STUDIES ON THE BEHAVIOUR OF SELF COMPACTING CONCRETE UNDER ELEVATED TEMPERATURE

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Abstract

This study investigates the behavior of Self-Compacting Concrete (SCC) under elevated temperatures, focusing on its mechanical properties, microstructural changes, and durability. SCC is widely used in construction due to its superior flowability and ability to fill complex molds without mechanical vibration. However, its performance under high-temperature conditions, such as those encountered during fires, remains a critical area of research. The study involves subjecting SCC specimens to temperatures ranging from 200°C to 800°C to simulate moderate to extreme heat exposure. The effects on compressive strength, tensile strength, modulus of elasticity, and microstructure are evaluated using various testing methods. The findings reveal significant changes in SCC's properties, including thermal cracking, spalling, and strength degradation, which are influenced by the temperature and duration of exposure. The study also explores mix design modifications and reinforcement strategies to enhance SCC's resistance to high temperatures. These insights contribute to the development of more resilient SCC formulations, offering better performance in structures exposed to elevated temperatures.

Keywords

Self-Compacting Concrete (SCC), Elevated Temperatures, Mechanical Properties, Microstructure, Durability, Thermal Cracking, Spalling, Fire Resistance, Mix Design, Reinforcement Strategies.

INTRODUCTION

Development of Self Compacting Concrete (SCC) is considered as the most sought development in construction industry due to its numerous inherited benefits. In India, this technology is yet to realize its full potential. With the introduction of super plasticizers and viscosity modifying admixtures, it is now possible to produce concrete with high fluidity and good cohesiveness that does not require external energy for compaction. Self compacting concrete is a form of concrete that is capable of flowing into the congested interior of formwork, passing through the reinforcement and filling it in a natural manner, consolidating under the action of its own weight without segregation and bleeding. Self compacting concrete has many advantages over the conventional concrete. Some of the advantages of SCC are reduction in manpower, excellent surface finishes, easier placing, free from honey-combs, reduced permeability, improved durability, reduction in noise levels, absence of vibration and ensured compaction. Self compacting concrete is a fluid mixture suitable for placing in structures with congested reinforcement without vibration. Self compacting concrete development ensures a good balance between deformability and stability. This hardened concrete is dense, homogeneous and has better engineering properties and durability when compared with the traditional vibrated concrete.

On the basis of manufacturing cost, SCC is about 20% costlier than the conventional concrete of similar compressive strength which is compensated by several benefits of using it such as saving in electricity, saving in labour cost related to compaction work, increase in productivity etc. SCC technology is considered as an energy conservation technique in construction industry as it eliminates electricity requirement for compaction of concrete. SCC provides ample opportunity to use the waste materials such as flyash, silica fume, quarry dust etc thereby reducing the disposal problems of these waste materials. The introduction of SCC can positively change the construction process and eliminate necessity for mechanical vibration thus improving the working environment and the health and safety of workers. Vibrators used for the compaction of concrete are a major source of noise on construction site and in concrete precast factories. Self compacting concrete technology eliminates the use of vibrating equipment and minimizes the risk of injuries or harm caused by exposure to continuous high frequency noises and mechanical vibration.

The development of self compacting concrete is considered to be one of the most significant developments in the building material domain. This is due to the following benefits that this concrete offers:

- The technology of producing self compacting concrete can be considered as an energy conservation process, since the electricity consumption for vibration is eliminated.
- The mix of self compacting concrete incorporates industrial wastes, such as flyash, silica fume, quarry dust etc.,
- Use of self compacting concrete increases the lifetime of the construction moulds and reduces the necessity for skilled workers.
- SCC can be used for all types of structures due to the fact that it can be pumped for very long distances without segregation.

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Aims and Significance of the Research

Fire resistance of structures is an important safety aspect which is to be considered in the design of buildings. The resistance of materials to fire had been studied by few researchers in the past. The behaviour of materials subjected to higher temperature is a known phenomenon. However the behaviour of composite structural members like Reinforced Cement Concrete (RCC) beams, column etc.,

where two or more members act together under fire load has not been studied extensively. The Indian standards for plain and reinforced cement concrete IS 456:2000 has a clause for fire resistance. As per this clause, fire resistance of RCC elements is a function of cover to the reinforcement and the size of the element. As per the code, higher cover results in higher fire resistance. However the fire resistance depends on many other parameters such as grade of concrete, grade of steel, density of concrete, reinforcement percentage, intensity and duration of fire etc. Since SCC is a new material, only very few literature is available on its fire resistance. In order to completely understand the behaviour of SCC beams under elevated temperature, an experimental and analytical investigation has been carried out during the present research work.

Objectives of the Research

The objectives of the research work are given below:

- To study the behaviour of self compacting concrete subjected to elevated temperatures.
- To carry out an experimental investigation and to determine the compressive strength, tensile strength, flexural strength, stiffness and energy absorption capacity of heated SCC specimens.
- To carry out an experimental and analytical investigation to understand the effect of cover on the performance of SCC beams subjected to elevated temperatures.
- To carry out an experimental and analytical investigation to understand the effect of tension reinforcement percentage on the performance of SCC beams subjected to elevated temperatures.

REVIEW OF LITERATURE

A detailed review of literature on the performance of different types of concrete specimens that were exposed to higher temperature is reported in this chapter. Shape of specimen, size of specimen, magnitude of temperature load applied on the specimen, duration of heating, time temperature curve, rate of heating, rate of cooling, time taken for hot test after curing period, time taken for load test after heating, stressed/unstressed test on hot members, type of cooling adopted on heated specimens etc are the parameters that influence the test results. To completely understand the behavior of concrete under elevated temperature, it is necessary to consider all the key factors involved while designing the experimental setup. Grade of concrete, type of cement, type of admixture, type of aggregate, water cement ratio, density of concrete, reinforcement percentage, cover to the reinforcement etc are some of the important factors that influence the performance of concrete at elevated temperature. However it is difficult to carry out experimental investigations considering all the parameters that influence the performance of concrete exposed to elevated temperatures. Hence different researchers considered different sets of parameters. This chapter summarizes the salient features of the experimental and analytical investigations reported in the literature. The analysis of the data indicates that the behaviors of Normal Compacting Concrete and Self Compacting Concrete are different. The effects of elevated temperatures on the properties of concrete such as compressive strength, tensile strength, flexural strength and spalling reported in the literature are summarized.

A review of methods used by various investigators for testing concrete at elevated temperature indicates that, the tests can be categorized into three types namely stressed test, unstressed test and unstressed residual strength test. In stressed tests, a preload is applied to the specimen prior to heating and the load is sustained during the heating period. Heat is applied at a constant rate until a target temperature is reached, and this temperature is maintained for a time until a thermal steady state is achieved. Load is then increased at a prescribed rate until the specimen fails. 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. Load is then applied at a prescribed rate until failure occurs. 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. The specimen is then allowed to cool, following a prescribed rate to room temperature. Load is applied on the specimen at room temperature until the specimen fails. The first two types of test are suitable for accessing the strength of concrete during high temperatures, while the later is excellent for finding the residual properties after the high temperature. It is reported by Abrams [1973]1 that the last method gives the lowest strength and is therefore more suitable for getting the limiting values of strength.

