STRENGTH AND PERMEABILITY STUDIES OF SELF-COMPACTING CONCRETE AT ELEVATED TEMPERATURES

A thesis

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CERTIFICATE

This is to certify that the thesis entitled, "**Strength and permeability studies of self-compacting concrete at elevated temperatures**", submitted by **Ms. Neelam Sharma** in partial fulfillment of requirements, for the award of degree of Doctor of Philosophy in Civil Engineering submitted in the Department of Civil Engineering, Thapar University,
Patiala is a record of the candidate original research work carried out by her under my guidance and supervision.

The matter embodied in this thesis has not been submitted in to any other university or institute for the award of any degree.

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DECLARATION

I here by certify that the work which is being presented in this thesis entitled, **"Strength and Permeability Studies of Self-Compacting Concrete at elevated temperatures,"** being in partial fulfillment of the requirements for the award of degree of Doctor of Philosophy in Civil Engineering submitted in Civil Engineering Department of Thapar University Patiala is an authentic record of my own work carried out by me under the supervision of Dr. Rafat Siddique and refers other research's work are duly listed in the reference section.

The matter presented in this thesis has not been submitted in part or full to any other university or institute for the award of any degree in India or abroad.

(Neelam Sharma)

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ABSTRACT

One of the major problems being faced by all the nations across the world is the disposal of waste materials and industrial by products due to its ever increasing quantities. There are several types of waste materials and industrial by products. Some of these can be put to use. The utilization of such materials in self-compacting concrete (SCC) makes it cost effective and helps in reducing disposal problem also. Fly ash is one of such industrial by products generated from combustion of coal in the thermal power plants. Another such by product is foundry sand obtained from ferrous and nonferrous metal casting industry and successfully used as a land filling material. But due to rapid increase in disposal cost, the use of fly ash and foundry sand for land filling is becoming a problem. Hence in the present research, awareness for using fly ash and foundry sand together as replacement of cement and fine aggregate are explored.

Pozzolanic concretes are used extensively throughout the world where oil, gas, nuclear and power industries are among the major users. Due to their superior structural performances, environmental friendliness, and energy conserving implications, the applications of such concretes are increasing day by day. These types of concretes are exposed to elevated temperatures for considerable periods of time in the above industries, apart from the usual risk of fire. Generally concrete is believed to be an excellent fire proofing material, but there is extensive damage at high temperatures. At high temperatures, chemical transformation of gel weakens the matrix bonding, which brings about a loss of strength of fly ash concrete.

Fly ash is used as a mineral addition in concrete to improve its strength and durability characteristics. Fly ash can also be used either as an admixture or as a partial replacement of cement or fine aggregates or total replacement of fine aggregates and as supplementary addition to achieve different properties of concrete.

In the present research, the experimental investigation was carried out to evaluate the strength properties (compressive strength, splitting tensile strength, and modulus of elasticity, mass loss, and porosity) and permeability (rapid chloride permeability) studies of SCC mixes at elevated temperatures up to 300ºC. Cement was replaced with three percentages (0%, 30%, 40%, and 50%) of fly ash and fine aggregate was replaced with 10% of foundry sand by weight. A total of four SCC mixes (SCC1, SCC2, SCC3, and SCC4) were developed. The control mix (SCC1) was developed without fly ash and foundry sand. Mix SCC2 was with 30% fly ash and 10% foundry sand, mix SCC3 was developed with 40% fly ash and 10% foundry sand, and the mix SCC4 was with 50% fly ash and 10% foundry sand. The specimens of each SCC mixture were heated up to different temperatures (100°C, 200°C, and 300°C). In order to ensure a uniform temperature throughout the specimens, the temperature was held constant at the maximum value for one hour before cooling. Tests were performed for compressive strength, splitting tensile strength, modulus of elasticity, mass loss, porosity, and rapid chloride permeability, after curing periods of 28, 91, and 365 days.

Test results showed that the compressive strength, splitting tensile strength, modulus of elasticity, mass loss, porosity, and rapid chloride permeability of SCC mixes made with 30%, 40%, and 50% of fly ash as cement replacement was lower than the control mix at all ages and that the strength of all mixes continued to increase with age. Test results also indicated that there is little improvement in compressive strength within the temperature range of 200°C-300°C as compared to 27°C-200°C. But the rate of splitting tensile strength and modulus of elasticity loss was higher than that of the compressive strength loss at elevated temperatures and with the increase in percentage of fly ash. In this research X-ray diffraction (XRD) and Scanning Electron Microscopic (SEM) studies were also made to explain the observed residual compressive strength increase between 200°C-300°C. Statistical analyses of the results were carried out at 28, 91, and 365 days of age. The results of correlation analysis depict that there is good correlation between actual properties and predicted properties.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER-1
INTRODUCTION

This chapter deals with general introduction about (i) self-compacting concrete (SCC), history of SCC, advantages and limitations of SCC, development of SCC mixes, (ii) effect of elevated temperature on SCC, damage mechanism of concrete under fire; (iii) fly ash, classifications of fly ash, properties of fly ash, applications of fly ash, foundry sand, types of foundry sand, properties of foundry sand, applications of foundry sand, applications of self-compacting concrete at elevated temperatures, objectives and scope of the work, and organization of thesis.

1.1. SELF-COMPACTING CONCRETE

Cement-based materials are the most abundant of all man-made materials and are among the most important construction materials, and it is most likely that they will continue to have the same importance in the future. However, these construction and engineering materials must meet new and higher demands. When facing issues of productivity, economy, quality and environment, they have to compete with other construction materials such as plastic, steel and wood. Out of all these materials concrete is the most widely used construction material in the world *(Mehta, 1999).* Concrete is a vital ingredient in infrastructure development with its versatile and extensive applications. The Indian construction industry today is consuming about 400 million tons of concrete every year and is expected to reach a billion tons in less than a decade. It is the most widely used construction material because of its ability that allows moulding into any required structural form and shape due to its fluid behaviour at early ages. However, there is a limit to the fluid behaviour of normal fresh concrete. Present day technology uses slow, heavy, noisy, expensive, energy consuming, and often dangerous mechanical vibration to compact the concrete in order to develop strength and durability. In situ pile concreting, under water-concreting, filling of congested sections and inaccessible areas are some of the several situations where concrete has to be placed in conditions in which compaction is extremely difficult. Thorough compaction, using vibration, is normally essential for achieving workability, the required strength and durability of concrete. Inadequate compaction of concrete results in large number of voids, affecting performance and long term durability of structures. Insufficient compaction drastically lowers the strength and durability performance of concrete, no matter how well it is designed. Improper or insufficient compaction not only results in inhomogeneous and non-uniform concrete but also drastically lowers the performance of concrete. Despite the rapidly growing use of pile foundations, it is presently difficult to assure the integrity and uniformity of the cross-sectional area of piles using normal concrete. Hence, a concrete which has the property of attaining compaction on its own weight without the need for any external aid would be very appropriate in such situations.

As the name signifies, it is able to compact itself without any additional vibration or compaction effort. Self-compacting concrete (SCC) is a modified product that, without additional compaction energy, flows and consolidates under the influence of its own weight. The use of SCC offers a more industrialized production. Not only will it reduce the unhealthy tasks for workers, it can also reduce the technical costs of in situ cast concrete constructions, due to improved casting cycle, quality, durability, surface finish and reliability of concrete structures and eliminating some of the potential for human error. However, SCC is a sensitive mix, strongly dependent on the composition and the characteristics of its constituents. It has to possess the incompatible properties of high flow ability together with high segregation resistance. This balance is made possible by the dispersing effect of high-range water-reducing admixture (super plasticizer) combined with cohesiveness produced by a high concentration of fine particles an additional filler material.

