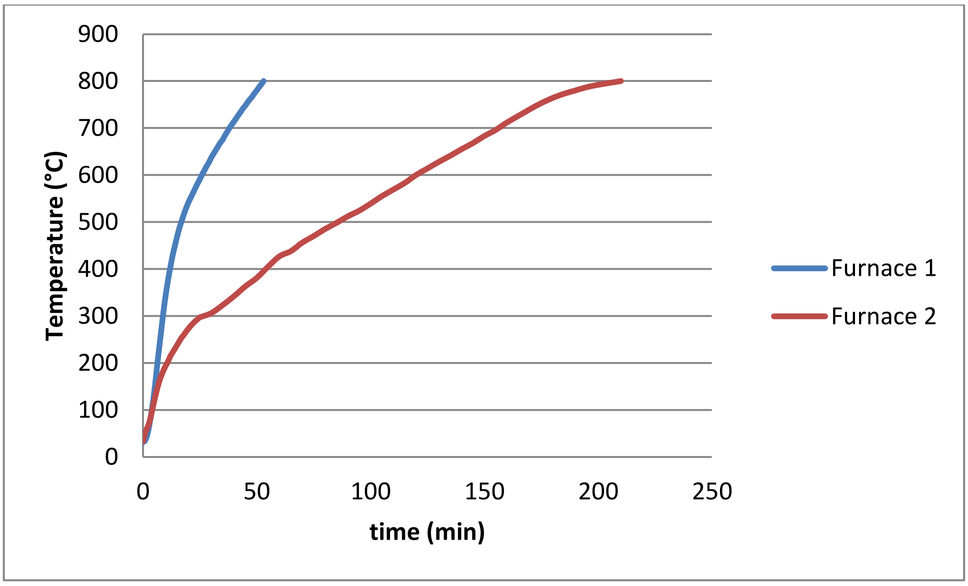


Fig. 3.2. Time temperature curve of furnace 1 and furnace 2

Table 3.16 Time taken to reach target temperatures

Temperature (°C)	Time taken (min)	
	Furnace-1	Furnace-2
200	6	11
300	9	25
400	12	52
500	17	85
600	26	120
700	38	156
800	53	210

Fig. 3.3 Interior of the furnace-1 with cube being heated

Fig. 3.4 Arrangement of 15 cubes inside the furnace-2

Cooling of heated concrete specimen

For furnace cooling the furnace was switched off and the specimen were left in the furnace until the interior of the furnace reached room temperature, with the furnace door closed. Furnace temperature was checked by switching on the furnace and noting the temperature shown in the display of the furnace at certain interval of time.

For sudden cooling the specimen are removed and immediately immersed in a small tub containing water at room temperature. The specimen are allowed to cool in the water till they are cooled to the room temperature. The specimen were later removed from water, wiped surface dry with cloth and tested for residual compressive strength.

Visual inspection of concrete cubes exposed to elevated temperatures

The specimen after cooling down to room temperature were removed from furnace and visual observations of colour change, cracking and spalling were made.

Determination of residual strength and UPV

Residual strength of concrete specimen is determined with the help of compressive testing machine as per the guidelines given in IS 516 1959. For each temperature and each exposure duration, three specimen were tested and the average is reported. Among the three specimen it was ensured that the individual results do not vary more than 15% on either side of the average. Those results with more than 15% variation were discarded. The residual strength is compared against the strength of concrete at ambient temperature. UPV is measured by using PUNDIT instrument with resolution of 0.1 microseconds and frequency range 24 to 150 kHz.

3.3.2 Recuring of Thermally Deteriorated Concrete

Concrete cubes exposed to regime 3 were transferred to curing tank where, they were subjected to recuring for 7, 14, 28 and 56 days. After specified days of recuring the cubes were removed from the curing tank and were tested on 7th, 14th, 28th and 56th day to determine the recovery of strength.

3.3.3 Application of Mortar to Coat Each Cube

For the third phase of study the protective coating is given to the concrete cubes in the form of plaster to act as heat shield. The cubes were plastered with the mortar containing two kind of aggregates, one is the normal river sand and the other is vermiculite.

The mortar required for each cube is mixed by hand and a coat of 10mm thickness is applied on all the six faces of the cube. For this the moulds of size 120mm x 120mm x 120mm is prepared as shown in figure 3.5.

Fig. 3.5 Mould of size 120mm x 120mm x 120mm

Moistened concrete cube is placed in the mould as shown in figure 3.6 at the centre of the mould and then the mixed mortar is filled and compacted from the sides. The whole set-up is vibrated on the vibrating table.

Fig. 3.6 Cube placed in the mould

After that the top surface is finished smooth with the help of the trowel. Later the whole arrangement is turned upside down as shown in figure 3.7 and the sixth face is finished with the help of slight vibration.

Fig. 3.7Application of plaster to the concrete cube

The set up was very lightly vibrated, since vermiculite being a light weight material, heavy vibration caused separation of aggregates and cement paste. Most of the compaction was done by hand. Care was taken to see that the mortar is uniformly coated on all the 6 faces of the cube. The cubes were cured for 28 days in water.

The plastered cubes are arranged in furnace 1 in the similar way as unplastered cubes. At each time 3 cubes are exposed to elevated temperatures starting from 200°C to 800°C at an increment of 100°C for exposure duration of 2hr. After that the furnace was switched off and the specimen were allowed to cool till room temperature is reached.

After room temperature is reached the cubes are removed from furnace and physical observations related to cracking and debonding of plastered surface from concrete core is made. Later they were tested for residual compressive strength.

3.4 CLOSURE

Details of the experimental program have been elaborated in this chapter. These include materials used in making of the test cube specimen, mix details and the detailed methodology adopted to accomplish the three major objectives of the research work envisaged.

CHAPTER 4

STRENGTH RETENTION CHARACTERISTICS OF OPC BASED CONCRETE

4.1 GENERAL

Compressive strength is the most desired property of structural concrete and strength deteriorate at elevated temperatures (Khoury 1988, Arioz 2007, Poon 2001). Strength deterioration of concrete has been found to depend on various material and environmental factors. Understanding strength retention characteristics at various levels of elevated temperatures, durations of exposure and cooling regimes is essential in evaluation of damage.

Results of the experimental investigation carried out to study the effect of exposure temperature, duration of exposure, heating and cooling rates on the strength retention characteristics of concrete exposed to elevated temperatures are discussed in this chapter.

Table 4.1 Heating and cooling regimes studied

Regime category	Heating	Cooling
1	Fast heating	Furnace cooling
2	Fast heating	Sudden cooling
3	Slow heating	Furnace cooling

Seven levels of elevated temperatures, 200°C to 800°C, at an increment of 100°C and six exposure durations of ½hr, 1hr, 1½hr, 2hr, 3hr and 4hr have been adopted. Three heating and cooling regimes as shown in Table 4.1 have been studied. Time taken by fast heating and slow heating furnace to reach the target temperatures considered are given in table 4.2.

Table 4.2 Time taken to reach target temperatures

Temperature (°C)	**Time taken (min)**	
	Furnace-1	**Furnace-2**
200	6	11
300	9	25
400	12	52
500	17	85
600	26	120
700	38	156
800	53	210

4.2 HEAT EFFECTS ON COLOUR AND CRACKING CHARACTERISTICS

Concrete has been found to undergo colour changes when subjected to elevated temperatures that are dependent on the temperature to which the concrete is exposed (Georgali 2005, Yuzer 2004, Arioz 2007,). These colour changes can therefore be used as an indicator of the maximum temperature to which the concrete would have been exposed to.

Concrete exposed to temperatures upto 400°C exhibited neither the colour change nor visible surface cracking for all the three regimes. At levels of 500°C and 600°C fine cracking has been observed. Cracks observed were well distributed all over the surface of the cubes however were more pronounced at the edges.

At higher temperature levels of 700°C and 800°C cracking was more pronounced and a mesh of interconnected cracks have been observed. In fig 4.1 the concrete specimens on the left is the one exposed to 800°C, while the other is an unexposed specimen. The observed crack patterns for each temperature level were similar for all the three regimes.

Concrete subjected to temperatures of 700°C and 800°C showed similar cracking characteristics for all exposure durations, heating rates and cooling regimes.

Fig.4.1 Surface of concrete exposed to 800°C

The concrete color has changed to pink after exposure to 400°C and to grey for 700°C-800°C exposure. Color changes have been found to be similar for concrete subjected to the three heating and cooling regimes.

4.3 STRENGTH OF THERMALLY DETERIORATED CONCRETE

Residual strength of concrete subjected to three regimes mentioned in table 4.1 is discussed in this section. Multiple regression analysis was carried out to relate the residual strength ratio (SR) of concrete to the exposure temperature (ET) and exposure duration (ED). Equations are proposed to predict the residual strength ratio of concrete for three regimes. Table 4.3 gives the strength retained for various elevated temperatures expressed as percentage of ambient strength.

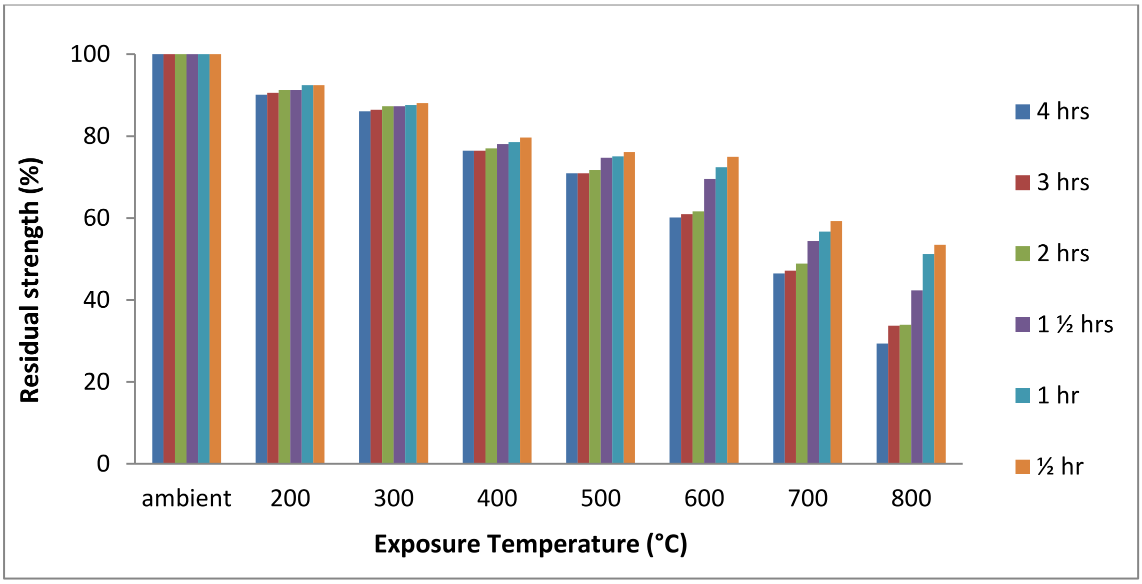


Fig.4.2 Residual strength of concrete subjected to Regime-1

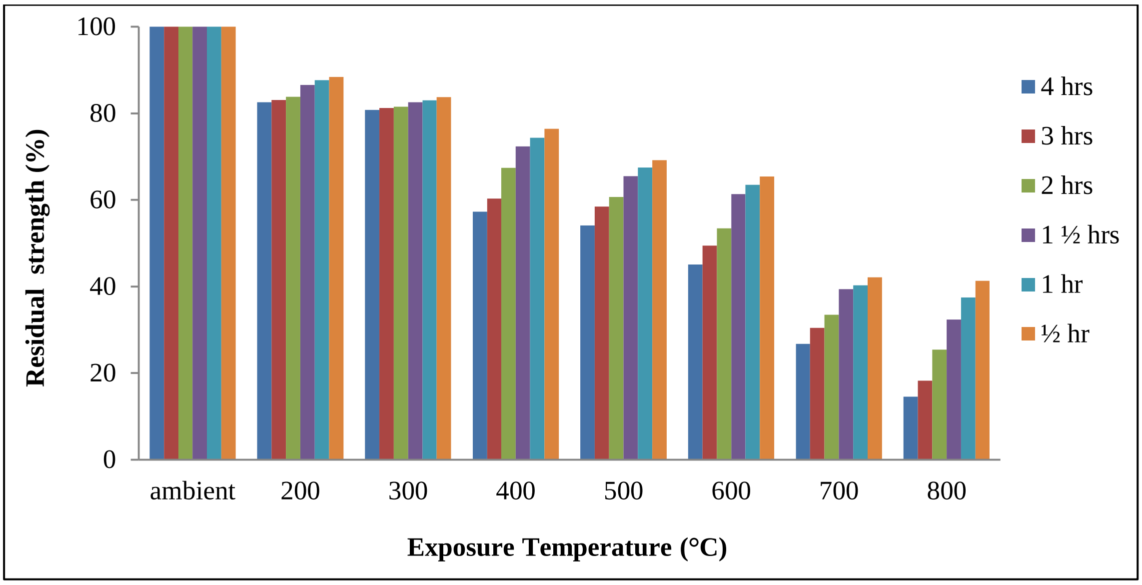


Fig. 4.3 Residual strength of concrete subjected to Regime-2

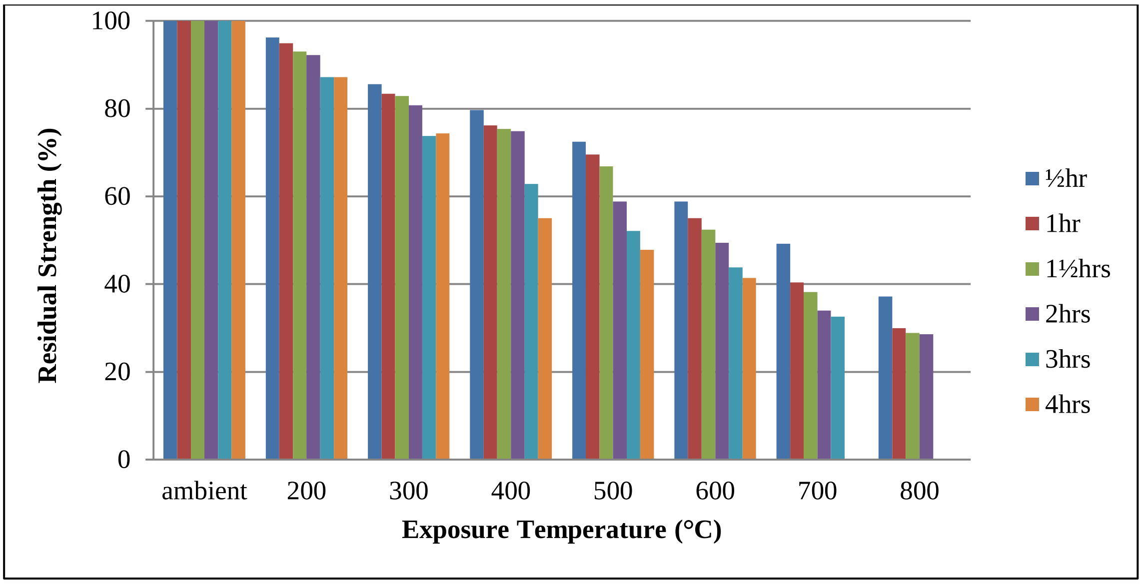


Fig. 4.4 Residual strength of concrete subjected Regime-3

From figure 4.2 it can be seen that the residual strength decreases with the increase in exposure duration for each temperature studied. However the deterioration of concrete strength with increase in exposure duration is less than 5% of ambient strength, with every ½ hr increase in the duration of exposure for temperatures upto 500°C.