Mustafa Sahmaran and Ozgur Yaman (2007)72 studied the fresh and mechanical properties of a fiber reinforced self compacting concrete incorporating high volume flyash that does not meet the fineness requirements of ASTM C 618. A poly carboxylic based super plasticizer was used in combination with a viscosity modifying admixture. In mixtures containing flyash, 50% of cement by weight was replaced with flyash. Two different types of steel fibers were used in combination, keeping the total fiber content constant at 60 kg/m3. Slump flow time and diameter, V-funnel, and air content were found to assess the fresh properties of the concrete. Compressive strength, splitting tensile strength, and ultrasonic pulse velocity were determined for the hardened concrete. The results indicated that high volume coarse flyash can be used to produce fiber reinforced self compacting concrete, even though there is some reduction in the strength because of the use of high volume coarse flyash.

Burak Felekoglu et al (2007)14 made an investigation on five self compacting concrete mixtures with different combinations of water/cement ratio and super plasticizer dosage levels. Slump flow, V-funnel and L-box tests were carried out to determine the optimum parameters for the self compactibility of mixtures.

Compressive strength development, modulus of elasticity and splitting tensile strength of mixtures were also studied. It was reported that optimum water/cement ratio for producing

SCC was in the range of 0.84 to 1.07 by volume. The ratios above and below this range may cause blocking or segregation of the mixture. The Splitting tensile strengths of the SCC mixes were found to be higher and the values of Modulus of elasticity were found to be lower than those of NCC.

Binu Sukumar et al (2007)11 replaced high volume flyash in the powder, based on a rational mix design method to develop self compacting concrete. High flyash content necessitated the study on the development of strength at early ages of curing which is a significant factor for the removal of formwork. Rate of gain of strength at different periods of curing such as 12 h, 18 h, 1 day, 3 days, 7 days, 21 days and 28 days were studied for various grades of different SCC mixes and suitable relations were established for the gain in strength at the early ages in comparison to the Conventional Concrete (CC) of same grades. Relations were also formulated for the compressive strength and the split tensile strength for different grades of SCC mixes. It was observed that the rate of gain in strength for different grades of SCC was slightly more than the expected strength of conventional concrete of the same grades.

aggregate concrete had lower strength than the other concretes. The salient features of the test are shown in Table 2.1.

Table 2.1 Salient Features of Test Carried out by Abrams M.S

Size of the specimen (m)	nperaturerange	Time duration	Time-temperature curve	Rate of heating	Rate of cooling/ coolant	pe oftest
Cylinder (0.076 x 0.152)	21 to 871^{o}C	Peak temperature maintained for 3 to 4 hours	Furnace temperature curve	-	-	Stressed, Unstressed, Un stressed residual strength test

Moetaz M. El-Hawaryet al (1996)[65] studied the effect of fire on the flexural behaviour of Reinforced Concrete (RC) beams. Four groups of RC beams were cast, exposed to fire at 650°C for time durations of 0, 30, 60 and 120 min and then cooled by water. Reduction in ultimate load, increase in deflection, increase in both compressive and tensile strains and reduction in concrete compressive strength were observed for the heated specimens. The salient features of the test are shown in Table 2.2.

Table 2.2 Salient Features of Test Carried out by Moetaz M. El-Hawary et al

Size of the specimen (m)	nperaturerange	Time duration	Time-temperature curve	Rate of heating	Rate of cooling/ coolant	ype oftest
Beam (1.8x0.12 x0.2)	650°C	Peak temperature maintained for 30min, 60min, 120min	Furnace temperature curve	-	Sprayed with water immediately	Un stressed residual strength test

Moetaz M. El-Hawary and Sameer A. Hamoush (1996)[66] carried out an experimental investigation to determine the effect of high temperature on the interfacial bond shear modulus between concrete and reinforcement. Steel bars of different diameters were embedded in concrete cylinders for a depth less than that required for total development to assure failure by loss of bond. Specimens were then kept in an oven for different time durations and different temperatures. Specimens were then cooled by either keeping cylinders at room temperature or immersing them in water. The interfacial bond shear modulus between concrete and steel reinforcement was calculated using an experimental analytical technique. The pull out test was applied, and loads and displacements were recorded. Results from the pull out test were then used along with an analytical model to calculate the bond shear modulus. The analytical model was based on the physical representation ofthe pull out test, assuming linear elastic behavior of both steel and concrete. The effects of temperature, duration of heating, size of steel bar and the method of cooling on the bond shear modulus were investigated. The bond shear modulus was found to be independent of the diameter of the reinforcing bars and was found to be much lower for concrete cooled by water than for concrete cooled gradually in air. Specimens heated to about 100°C for short durations and cooled in air experienced an increase in the bond shear modulus. For all other specimens, a reduction in the bond shear modulus was noticed. The reduction increased with the increase of the heating temperature or duration of heating. The salient features of the test are shownin Table 2.3.

Table 2.3 Salient Features of Test Carried out by Moetaz M. El-Hawary andSameer A. Hamoush

Size of the specimen (m)	nperaturerange	Time duration	Time-temperature curve	Rate of heating	Rate of cooling/ coolant	ype oftest
Cylinder (0.1 x 0.2)	100,300 500°C	Peak temperature maintained for 2,4 & 8 hours	Furnace temperature curve	-	Natural cooling byair, immersion in water	Un stressed residual strength test

Moetaz M. El-Hawary et al (1997)[22] studied the effect of duration of fire exposureand the concrete cover thickness on the behaviour of RC beams subjected to fire in shear zone and cooled by water. Investigation was carried out on eight reinforced concrete beams of size 1800 x 200 x 120 mm. The beams were divided into two groups. Group (1) consisted of four beams with a cover thickness of 20 mm and group (2) consisted of four beams with a cover thickness of 40 mm. Each group was subjected to a temperature of 650°C for different periods of time, i.e. 0, 30, 60. 120 min. The compressive strength of the beams was determined non-destructivelyusing a Schmidt hammer on the next day after exposure to fire. The beams were tested by applying two transverse loads incrementally. Strains and deformations were measured at each load increment. Cracking loads, crack propagation and ultimate loads were recorded for each beam. The behaviour of the beams exposed tofire in the shear zone was found to be highly affected by the fire exposure time and the change of the cover thickness. The salient features of the test are shown in Table2.4.

Table 2.4 Salient Features of Test Carried out by Moetaz M. El-Hawary et al

Size of the specimen (m)	nperature range	Time duration	Time-temperature curve	Rate of heating	Rate of cooling/ coolant	ype oftest
Beam (1.8x0.2 x0.12)	650°C	Peak temperature maintained for 30min, 60min, 120min	Furnace temperature curve	-	Sprayed with water immediately	Un stressed residual strength test

Y.N.Chan et al (1999)[17] carried out an investigation on the fire resistance of Normal Strength Concrete (NSC) and High Strength Concrete (HSC), with compressive strengths of 39, 76 and 94 MPa respectively. After exposure to temperatures upto 1200°C, compressive strength and tensile splitting strength were determined. The pore structure in HSC and in NSC was also investigated. Results indicated that HSC lost its mechanical strength in a manner similar to that of NSC. The range between 400 and 800°C was found to be critical to the strength loss.High temperatures had a coarsening effect on the microstructure of both HSC and NSC. On the whole, HSC and NSC suffered damage to almost the same degree, although HSC appeared to suffer a greater worsening of the permeability related durability. The salient features of the test are shown in Table 2.5.