1.1.1. History of self-compacting concrete

In the beginning of 1983, their was a problem of durability of concrete structure in Japan. For the construction of durable concrete structures skilled labour for placing and compacting concretes was needed. At the time of its development in Japan and Europe, the availability of skilled workers was on the decrease *(Okamura et al., 2003)*. However, the gradual reduction in No. of skilled workers in Japan construction industry has lead to a similar reduction in the quality of construction work. Consequently, there was a need to render the durability of concrete structure to be independent of the quality of construction work. One solution for the achievement of durable concrete structure, independent of the quality of construction work is the employment of

SCC which can be compacted into every corner of formwork, purely by means of its own weight and without the need for vibrating compaction. However, as SCC developed it became evident that SCC provided many other additional benefits, irrespective of the skill of the construction worker. The development of SCC, also referred to as “Self-Consolidating-Concrete” and “High-Performance-Concrete,” has recently been one of the most important developments in the building industry. It is a kind of concrete that can flow freely under its own weight both horizontally and vertically and completely fill the formwork of any dimension and shape without leaving voids. During the time of placement and flowing, the concrete retains its homogeneity without separation of aggregate from paste or water from solids, and without the tendency for coarse aggregate to sink downwards through the fresh concrete mass. The necessity of this type of concrete was proposed by Okamura in 1986. Professor Ozowa of Japan (*Ozowa et al., 1989)* introduced the term ‘Self-compacting concrete’ (SCC) and than developed it at the University of Tokyo (*Bartos et al., 1999)* and after that it was developed by Okamura and Ouchi *(Okamura and Ouchi, 2003).* The concept of SCC was to revolutionize concrete technology and open up new horizons in the concrete applications that were unthinkable before. SCC was very different from normal concrete and was characterized by its ability to flow freely under its own weight with the absence of segregation and bleeding or the requirement for compaction the development of SCC carried out by (*Okamura and Ouchi, 2003)* is referred to as Japanese Method.

By definition, SCC is capable of flowing to every corner of formwork influenced only by the concrete’s self-weight and casting technique while remaining stable (no blocking or segregation). The working environment may improve due to the elimination of health problems (white fingers, noise) derived from vibration, a shortened construction period, and a reduction in labor cost. The development of SCC has contributed to an increasing degree of architectural freedom to carry out more complicated and advanced construction geometries, which may have been impossible to cast when using conventional concrete. It is used to facilitate and ensure proper filling and good structural performance of restricted areas. SCC was developed in Japan in the late 1980s to be mainly used for highly congested reinforced structures in seismic regions. Recently, this concrete has gained wide use in many countries for different applications and structural configurations. SCC can also provide a better working environment by eliminating the vibration noise. It is a concrete that flows and compacts under gravity.

To achieve the required fresh properties of deformability, segregation resistance and passing ability (or no blocking), SCC often uses a combination of greater number of constituent materials than in normal concrete. For example, the paste can contain one or more cement replacement materials, inert fine fillers, super plasticizers, and viscosity agents. A combination of powder materials is also used to control the hardened properties, such as strength. The workability and workability retention properties are of prime importance, and studies have shown that these are influenced by the properties of individual each constituent and the physical and chemical interaction between them.

1.1.2. Advantages of self-compacting concrete

- Reducing the construction time and labor cost
- Eliminating the need for vibration
- Reducing the noise pollution
- Improving the filling capacity of highly congested structural members
- Where access to allow vibration is impossible
- Complicated form works with very congested reinforcement (tunnel linings, dome structures)
- Where there are noise restrictions in the local area (hospitals, residential areas)
- Where pouring of concrete, only from a single point is practicable (tunnel lining)
- Where speed of placement is critical (SCC has a much higher speed of placement due to no vibration and speed of flow and hence cost savings to a project)
- Improving the interfacial transitional zone between cement pastes aggregate or reinforcement
- Higher strength
- Decreasing the permeability and improving the quality and durability of concrete
- Facilitating constructability and ensuring good structural performance
- Advantage with respect to sound pollution
- Major advantage of this method is that SCC technology offers the opportunity to minimize or eliminate concrete placement problems in difficult conditions. And it avoids

having to repeat the same kind of quality control test on concrete, which consumes both time and labor

1.1.3. Limitations

- Although the use of SCC has many technical, social, and overall economical advantages, its supply cost could be two to three times higher than that of normal concrete depending upon the composition of the mixture and quality control of concrete producer. Such a high premium has somehow limited the use of SCC application to general construction. SCC is specified only to areas where it is most needed. These include places where access to conventional vibration is difficult, or where there are congested reinforcements.

- The major difficulty which was faced in development of SCC was on account of contradictory factors that the concrete should be fully flowable but without bleeding or segregation. It is required that the cement mortar of the SCC should have higher viscosity to ensure flowability while maintaining non-sedimentation of bigger aggregates.

- To minimize the material cost of construction a sandwich concept of construction was introduced. This involves the casting of SCC and conventional concrete in layers within the same structural member. This concept is particularly applicable to large elements, where congested reinforcements occur only in limited areas of structural member. These could include foundation and post-tensioned members.

- However, the drawbacks of Okamura's method are that (i) it requires quality control of paste and mortar prior to SCC mixing, while many ready-mixed concrete producers do not have the necessary facilities for conducting such tests and (ii) the mix design method and procedures are too complicated for practical implementation.

1.1.4. Developing self-compacting concrete mixes

SCC mixes must meet the following three key properties *(Ouchi et al., 2006)*:

- Ability to flow into and completely fill complex forms under its own weight
- Ability to pass through the congested reinforcement under its own weight

- High resistance to aggregate segregation

In Japan, when an SCC mix was being designed, a suitable mix was selected i.e. Powder type, by increasing the powder content, VMA type, using viscosity modifying admixture and combined-type, by increasing powder content and using viscosity agent in consideration of structural conditions, available material, restrictions in concrete production plant etc.
In Europe, lime stone powder was used in addition with the materials used in Japan. In the U.S. also the above constituent materials were used in different proportions for different mixes.

SCC is not a specific concrete mix design; rather it is a continuum of mixes exhibiting similar flow characteristics. The rheological properties are developed by altering the mix design and possibly by the use of other admixtures. First, a high range water reducing admixture (super plasticizer) is used to provide the high flow ability of mix, much like a high slump concrete. Second the aggregate content is proportioned. The size and shape of the coarse aggregate are very important to the successful manufacture of SCC. Third the fluid properties are altered to provide a cohesive mix that will keep the aggregate and paste together. Traditional high range water reducing admixtures are used to provide the high flow required of the mix.

Aggregate size, shape, content and gradation play a critical role in the successful development of an SCC. As with any concrete mix, aggregate size must be limited to that which will pass through rebar opening. In SCC, the top size is often 1/2 to 3/8 inch. Rounded aggregate is desirable over angular aggregate because angular aggregates will have a tendency to lock together. Course aggregate content usually drops in as SCC mix resulting in sand and aggregate ratio of 0.50 or greater.

As the use of large quantity of cement increases cost and results in greater temperature rise, the use of mineral admixtures such as fly ash, lime stone filler, blast furnace slag, silica fume, glass or quartzite filler (fine sand) could increase the slump of concrete mix while reducing its cost and the dosage of super plasticizer needed to obtain the similar slump flow compared to concrete made with Portland cement only. These mineral admixtures are also used in order to avoid gravity segregation of larger particles in SCC mix.