Highest reduction in strength has been recorded between with the exposure durations of 1½hr to 2hr. Beyond for 3hr and 4hr effect of exposure duration on strength retention is marginal for all exposure durations.

In regime 2, the concrete specimen after heating have been subjected to sudden cooling in order to study the effect of sudden cooling on strength retention characteristics of concrete. From figure 4.3 it can be seen that concrete retains larger strength for smaller exposure duration. However the deteriorating effect of higher exposure duration increases with the exposure temperature, expecially for temperatures above 400°C.

Table 4.3 Residual Strength for three regimes

Exposure Temperature (°C)	Exposure duration (hr)	Residual Strength (%)		
		Regime-1	Regime-2	Regime-3
200	½	92.5	88.4	96.3
	1	92.5	87.7	94.9
	1½	91.3	86.6	93.1
	2	91.3	83.8	92.3
	3	90.6	83.1	87.2
	4	90.1	82.6	87.2
300	½	88.1	83.7	85.6
	1	87.7	83.0	83.4
	1½	87.3	82.5	82.9
	2	87.3	81.5	80.8
	3	86.5	81.3	73.8
	4	86.1	80.8	74.3
400	½	79.7	76.5	79.7
	1	78.6	74.4	76.2
	1½	78.1	72.4	75.4
	2	77.0	67.5	74.9
	3	76.5	60.3	62.8
	4	76.5	57.3	55.1
500	½	76.2	69.2	72.5
	1	75.1	67.5	69.5
	1½	74.8	65.5	66.9
	2	71.8	60.7	58.8
	3	70.9	58.5	52.1
	4	70.9	54.1	47.9
600	½	75.0	65.4	58.8
	1	72.4	63.5	55.1
	1½	69.6	61.4	52.4
	2	61.6	53.5	49.5
	3	60.9	49.5	43.9
	4	60.2	45.1	41.5
700	½	59.3	42.2	49.2
	1	56.7	40.3	40.4
	1½	54.5	39.4	38.2
	2	48.9	33.5	34.0
	3	47.2	30.4	32.6
	4	46.5	26.8	-
800	½	53.5	41.3	37.2
	1	51.2	37.5	30.0
	1½	42.4	32.4	28.9
	2	34.0	25.5	28.6
	3	33.7	18.3	-
	4	29.4	14.5	-

Strength retained after subjecting the concrete to Regime-3 is represented in figure 4.4. Effect of exposure duration can be seen for each of the temperatures studied. Concrete retained lower strength for all the exposure temperatures with increase in exposure duration.

Effect of exposure duration on strength deterioration is higher in Regime-3 compared to Regime-1 and Regime-2. For each temperatures studied, deterioration in strength retained is found to be the most when exposure duration is increased from 2hr to 3hr.

Prediction equations proposed for the three regimes and the range of their validity are tabulated in table 4.4.

Table 4.4. Prediction equations for three regimes

Sl. No	**Prediction equation**	**Exposure Duration Range (min)**	**Temperature range (°C)**	**Mean error** (%)
Regime 1	SR = 1.13 - 0.000751 ET - 0.000337 ED	30 to 240	200 to 700	3.9
Regime 2	SR = 1.08 - 0.000723 ET - 0.000720 ED	30 to 180	200 to 600	2.8
Regime 3	SR = 1.24 - 0.00107 ET - 0.000871 ED	30 to 180	200 to 700	3.9

4.4 COMPARISONS OF STRENGTH RETENTION CHARACTERISTICS FOR THREE REGIMES

A comparative study on strength performance of concrete subjected to three heating and cooling regimes at seven elevated temperature levels are presented in this section. Influence of heating rates and cooling method varies with the exposure temperature. Retained strengths are expressed in terms of strength ratio in figures 4.5 (a) – (g).

4.4.1 Strength Retention Characteristics for Concrete Exposed to 200°C

As it is evident from figure 4.5(a) for each of the exposure durations studied, Regime-2 retains the lowest residual strength, while Regime-1 retains the highest strength, for all the exposure durations.

Lowest residual strength of Regime 2 suggests that the sudden cooling of heated concrete produced higher deterioration for all exposure durations. The effect of sudden cooling is thus found to be most severe deteriorating mechanism for concrete exposed to elevated temperature of 200°C.

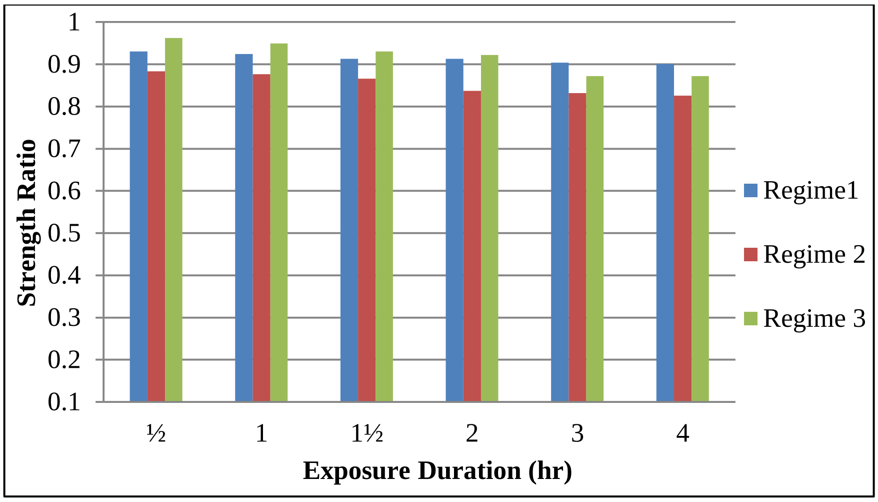


Fig. 4.5(a) Strength retained for concrete exposed to 200°C

Regime 3 (slow heating) performs better than Regime 1 (fast heating) upto 2hr, however the trend gets reversed for 3hr and 4hr. For slower heating the presence of heat is for larger duration, however faster heating produces higher gradient according to Hager et.al (2006). For lower durations upto 2hr faster heating has produced larger deterioration, while for 3hr and 4hr slower heating has produced larger deterioration.

4.4.2 Strength Retention Characteristics for Concrete Exposed to 300°C

Figure 4.5 (b) shows the strength ratio for concrete subjected to 300°C for three heating and cooling regimes. For the exposure duration of ½hr, 1hr and 1½hr, Regime-2 retains the lowest strength. For Regime 3 the concrete strength deteriorated more rapidly for increase in exposure duration. For exposure durations of 1 and 1½hr concrete subjected to Regime 2 and Regime 3 retains almost equal amounts of strength. For exposure durations of 2hr, 3hr and 4hr Regime 3 retains the lowest strength and the effect of Regime 3 appears to be more severe for higher exposure durations

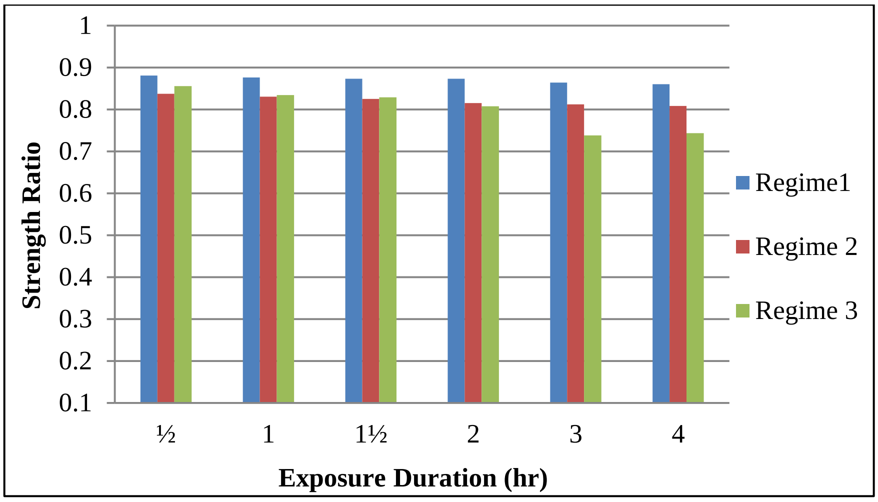


Fig. 4.5 (b) Strength retained for concrete exposed to 300°C

Effect of sudden cooling of heated concrete specimen due to quenching was more severe in strength deterioration for exposure durations of ½hr to 1½hr, while effect of heating rate produced more severe deterioration of strength for higher exposure duration studied. Sudden cooling produces higher thermal gradients during the cooling phase (Janotka 2005, Lee 2008), hence Regime 2 has retained lowest strength. For higher exposure durations, presence of heat is for larger duration during the temperature build-up stage associated with larger holding time after the temperature is reached has caused temperature gradient to move inside towards the core which is cooler. Thereby allowing the heat to penetrate more towards the core.

4.4.3. Strength retention characteristics for concrete exposed to 400°C

Regime-1 retained largest residual strength for all the exposure durations studied as it appears in figure 4.5(c). For the exposure duration of ½hr concrete subjected to Regime-1 and Regime-3 retains about 79.6% of ambient strength, while concrete subjected to Regime-2 retains about 76.5% of the ambient strength. For 1hr, 1½hr, 2hr and 3hr Regime-2 retains the lowest strength. Since sudden cooling has caused high thermal gradient as well as the chemical decompositions taking place in the hardened cement paste at 400°C (Alonso 2004), Regime 2 has suffered higher deterioration.

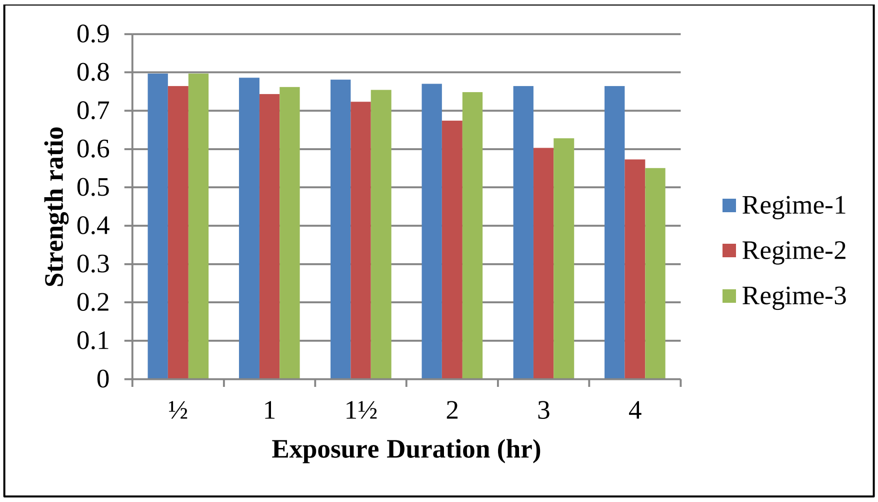


Fig. 4.5 (c) Strength retained for concrete exposed to 400°C

The deterioration of strength increased with increase in the exposure duration for all three regimes, however for Regime-3, higher variation is noted for increase in duration from 2hr to 3hr, which signifies deteriorating effect of chemical changes (Alonso 2004) as well as heat penetrating deep into the concrete cube with increased duration of holding time.

4.4.4. Strength retention characteristics for concrete exposed to 500°C

It is seen from figure 4.5 (d) that Regime 1 retains the highest strength and regime 3 the lowest for the concrete exposed to 500°C.