Table 2.5 Salient Features of Test Carried out by Y.N.Chan et al

Size of the specimen(m)	ıperaturerange	Time duration	Time-temperature curve	Rate of heating	Rate of cooling/ coolant	ype oftest
Cube (0.1x0.1x0.1)	20, 400, 600, 800, 1000 & 1200°C	Peak temperature maintained for 1 hour	Furnace temperature curve	-	Natural cooling by air	Un stressed residual strength test

Y.N.Chan et al (2000)[16] carried out an experimental investigation to study the mechanical properties and pore structure of high performance concrete and normal strength concrete after exposure to high temperature. After the concrete specimens were subjected to a temperature of 800°C, their residual compressive strength was measured. The porosity and pore size distribution of the concrete were investigated using mercury intrusion porosimetry. Test results indicated that HPC had higher residual strength than the normal strength concrete after exposure to high temperature. It was reported that the changes in pore structure could be used to indicate the degradation of mechanical property of HPC subjected to high temperature. The salient features of the test are shown in Table 2.6

DEVELOPMENT OF SELF COMPACTING CONCRETE

Introduction

Concrete is a composite material composed of coarse granular materials embedded in hard matrix that fills the space between the aggregate particles and glues them together. Concrete can also be considered as a composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregates. Admixtures are defined as materials other than aggregate (fine and coarse), water, fibre and cement, which are added into concrete batch immediately before or during mixing. The widespread use of admixtures is mainly due to the many benefits made possible by their application. Chemical admixtures can modify the setting and hardening characteristics of cement paste by influencing the rate of cement hydration. Water reducing admixture can plasticize fresh concrete mixtures by reducing surface tension of water. Air entraining admixtures can improve the durability of concrete, and mineral admixtures can reduce thermal cracking.

With the advancement of technology and use of modern building materials, it has become possible to construct high rise structures having even more than hundred storeys. As per the revised seismic code, major part of India comes under severe earthquake zone. In order to satisfy the requirements of code and to make the structure ductile, heavy reinforcement is required specially at the beam column joints. Under this circumstance, proper vibration becomes impossible which may lead to poor compaction thereby reducing the quality and durability of the concrete. Vibrating concrete in congested locations may cause risk to the construction workers in addition to noise stresses. Concrete that does not require vibration was a challenge to the construction industry.

Self-Compacting Concrete

With the introduction of super plasticizers and viscosity modifying admixtures, it is now possible to produce concrete with high fluidity and good cohesiveness. Self compacting concrete is a form of concrete that is capable to flow into the congested interior of the formwork, passing through the reinforcement and filling it in a natural manner, consolidating under the action of its own weight without having defects due to segregation and bleeding. Partial replacement of cement or aggregates with industrial by-products such as flyash and silica fume is one of the methods to improve the workability and reduce the segregation.

Inadequate homogeneity of the cast concrete due to poor compaction or segregation may drastically lower the performance of in-situ concrete. SCC has been developed to ensure adequate compaction and facilitate placement of concrete in structures with congested reinforcement and in restricted areas. SCC was developed first in Japan in the late 1980s to be mainly used for highly congested reinforced structures in seismic regions. As the durability of concrete structures became an important issue in Japan, an adequate compaction by skilled labors was required to obtain durable concrete structures. The non-availability of skilled man power led to the development of SCC.

Development of Self Compacting Concrete

The method for achieving self compactibility involves not only high deformability of paste or mortar, but also resistance to segregation between coarse aggregate and mortar when the concrete flows through the confined zone of reinforcing bars. Homogeneity of SCC is the ability to remain in unsegregated condition during transport and placing. High flowability and high segregation resistance of SCC are obtained by:

- Larger quantity of fine particles and limiting the coarse aggregate little lower than the fine aggregate content.
- Low water/powder ratio, powder is defined as cement plus the pozzolonic material such as flyash, silica fume etc.,)
- The use of superplasticizer and viscosity modifying admixture.

Because of the addition of a high quantity of fine particles, the internal material structure of SCC shows some resemblance to high performance concrete having self compactibility in fresh stage, no initial defects in early stage and protection against external factors after hardening. Self compacting concrete can be produced using standard cements and additives.

Characteristics of Self Compacting Concrete

Three basic characteristics that are required to obtain SCC are: high deformability, restrained flowability and a high resistance to segregation. High deformability is related to the capacity of the concrete to deform and spread freely in order to fill all the space in the formwork. It is usually a function of the form, size, quantity of the aggregates and the friction among the solid particles, which can be reduced by adding a High Range Water Reducing Admixture (HRWRA) to the mixture. Restrained flowability represents how easily the concrete can flow around obstacles, such as reinforcement, and is related to the member geometry and the shape of the formwork. Segregation is usually related to the cohesiveness of the fresh concrete, which can be enhanced by adding mineral admixtures and viscosity modifying admixture along with a HRWRA.

Testing of Materials

Ordinary Portland Cement

In this present study, Ordinary portland cement of grade 53 conforming to IS: 12269–1987 was used. The standard consistency of the cement found according to IS: 4031 (Part 4) –1988. Initial and final setting times of cement were found as per IS: 4031 (Part 5) –1988. Compressive strength of cement was determined as per IS: 4031 (Part 6) –1988. The cement was purchased from single source and was used for casting of all specimens. The specific gravity of this cement was 3.15. The physical characteristics of the cement are given in Table 3.1.

Table 3.1 Properties of Ordinary Portland Cement

Type of Cement	Ordinary Portland Cement (53 Grade)
Conforming code	IS: 12269 – 1987
Fineness (retained on 90µ sieve)	5%
Normal Consistency	35%
Compressive strength 3 days (MPa)	20
Compressive strength 7 days (MPa)	36
Compressive strength 28 days(MPa)	52
Specific Gravity	3.15
Bulk Density (kg/m^3)	1610

Fine Aggregate

The influence of fine aggregates on the fresh properties of the SCC is significantly greater than that of coarse aggregate. The high volume of paste in SCC mixes helps to reduce the internal friction among the sand particles but a good grain size distribution is still very important.

The fine aggregate used during the investigation was natural river sand brought from the Amaravathi riverbed, Karur complying with IS: 383 -1970. Specific gravity of the aggregate was determined as per IS: 2386(PIII)-1963. The specific gravity of fine aggregate was found to be 2.62. Sieve analysis was carried out and it was found that the sand was confirming to grading Zone II. Bulk density of fine aggregate used was found to be 1533 kg/m^3. Fineness modulus of sand was found tobe 2.7. The properties of fine aggregate are given in Table 3.2.

Table 3.2 Properties of Fine Aggregate

Type of Fine aggregate	River sand
Conforming code	IS: 383 -1970
Fineness modulus	2.7
Specific gravity	2.62
Bulk density	1533
Water absorption	Nil
Zone	II

Coarse Aggregate

Coarse aggregate is an important constituent of concrete as it occupies three quarters of the volume of the concrete. It contributes significantly to the structural performance of concrete, especially strength, durability and volume stability. The reinforcement spacing is the main factor in determining the maximum aggregate size. The particle size distribution and the shape of coarse aggregate directly influence the flow and passing ability of SCC. In this study, crushed granite stones were used as normal weight coarse aggregates. The coarse aggregate used was hard broken granite stones drawn from an approved quarry at Sulur near Coimbatore. Crushed granite aggregates of size 10mm were used. The specific gravity of coarse aggregate was 2.87 and it was confirming to IS 383-1970. The properties of coarse aggregate are given in Table 3.3

Table 3.3 Properties of Coarse Aggregate

Type of Coarse aggregate	Crushed granite
Conforming code	IS: 383 -1970
Specific gravity	2.87
Bulk density	1562
Size of aggregate	10mm

Water

Water is the key ingredient, which when mixed with cement, forms a paste that binds the aggregate together. Potable water available in the laboratory was used for casting and curing of all the specimens. The quality of water was found to satisfy the requirements of IS: 456-2000.