Among these materials fly ash, a by product of thermal power plants, has been reported to improve the mechanical properties and durability of concrete when used as a cement replacement material (*Bilodeau et al., 1994)*. It is required that the cement mortar of the SCC should have higher viscosity to ensure flow ability while maintaining non-sedimentation of bigger aggregates. The successful development of SCC must ensure a good balance between deformability and stability. Researchers have set some guidelines for mixture proportioning of SCC, which include i) reducing the volume ratio of aggregate to cementitious material, (ii) increasing the paste volume, (iii) carefully controlling the maximum coarse aggregate particle size and total volume, (iv) using various viscosity modifying admixtures *(Ozawa et al.,1989).* To achieve the required fresh properties of deformability, segregation resistance and passing ability (or no blocking), SCC often uses a combination of greater number of constituent materials than in normal concrete. For example, the paste can contain one or more cement replacement materials, inert fine fillers, super plasticizers, and viscosity modifying admixtures to fine-tune the balance between deformability and stability. In the fresh mix, normally, the sum of cement and all filler varies between 450 and 650 kg/m^3 for SCC, i.e. about 200 kg/m^3 more fines than for VC. The fines in SCC prevent the larger aggregate from segregation in the fresh mix due to differences in gravity to the water and the cement in the fresh mix. Large amount of fillers in the concrete affects the durability, especially chloride ingress and fire resistance even though economical and ecological reasons talk of replacing Portland cement as much as possible by fillers *(Persson et al., 1999)*.

For SCC, it is generally necessary to use super-plasticizers in order to obtain high mobility.The addition of large volume of powdered material or viscosity modifying admixture can eliminate the problem of segregation. Since self-compactibility is largely affected by the characteristics of materials and the mix proportions, it becomes necessary to evolve a procedure for mix design of SCC. In this procedure, the coarse aggregate and fine aggregate contents are fixed and self-compactibility is to be achieved by adjusting the water/binder ratio and super plasticizer dosage *(Okamura et al., 1995)*. The coarse aggregate content in concrete is generally fixed at 50 percent of the total solid volume, the fine aggregate content is fixed at 40 percent of the mortar volume and the water/powder ratio is assumed to be 0.9-1.0 by volume depending on the properties of the powder and the super plasticizer dosage. The required water/binder ratio is determined by conducting a number of trials. One of the limitations of SCC is that there is no established mix design procedure yet.

An SCC mix must have the following characteristics:

- Non-Segregation: The aggregate should stay in suspension in the mix as it flows into the form
- Non-Bleeding: Water should not rise to the top of mix
- Vibration: No vibration is required during placement
- Flow spreads: Flow spreads of 18-inch diameter or greater should be obtained

There is no general requirement for any specific mixer type. Generally, mixing time needs to be longer then that for conventional mixes. SCC tends to dry faster than the conventional concrete because there is little or no bleed water at the surface. Curing should be started as soon as practicable, after placing the concrete, to control shrinkage cracks.

1.2. EFFECTS OF ELEVATED TEMPERATURE ON SCC

As the use of SCC becomes common, the risk of exposing it to elevated temperatures increases. Concrete structures including furnace walls, pipes and vessels are possibly exposed to elevated temperatures during fire or when SCC is near to furnaces and reactors; this significantly reduces the mechanical properties of SCC such as strength and modulus of elasticity during these high temperature exposures. Elevated temperature can cause the development of cracks. These cracks like any other crack propagation may cause loss of structural integrity and lead to shortening of structure life or undesirable structural failure.

The effects of elevated temperature on the mechanical properties of concrete have been investigated since 1940s *(Malhotra, 1956)*. Concretes containing mineral admixtures or pozzolanic concretes are used extensively throughout the world for their good performance and economic reasons, especillaly where oil, gas, nuclear and power industries are among the major users. The applications of such concretes are increasing day by day due to their superior structural performance, environmental friendliness, and energy conserving implications. Apart from the usual risk of fire these concretes are exposed to elevated temperatures for considerable periods of time in the above mentioned industries. Although concrete is generally believed to be an excellent fire proofing material, but there is damage at elevated temperatures. At elevated temperatures, chemical transformation of gel weakens the matrix bonding, which leads to a loss of strength of fly ash concrete.

There are changes in the properties of concrete particularly in the range of 100-300^{o}C. At early stages of heating the evaporable water from concrete is lost over in the range of 20°C to 110°C. As the cement paste is exposed to increasing temperature, the effects that can takes place are, explosion of evaporable water (100^{o}C), and at this temperature level concrete is normally considered healthy. Above 110°C the cement hydrates decompose, calcium hydroxide is broken down and the calcium carbonate suffers decarbonation. At about 180^{o}C, the beginning of the dehydration of the hydrated calcium silicate takes place and thermal expansion of aggregates increases internal stresses. The aggregate also suffers changes, which contributes to the general loss of structure safety. At early stages internal vapour, decomposition, and interface cracking cause a decrease in the strength of concrete structure. Generally at elevated temperatures, the cement paste shrinks due to dehydration/decomposition of the hydrates while the aggregates usually expand before disintegration *(Luston, 1979)*. Hardened cement paste expands on heating from room temperature to about 150°C. With a rise of temperature from 150 to 300°C, cement paste starts to shrink. From 300^{o}C, micro crakes are induced and parts of concrete structure get a pink colour. Thus thermal stresses and cracks develop under conditions of high temperature exposure *(Philleo, 1958).* Above 300^{o}C there is decrease in mechanical characteristics.

The decrease in strength depends on a variety of elevated temperature conditions used and on the variety of constituent materials used. The behavior of concrete subjected to elevated temperature is a result of many factors, such as heating rate, peak temperature, dehydration of C-S-H gel and thermal incompatibility between cement paste and aggregates. Elevated temperature induces several micro structural changes that alter mechanical properties of Portland cement concrete. The physical and chemical changes in concrete under elevated temperature depend not only on the matrix composition but also on the type of aggregates. The other factors that influence are w/c ratio, porosity, humidity, age of concrete, and the initial moisture content of the specimen. The alterations produced by elevated temperatures can be more when the temperature reaches 500^{o}C. Most changes experienced by concrete at this temperature level can be considered irreversible. C-S-H gel, which is the strength giving compound of cement paste, decomposes further above 600°C. At 800°C, concrete usually crumbles. As a result, a severe micro structural change is induced and concrete loses its strength and durability. The rise in temperature of the concrete over 1000°C is enough to destroy the original material. *(Sakr and Omar, 2005& 2007).*

1.2.1. Damage mechanism of concrete under fire

The effects of elevated temperatures on high strength concrete materials have also been studied during the past decade. Although there are significant differences between normal and high strength concretes in fire performance, their thermal damages (crack formation, explosive spalling, and degradation of mechanical /durability properties) are similar and mainly arise from (i) thermal mismatch, (ii) decomposition of hydrates, and (iii) pore pressure.

(i) Thermal mismatch

When a concrete member is subjected to an ideal uniform temperature field across its thickness, thermal stresses can still be developed because of the incompatibility of the coefficient of thermal expansion of the constitutive material in concrete. Concrete is a brittle composite material that consists of binder (cement) paste and aggregates. These materials have different physical and mechanical properties including different coefficient of thermal expansion. At a lower elevated temperature say 100°C, the thermal expansion of cement paste is slightly greater than that of granite. Consequently, in the concrete matrix the cement paste is under hydrostatic compression and the granite aggregates are under biaxial compression and tension. As the temperature further increases, for example over 400°C, the thermal strain of concrete changes to negative (shrinkage) due to chemical changes, whereas granite continue to expand. The corresponding stresses in concrete are that the granite aggregates are under hydrostatic compression and cement paste is under biaxial compression and tension.