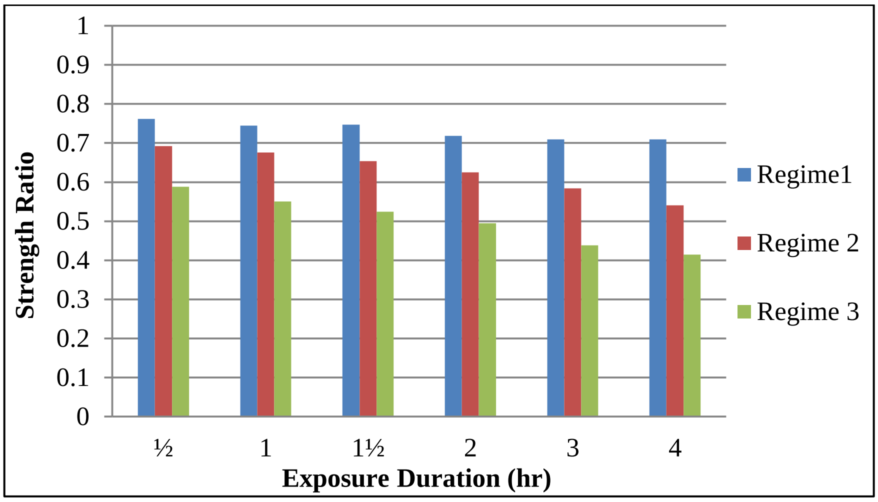


Fig 4.5. (d) Strength retained for concrete exposed to 500°C

The diffreences between regimes1 and regime 3 is higher for higher exposure durations. Thus for concrete exposed to 500°C the slower heating rate caused larger deterioration of strength because the presence of heat is for larger duration during the temperature build up. Faster heating takes only 17 minutes to reach 500°C as against 85 min for slower heating. Concrete has ssustained higher temperature for 68 mintes more than faster heating, which has created deterioration of strength

4.4.5. Strength retention characteristics for concrete exposed to 600°C

For exposure temperature of 600°C concrete experienced about 25 to 60% of strength loss, maximum being for Regime-3 as it can be visualized from figure 4.5 (e). For all the exposure durations studied concrete subjected to regime-3 retained the lowest residual strength while Regime-1 retained the highest. Deteriorating effect of slow heating and water quenching is more severe at this exposure temperature.

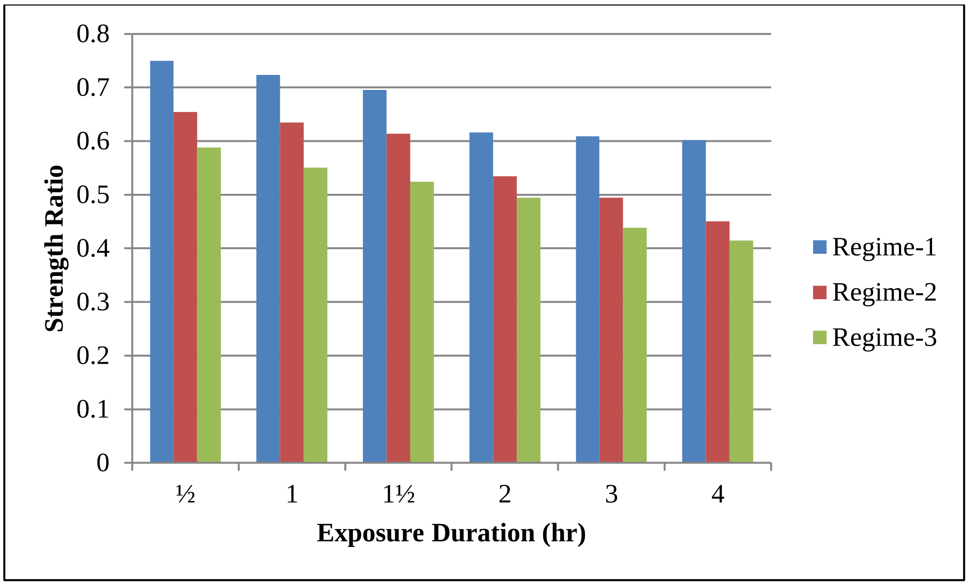


Fig. 4.5 (e) Strength retained for concrete exposed to 600°C

The difference between retained strengths for Regime-1 and Regime-2 increases with the exposure duration. For concrete exposed to 600°C the deteriorating effect of slower heating is more severe than sudden cooling for all the exposure durations because slower heating has taken 94 minutes higher duration to reach 600°C as compared to fast heating.

4.4.6. Strength retention characteristics for concrete exposed to 700°C

Concrete suffers large deterioration at this temperature and the deteriorating effects of slow heating and sudden cooling is more severe with increase in exposure durations. This fact is clearly visible from figure 4.5 (f). For the exposure durations of 1hr to 3hr Regime-3 and Regime-2 suffers almost same amount of deterioration in strength, the difference between them being only about 1% to 2% of the ambient strength. For exposure duration of 4hr, however, Regime-3 samples were highly damaged with severe cracking and were sensitive to handle. They were therefore not amenable for testing.

Regime-1 retains about about 10% to 15% higher strength for all the exposure durations studied. After 3hr and 4hr exposure concrete cubes were damaged and retained no strength. Effect of slower heating created worse deterioration compared to lower temperatures, since it takes about 156 minutes to reach 700°C as compared to 38 minutes for faster heating.

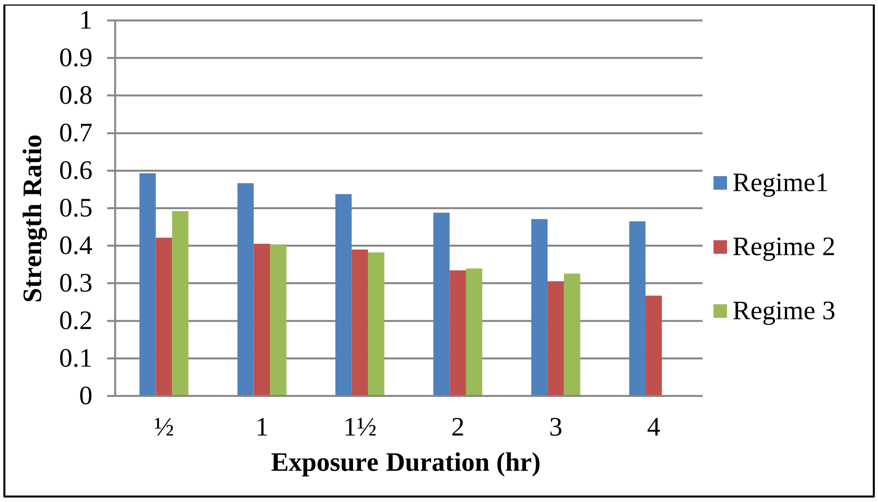


Fig. 4.5 (f) Strength retained for concrete exposed to 700°C

4.4.7. Strength retention characteristics for concrete exposed to 800°C

As expected very severe deterioration of strength was experienced by concrete exposed to 800°C. It is evident from fig 4.5 (f) that Regime 1 retains largest strength for all exposure durations. For the exposure durations of ½hr, 1hr and 1½hr, Regime-3 retains the lowest because slower heating produced higher deterioration. For 2hr exposure duration, Regime-2 retains the lowest strength because the gradient produced during sudden cooling of concrete from 800°C to room temperature is large and regime 3 shows slightly better performance.

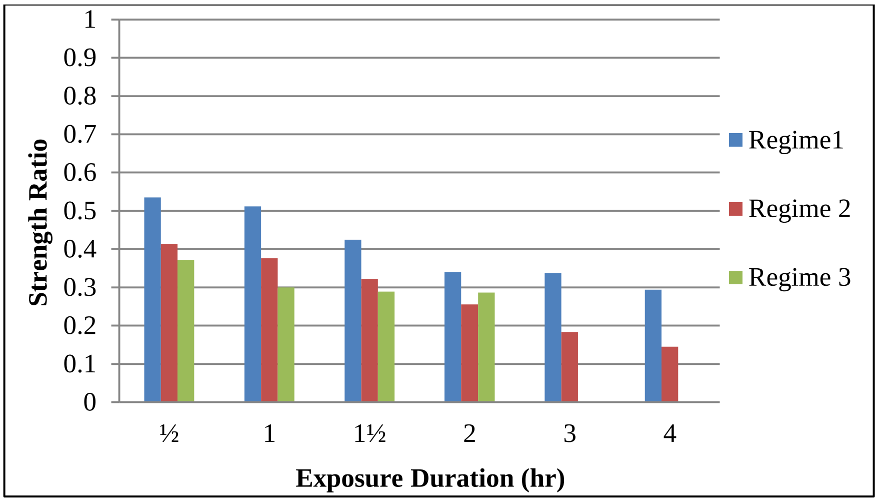


Fig. 4.5 (g) Strength retained for concrete exposed to 800°C

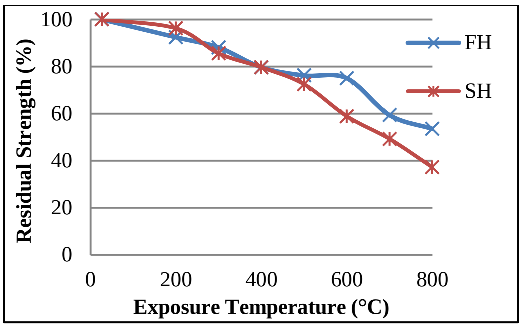
Concrete exposed to 3hr and 4hr suffered severe damage and specimen were not amenable for testing because the cracks were observed to be penetrated deeper into the cube because of which cubes had become too sensitive to handle. This signifies that concrete had retained no strength, because of chemical degradation of cement paste (Alonso 2004), coupled with extensive cracking and higher thermal gradient associated with higher temperature exposure.

4.5 INFLUENCE OF TWO HEATING RATES ON STRENGTH RETENTION CHARACTERISTICS OF CONCRETE EXPOSED TO ELEVATED TEMPERATURES

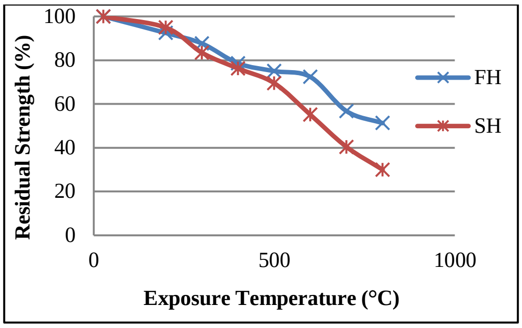
A comparative study of strength performance of concrete subjected to Regime 1 and Regime 3, is made in order to study the influence slow heating (SH) and fast heating (FH) on strength retention characteristics of thermally deteriorated concrete.

Therefore Regime 2 is omitted from this discussion. Time taken to reach target temperatures by two furnaces is mentioned in table 4.2.

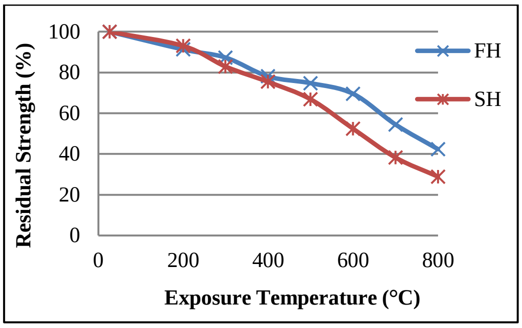
Figures 4.6 (a) – (f) shows the strength retained at various elevated temperatures for concrete heated with two heating rates SH and FH, where SH (Regime-3) represents slow heating and FH (Regime-1) represents fast heating.



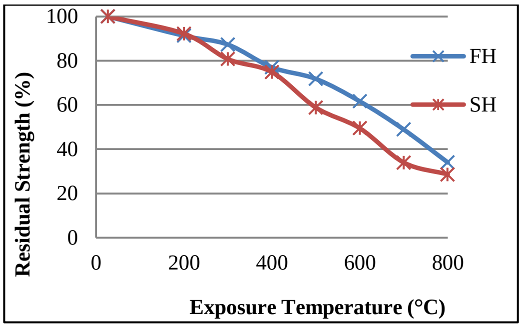
(a) ½ hr



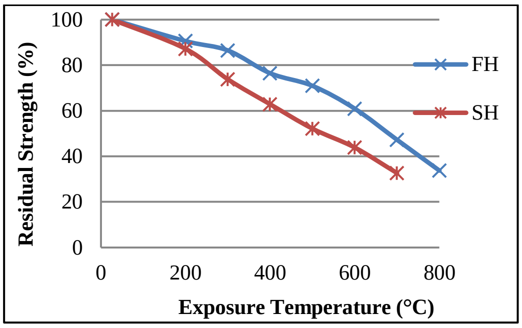
(b) 1 hr



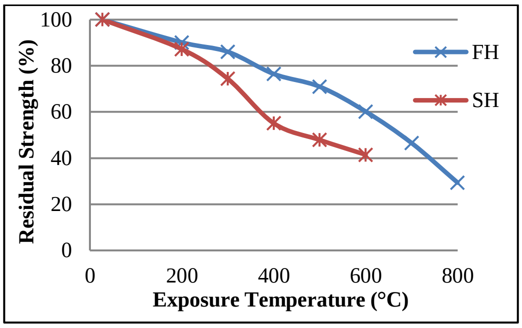
(c) 1½ hr



(d) 2 hr



(e) 3 hr



(f) 4 hr

Fig 4.6 (a)-(f) Strength deterioration of concrete subjected to elevated temperatures for six exposure durations

From figures 4.6 (a) and (b) it can be seen that less than 5% difference between SH and FH in retained strengths is obtained for concrete subjected to elevated temperatures upto 500°C. For higher exposure temperatures SH retains lower strength and the difference between retained strengths for SH and FH increased with the exposure temperatures.

For the case of 1½hr retention time as shown in figure 4.6 (c), except for the exposure temperature of 200°C, for all other temperatures, SH retained lower strength as compared to FH.