FlyAsh

Flyash is one of the numerous substances that cause air, water and soil pollution. It disrupts ecological cycles and sets off environmental hazards. The combustion of powdered coal in thermal power plants produces flyash. Flyash produced thus possesses both ceramic and pozzolanic properties. Flyash is of two basic types namely, Class F type and Class C type. Both Class F and Class C flyashes undergo a pozzolanic reaction with the lime (calcium hydroxide) created by the hydration of cement and water, to create secondary calcium silicate hydrate gel. Class F flyash, with particles covered in a kind of melted glass, greatly reduces the risk of expansion due to sulphate attack. Class F flyash is particularly beneficial in high performance concrete applications where high compressive strengths are required or where severe exposure conditions demand highly durable concrete. Class F flyash is also very effective at mitigating problems associated with alkali-silica reactions. The present investigations were carried out using Class F flyash which was obtained from Mettur thermal power station, Tamil Nadu, India. The physical properties of flyash are given in Table 3.4.

Table 3.4 Properties of Class F Flyash

Mineral Admixture	Flyash (Class F)
Specific gravity	2.00
Silica (SiO_2) %	58.55
Iron Oxide (Fe_2O_3) %	3.44
Alumina (Al_2O_3) %	28.20
Calcium Oxide (CaO) %	2.23
Magnesium Oxide (MgO) %	0.32
Sodium Oxide (Na_2O) %	0.58
Potassium Oxide (K_2O) %	1.26
Total Sulphur (SO_3) %	0.07
Bulk Density (kg/m^3)	995
Surface area	2000 m^2/ kg
Colour	light gray

Super Plasticizer

Super plasticizers are linear polymers containing sulphuric acid groups attached to the polymer backbone at regular intervals. The super plasticizer used for the present study is Glenium B233. It is an admixture of a new generation based on modified polycarboxylic ether. The product has been primarily developed for applications in high performance concrete where the highest durability and performance is required. Glenium B233 is free of chloride, has a low alkali content and compatible with all types of cements. Glenium B233 consists of a carboxylic ether polymerwith long side chains. At the beginning of the mixing process, it initiates the same electrostatic dispersion mechanism as the traditional super plasticisers, but the side chains linked to the polymer backbone generate a steric hindrance which greatly stabilises the cement particles ability to separate and disperse. With this process, flowable concrete with a large reduction in the water content is obtained. The properties of Glenium B233 are given in Table 3.5.

Table 3.5 Properties of Glenium B233

Sl. No.	Property	Super Plasticizer
1	Chemical type	Polycarboxylic ether
2	Specific gravity	1.09
3	Chloride content	Nil
4	Approx. air entrainment	1% at normal dosages
5	Relative Density	1.09 ± 0.01 at 25°C
6	pH	6
7	Dosage	500 ml to 1500 ml per 100 kg of cementitious material
8	Solid content	30%
9	Conforming standard	ASTM C 494 Type F
10	Colour	Light brown

12	Form	Viscous liquid
13	Transport	Not classified as dangerous
14	Labelling	No hazard label required

Viscosity Modifying Admixture

Viscosity modifying admixtures can be used to produce concrete with better robustness against the impact of variations in the concrete constituents and in site conditions, making it easier to control. The key function of a VMA is to modify the rheological properties of the cement paste. VMA changes the rheological properties of concrete by increasing the plastic viscosity but usually cause only a small increase in the yield point.

The viscosity modifying admixture used for the present study is Glenium stream 2. It is a premier ready-to-use liquid, organic viscosity modifying admixture specially developed for producing concrete with enhanced viscosity and controlled rheological properties. Concrete containing Glenium stream 2 admixture exhibits superior stability and controlled bleeding characteristics, thus increasing resistance to segregation and facilitating placement. Glenium stream 2 consists of a mixture of water soluble copolymers which is absorbed onto the surface of the cement granules, thereby changing the viscosity of the water and influencing the rheological properties of the mix. It is chloride free and compatible with all cements and is incompatible for use with naphthalene sulphonate based super plasticiser admixtures. The properties of Glenium stream 2 are given in Table 3.6

Table 3.6 Properties of Glenium Stream 2

Sl. No.	Property	Viscosity ModifyingAdmixture
1	Chemical type	Water soluble polymer
2	Specific gravity	---
3	Chloride content	Nil
4	Approx. air entrainment	---
5	Relative Density	1.01 ± 0.01 at 25°C
6	pH	6
7	Dosage	50 ml to 500 ml per 100 kg of cementitious material
8	Solid content	---
9	Conforming standard	---
10	Colour	Colourless
12	Form	Viscous liquid
13	Transport	Not classified as dangerous
14	Labelling	No hazard label required

Mix Design

A mix design procedure developed by Prince Arulraj and Jemi Elizabeth (2008)[83] has been adopted for the present study. Using the mix design procedure, M25, M30, M35 and M40 grades of SCC were designed. Concrete was made self compactable by adjusting the proportions of the normal concrete obtained as per IS 10262:2009 method. Cement was not replaced with flyash. Flyash was added to the mix such that it replaces either the fine aggregate or coarse aggregate whichever is more till the coarse aggregate content is slightly less than the fine aggregate. The flow properties such as filling ability, passing ability and segregation resistance were checked by conducting the Slump flow test, J-ring test and V-funnel test and found to be satisfactory. Hardened properties of SCC such as compressive strength, tensile strength and flexural strength were found following the procedures given in respective Bureau of Indian Standards. The methodology followed for the design of mixes for various grades of SCC is shown in Figure 3.1.

DEVELOPMENT AND VALIDATION OF FINITE ELEMENT MODEL

Introduction

Finite Element Method (FEM) is a numerical technique for finding approximate solutions to boundary value problems. It minimizes an error function and produces a stable solution to many engineering problems. ANSYS is a popular finite element analysis package that can be used to simulate the response of a physical system subjected to structural and thermal loading. Experimental investigations are more reliable to understand the behaviour of SCC beams subjected to elevated temperatures, but the cost of carrying out experimental investigations is high. Moreover handling beams subjected to temperature of 500°C and more is risky. In case of analytical modelling, it is easy to vary the parameters such as grade of concrete, cover, reinforcement percentage, intensity of temperature, duration of heating, rate of cooling etc., Hence an attempt has been made to carry out an analytical investigation using the software ANSYS to determine the performance of SCC beams subjected to elevated temperatures. Since the behaviour of concrete is nonlinear, the nonlinear behaviour properties were incorporated in the model and the model was solved using a coupled thermal structural analysis feature available in the ANSYS software. The details of the elements used in the model are given below.

SOLID65: 3D Reinforced Concrete Solid

SOLID65 was used for the 3D modelling of concrete. This element is capable of cracking in tension and crushing in compression. The element is defined by eight nodes having three degrees of freedom at each node such as translations in the nodal x, y and z directions. The most important aspect of this element is the treatment of nonlinear material properties. The concrete is capable of cracking (in three orthogonal directions), crushing, undergoing plastic deformation and creep. SOLID65 element can effectively model these features of concrete. The geometry details of SOLID65 element are shown in Fig 4.1.