(ii) Decomposition of hydrates

The mechanical properties of concrete depend largely on the hydration products (calcium silicate hydrate gel, calcium hydroxide, and ettringite) formed during the hydration reaction between the cementitious constituents and water. When concrete is exposed to fire attack, the free water in the concrete matrix will firstly be removed through a physical process such as evaporation at a lower elevated temperature. As the temperature further increases, disintegration of hydrates and loss of chemically bonded water will take place.

(iii) Pore pressure

Pore pressure developed in a heated concrete is derived from the evaporation of water within the porous media (free water) and from the decomposition of C-S-H gel and calcium hydroxide (chemically bonded water). The highest pore pressure occurred between 220^{o}C and 240^{o}C in high strength concrete and between 190^{o}C and 210^{o}C in normal strength concrete. The magnitude of pore pressure depends on, i) the moisture level (degree of saturation), ii) the permeability of concrete, and iii) the heating rate.

The influence of elevated temperatures on mechanical properties of concrete is very important for fire resistance studies and also for understanding the behavior of containment vessels, chimneys, nuclear reactor, pressure vessels during service and ultimate conditions structures like storage tanks for crude oil, hot water, coal gasification, liquefaction vessels used in petrochemical industries, foundation for blast furnace, coal and coke industries, furnace walls, industrial chimney, and air craft runways as these can be subjected to elevated temperatures. When these concrete structures exposed to elevated temperature, then it induces a material degradation, decrease in strength, cracking and in some conditions spalling also occurs. The effects of elevated temperature on SCC containing fly ash or natural pozzolans has not been investigated in detail unlike fly ash concrete that has been under investigation since the 1960s. Hence to predict the response of structure after exposure to elevated temperatures, it is essential that the strength properties of concrete be clearly understood.

1.3. FLY ASH

Fly ash is a finely divided residue resulting from the combustion of pulverized coal and is collected by mechanical and electrostatic separators from the fuel gases of thermal power plants where coal is used as a fuel. It is available in large quantities in the country, as a waste product, from a number of thermal power stations and industrial plants using pulverized coal as fuel from boilers. Fly ash resulting from the combustion of pulverized coal in boiler of thermal plant is grey in colour and alkaline in nature. Its availability is likely to increase with the increased industrialization in the country *(Bilodeau et al.,1994).* The amount of fly ash released annually by thermal plants world over is around 780 million tons. The amount of fly ash released annually by thermal plants in India is above 100 million tons and the percentage utilization in concrete is limited to 15-25% of the total cementitious material.

In the 1980s, CANMET developed a concrete incorporating large volume of fly ash that has all the attributes of high performance concretes, that is, one that has excellent mechanical properties, low permeability, superior durability, and that is environmentally friendly. Concretes having large amounts of fly ash (usually above 50%) are termed as high volume fly ash concretes. High-volume fly ash concrete has emerged as construction material in its own right. Fly ash has been shown to be an effective addition for SCC providing increased cohesion and reduced sensitivity to changes in water content. The disposal of fly ash is one of the major issues for environmentalists as dumping of fly ash as a waste material may cause severe environmental problems.*(Bilodeau and Malhotra, 2000).*

The ultimate compressive and tensile strengths of concrete mixtures made with partial replacement of cement with fly ash are almost always higher than those of plain Portland cement concrete. However, the setting and hardening rates of concrete at early ages are slower, especially under cold weather conditions, and when less reactive fly ashes are used. This has been the primary reason underlying the strong resistance by the concrete construction industry to the use of large amount of fly ash in concrete mixtures. It is now possible to make concrete incorporating large amount of fly ash concrete that is able to produce strength development rates at early ages similar to plain Portland cement concrete. Well cured concrete containing large amount of fly ash not only gives very low permeability and fewer cracks due to thermal and drying shrinkage effects, thus providing high resistance to the penetration of chloride ions, but it also provides excellent protection against expansive chemical reactions, such as sulfate attack and the alkali- silica reaction.

In commercial practice, the dosage of fly ash is limited to 15-20% by mass of total cementitious material. Usually this amount has a beneficial effect on the workability and cost economy of concrete but may not be enough to sufficiently improve the durability to sulfate attack, alkali-silica expansion, and thermal cracking. For this purpose large amount of fly ash, on the order of 25%-35% is being used. With 50% or more cement replacement by fly ash, it is possible to produce sustainable, high performance concrete mixtures that show high workability, high ultimate strength, and high durability.

1.3.1. Classifications of fly ash

Fly ashes are classified into the following three categories:

(i) Class N Fly ash: Raw or calcined natural pozzolans such as some diatomaceous earths, volcanic ashes and pumice come in this category.

(ii) Class F Fly ash: Fly ash normally produced from burning anthracite or bituminous coal falls in this category.

(iii) Class C Fly ash: Fly ash normally produced from burning anthracite or sub bituminous coal is the only material included in this category.

1.3.2. Physical properties of fly ash

Physical properties of fly ash are given below:

(i) Partial morphology: As per morphological studies, fly ash particles usually consist of clear glassy spheres and spongy aggregate ranging in diameter from 1 to 150µm, the majority being less than 45µm as seen under dispersive x-ray analysis.

(ii) Fineness: Fineness is one of the primary physical characteristics of fly ash that relates to its pozzolanic activity. A large fraction of ash particles is smaller than 3µm in size. In bituminous ashes, the particle sizes range from less than 1 to over 100µm.

(iii) Specific gravity: Specific gravity of fly ash is related to shape as well as chemical composition of particles. Specific gravity of fly ash usually varies from 1.3 to 4.8. Coal particles with some minerallic impurities have specific gravity in between 1.3 to 1.6.

1.3.3. Chemical properties of fly ash (IS: 3812-2003)

Table 1.1 gives the chemical properties of fly ash.

Table 1.1: Chemical properties of fly ash

Constituents	**Percent by weight**
Loss on ignition	4.17
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
Total sulphur (SO_3)	0.07
Insoluble residue	-
Alkalies (a) Sodium oxide (Na_2O) (b) Potassium oxide (K_2O)	 0.58 1.26

1.3.4. Applications of fly ash

Fly ash can normally be used to replace large proportion of cement in the concrete industry. As fly ash is a fine inorganic material with pozzolonic properties, it can be added to SCC to improve the number of concrete properties, resulting in better workability, higher ultimate strengths and improvement in concrete durability, which directly increases sustainability. The unit cost of concrete can be reduced by partial replacement of cement with fly ash. The utilization of fly ash instead of dumping it as a waste material can be partly used on economic grounds as pozzolana for partial replacement of cement and partly because of its beneficial effects such as lower water demand for similar workability, reduced bleeding, and lower evolution of heat. With high volume fly ash concrete mixtures, depending upon the quality of fly ash and amount of fly ash replaced, up to 20% reduction in water requirements can be achieved. This means that good fly ash can act as a superplasticizing admixture when used in high volume. High volume fly ash concrete has been used particularly in mass concrete applications to reduce the heat of hydration, and also helps in reducing cracking at early ages. The major use of fly ash in concrete in the construction of gravity dam is to control temperature rise in mass concrete. Beside the environmental benefits, the use of high volume fly ash concrete can also lead to significant cost savings. Increased utilization of fly ash also reduces land filling with fly ash. Use of fly ash as cement replacement in concrete reduces the temperature rise by reducing the amount of cement used for unit volume.