As shown in figure 4.6(d), the concrete exposed to 200°C for 2hr retained about 92% of the unexposed strength for both the heating rates. For exposure temperatures of 300°C and 400°C FH retains about 6.5% and 2.1% higher residual strength than SH. For higher exposure temperatures of 500°C, 600°C and 700°C, SH retains lower strength as compared to FH. The difference between retained strengths after exposure to FH and SH reduced to about 5.4% for exposure temperature of 800°C.

SH shows larger deterioration than FH for all the exposure temperatures when concrete is exposed to elevated temperatures and retained for duration of 3hr as shown in figure 4.6(e). The difference increases with the increase in exposure temperature. Concrete specimen after exposure to 800°C, SH, had undergone severe damage and were not amenable for testing.

Difference seen in both the curves appears to be wider compared to lower durations, for all the exposure temperatures except for exposure temperature of 200°C as shown in figure 4.6(f). This is because the deteriorating effect of slower heating becomes more severe as the exposure duration increases. Higher exposure durations allow the heat to penetrate through the cracks that are formed as a result of elevated temperature exposure for concrete exposed to elevated temperatures with two heating rates. For 200°C exposure, FH retains about 90% of strength at ambient conditions and SH retains about 3% lower strength i.e. about 87%. The difference between retained strengths for FH and SH increases with the increase in the exposure temperature up to 600°C.

4.6. EFFECT OF COOLING REGIMES ON STRENGTH RETENTION CHARACTERISTICS OF CONCRETE

Results of experiments carried out to quantify the extent of influence of sudden cooling by quenching in water at room temperature is reported in this section. The residual strengths of concrete subjected to Regime 1 and Regime 2 are compared.

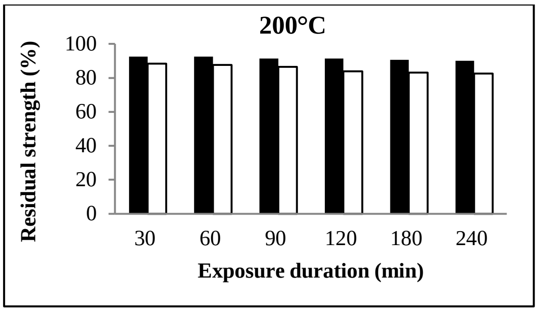
Table 4.5 Percentage difference between furnace cooling and sudden cooling

Exposure Temperature (°C)	Retention time (hr)					
	½	1	1½	2	3	4
200	4.1	4.8	4.8	7.5	7.5	7.6
300	4.4	4.6	4.8	5.8	5.2	5.2
400	3.2	4.2	5.7	9.6	16.1	20.0
500	7.0	7.6	9.3	11.1	12.5	16.9
600	9.6	8.9	9.0	8.2	11.5	15.1
700	17.6	16.5	15.1	15.4	16.8	19.8
800	12.2	13.8	10.0	8.6	15.4	14.8

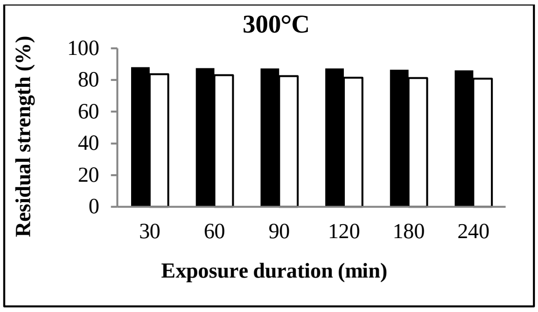
Table 4.5 shows the amount of higher deterioration caused (expressed as percentage of strength of the control specimen) when the concrete is heated to various elevated temperatures from 200°C to 800°Cand subjected to furnace and sudden cooling (Regime-1 and Regime-2).

Figure 4.7 (a)-(g) shows the strength retained after concrete is heated to various elevated temperatures from 200°C to 800°C and subjected to Furnace Cooling (FC) or Sudden Cooling (SC) due to quenching. At each temperature from 200°C to 800°C the strength loss due to sudden cooling is found to be higher than the strength loss due to furnace cooling. This is attributed to high temperature gradients that are developed due to quenching of heated specimens in water [Chan (2000), Lee (2009)].

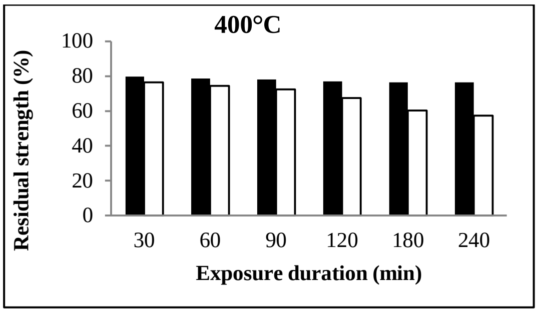
For the exposure temperature of 200°C to 500°C the residual strength is found not to be sensitive to the exposure duration for furnace cooled case, however for exposure temperature of 600°C to 800°C the strength is found to deteriorate more for exposure duration of 2hr to 4hr and the residual strength is about 60% to 30% respectively of the ambient strength.



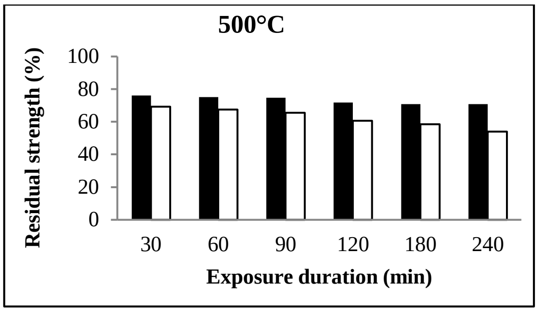
(a) 200°C



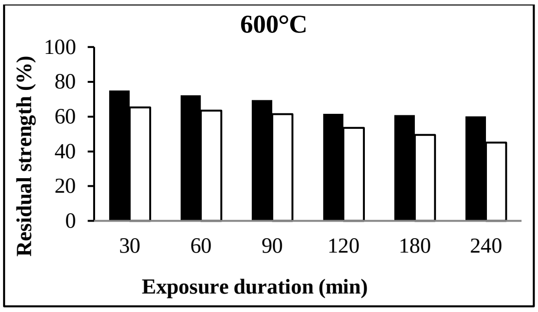
(b) 300°C



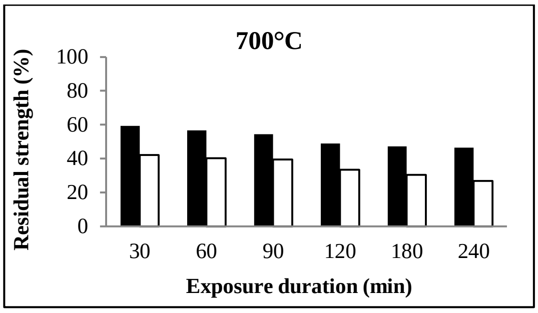
(c) 400°C



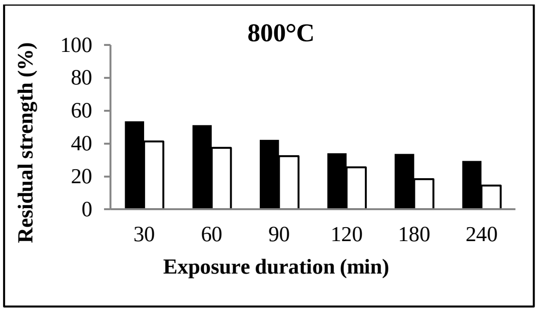
(d) 500°C



(e) 600°C



(f) 700°C



(g) 800°C

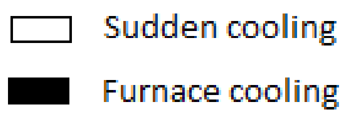


Fig.4.7 (a)-(g)Cooling effect on concrete exposed to 200°C, 300°C, 400°C, 500°C, 600°C, 700°C and 800°C

But for the case of sudden cooling the strength deteriorates with increase in exposure duration for temperatures above 400°C. The difference between residual strengths due to furnace cooled and quenched concrete, increases with the exposure duration for all exposure temperatures.

Concrete exposed to lower temperatures of 200°C and 300°C, the difference in the retained strengths for furnace cooled and quenched concrete, varies slightly with the exposure duration. While it is found be lower for exposure duration of 2hr, 3hr and 4hr. The difference is largest for 700°C exposure for all the exposure durations.

4.7 UPV IN DAMAGE DETECTION OF CONCRETE SUBJECTED TO ELEVATED TEMPERATURES

Ultrasonic Pulse Velocity (UPV), a non-destructive technique to evaluate concrete quality, has been adopted as potential application in strength evaluation of concrete after elevated temperature exposure.

Figure 4.8 shows the variation in pulse velocity in km/sec for 3 hr exposure duration exposed to elevated temperatures and two cooling regimes.

From figure 4.8, lower UPV values for concrete subjected to temperatures above 400°C signifies deterioration of concrete quality. This has reflected the lower residual strength. The concrete subjected to thermal shock due to sudden cooling has shown lower values of UPV as compared to the concrete cooled naturally in furnace at all temperatures.

For specimen subjected to 700°C and 800°C, the UPV values fail to indicate the true extent of damage as the pulse velocity passing through these specimen were not measurable.

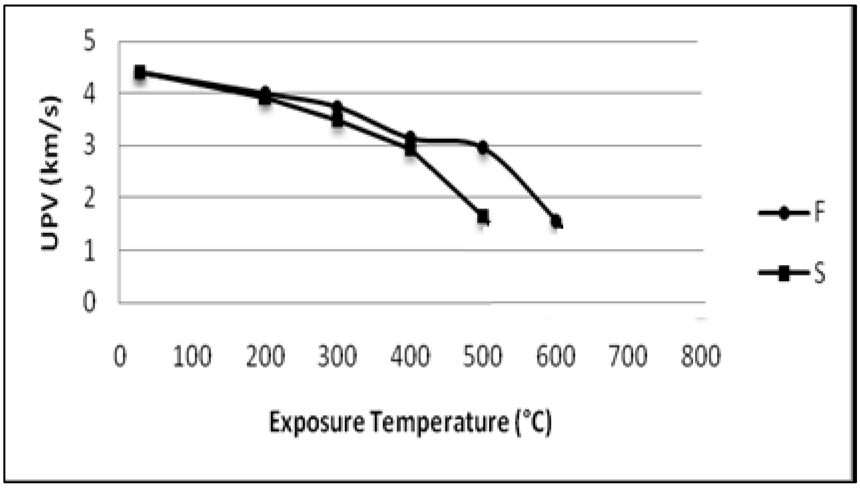


Fig. 4.8 Deterioration of UPV for various exposure temperatures

Figures 4.9 and 4.10 show the comparison of strength ratio by destructive testing and UPV ratio for various exposure temperatures from 200°C to 800°C and subjected to sudden cooling and furnace cooling respectively. UPV ratio is the ratio of UPV values of thermally exposed concrete to the UPV value of control concrete.

Residual strength as well as the UPV ratio decreases with an increase in exposure temperature for both the cooling conditions. However the variation of UPV is more compared to the variation in residual strength ratio for sudden cooling as seen in figure 4.9. This is because of presence of moisture in the concrete specimen which had been absorbed because of quenching of the heated specimen.

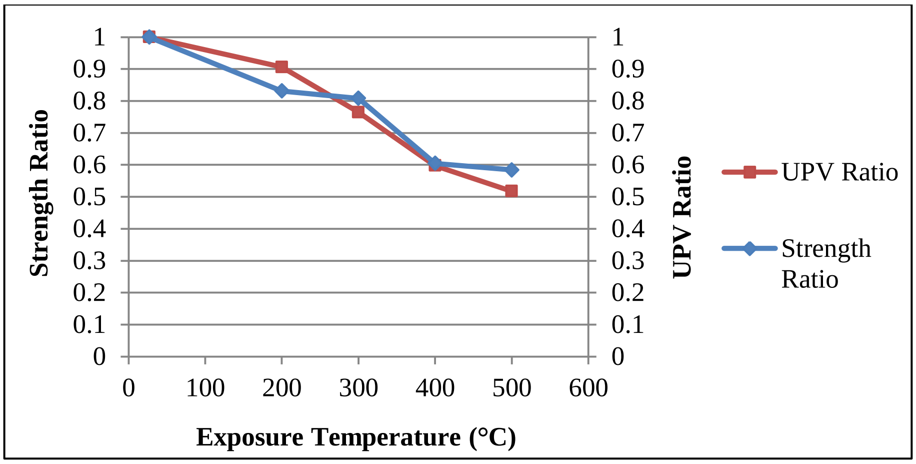


Fig. 4.9 Deterioration in strength by destructive testing and UPV for concrete heated and suddenly cooled

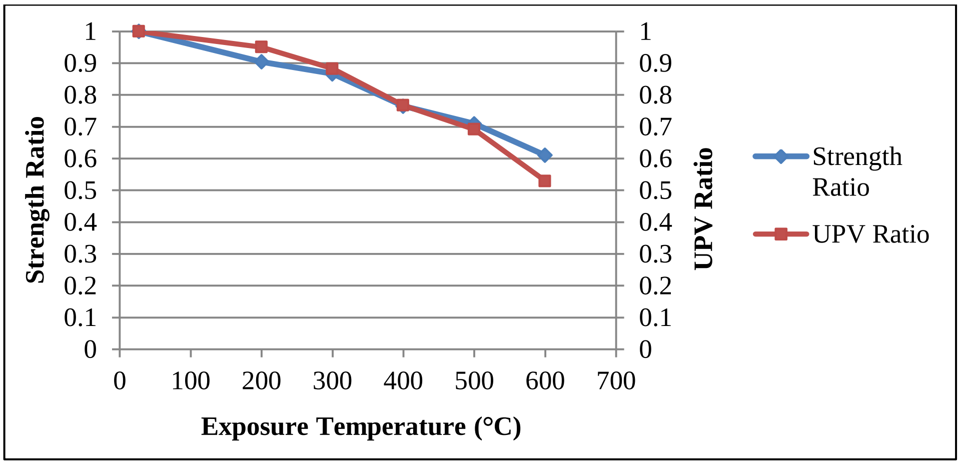


Fig. 4.10 Deterioration in strength by destructive testing and UPV for concrete heated and furnace cooled

For the case of furnace cooled concrete as in figure 4.10, for the exposure temperature of 200°C - 500°C the strength and UPV follows the same trend of deterioration. Both the curves coincide at temperatures of 300°C, 400°C and 500°C.For higher temperatures the larger drop in UPV values has been noted. Thus UPV technique can be employed to estimate the deterioration that has occurred in the concrete exposed to temperatures upto 500°C.