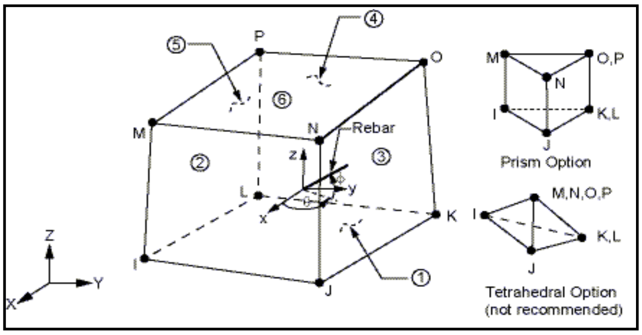


Fig 4.1 Geometry of SOLID65 Element

SOLID70: 3D Thermal Solid

SOLID70 was used for modelling concrete with thermal load. This element has a 3D thermal conduction capability. It has eight nodes with a single degree of freedom, temperature, at each node. It is applicable to a 3D, steady state or transient thermal analysis. It can also compensate for mass transport heat flow from a constant velocity field. If the model containing the conducting solid element is also to be analyzed structurally, the element should be replaced by an equivalent structural element.The geometry details of SOLID70 element are shown in Fig 4.2.

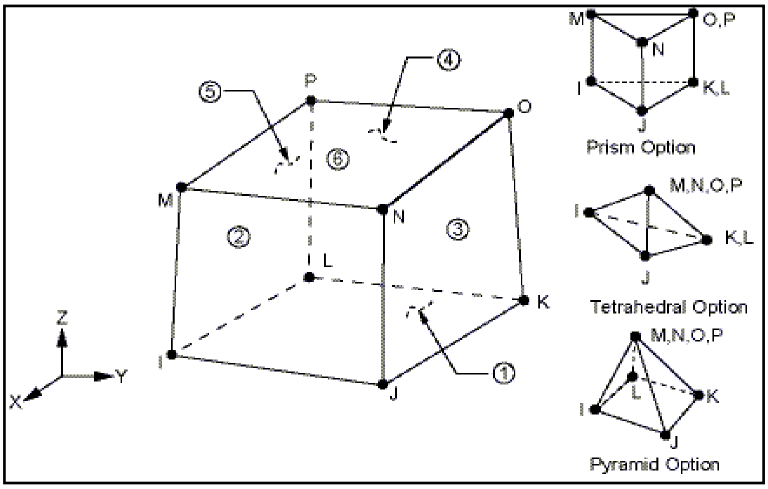


Figure 4.2 Geometry of SOLID70 Element

LINK8 (3D Spar)

LINK8 is used for modelling the rebars. Link 8 is a spar which may be used in a variety of engineering applications. The 3D spar element is a uniaxial tension- compression element with three degrees of freedom at each node: translations in the nodal x, y, and z directions. Plasticity, creep, swelling, stress stiffening and large deflection capabilities are included in it. The geometry details of LINK8 element are shown in Fig 4.3.

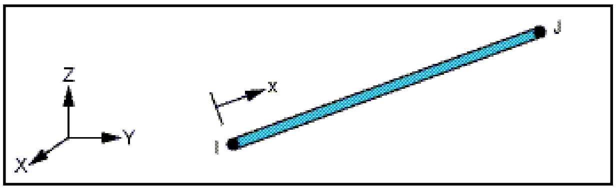


Figure 4.3 Geometry of LINK8 Element

LINK33: 3D Conduction Bar

LINK33 is an uniaxial element with the ability to conduct heat between its nodes. The element has a single degree of freedom, temperature, at each node point. The conducting bar is applicable to a steady state or transient thermal analysis. If the model containing the conducting bar element is also to be analyzed structurally, the bar element should be replaced by an equivalent structural element. The geometry details of LINK33 element are shown in Fig 4.4.

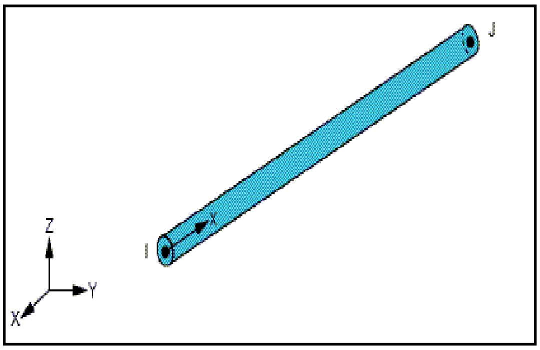


Figure 4.4 Geometry of LINK33 Element

Nonlinear Coupled Thermal Structural Transient analysis was carried out using the appropriate elements of the ANSYS software. In order to model the reinforced self-compacting concrete specimens subjected to elevated temperature, stress strain relationship, compressive strength, tensile strength, modulus of elasticity for self compacting concrete and time temperature graphs are to be given as input in the ANSYS model. Self compacting concrete mixes of grade M25, M30, M35, M40 were designed. Cubes and cylinders were cast. Compressive strength, density of the cubes, tensile strength of cylinders and the values of modulus of elasticity were found in hot condition. The cylinders were used to derive the stress-strain behaviour of SCC using uniaxial compression test. Time-temperature curves (Rate of heating and Rate of cooling) were obtained for the specimens heated inside the electrical furnace using an IR thermometer for the following cases.

a) Specimens were kept inside the furnace and heated from 27°C to 900°C

b) Specimens were placed in the furnace after achieving a furnace temperature of 900°C and the specimens were kept inside the furnace for the duration of 90minutes. The details of the specimens cast for unstressed test are given in Table 4.1.

Table 4.1 Details of Unstressed Test

Grade of concrete	Temperature(°C)	No of Cubes tested	No of Cylinders tested
M25, M30, M35, M40	Reference Specimen	12	24
M25, M30, M35, M40	300	12	24
M25, M30, M35, M40	600	12	24
M25, M30, M35, M40	900	12	24

Table 4.2 gives the details of the Compressive strength of reference and hotspecimens.

Table 4.2 Compressive Strength of Self Compacting Concrete

Grade of Concrete	Compressive Strength (N/mm^2)			
	Reference Specimen	300°C	600°C	900°C
M25	26.04	21.36	14.05	5.82
M30	30.33	24.46	16.41	6.05
M35	35.67	28.24	18.62	6.41
M40	39.63	31.54	20.75	6.88

Table 4.3 gives the details of the Tensile Strength of reference and hot specimens.

Table 4.3 Tensile Strength of Self Compacting Concrete

Grade of Concrete	Tensile Strength (N/mm^2)			
	Reference Specimen	300°C	600°C	900°C
M25	2.72	2.46	1.62	0.67
M30	3.56	3.22	2.16	0.80
M35	4.02	3.64	2.40	0.83
M40	4.45	4.03	2.65	0.88

Table 4.4 gives the details of the Modulus of elasticity of reference and hotspecimens.