1.4. FOUNDRY SAND

Foundry sand is high quality silica sand with uniform physical characteristics. It is a by product of ferrous and nonferrous metal casting industries, where sand has been used for centuries as a molding material because of its thermal conductivity. It can be reused several times in foundries but, after a certain period cannot be used further and becomes a waste material, referred to as used or spent foundry sand. The majority of spent molding sands are classified as nonhazardous waste (i.e. not corrosive, ignitable, reactive or toxic). Metal foundries use large amounts of sand as part of the metal casting process. Foundries successfully recycle and reuse the sand many times in a foundry. When the sand can no longer be reused in the foundry, it is removed from the foundry and is termed as "foundry sand*"(Khatib and Ellis, 2001).* Like many waste products, foundry sand has beneficial applications to other industries.

The physical and chemical characteristics of foundry sand depend upon the type of casting process and the industry sector from where it originates. In modern foundry practices, sand is typically recycled and reused through many production cycles. Industry estimates reveal that approximately 100 million tons of sand is used in production annually, of that, 6-10 million tons are discarded and are available to be recycled into other products and in industry. In India, there are about 4700 foundry industries. They generate about 50 lakh tons of waste sand every year. It causes land, air and ground water pollution. The waste produced is not well utilized and most of the foundry waste sand is disposed of in landfill in low-lying areas available in the premises. The automotive industry and its parts are the major generators of foundry sand. Foundries purchase high quality size-specific silica sands for use in their molding and casting operations. The raw sand is normally of a higher quality than the typical bank run or natural sands used in fill construction sites. The sands form the outer shape of the mold cavity. These sands normally rely upon a small amount of bentonite clay to act as the binder material. Chemical binders are also used to create sand “cores”. Depending upon the geometry of the casting, sand cores are inserted into the mold cavity to form internal passages for the molten metal. Once the metal has solidified, the casting is separated from the molding and core sands in the shakeout process. In the casting process, molding sands are recycled and reused multiple times. Eventually, however, the recycled sand degrades to the point that it can no longer be reused in the casting process. At that point, the old sand is displaced from the cycle as byproduct, new sand is introduced, and the cycle begins again.

1.4.1. Types of Foundry Sand

Classification of foundry sands depends upon the type of binder systems used in metal casting. Two types of binder systems are generally used, and on the basis of that foundry sands are categorized as: clay-bonded sands (green sand) and chemically bonded sands. Clay-bonded (Green) sand is composed of naturally occurring materials which are blended together; high quality silica sand (85-95%), bentonite clay (4-10%) as a binder, a carbonaceous additive (2-10%) to improve the casting surface finish and water (2-5%). It is black in color due to carbon content. Green sand is the most commonly used molding media by foundries. The silica sand is the bulk medium that resists high temperatures while the coating of clay binds the sand together. The water adds plasticity. The carbonaceous additives prevent the “burn-on” or fusing of sand onto the casting surface. Green sands also contain trace chemicals such as MgO, K_2O, and TiO_2. The green sand used in the process constitutes upwards of 90% of the molding materials used. Chemically bonded sands are used both in core making where high strengths are necessary to withstand the heat of molten metal, and in mold making. Chemically bonded sand consists of 93-99% silica and 1-3% chemical binder. Silica sand is thoroughly mixed with the chemicals; a catalyst initiates the reaction that cures and hardens the mass. There are various types of chemical binder systems used in the foundry industry. The most common chemical binder systems used are phenolic-urethanes, epoxy-resins, furfyl alcohol, and sodium silicates. Chemically bonded sands are generally light in color and in texture than clay bonded sands. Waste foundry sand (WFS) is also referred to as spent foundry sand (SFS) or used foundry sand (UFS).

1.4.2. Physical properties and chemical oxide composition of foundry sand

Typical physical properties and chemical composition of foundry sand reported by different researchers is given in Tables 1.2. and 1.3, respectively.

Table 1.2: Typical physical properties of foundry sand

Property	**Javed and Lovell (1994)**	**Guney et al. (2010)**
Specific Gravity	2.39-2.55	2.45
Materials finer than 75µm (%)	-	24
Absorption (%)	0.45	-
Moisture content (%)	0.1-10.1	3.25
Clay lumps and Friable Particles	1-44	-
Coefficient of Permeability (cm/sec)	10^{-3} - 10^{-6}	-
Plastic Limit/Plastic Index	Nonplastic	-

Table 1.3: Foundry sand sample chemical oxide composition

Constituent	Value (%)	
	American Foundrymen;s Society (1991)	**Guney et al. (2010)**
SiO_2	87.91	98
Al_2O_3	4.70	0.8
Fe_2O_3	0.94	0.25
CaO	0.14	0.035
MgO	0.30	0.023
SO_3	0.09	0.01
Na_2O	0.19	0.04
K_2O	0.25	0.04
TiO_2	0.15	-
P_2O_5	0.00	-
Mn_2O_3	0.02	-
SrO	0.03	-
LOI	5.15	-
Total	**99.87**	**99.02**

1.4.3. Applications of foundry sand

Since foundry sand has nearly all the properties of natural or manufactured sands, it can normally be used as a sand replacement. Foundry sand can be used beneficially in concrete productions as a fine aggregate replacement. It can be used as a filling material in embankments, sand replacement in hot mix asphalt, flow able fills and Portland cement concrete. It can also be blended with either coarse or fine aggregates and used as a road base or sub base material. Foundry sand can be used in embankments, barrier layers construction, in roadway construction and in flow able fills. Flow able fill is an ideal application for beneficial reuse of spent foundry sands, because the sand represents a large fraction of the flow able fill mix. Roadway structural fill applications provide an opportunity for high volume reuse of foundry sand. Using foundry sand can produce strong and durable road bases. Another application of foundry sand is in earthwork construction, where large volume of sand can be beneficially reused. Compressive strength of concrete generally increases with an increasing amount of foundry sand up to a certain limit, and than decreases.

1.5. APPLICATIONS OF SCC AT ELEVATED TEMPERATURES

SCC is applicable for production of architectural and textured surfaces. It is applicable in highways, bridges, tunnel linings, and construction and repair of concrete structures. SCC can be used in the production of tall walls, and complex shaped members. SCC is specified only to areas where it is most needed. The use of SCC is desirable where congestion of reinforcement is involved and also speed of construction is required to be accelerated with enhanced quality of concrete. SCC is applicable in special applications such as underwater concreting, where fresh concrete is always required and concrete could be placed without the need of compaction. In such circumstances vibration has been simply impossible. SCC is usefull in precast/ prestressed concrete plants. It is well suited for producing both vertical and horizontal components with block-outs and crowded reinforcements. SCC can be used everywhere there normal concrete is used and in such cases where there are chances of temperature rise. SCC is applicable in case of containment vessels, chimneys, nuclear reactors, pressure vessels, structures like storage tanks for crude oil, hot water, coal gasification, liquefaction vessels used in petrochemical industries, furnace walls, industrial chimneys, and in air craft runways subjected to elevated temperatures. SCC is applicable where poring of concrete only from a single point is possible. SCC can be applicable in such places where their are requirements for high strength, low permeability and it can perform in a similar way to any normal high strength concrete under fire conditions.

SCC was used in the construction of two anchorages of Akashi Streaights Bridge opened in 1988, a suspension bridge with the longest span in the world *(Ouchi et al., 2006)*. In India this concrete had been used by Nuclear Power Corporation in Kaiga Project and Delhi Metro Rail Corporation work at Delhi *(Sivram, 2006).* SCC had been used for 19 highway bridges so far and for slabs in dwelling house in Sweden where 60% increase in productivity was observed. In Europe SCC was used in the Consolis SAS group which was the largest manufacturer of precast concrete. SCC was used mainly for the manufacturing of beams, columns, walls, and special elements. The annual use of SCC in Europe in 2006 exceeded 3, 00,000m^3 and made up about 35% of all concrete production in Consolis with flow able concrete *(Juvas, 2006).*

Many researchers studied the properties of SCC at room temperature but studying SCC properties at elevated temperatures were very limited. The aim of this research is to study the properties of SCC such as compressive strength, splitting tensile strength, modulus of elasticity, mass loss, porosity and rapid chloride permeability when exposed to elevated temperatures (100^{o}C, 200^{o}C, 300°C). In this research four series of concrete mixtures were manufactured: one with cement only, another with 30% by mass replacement of cement with fly ash, and third with 40% by mass replacement of cement with fly ash and fourth with 50% replacement of cement with fly ash.