4.8 CLOSURE

Residual strength retention characteristics of concrete after elevated temperature exposure have been found to be function of maximum temperature to which the concrete is exposed, duration of exposure, rate of heating and the method of cooling. Deteriorating effect of elevated temperatures is found to be more severe with increasing exposure durations and slower rate of heating. For lower temperatures upto 300°C faster heating and lower retention times produces larger deterioration , while for higher temperatures slower heating and higher durations produces larger deterioration. Quenching produces larger deterioration, however for higher temperatures of greater than 600°C deteriorating effect of slower heating is more severe than sudden cooling. Prediction equations are proposed to predict the strength ratio for all three regimes.

If the duration of exposure is known and cores taken from various locations of a fire damaged structure are tested for strength estimation then these equations can be used to estimate the temperatures of exposure at those locations of a fire damaged concrete structure. This information can be of vital importance in order to plan the repair strategy for the structure.

CHAPTER 5

RECURING AS A MEASURE OF STRENGTH RECOVERY

5.1 GENERAL

Recuring has been demonstrated as a simple technique by way of which the thermally deteriorated concrete recovers the lost strength by itself (Poon 2001, Alonso 2004 Mendes 2011). In this chapter results of the experimental investigation carried out to quantify the amount of strength recovered for concrete subjected to elevated tempearatures upto 800°C and six exposure durations of ½hr, 1hr, 1½hr, 2hr, 3hr and 4hr, for which the IS-456 provides guidelines for fire endurance. Concrete subjected to elevated temperatues were subjected to recuring for 7, 14 28 and 56 days.

5.2 STRENGTH RECOVERY OF CONCRETE EXPOSED TO ELEVATED TEMPERATURES BY RECURING

Effect of recuring on strength recovery of thermally deteriorated concrete on strength recovery is presented in this section. Concrete cubes were exposed to elevated temperatures from 200°C to 800°C and retained for six exposure durations of ½hr, 1hr, 1½hr, 2hr, 3hr and 4hr. They were tested for strength recovery after 7, 14, 28 and 56 days of recuring. The results of the experimental investigation are presented in figures. 5.1 (a) – (f). Strength recovered after recuring for 7, 14 28 and 56 days are tabulated in table 5.1.

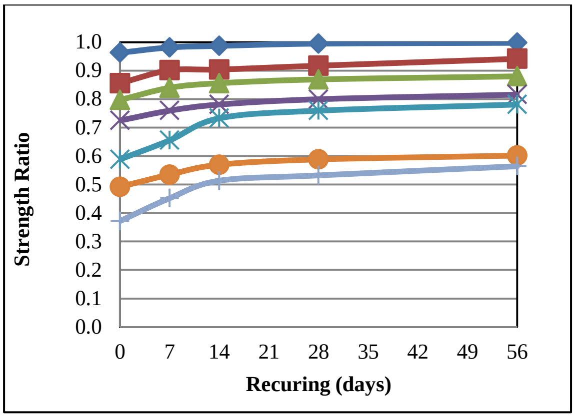


Fig. 5.1 (a) ½ hr

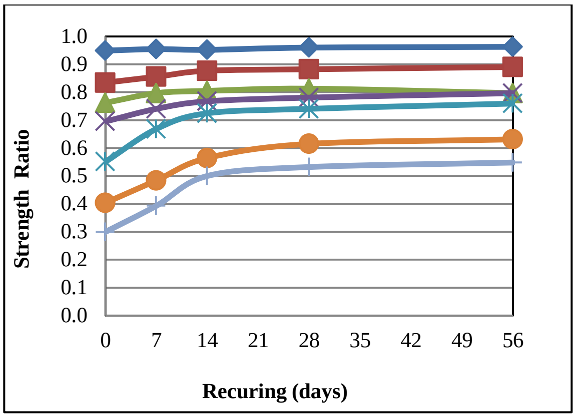


Fig. 5.1 (b) 1hr

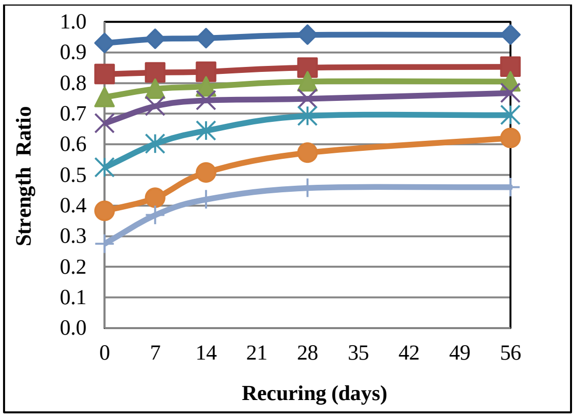


Fig. 5.1 (c) 1½hr

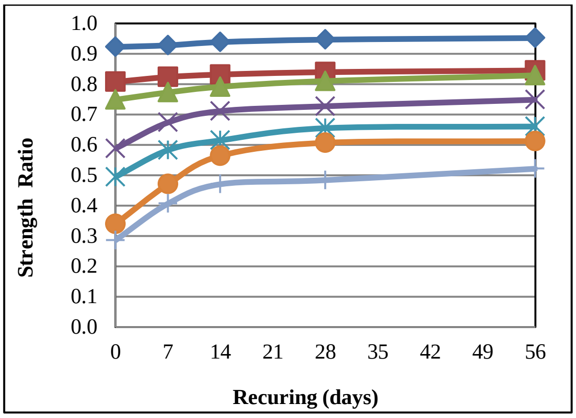


Fig. 5.1 (d) 2hr

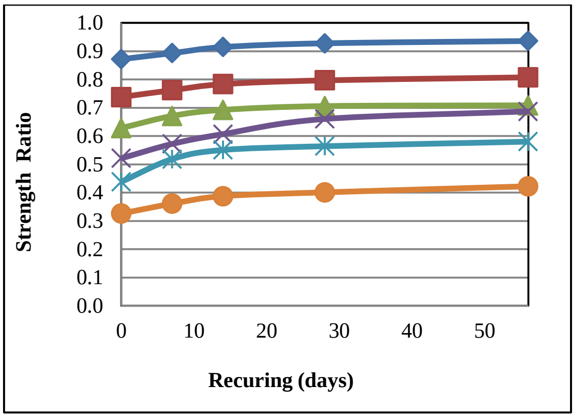


Fig. 5.1 (e) 3 hr

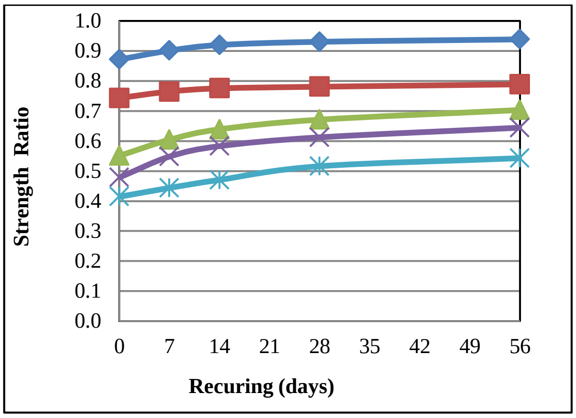


Fig. 5.1 (f) 4hr

Fig 5.1 (a) – (f) Strength recovery of concrete subjected to elevated temperatures and retained for different retention periods

Table 5.1 Strength recovery of concrete exposed to elevated temperatures after recuring for 56 days

Exposure Duration (hr)	Exposure Temperature (°C)	Residual strength (MPa)	Strength after recuring for (MPa)			
			7 days	14 days	28 days	56 Days
	ambient	**62.3**				
½	200	60	61.2	61.5	62	62.2
	300	53.3	56.2	56.3	57.2	58.7
	400	49.7	52.3	53.3	54.2	54.8
	500	45.2	47.3	48.7	49.8	50.8
	600	36.7	40.8	45.7	47.3	48.6
	700	30.7	33.3	35.5	36.7	37.6
	800	23.2	28.2	32	33.2	35.3
1	200	59.2	59.5	59.3	59.8	60
	300	52	53.3	54.7	55	55.5
	400	47.5	49.7	50.2	50.7	51.7
	500	43.3	46.2	47.8	48.7	49.7
	600	34.3	41.7	45.2	46.2	47.3
	700	25.2	30.2	35.2	38.3	39.3
	800	18.7	24.5	31.2	33.2	34.2
1½	200	58	58.8	59	59.7	59.7
	300	51.7	52	52.2	53	53.2
	400	47	48.7	49.2	50.2	50.2
	500	41.7	45.2	46.3	46.7	47.8
	600	32.7	37.5	40.2	43.2	43.3
	700	23.8	26.5	31.7	35.7	38.7
	800	18	23	26.2	28.5	28.7
2	200	57.5	57.8	58.5	59	59.3
	300	50.3	51.3	51.8	52.3	52.7
	400	46.7	48.2	49.3	50.5	51.7
	500	36.7	42	44.3	45.3	46.7
	600	30.8	36.3	38.3	40.8	41.2
	700	21.2	29.3	35.2	37.8	38.2
	800	17.8	25.3	29.3	30.2	32.5
3	200	54.3	55.7	57	57.8	58.3
	300	46	47.5	48.8	49.7	50.3
	400	39.2	41.8	43.2	44	44.2
	500	32.5	35.7	37.8	41.2	42.8
	600	27.3	32.3	34.3	35.2	36.2
	700	20.3	22.5	24.2	25	26.3
4	200	54.3	56.2	57.3	58	58.5
	300	46.3	47.7	48.3	48.7	49.2
	400	34.3	37.7	39.8	41.8	43.8
	500	29.8	34.2	36.3	38.2	40.2
	600	25.8	27.7	29.3	32.2	33.8

From the figures it can be noted that recuring resulted in strength recovery for concrete exposed to all the exposure temperatures and durations studied. Recovery is not very appreciable especially for the exposure durations of 3hr and 4hr. The deterioration occurred for concrete subjected to elevated temperatures for 4hr could be recovered to about 60% for exposure temperatures upto 500°C, while concrete exposed to 700°C and 800°C could not be recured.

For exposure durations upto 2hr and exposure temperatures below 500°C the concrete could recover about 70% of the ambient strength, which is quite encouraging. For exposure temperature of 600°C and retained for 2hr, concrete recovered about 65% of strength at ambient conditions with 28 days of recuring.

5.3 COMPARISON OF LOSS AND RECOVERY OF STRENGTH AT VARIOUS ELEVATED TEMPERATURES

In the previous section it was found that recuring helps to recover the lost strength partially for thermally deteriorated concrete irrespective of exposure temperature and duration of exposure. However the amount of strength recovered varies with the exposure temperature and duration. In this section the amount of strength recovered due to recuring at each exposure temperature is studied and quantified.