Table 4.4 Modulus of Elasticity of Self Compacting Concrete

Grade of Concrete	Modulus of Elasticity (N/mm^2)			
	Reference Specimen	300°C	600°C	900°C
M25	20650.8	19411.1	15930.4	10132.4
M30	21576.01	20277.4	16811.3	10084.7
M35	22905.02	21522.2	17691.9	10253.8
M40	23616.94	22464.2	18448.6	10360.8

Figure 4.5 shows the stress strain behaviour of M25 grade SCC reference andheated specimens that were at 300°C, 600°C and 90

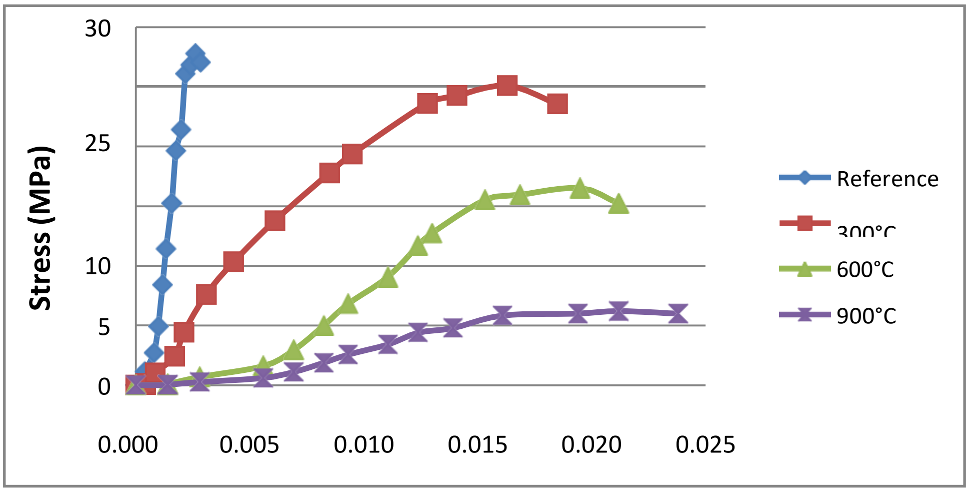


Figure 4.6 Stress Strain Behaviour of M30 Grade Concrete

Figure 4.7 shows the stress strain behaviour of M35 grade SCC reference andheated specimens that were at 300°C, 600°C and 900°C.

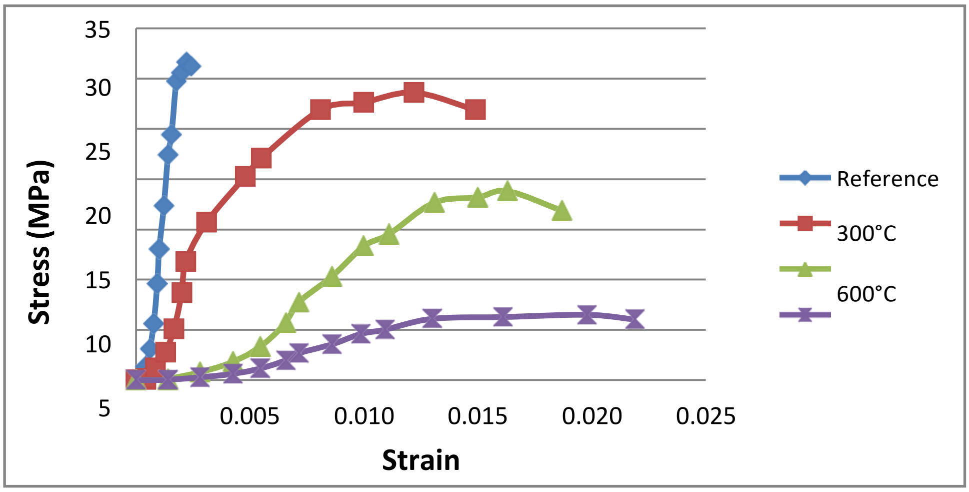


Figure 4.7 Stress Strain Behaviour of M35 Grade Concrete

Figure 4.8 shows the stress strain behaviour of M40 grade SCC reference andheated specimens that were at 300°C, 600°C and 900°C.

Grade of concrete	Density (kg/m^3)		
	Reference specimen	Specimens heated from 27^{o}C -900^{o}C	Specimens kept at 900^{o}C for 90 minutes
M25	2411.85	2216.3	2278.52
M30	2503.70	2222.2	2346.66
M35	2554.07	2228.15	2385.18
M40	2645.92	2237.1	2432.60

Time -Temperature Relation

In order to obtain the time-temperature relationship, an Infrared (IR) thermometer was used to find the temperature of the specimens at specified durations. A typical time-temperature relationship for the SCC specimen that was heated from 27°C to 900°C is shown in Fig 4.9.

Rate of Heating

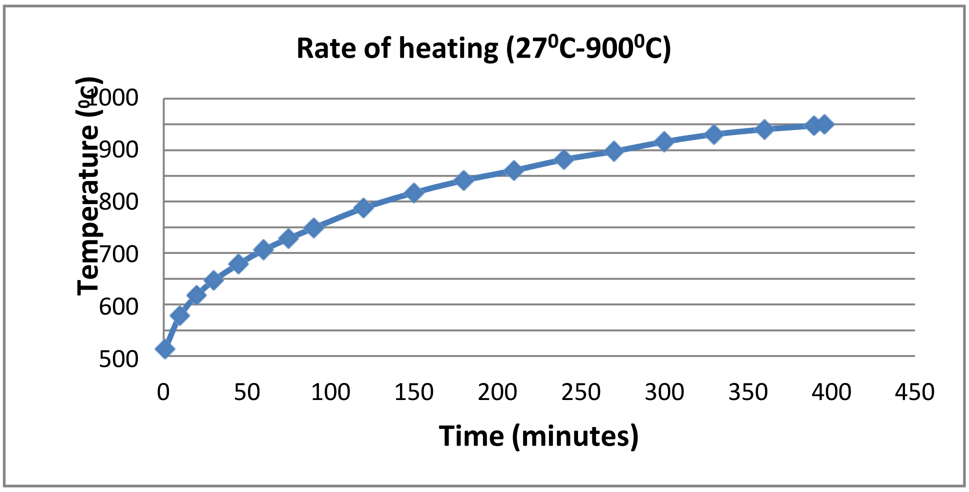


Fig 4.9 Rate of Heating (27°C to 900°C)

From the above figure, it can be seen that the target temperature (900°C) was obtained only after 396 minutes. Figure 4.10 shows the time – temperature relationship for the specimen kept at 900°C for 90 minute duration.

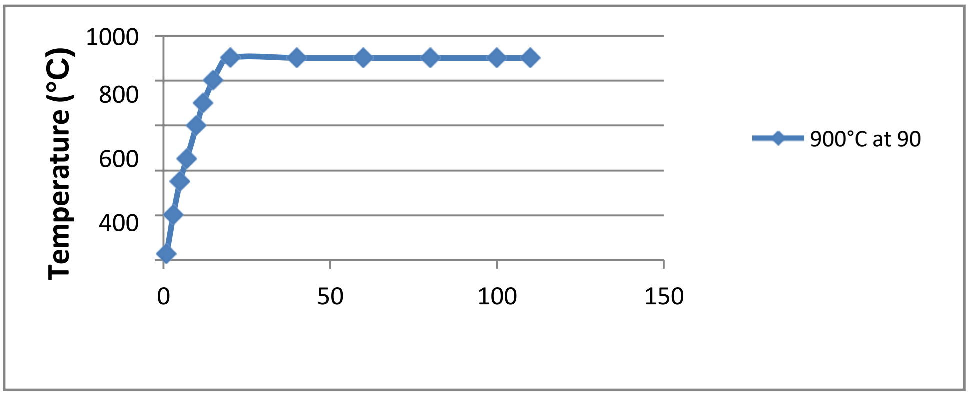


Fig 4.10 Rate of Heating (900°C at 90 min)

Rate of Cooling

In order to obtain the time – temperature relationship during the cooling phase, the same IR thermometer was used and a typical time – temperature relationship for a specimen that was cooled by water from 900°C to 27°C is shown in Fig 4.11

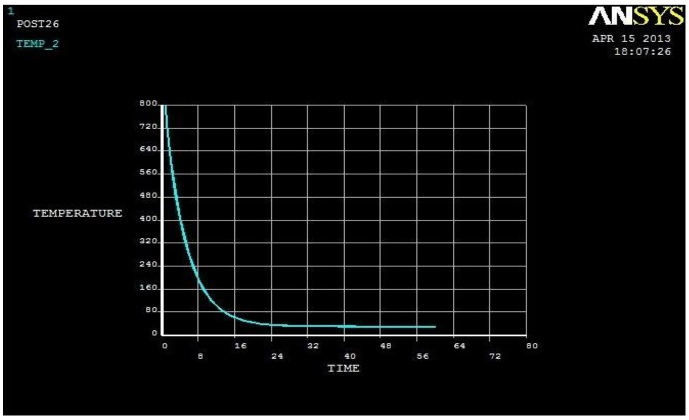


Fig 4.11 Rate of Cooling from 900°C to 27°C (Water Cooling)

From the above figure, it can be seen that the specimen reaches 27°C after 45 minutes. Figure 4.12 shows the time – temperature relationship for the specimen cooled by air from 900°C to 27°C.