1.6 OBJECTIVES AND SCOPE OF THE WORK

The main objectives of the present work were as follows:

- Study the strength properties (compressive strength, splitting tensile strength and modulus of elasticity) of SCC at elevated temperatures (100^{o}C, 200^{o}C, 300^{o}C) by replacing cement with fly ash (30-50%) and by replacing fine aggregates with foundry sand (0-10%)
- Study the permeability (chloride permeability) of SCC at elevated temperatures (100^{o}C, 200^{o}C, 300^{o}C) by replacing cement with fly ash (30-50%) and by replacing fine aggregates with foundry sand (0-10%)
- To carry out the statistical analysis

The scope of the present work includes studying first of all the effect of elevated temperature on compressive strength, splitting tensile strength, modulus of elasticity, rapid chloride permeability, porosity, and mass loss. To achieve this firstly, mix design was finalized on the basis of trial mixes. After that casting and testing work was carried out and the analysis of the data was done. X-ray diffraction and scanning electron microscopic observations were also made. In the end efforts were made to develop a mathematical model for calculating the compressive strength, splitting tensile strength, modulus of elasticity, rapid chloride permeability, porosity, and mass loss. The mathematical model so developed is validated with the experimental results obtained from the test programme undertaken.

1.7. ORGANIZATION OF THE THESIS

The thesis is presented in the six chapters as detailed below:

Chapter-1 Introduces about self-compacting concrete, elevated temperature's effects on concrete, fly ash, foundry sand and applications of self-compacting concrete at elevated temperatures.

Chapter-2 Presents literature review and presents the work done by various researchers on self-compacting concrete and elevated temperatures effect on concrete.

Chapter-3 Gives the details of experimental programme, materials used, techniques adopted for casting, curing, heating and testing of the specimens.

Chapter-4 Deals with the mathematical model of the experimental programme using support vector machine approach.

Chapter-5 Deals with the discussion of results obtained from experimental data. The results are presented both in tabular as well as graphical form.

Chapter -6 Gives the major conclusions of the study.

A list of references referred to in this work is presented after chapter-6.

CHAPTER - 2
LITERATURE REVIEW

This chapter deals with the literature review on the properties of self-compacting concrete (SCC) using fly ash, silica fume, lime stone powder, and other materials, and literature review on the properties of self-compacting concrete (SCC) at elevated temperatures using fly ash, silica fume, lime stone powder, and other materials.

2.1. LITERATURE REVIEW ON SCC

2.1.1. Properties of SCC made with fly ash

Khayat (1999) studied workability, testing, and performance of the SCC by using fly ash. According to the author, self-consolidating concrete should be designed to meet specific applications requiring high deformability, high flowability, and high passing ability. Observations of the author showed that the rheological properties of SCC vary in a wide range.

Persson (2001) carried out an investigation on the mechanical properties of SCC, such as strength, elastic modulus, creep and shrinkage and the corresponding properties of normal concrete by using Portland cement, fly ash and glass filler as binding material, and quartzite sandstone as aggregates. A comparison between SCC with quartzite filler and NC without filler showed that SCC obtained about 20MPa higher strength at w/b ratio of 0.40 and about 5MPa higher strength at w/b ratio of 0.80 compared with NC.

Bouzoubaa et al. (2001) studied the mechanical properties and durability of concrete made with high-volume fly ash (HVFA) blended cements using a course fly ash that does not meet the fineness requirement of ASTM C-618. The results were compared with those of the HVFA concrete in which ungrounded fly ash had been added to the concrete mixer. The properties of fresh concrete as well as hardened concrete were studied. The results showed that except for the resistance of concrete to the deciding salt scaling, mechanical and durability properties of concrete made with this blended cement were superior to the concrete in which the ungrounded fly ash and the cement had been added separately at the mixer.

Bouzoubaa and Lachmi (2001) reported the use of SCC incorporating high volumes of class F fly ash. Self-compacting mixture had a cement replacement of 40%, 50%, and 60% by class F fly ash and developed compressive strength ranging from 26 to 48 MPa. The results showed that an economical SCC could be successfully developed by incorporating high volume of Class F fly ash.

Zhu et al. (2001) studied the uniformity of in situ properties of the SCC in full scale structural elements. They reported significant reduction of chloride diffusivity of SCC with fly ash.

Youjun et al. (2002) carried out an investigation on the optimum mix parameters of high strength SCC with ultra pulverized fly ash. The results of this research indicated that the sand ratio could not be less than 40%. If the sand ratio is higher, the workability of fresh SCC would be better, and smaller the compressive strength difference between SCC and normal concrete.

Persson (2003) studied the primary durability properties of SCC i.e. internal frost resistance and salt frost scaling and their comparison with normal concrete. In this study, the effect of fly ash, ground blast furnace slag, and silica fume on the salt frost scaling of SCC was investigated. The results indicated a substantial improvement of the internal frost resistance of SCC as compared to NC. The salt frost scaling performed more or less in the same way in SCC and in NC.

Nehdi et al. (2003) reported the results on the durability of self-consolidating concrete incorporating high-volume replacement composite cements. 50% of cement was replaced by class F fly ash and rapid chloride ion penetrability test, sulphate expansion and deicing salt surface scaling resistance of SCC mixtures were performed. Results indicated that high-volume replacement SCC cannot only have the workability and ease of construction benefits associated with conventional SCC, but also achieved much enhanced long-term durability.

Okamura et al. (2003) established a rational mix design method using fly ash and self-compatibility testing method from the view point of making self-compacting concrete a standard concrete.

Mohammed Sonebi (2004) investigated the medium strength SCC containing fly ash. A factorial design was carried out to mathematically model the influence of five key parameters on filling and passing abilities, segregation and compressive strength, which were important for the development of medium strength SCC incorporating fly ash. The parameters studied were the contents of cements and fly ash, w/p ratio and dosage of SP. The results showed that the medium strength SCC can be achieved with a 28 days compressive strength of 30 to 35 MPa by using up to 210 kg/m^3 of PFA.

Poon et al. (2004) reported the preliminary results of rejected fly ash that could be used as a part of powder content. Based on the materials used in this study, the results suggested that it was technically feasible to utilize rejected fly ash as part of the powder content in the production of SCC.

Siddique (2004) studied the performance characteristics of high-volume Class F fly ash concrete. In this research Portland cement was replaced with three percentages (40%, 45%, and 50%) of Class F fly ash. Tests were performed for fresh concrete properties such as slump flow, air content, unit weight, and temperature of concrete. Compressive, splitting tensile, flexural strengths, modulus of elasticity, and abrasion resistance were determined up to 365 days of testing. Test results indicated that the use of high volumes of Class F fly ash as a partial replacement of cement in concrete decreased its 28-day compressive, splitting tensile, flexural strengths, modulus of elasticity, and abrasion resistance of the concrete. However, all these strength properties and abrasion resistance showed continuous and significant improvement at the ages of 91 and 365 days, which was most probably due to the pozzolanic reaction of fly ash. Based on the test results, it was concluded that Class F fly ash could be suitably used up to 50% level of cement replacement in concrete for use in precast elements and reinforced cement concrete construction.