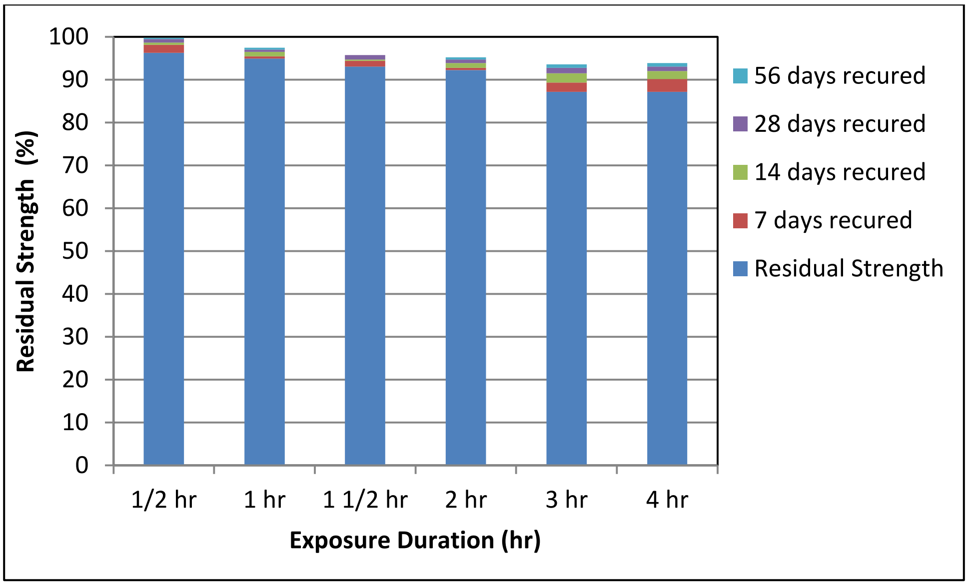


Fig. 5.2 (a) Strength recovery of concrete exposed to 200°C

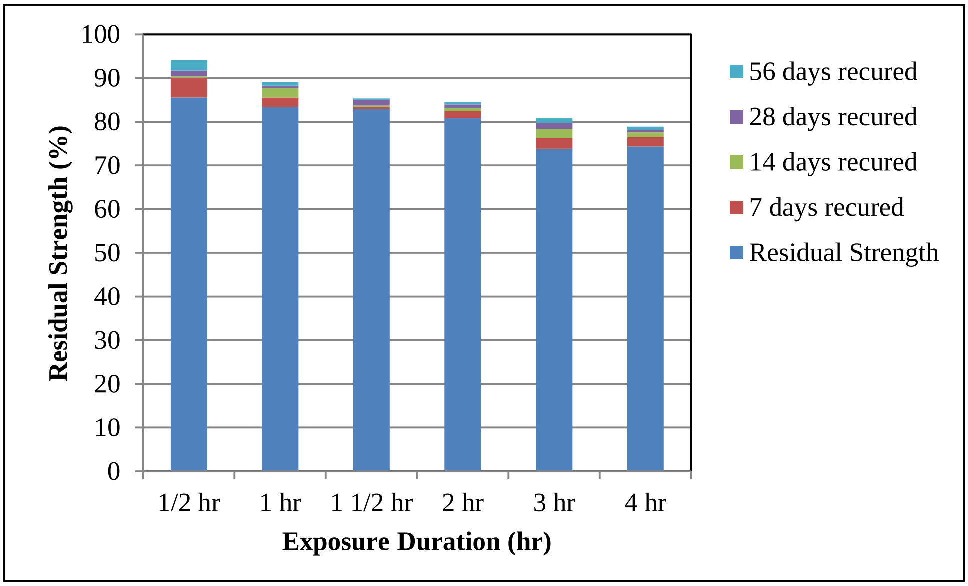


Fig. 5.2 (b) Strength recovery of concrete exposed to 300°C

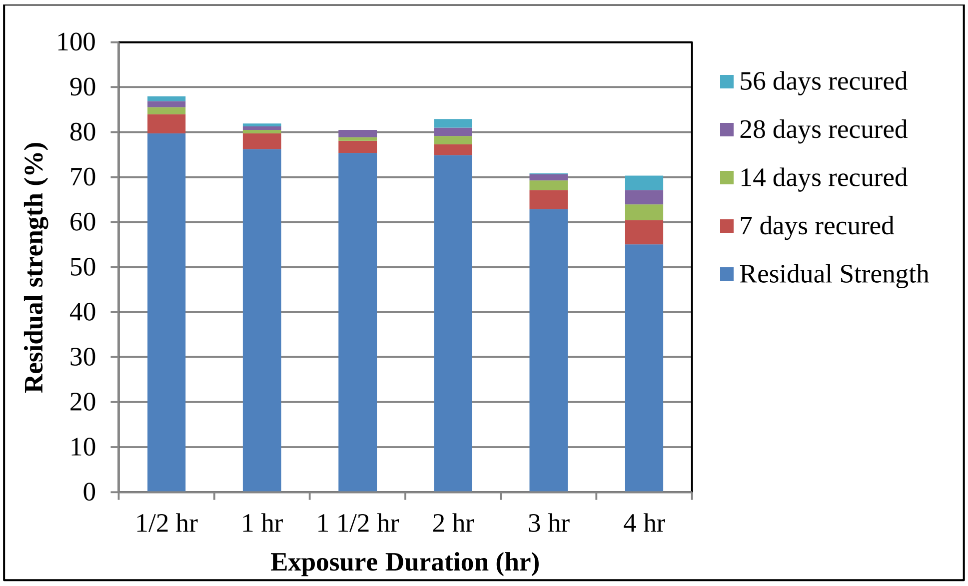


Fig. 5.2 (c) Strength recovery of concrete exposed to 400°C

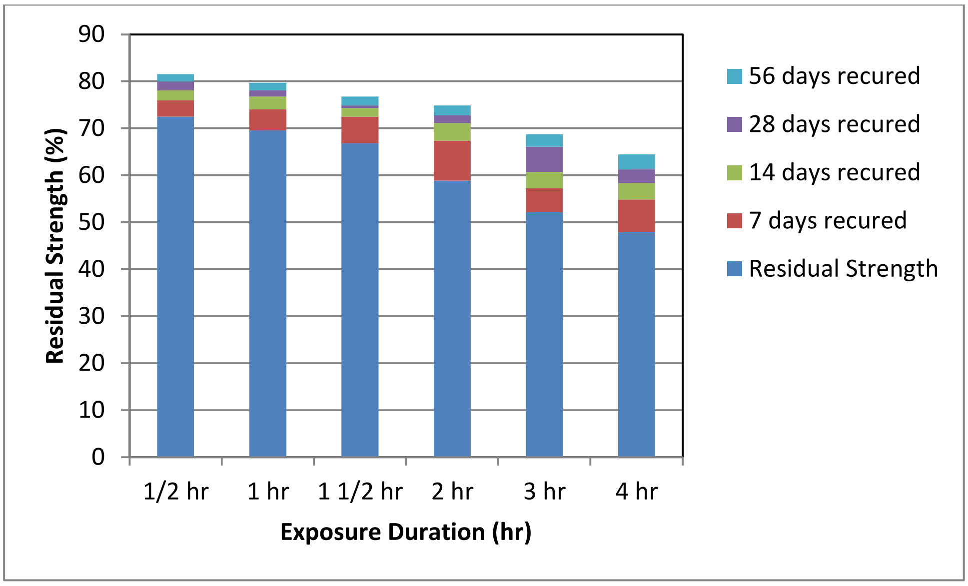


Fig. 5.2 (d) Strength recovery of concrete exposed to 500°C

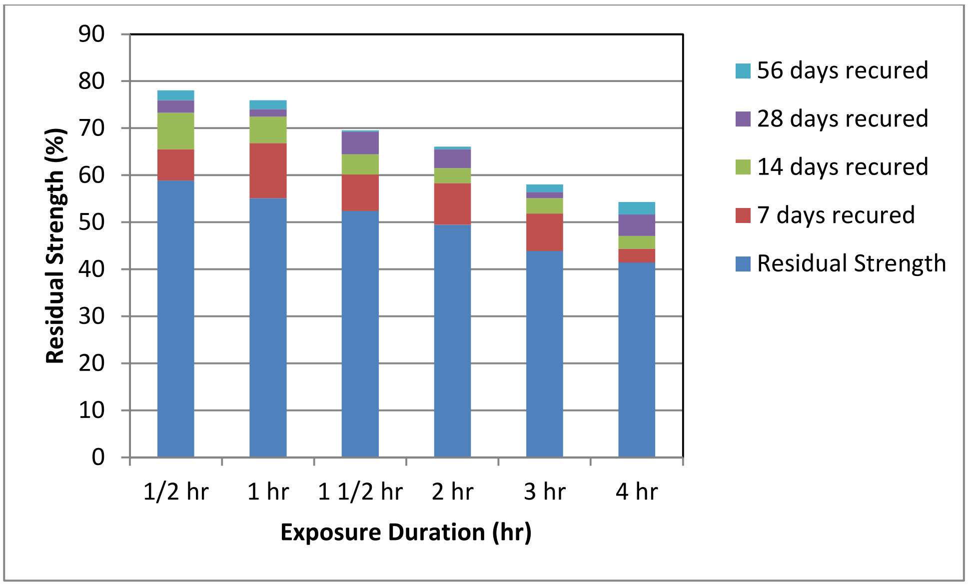


Fig. 5.2 (e) Strength recovery of concrete exposed to 600°C

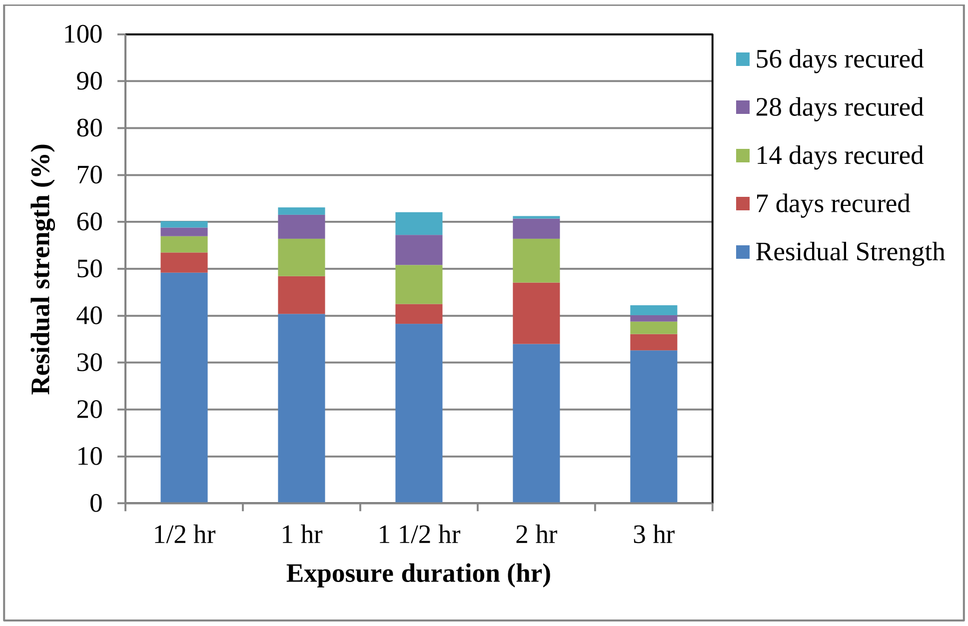


Fig. 5.2 (f) Strength recovery of concrete exposed to 700°C

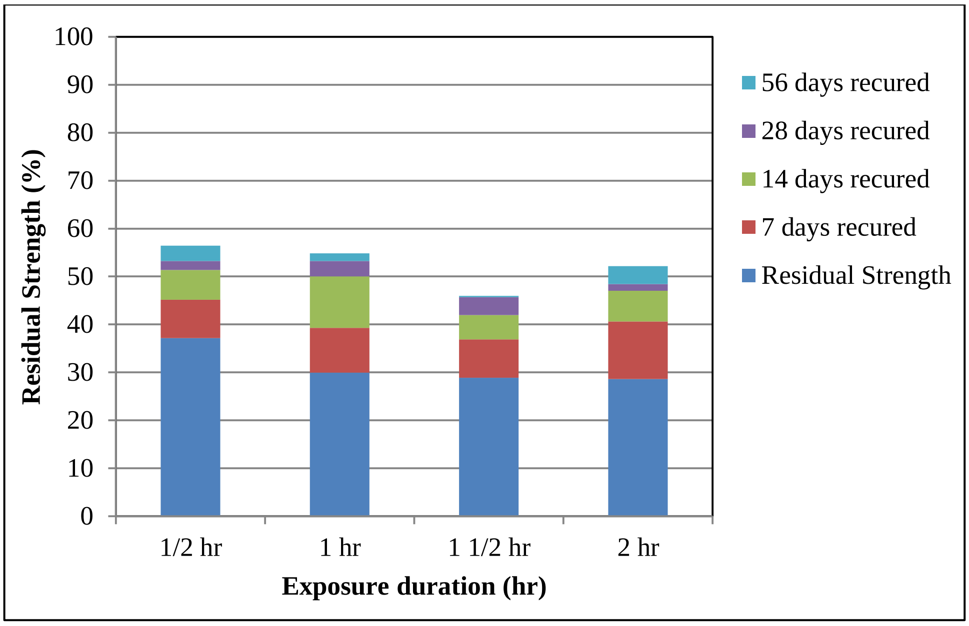


Fig. 5.2 (g). Strength recovery on concrete exposed to 800°C

Figures 5.2 (a) – (g) shows the strength recovered after recuring of concrete exposed to exposure temperatures of 200°C to 800°C. For lower temperatures of 200°C and 300°C concrete retains more than 80% of ambient strength after recuring.

For all the cases the temperatures strength recovery is maximum during the initial period of recuring. Strength recovery from 28 to 56 days is less than 5% of the ambient strength. Thermally deteriorate concrete exposed to 700°C and 800°C has shown strength recovery upto 60% of the ambient strength. concrete has shown about 12% to 20% recovery for exposure durations below 2hr.

For temperatures of 400°C to 600°C upto 80% of the ambient strength has been recovered, maximum being during the initial 7 days of recuring. However the case of 1½hr the recovery is only about 5% to 10% of the ambient strength. The presence of unhydrated lime (produced as a result of decomposition of calcium hydroxide at elevated temperatures) hampers the strength recovery process according to Poon et.al (2001) since its reaction with water is associated with increase in volume.

5.4 REGRESSION ANALYSIS OF THE EXPERIMENTAL DATA

From experimental results it was clear that the effect of recuring on strength recovery of thermally deteriorated concrete is dependent on temperature to which the concrete specimen were exposed and the time to which the specimen were held at that temperature. Regression analysis is a statistical technique for estimating the relationships among variables. Regression analysis was carried out in order to relate the strength ratio in terms of exposure temperature, holding time and recuring days by using Minitab 15 software.

Empirical equation obtained by regression analysis can be employed to predict the recovery of strength after recuring for 28 days. There was no appreciable recovery from 28 to 56 days, hence the experimental data upto 28 days was used for analysis.

The technique of recuring did not result into substantial recovery (only 5 to 14%) of strength for 700°C and 800°C exposure temperature. Prediction equation is therefore proposed to predict the improvement in strength ratio after recuring for 28 days of thermally deteriorated concrete subjected upto 600°C and exposure duration from 30 min to 180 min through regression analysis. Regression equation can be used to predict the possible strength recovery after recuring for 28 days with average error of less than 4%.

$$SR = 1.14 - 0.000920\ ED + 0.00175\ RD - 0.000729\ ET \ldots\ldots\ldots (5.1)$$

In equation 5.1, SR is the strength ratio, ED is the exposure duration, RD is the duration of recuring in days and ET is the exposure temperature.