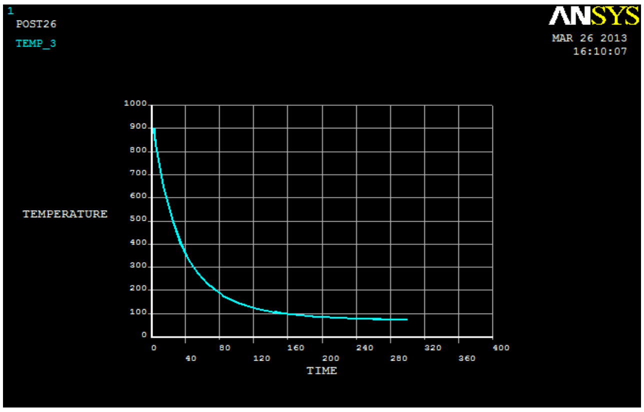


Fig 4.12 Rate of Cooling from 900°C to 27°C (Air Cooling)

From the above figure, it can be seen that the specimen reaches 27°C by air cooling after 300 minutes.

Validation of ANSYS Modelling

As software packages require to be validated for checking the accuracy of results, ANSYS results need to be validated with experimental results. In order to validate the results of the ANSYS model, an experimental investigation was carried out. The results of the ANSYS model were compared with the experimental results. The results of the ANSYS model were also compared with the results available in the literature. Three beams of size 500mmx100mmx100mm were cast. All the beams were reinforced with 2 number of 6mm diameter bars at top and 2 number of 8mm diameter bars at the bottom. Two legged 6mm stirrups at 50mm c/c were used as shear reinforcement. The first specimen was kept as the reference specimen. The second specimen was heated from 27°C to 900ºC and cooled by air. The third specimen was heated from 27°C to 900ºC and cooled by water. These conditions were reproduced in ANSYS modelling. The ANSYS model of the specimen is shown in Fig 4.13 and the crack pattern of the analysed model is shown in Fig 4.14.

Fig 4.13 ANSYS Model

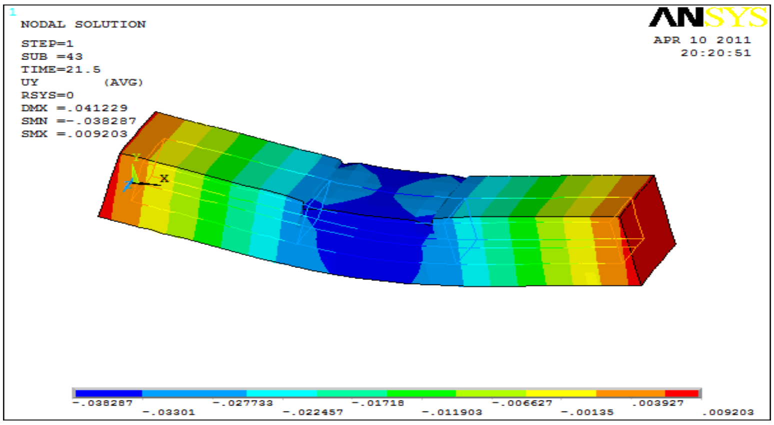


Fig 4.14 Crack Pattern in ANSYS Model

Fig 4.15 shows the comparison between the load deflection values of the experimental investigation and the ANSYS model for the reference specimen of grade M25.

EXPERIMENTAL AND ANALYTICAL INVESTIGATION ON SCC SPECIMENS UNDERELEVATED TEMPERATURES

Experimental Investigation on SCC

Introduction

In order to understand the effects of elevated temperature on the properties of SCC, an extensive laboratory investigation was carried out. Tests were carried out on cubes of size 150x150x150mm, cylinder of diameter 150mm and height 300mm and beams of size 500x100x100mm. The specimens were heated in an unloaded condition to test temperature and cooled either by air or water to reach the room temperature. This type of test is known as unstressed residual strength test. Unstressed residual strength test was carried out to determine the effect of cover, reinforcement percentage and different grades of concrete on the performance of SCC specimens subjected to elevated temperatures.

Test on Cube Specimens

Experimental investigation was carried out to determine the effect of grade ofconcrete on the compressive strength of SCC subjected to elevated temperatures. Sixty cube specimens of different grades were cast. Cube specimens were of standard size 150x150x150mm. After 28 days of curing, all the specimens were air dried prior to high temperature exposure or for load test. The reference specimens were tested using compression testing machine. The other specimens were subjected to elevated temperatures and cooled either by air or by spraying water. Table 5.1 gives the details of cube specimens that were cast for unstressed residual strength test.

Test on Cylinder Specimens

Experimental investigation was carried out to determine the effect of grade ofconcrete on the tensile strength of SCC subjected to elevated temperatures. Sixty cylinder specimens of different grades were cast. Cylinder specimens were of standard size 150X300mm. After 28 days of curing, all the specimens were air driedprior to high temperature exposure or for load test. The reference specimens were tested using compression testing machine. The other specimens were subjected to elevated temperatures and cooled either by air or by spraying water. Table 5.1 givesthe details of cylinder specimens that were cast for unstressed residual strength test.

Test on Beam Specimens without Reinforcement

Experimental investigation was carried out to determine the effect of grade ofconcrete on the flexural strength of SCC subjected to elevated temperatures. Sixty beam specimens of different grades were cast. The beams were of standard size 500x100x100mm. After 28 days of curing, all the specimens were air dried prior to high temperature exposure or for load test. The reference specimens were tested using universal testing machine. The other specimens were subjected to elevated temperatures and cooled either by air or by spraying water. Table 5.1 gives the details of beam specimens that were cast for unstressed residual strength test.

Table 5.1 Details of Specimens Used for Experimental Investigation(Effect of Grade of Concrete)

Size of beam (mm)	Size of cube (mm)	Size of cylinder (mm)	Grade of concrete	Temperature	Type of cooling	Designation of specimen
500x100x 100	150x150 x150	150x 300	M25, 30, M35, 40	Reference specimen	-	-
500x100x 100	150x150 x150	150x 300	M25, 30, M35, 40	27°C to900^{0}C	Water	T1Wc
500x100x 100	150x150 x150	150x 300	M25, 30, M35, 40	900^{0}C @ 90min	Water	T2Wc
500x100x 100	150x150 x150	150x 300	M25, 30, M35, 40	27°C to900^{0}C	Air	T1Ac
500x100x 100	150x150 x150	150x 300	M25, 30, M35, 40	900^{0}C @ 90min	Air	T2Ac

During the present investigation 60 cube specimens, 60 cylinder specimens and 60 beam specimens without reinforcement were tested.