Bapat et al. (2005) carried out an investigation on the use of SCC in nuclear power plant construction. M30 grade concrete mix with fly ash was used in this study and the results of fresh and hardened concrete satisfied the requirements of SCC.

Cenzin (2005) reported the strength properties of high volume fly ash roller compacted and super plasticized workable concrete cured at moist and dry curing conditions. Concrete mixtures made with 0%, 50% and 70% replacement of normal Portland cement with two different low lime class F fly ashes were prepared with water-cementitious material ratios ranged from 0.28 to 0.43. The results showed that producing high strength concrete was possible with high volume fly ash concrete.

Shi and Yanzhong (2005) carried out an investigation on mixture proportioning and properties of self consolidating light weight concrete containing glass powder. As compared with the fly ash the use of ground glass powder decreased setting times and increased chloride migration resistance, the strength and drying shrinkage of the concrete. According to the authors the use of supplementary cementing material such as fly ash may have a significant effect on the chloride migration of concrete as measured by the rapid chloride permeability test.

Domone (2006) analyzed the case study of 11 years of SCC. The author analyzed the case studies of sixty eight applications of SCC, published from 1993 to 2003, the period of increasing widespread use of SCC in many countries. The ranges of properties, component materials and mix proportions showed the diverse nature of SCC, and confirmed that it should be considered as a family of mixes suitable for a wide range of applications to widely varying requirements**.**

Malathy et al. (2006) studied the development of mix design chart for various grades of SCC. A mix design of SCC had been developed following European Federation for Specialist Construction Chemicals and Concrete system (EFNARC) specifications. The mix design of SCC for different grades, M20 to M60 was developed and their flow properties and strength properties were studied. Compressive strength of concrete was checked after 7 and 28 days curing and also the splitting tensile strength was obtained after 28 days curing. The charts had been developed for obtaining quantity of cement, fly ash and coarse aggregate required for different grades. Authors had concluded that flow properties of developed SCC for various grades were satisfying the recommended values. Also the quantity of cement required for SCC was about 5-20% less than that of normal concrete.

Ozkul et al. (2006) studied the rheological properties and segregation resistance of SCC prepared by Portland cement and fly ash. According to the authors SCC provides high flowability, high filling capacity, high passing ability through reinforcing bars, which were owned by using a powerful superplasticizer as well as reducing both the coarse aggregate content and water/powder ratio. The total binder content (including both cement and fly ash) varied between 450 and 650 kg/m^3. The maximum aggregate sizes were chosen as 12, 16 and 20 mm. In the experiments a specially designed apparatus, had been used for conducting the slump-flow and L-shape box test,. This apparatus also allowed the measurement of segregation resistance. All the tests satisfied for the rheological properties and segregation resistance of SCC.

Sivarama et al. (2006) discussed the novel method of placing SCC by bottom up pumping in their study. It was the first innovative attempt in India, that L & T had developed a mechanism to pump the concrete from bottom up. An experimental trial had been made with M50 grade concrete and experimental data proved that concreting could be done by the novel method of bottom up which sets a new trend in construction practices in near future.

Domone (2007) reviewed the hardened mechanical properties of SCC. Data from more than 70 recent studies on the hardened mechanical properties of SCC had been analyzed and correlated to produce comparisons with the properties of equivalent strength normally vibrated concrete (NVC). The significant scatter obtained in much of the data was a consequence of the wide range of materials and mixes used for SCC, but clear relationships had been obtained between cylinder and cube compressive strength, tensile and compressive strengths, and elastic modulus and compressive strength. It was also clear that limestone powder, a common addition to SCC mixes, made a substantial contribution to strength gain.

Felekoglu et al. (2007) showed that the optimum w/c ratio for producing SCC should be in the range of 0.84-1.07 by volume. The ratio above and below this range may cause blocking or segregation of the mixture.

Khatib et al. (2007) studied the performance of SCC containing fly ash. Portland cement was replaced with 0-80% of fly ash. The water/binder ratio was maintained at 0.36 for all mixes.

Properties included were workability, compressive strength, ultrasonic pulse velocity, absorption and shrinkage. The results indicated that high volume fly ash could be used in SCC to produce high strength and low shrinkage. Replacing 40% of cement with fly ash resulted in strength of more than 65N/mm^2 at 56 days. Increasing the admixture content beyond a certain level leads to a reduction in strength and increase in absorption. Correlation between strength and absorption indicated that there was a sharp decrease in strength as absorption increases from 1 to 2%. After 2% absorption, the strength reduced at a much slower rate.

Mustafa et al. (2007) examined the mechanical properties of hybrid fiber reinforced SCC with a high-volume coarse fly ash. In this research 50% of cement by weight was replaced by coarse fly ash. Two different types of steel fibers were used in combination, keeping the total fiber content at 60 kg/m^3. Slump flow time and dia., V-funnal, and air content were performed to access the fresh properties of the concrete. Compressive strength, splitting tensile strength, and ultrasonic pulse velocity of the concrete were determined for the hardened properties. The results indicated that high volume coarse fly ash could be used to produce fiber reinforced SCC, even though there was some reduction in the concrete strength because of the use of high-volume coarse fly ash.

Aggarwal et al. (2008) evolved a procedure for mix design of the SCC. Their research presented an experimental procedure for the design of the SCC mixes. The test results for acceptance characteristics of the SCC such as slump flow, J-ring, V-funnel and L-Box were presented. Further, compressive strength at the ages of 7, 28, and 90 days were also determined and the results concluded that the SCC could be developed without using viscosity modifying admixtures and by using the OPC 43 grade, normal strength of 25 MPa to 33 MPa at 28 days was obtained, provided the cement content was kept around 350 kg/m^3 to 414 kg/m^3.

Aggarwal et al. (2008) studied modeling properties of the SCC by using support vector machines approach. This research explores the potential of support vector machines approach in predicting 28 days compressive strength and slump flow of SCC. The total of 80 data collected from the existing literature were used in present work. To compare the performance of the technique, prediction was also done using a back propagation neural network model. Results obtained for root mean square error and correlation coefficient suggested a comparable performance by support vector machine approach to neural network approach for both 28 days compressive strength and slump flow prediction.

Aggarwal et al. (2008) predicted the compressive strength of the SCC with fuzzy logic. In the present research comparisons of fuzzy logic and neural network techniques for predicting the compressive strength for SCC mixtures was done. The authors concluded that the fuzzy logic model showed better performance than neural network model.

Dinakar et al. (2008) studied the durability properties of high volume fly ash SCC . Eight fly ash SCC of various strength grades were designed at desired fly ash percentages of 0, 10, 30, 50, 70 and 85%, in comparison with five different mixtures of normal vibrated concretes at equivalent strength grades. The durability properties were studied through the measurement of permeable voids, water absorption, acid attack and chloride permeation. The chloride ion penetrability limits suggested by ASTM C1202 were compared with the results. It was seen that (except 20 MPa SCC) all self-compacting fly ash concretes showed less than 1000 Coulombs total charge passing and these were assessed as 'very low' chloride permeability concretes as per ASTMC 1202-94 assessment criteria. The corresponding normal concretes showed values in the range 'low' to 'moderate' according to the assessment criteria. This clearly indicated that the high volume fly ash SCC mixes performed much better with respect to chloride penetrability.

Mohammad (2008) described a novel apparatus for measurement of porosity of normal and high strength mortar and concrete using pressure saturation method. In this research 40% of cement was replaced with fly ash and 10% with silica fume. Porosity values obtained using the apparatus were highly repeatable and reproducible. The apparatus was sensitive to the age, influence of water-binder ratio and replacements of cement by cementitious materials. The apparatus yielded full saturation for high strength and dense mortar and concrete. The porosity values for normal strength concrete using the pressure saturation apparatus were in good agreement with the results obtained using vacuum saturation method proposed by RILEM.