5.5 CLOSURE

Strength recovery due to recuring has been found to depend on exposure temperature and duration. From the experimental results it was found that recuring can help the concrete recover the lost strength partially for temperatures upto 600°C and exposure durations upto 2hr. Regression analysis was carried out from the experimental data and prediction equation has been proposed for assessment.

Structural concrete that has undergone thermal exposure can be assessed by visual inspections which gives the preliminary information on the extent of damage through colour change and cracking. After which non-destructive tests and the empirical equations presented in the previous chapter can be employed to obtain the data on maximum temperature to which the concrete could have been exposed and strength retained in the concrete after exposure. For the concrete that has experienced exposure levels of upto the range of 500°C to 600°C can be recured for two weeks and asses the strength recovery.

CHAPTER 6

MORTAR AS PROTECTIVE COATING FOR CONCRETE

6.1 GENERAL

Structural concrete is usually covered with plaster in order to render a smooth finish and enhance the architectural features. This can also play the role of a thermal barrier if made with heat resisting material. Plaster can act as a barrier to the heat or delay the heat from reaching the structural concrete thereby preserving the structural integrity of concrete for a comparably larger duration. Vermiculite is found to be one such material that can resist elevated temperatures 1150°C (Koksal et.al, 2012), since it is exfoliated at temperatures above 1150°C.

An experimental investigation was therefore planned to study the effectiveness of vermiculite mortar in shielding the concrete specimen from damage during thermal exposure. A comparative study has been made between the performance of the mortar prepared with fine aggregates and the vermiculite aggregates. Six kinds of mortars prepared for the investigation are given in table 6.1.

Table 6.1. Mortar mix proportions

	Cement (gms)	Bonding agent (ml)	Water (ml)	GGBS (gms)	Flyash (gms)	River sand (gms)	Vermiculite (gms)
SC	400	40	120	-	-	1200	-
SCG	200	40	120	200	-	1200	-
SCF	200	40	120	-	200	1200	-
VC	400	40	525	-	-	-	214
VCG	200	40	525	200	-	-	214
VCF	200	40	525	-	200	-	214

For the mortar to act as a thermal barrier it should firmly bond with the concrete structural member and should not lose bond at elevated temperatures. Cracking in mortar allows the heat to penetrate and thereby expose the concrete to heat and cause deterioration in strength.

6.2 VISUAL OBSERVATIONS

Figure 6.1 shows the picture of concrete cube coated with mortar made of sand and cement (SC). Mortar made with sand and cement could not withstand the effect of elevated temperature exposure and the mortar coating got separated from the concrete cube.

Fig. 6.1 Separation of mortar coating

The mortar lost the bonding with the concrete cube when subjected to temperatures above 300°C. There was a separation of plaster from the concrete with a sound when the temperature of the furnace rose to about 290°C. The figure 6.1 shows total delamination of plaster surface from the cube. Delamination of mortar coat was observed for the concrete cubes coated with mortar mixes made with sand, cement and GGBS (SCG) and sand, cement and flyash (SCF). However the delamination occurred at temperatures around 350°C. Because of delamination, the protection to the concrete was lost and the concrete surface got exposed to elevated temperatures. The physical observations of the encased concrete cube after cooling were similar to those reported previously in chapter 4.

The concrete mixes with vermiculite aggregates VC, VCG and VCF performed extremely well under elevated temperature conditions. They showed no signs deterioration such as cracking till 600°C. Figure 6.2 shows the surface of plastered concrete cube subjected to 600°C.

Fig. 6.2 Surface of VC mortar exposed to 600°C

Plastered concrete cube exposed to 700°C experienced minor cracks on the plaster surface. However, there was no delamination of the plaster surface till 800°C. The vermiculite plaster acted as a thermal barrier and prevented the heat to penetrate to the concrete cube.

6.3 RESIDUAL STRENGTH OF CONCRETE COATED WITH DIFFERENT MORTARS

Concrete plastered with mortar containing river sand and vermiculite as aggregates were subjected to elevated temperatures. Residual strengths of the concrete cubes were determined after removing the damaged plaster coat.

6.3.1 Concrete with SC Mortar

Comparison of residual strengths of plastered and unplastered concrete is shown in figure 6.3. The concrete cube coated with SC mortar exposed to 200°C retains 97% of the ambient strength as against 91.32% for the unplastered concrete. Similarly the concrete exposed to 300°C retained about 95% of the ambient strength as against 87.32% for the unplastered concrete cube. The plastered concrete exposed to 400°C retained about 77.3% of the ambient strength, almost equal to 78% for unplastered concrete strength.

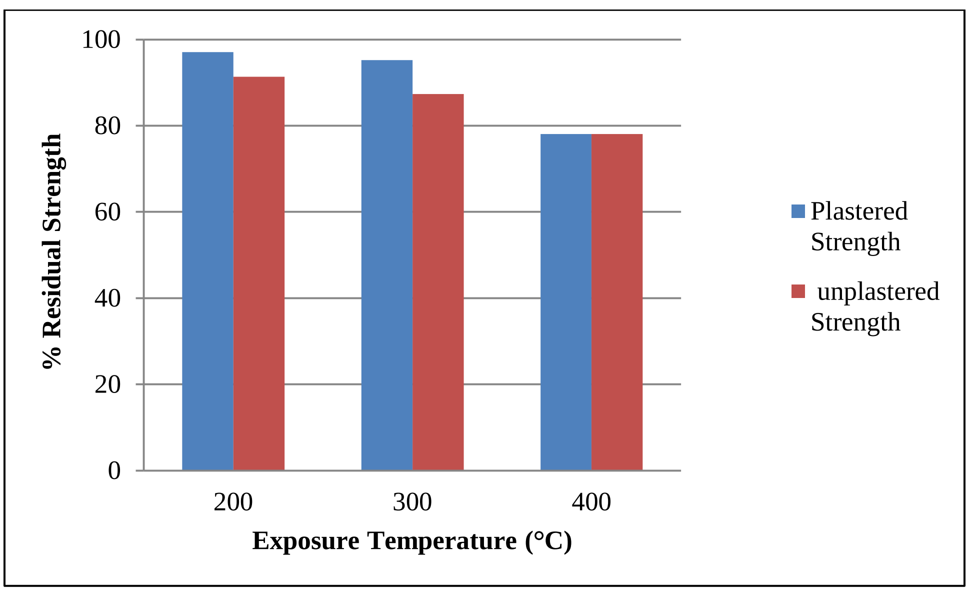


Fig. 6.3 Residual strength of concrete coated with SC mortar

6.3.2 Concrete with SCF Mortar

Strength performance of concrete coated with SCF mortar and its comparison with the unplastered concrete strength performance is shown in figure 6.4. The concrete cubes coated with SCF mortar exposed to 200°C retains 97.87% of the ambient strength as against 91.32% for the unplastered concrete. The plastered concrete exposed to 400°C retained about 87%, while for unplastered concrete strength was 78% of the ambient strength, because there was a separation of plaster coat and the concrete surface. For the case of 400°C exposed the plaster had experienced heavy cracking and separation of plaster at about 350°C, which allowed the heat to reach the concrete core.

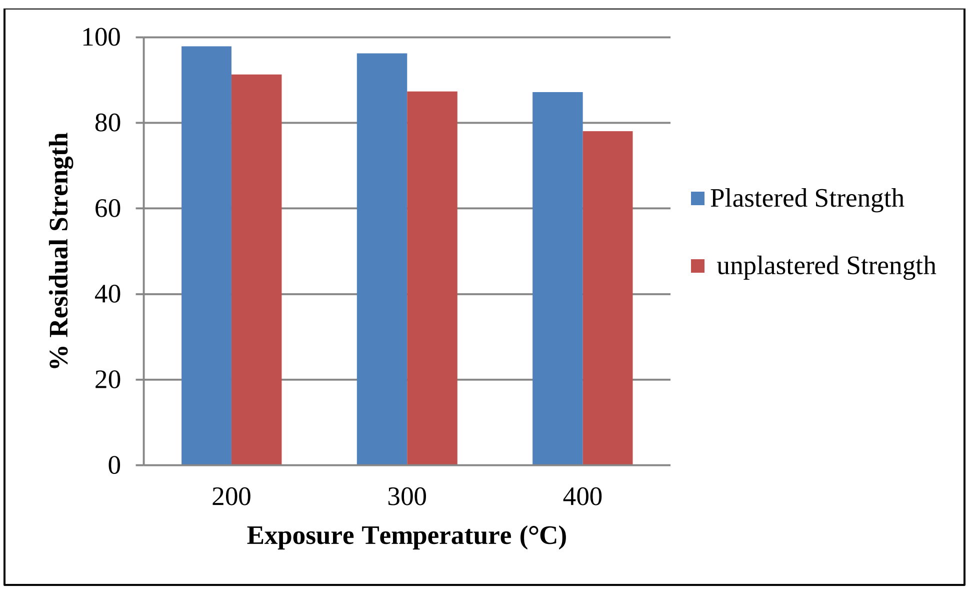


Fig. 6.4 Residual strength of concrete coated with SCF mortar

6.3.3 Concrete with SCG Mortar

The concrete cube coated with SCG mortar and exposed to 200°C retain 97.60% of the ambient strength as against 91.32% for the unplastered concrete. Similarly the concrete exposed to 300°C retained about 96.26% of the ambient strength as against 87.32% for the unplastered concrete cube. The plastered concrete exposed to 400°C retained about 83% of the ambient strength as observed from figure 6.4.

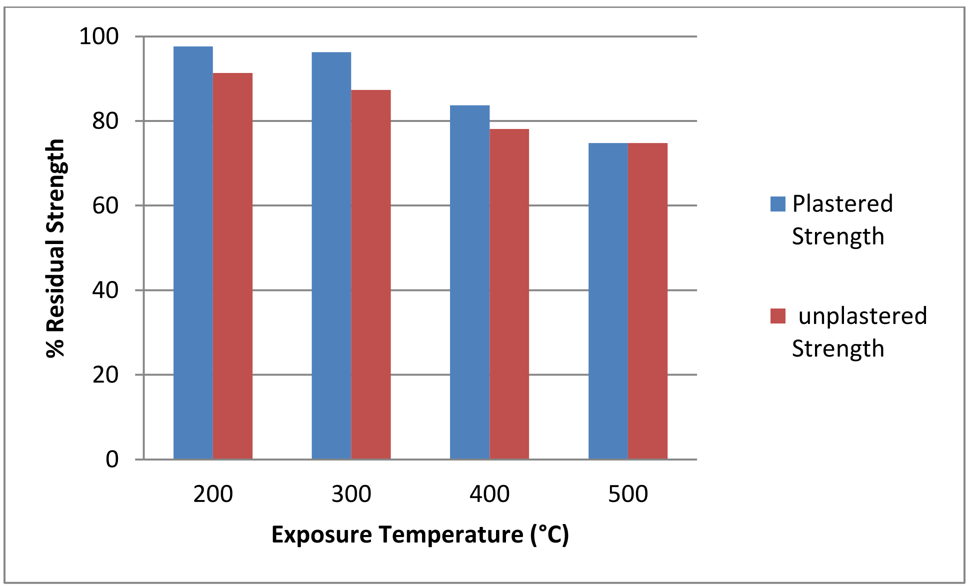


Fig. 6.5 Residual Strength of concrete coated with SCG mortar

6.3.4 Concrete with VC Mortar

From the figure 6.6 it is evident that VC mortar has provided excellent protection for the concrete upto the exposure temperature of 500°C. The concrete coated with VC mortar, exposed to 600°C experienced cracking all over the plaster surface. The VC plastered concrete retained about 74% of ambient strength as against 69.5% of ambient strength for unplastered concrete cubes. It is seen that even after cracking the mortar protected the concrete core since fine cracking may result into increase in the surface area of the maotar that can absorb heat.

Hence even after cracking the mortar continues to protect the concrete encased inside. However the thermal gradient created across the plaster coat because of rising temperature in the furnace resulted into widening of cracks.

The concrete exposed to 700°C retained about 54.5% of ambient strength, while the concrete coated with VC mortar retained 67.12% of the ambient strength. The plastered surface had cracked heavily however there has been no debonding from the concrete. Even for tempertaures of 600°C and 700°C the strength of plastered surface has been found to be higher than the unexposed strength.

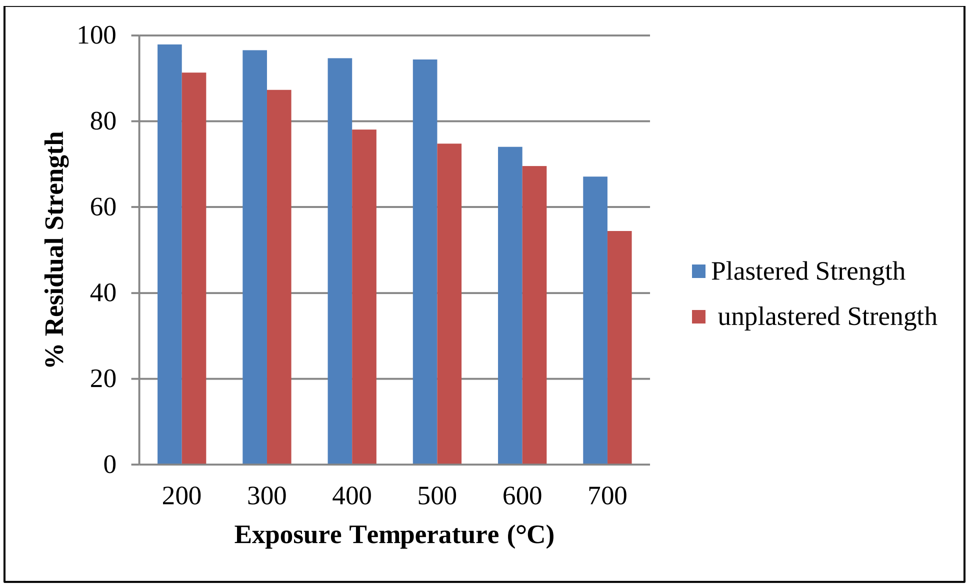


Fig. 6.6 Residual Strength of concrete coated with VC mortar

6.3.5 Concrete with VCF Mortar

The performance of VCF mortar is also encouraging and it provides protection to the encased concrete. The concrete coated with VCF mortar and exposed to 600°C experienced cracking all over the plaster surface. Eventhough the VCF plastered concrete had undergone cracking, it could retain about 74.60% of ambient strength as against 69.50% of ambient strength for unplastered concrete cubes.