Test on Beam Specimens with Reinforcement

Experimental investigation was carried out to determine the ultimate load, deflection, stiffness and energy absorption capacity of different grade of SCC beams. Four hundred and eighty beam specimens of different grades were cast. The beams were of standard size 500x100x100mm. After 28 days of curing, all the specimens were air dried prior to high temperature exposure or for load test. The reference and heated specimens were tested using universal testing machine. The other specimens were subjected to elevated temperatures and cooled either by air or by spraying water. Table 5.2 gives the details of beam specimens that were cast for unstressed residual strength test. The details of the specimens tested are given in Table 5.2.

Table 5.2 Details of Specimens Used for Experimental Investigation

Grade ofconcrete	**Cover**	**Detail**	**Temperature(°C)**	**Duration of Heating (min)**	**Nature of cooling**
M25, M30, M35, M40	10,15, 20,25	D1	Reference Specimen	-	-
M25, M30, M35, M40	10,15, 20,25	D2	Reference Specimen	-	-
M25, M30, M35, M40	10,15, 20,25	D1	27°C to 900°C	-	Air
M25, M30, M35, M40	10,15, 20,25	D1	27°C to 900°C	-	Water
M25, M30, M35, M40	10,15, 20,25	D2	27°C to 900°C	-	Air
M25, M30, M35, M40	10,15, 20,25	D2	27°C to 900°C	-	Water
M25, M30, M35, M40	10,15, 20,25	D1	900°C	90	Air
M25, M30, M35, M40	10,15, 20,25	D1	900°C	90	Water
M25, M30, M35, M40	10,15, 20,25	D2	900°C	90	Air
M25, M30, M35, M40	10,15, 20,25	D2	900°C	90	Water

D1- 2 no of 6mm dia bars at top & 2no of 6mm dia bars at bottom, D2- 2 no of 6mm dia bars at top & 2 no of 8mm dia bars at bottom T1 – Refers to beams heated from 27°C to 900^{0}C, T2 – Refers to beams kept at 900^{0}C for 90min duration, Ac - Refers to beams cooled by natural air and Wc - Refers to beams cooled by water, RT – Refers to room temperature (27°C)

From Table 5.2 it can be seen that four grades of concrete, four cover thicknesses, two different reinforcement percentages, two exposure conditions and two types of cooling were tried.

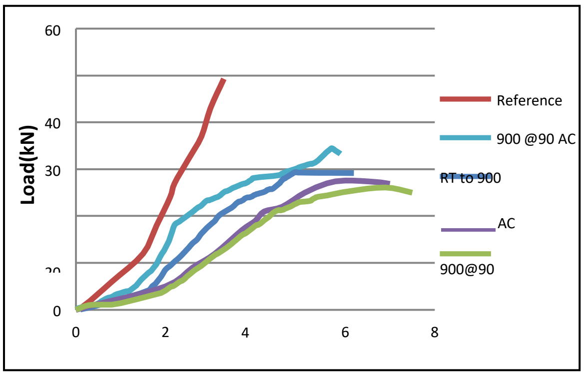
In order to determine the effect of reinforcement percentage on the load carrying capacity of SCC subjected to elevated temperature, four hundred and eighty beam specimens of different grades were cast. Table 5.3 gives the details of beam specimens that were cast for unstressed residual strength test.

Table 5.3 Details of Specimens Used for Experimental Investigation(Effect of Reinforcement Percentage)

Figure 5.2 Different Views of the Electrical Furnace

Figure 5.5 Load Deflection Behaviour of M25 M25Concrete (D1, 10mm cover)

Figure 5.6 Load Deflection Behaviour of Concrete (D1, 15mm cover)



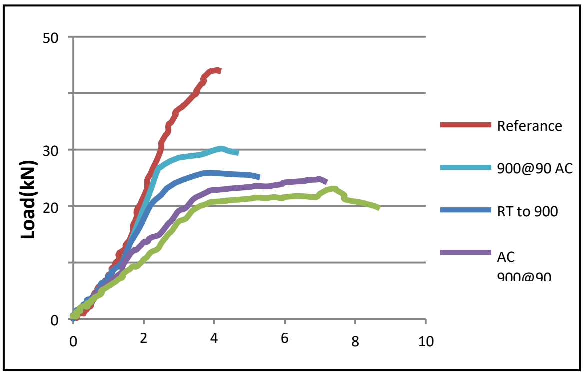


Figure 5.7 Load Deflection Behaviour of M25 of M25Concrete (D1, 20mm cover)

Figure 5.8 Load Deflection Behaviour Concrete (D1, 25mm cover)

Conclusions

General

- ✓ The reductions in the ultimate load carrying capacity of heated SCC beams were found to be in the range 36.25% to 60.65%. Ultimate load carrying capacities of heated SCC beams were found to be the least in the case of specimens heated from 27°C to 900°C and cooled by water.
- ✓ The deflections of heated beams were found to be more than those of the reference beams. The increase in deflection was found to be maximum for beams heated from 27°C to 900°C and cooled by water. The increase in deflection was found to be minimum for beams heated at 900°C for 90minutes duration and cooled by air.
- ✓ The reduction in the stiffness of heated SCC beams ranges from 61.75% to 81.65%. Stiffness of heated SCC beams was found to be the least in the case of specimens heated from 27°C to 900°C and cooled by water. The lowest reduction was in the case of M25 concrete with a reinforcement percentage of 0.57 having a cover thickness of 25mm. The highest reduction was in the case of M40 concrete with a reinforcement percentage of 1.01 having a coverthickness of 10mm.
- ✓ The reductions in the energy absorption capacity of heated SCC beams were found to be in the range 61.55% to 81.95%. Energy absorption capacities of heated SCC beams were found to be least in the case of specimens heated from 27°C to 900°C and cooled by water. The lowest reduction was in the case of M25 concrete with a reinforcement percentage of 0.57 having a cover thickness of 25mm. The highest reduction was in the case of M40 concrete with a reinforcement percentage of 1.01 having a cover thickness of 10mm.

Effect of Cover

- ✓ Based on the investigation, it was found that optimal cover exists for different grades of concrete for different types of heating and cooling conditions. Optimal cover was found to increase as the span increases from 4.5m to 9m. The value of optimal cover was found to decrease as grade of concrete increases. Also the value of optimal cover was found to be lower for the specimens cooled by water than that of the specimens cooled by air.
- ✓ The optimal cover of SCC beam of span 4.5m with M25&M30 concrete was found to be 40mm for the specimens heated from 27°C to 900°C as well as for the Specimens kept at 900ºC for 90 min duration and cooled by water.
- ✓ The optimal cover of SCC beam of span 4.5m with M35&M40 concrete was found to be 35mm in the case of specimens heated from 27°C to 900°C and also for the Specimens kept at 900ºC for 90 min duration and cooled by water.
- ✓ The optimal cover of SCC beam of span 6m with M25&M30 concrete was found to be 45mm in the case of specimens heated from 27°C to 900°C and also for the Specimens kept at 900ºC for 90 min duration and cooled by water.
- ✓ The optimal cover of SCC beam of span 6m with M35&M40 concrete was found to be 40mm in the case of specimens heated from 27°C to 900°C and also for the Specimens kept at 900ºC for 90 min duration and cooled by water.

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