The concrete exposed to 700°C retained about 54.45% of ambient strength, while the concrete coated with VCF mortar retained 67.38% of the ambient strength.

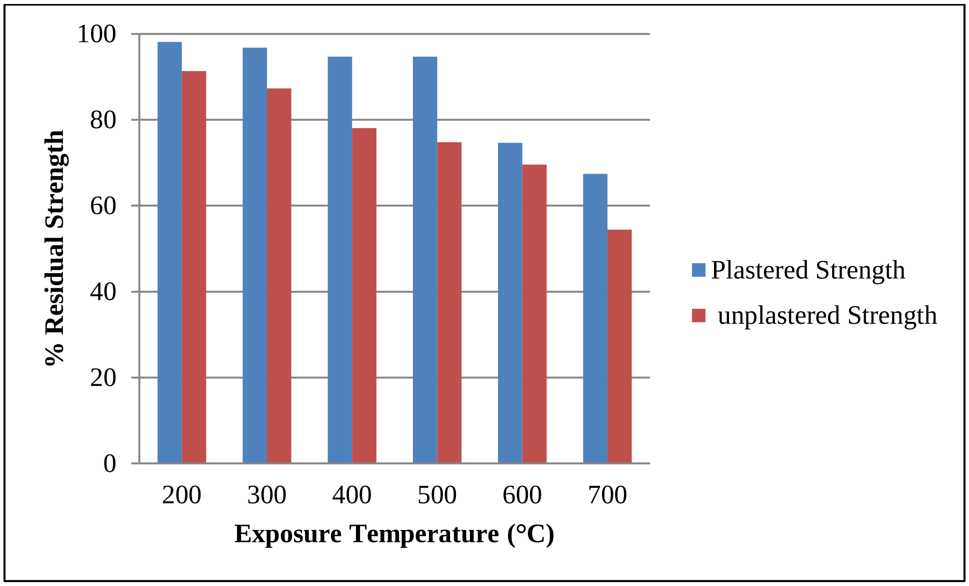


Fig. 6.7 Residual Strength of concrete coated with VCF mortar

6.3.6 Concrete with VCG Mortar

Performance of vermiculite mortar with GGBS as a heat shield Concrete cube plastered with VCG mortar retained more than 90% of the ambient strength for the exposure temperatures upto 500°C. Figure 6.8 shows that the plastered concrete performs better at all the temperatures upto 700°C.

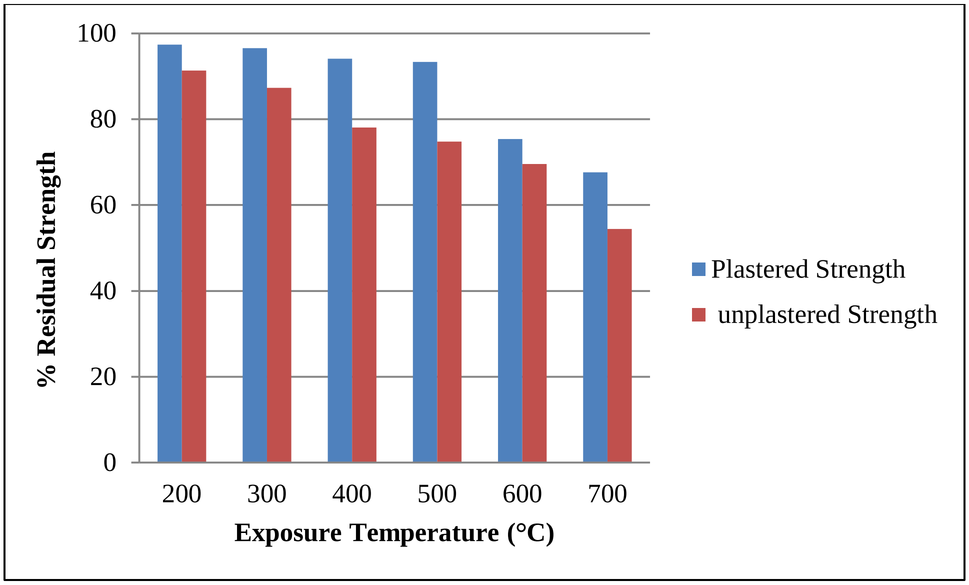


Fig. 6.8 Residual Strength of concrete coated with VCG mortar

6.4 COMPARISON OF PERFORMANCE OF VARIOUS MORTARS STUDIED AS THERMAL BARRIER

Figure 6.9 shows the strength retained expressed in percentage of ambient strength for the concrete cubes coated with six mixes of mortar. The trend of strength deterioration with increase in exposure duration, for SC, SCF and SCG mortars is different from the trend of strength.

Replacement of sand with vermiculite aggregates proved to be beneficial in protecting the concrete against thermal exposure. Concrete coated with VC mortar performed well when subjected to elevated temperatures and did not experience debonding till 700°C. The plaster surface did not experience cracking till 500°C, hence the concrete could retain about 93% of the ambient strength for 500°C. However sudden drop in strength is observed for 600°C, this is due the cracking that was observed on the plaster surface which allowed the heat to penetrate into the mortar coating reaching the concrete cube. For 700°C the strength retained is about 67%.

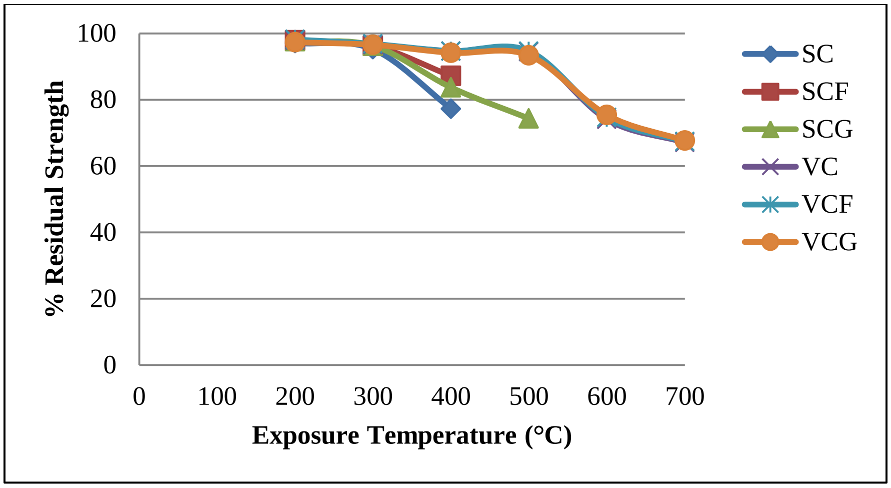


Fig. 6.9 Residual strength of concrete coated with mortar subjected to elevated temperatures

The trend of strength deterioration is similar for the concrete specimen coated with VCF and VCG mortar. The graphs of VC, VCF and VCG almost coincide. This shows that mortar made of vermiculite aggregates performs extremely well as a thermal barrier and protects the concrete against thermal exposure. Using VCF or VCG is a better choice since for the same level of performance the cement consumption is less.

6.5 CLOSURE

Plastering can play an important role in protecting the structural concrete against thermal exposure. Performance of six kinds of mortars were studied and it has been found that mortar made of vermiculite aggregates act as thermal barrier and protect the structural concrete without undergoing cracking upto 500°C. Cracked surface of mortar also continues to protect the concrete. This can be beneficial for making the structural concrete fire proof where the concrete is not designed for heat resistance.

Existing structures as well as thermally damaged structures after retrofitting can be plastered with VC, VCF or VCG mix. Use of VCF and VCG mixes is rather economical since 50% of the cement content is replaced by either flyash or GGBS respectively. These mixes are also eco-friendly because of reduced cement consumption and use of pozolanas.

CHAPTER 7

CONCLUSIONS

7.1 GENERAL

Strength retention characteristics of concrete subjected to elevated temperatures are studied experimentally. Recuring has been adopted as means to recover the lost strength and its efficacy is studied. An attempt has been made to validate the use of vermiculite aggregates as a potential plaster material to provide protection to the structural concrete during elevated temperature exposure.

This chapter summarizes the major outcomes of the investigation which include visual observations, strength deterioration at various elevated temperatures, heating rate, exposure durations and cooling regimes, strength regain due to recuring, effectiveness of mortar to endure elevated temperatures, made by sand and vermiculite aggregates.

7.2 VISUAL OBSEVATIONS

Concrete underwent colour change and cracking on exposure to elevated temperature. Visual colour observations suggested that the colour change depended on the exposure temperature and not on the exposure duration and the heating rate. Following conclusions can be drawn from the visual observations of thermally deteriorated concrete.

1) Concrete colour changes from normal to pink for 400°C exposure, to grey for 700°C to 800°C. Color changes were independent of the regimes studied.
2) Concrete experienced cracking with increase in the exposure temperature irrespective of exposure duration and heating rate.

3) Concrete exposed to 700°C and 800°C suffered extensive cracking for both the heating rates and for all the exposure durations. This is because high temperatures create larger thermal gradient in concrete making the hardened cement paste shrink.

Thus colour changes provide the preliminary information on maximum temperature to which the concrete has been exposed.

7.3 STRENGTH DETERIORATION DUE TO ELEVATED TEMPERATURE EXPOSURE

Concrete residual strength after exposure to elevated temperature is influenced by the maximum temperature, to which it is exposed, duration for which it maintained at the target temperature and the heating and cooling rates. Following conclusions are drawn from the experimentation.

1) For all the heating and cooling regimes studied concrete exposed to high temperature for larger duration experience higher deterioration since larger durations of exposure allows the heat to penetrate deeper into the concrete surface.

2) For 200°C and for 300°C with exposure durations upto 2hr faster heating caused larger deterioration of strength. For all other cases slower heating caused higher deterioration. As since for slower heating, the presence of heat is for a larger duration.

3) Sudden cooling of heated concrete specimen creates a thermal shock and causes higher deterioration when compared to specimen cooled in furnace naturally. However for higher temperatures above 500°C deteriorating effect of slower heating is more severe compared to the deterioration created by quenching.

4) Slower heating caused higher deterioration compared to faster heating and sudden cooling because the thermal gradient produced during sudden cooling is only at surface of concrete, however slower heating causes the specimen to be heated for longer duration during which the heat penetrates to a larger depth inside the concrete.

7.4 STRENGTH RECOVERY DUE TO RECURING

Self-healing capacity of thermally deteriorated concrete has been explored and the concrete is allowed to heal by supplying it with moisture by way of water curing for 7, 14, 28 and 56 days. Some of the important findings are as follows.

1) Recuring can restore the lost strength, however the amount of strength recovered depends on the exposure temperature and exposure duration. For exposure temperatures exceeding 400°C and exposure durations below 2hrs, 30% to 40% of the lost strength is recovered after recuring for 56 days. After exposure to 800°C for 2hrs the concrete lost about 71% of the ambient strength and at the end of recuring cycle of 56 days 23% of ambient strength was recovered.
2) For temperatures upto 400°C, 70 to 90% of the lost strength is recovered after recuring for 56 days. Strength recovery was maximum during the initial 14 days of recuring.
3) The technique of recuring can thus be useful in recovering lost strength of thermally deteriorated concrete exposed to 600°C and below.

Recuring technique can help recover the lost strength partially and depends on extent of damage occurring during elevated temperature exposure. There is a potential for its application in situations where recuring could be resorted to before the necessary retrofitting, if needed to be recommended.

7.5 EFFECTIVENESS OF MORTAR COATING AS A THERMAL BARRIER

Mortar made with refractory material acts as thermal barrier during the high temperature exposure when used as a plastering material. Vermiculite aggregates have been found to perform much better compared to regular fine aggregates in this aspect.

1) Sand-cement (SC) mortar lost its bond with concrete and got separated when the exposure temperature reached 290°C. Sand-cement-flyash (SCF) and sand-cement-GGBS (SCG) mortars maintained their bond with concrete till 400°C.

2) Mortar made with vermiculite aggregates does not show any sign of damage such as cracking, upto 500°C.
3) Replacement of sand with vermiculite aggregates provides good thermal protection to the concrete. The concrete maintains more than 90% of its ambient strength for exposure temperatures upto 500°C.
4) For exposure temperatures of 600°C and 700°C the plastered suffered cracking, but there was no debonding.

Vermiculite aggregates can be used as a potential material to resist heat in form of plaster to the structural concrete. Existing structures can be made heat resistant by plastering it with vermiculite plaster.

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CURRICULUM VITAE

Name : SHREE LAXMI PRASHANT

Contact No. : +91-8722614244/9035673233

E-Mail : shrilaxmi.civil@gmail.com

Date of Birth : 05-06-1982

Educational Qualifications

Degree	University	Year of Passing	Division
B. E. (Civil)	Shivaji University, Kolhapur, Maharashtra, India.	2004	I^{st} class
M. E. (Structures)		2007	I^{st} class

Teaching Experience

Name of Institute	Post held	Period
National Institute of Technology, Karnataka	Asst. Lecturer	July 2006 to May 2007

Research Publications

	International	National
Journal Papers	2	--
Conference Publications	5	2