Kraus et al. (2009) used foundry silica dust as a replacement material for fly ash in manufacturing economical self-consolidating concrete. Foundry silica dust replaced with 30% of class C fly ash, reported some reduction in 3 days compressive strength and considerable reduction in 28 days compressive strength.

Gettu et al. (2009) studied the evolution of the robustness of SCC. This research analysis the robustness of typical SCC, in terms of fresh properties and strength, when changes were made in the dosages of the constituents within the tolerances that could occur in ready mix concrete plants. The results indicated that the most critical changes that can render an SCC unacceptable were excess cement, excess fly ash, less fly ash, less water, excess super plasticizer, excess sand and excess gravel. The incorporation of viscosity modifying admixtures seems to increase the robustness of SCC in this research.

Karjinni et al. (2009) developed mixture proportion procedure for SCC by using fly ash, silica fume, and metakolin. According to the author no method specified the grade of concrete in SCC except the Nan Su method. But the limitations of Nan Su method was that it gives required mix proportions for the grades which were more than M50, this was observed during experimental work on normal grade of concrete in SCC (grade less than M50). In this research an attempt had been made to modify the Nan Su method and obtain a mix design in normal grades with three mineral admixtures. With all the three mineral admixtures incorporated, the compressive strength and flow properties of SCC were studied. It was concluded from this research that to satisfy the strength and durability of the concrete, some modification in the available Nan Su method was required for the normal grades of concrete.

Mattur at al. (2009) studied the strength and durability of high volume fly ash SCC. This research presented the initial experimental efforts for development of SCC mixes employing high volume of fly ash additionally mixed with other mineral admixtures such as ground granulated blast furnace slag and silica fume. Three set of mixes were prepared and their properties were studied. In the first case, 50% of cement was replaced with fly ash. In the second case, cement was replaced with 50% of fly ash and 20% of ground granulated blast furnace slag. In the third case, cement was replaced with 50% fly ash, 20% of ground granulated blast furnace slag, and 5% of silica fume. The results of test for cube compressive strength, the weight changes and resistance to chloride ion penetration indicated very good performance of all the three SCC mixes in sulphate and chloride environments.

Mustafa et al. (2009) studied the transport and mechanical properties of self-consolidating concrete with high volume fly ash. SCC containing five different contents of high lime fly ash and low lime fly ash as a replacement of cement (30, 40, 50, 60 and 70% by weight of total cementious material) were examined. For comparison, a control SCC without fly ash was also produced. The test results confirmed that it was possible to produce SCC with a cement replacement of up to 70% by both types of fly ash. The use of high volume of fly ash in SCC not only improved the workability and transport properties but also made it possible to produce concretes between 33 and 40 MPa compressive strength at 28 days, which exceed the normal compressive strength for normal concrete (30MPa).

Peter et al. (2009) used SCC for under-reamed piles. An experimental study conducted at the Structural Engineering Research Centre (SERC), Chennai, clearly demonstrated the control on geometry of self-compacting concrete under reamed piles when cast against soil form work. Three piles made of SCC and three of conventional vibrated concrete having similar strength, were cast and tested to evaluate their dynamic and static behaviour. The authors had observed the similar performance of SCC and conventional vibrated concrete piles under dynamic action.

Mehmet et al. (2009) studied the properties of SCC made with binary, ternary, and quaternary cementitious blends of fly ash, blast furnace slag, and silica fume. A total of 22 concrete mixtures were designed having a constant water/binder ratio of 0.44 and a total binder content of 450kg/m^3. The control mixture included only a Portland cement (PC) as the binder while the remaining mixtures incorporated binary, ternary, and quaternary cementitious blends of PC, fly ash (FA), ground granulated blast furnace slag (S), and silica fume (SF). Fresh properties of the SCCs were tested for slump flow diameter, slump flow time, L-box height ratio, and V-funnel flow time. Furthermore, the hardened properties of the concretes were tested for sorptivity, water permeability, chloride permeability, electrical resistivity, drying shrinkage, compressive strength, and ultrasonic pulse velocity. The results indicated that when the durability properties of the concretes were taken into account, the ternary use of ground granulated blast furnace and silica fume provided the best performance.

Sengupta et al. (2009) studied the influence of aggregate characteristic on the uniformity of SCC. According to the author the property that was affected by the aggregate characteristics was passing ability. The size and gradation of coarse aggregate, along with the presence of flaky and elongated particles, were factors that affect passing ability, and thus the uniformity of SCC. In the present research an attempt was made to analyze the influence of aggregate characteristics on the passing ability through a probabilistic model. The probabilistic model developed in this study allowed the mix designer to decide on the maximum allowable coarse aggregate content of a specific maximum size and gradation for a given blocking tolerance. The results of the experimental study showed that the fraction of large sized and longer aggregates decreased considerably as the SCC flowed through successive set of barriers.

Sood et al. (2009) highlighted the use of European standards by various researchers for testing SCC in Indian conditions. According to the authors, wide spread applications of SCC had been restricted due to lack of standard mix design procedure and testing methods. It was mentioned in this study that only the features of SCC had been included in Indian Standard Code for the present. Slump flow test, L-box test, V-funnel test, U-box test, Orimet test & GTM Screen test are recommended by EFNARC (European Federation for Specialist Construction Chemicals and Concrete system) for determining properties of SCC in fresh state. This research presented the experimental investigation of self-compacting concrete using fly ash and rice husk ash as mineral admixtures and testing rheological properties as per European Standards. The authors concluded that addition of fly ash in mix increases filling and passing ability of concrete, whereas rice husk ash imparts viscosity to concrete improving segregation resistance of concrete mix. Fly ash and rice husk ash blend well to improve the rheological properties of SCC. From this experimental study it was also concluded that fly ash and rice husk ash blend well improving overall workability, which is the prime important characteristics of SCC.

Krishna et al. (2010) studied the effect of different sizes of coarse aggregate (C.A.) on the properties of NCC and SCC (20 mm, 16 mm, 12.5 mm and 10 mm). Eight mixes were investigated for M30 grade concrete. The water-powder ratio was kept fixed throughout the SCC mixes. The super plasticizer and viscosity modifying admixture dosages were determined from mortar trails. To achieve the SCC, successive replacement of C.A by fine aggregate was adapted. Slump flow test, V-funnel test, J-ring test and L-box test on fresh concrete were carried out as per EFNARC (European Federation for Specialist Construction Chemicals and Concrete system) guidelines. The compressive strength, split tensile strength and flexural strength of the concrete after 7, 28 & 56 days curing were also investigated. The test results showed how self-compacting properties were achieved at different sizes of C.A**.** The fresh properties of SCC reduce with increase in size of C.A. The compressive strength, split tensile strength and flexural strength of NCC and SCC are maximum at 20 mm size of C.A. used in the mix. The authors also concluded that as the size of C.A. increases the tendency of the mix to segregate increases.

Miao (2010) investigated the SCC with levels of up to 80% of cement replacement by fly ash in mixes adjusted to give constant fresh concrete properties. The hardened concrete and the relationships between hardened properties were then studied. The results showed that SCC with up to 80% cement replaced by fly ash was possible. All mixes exhibited satisfactory fresh properties. Inclusion of fly ash leads to a reduction in the consistence retention and passing ability when the filling ability was kept constant. A non-linear correlation exists between the required super plasticizer dose and fly ash content. Higher replacement levels led to a reduction in the compressive strength and splitting strength. The reduction was higher at early ages but decreases at later age. Depending on the water/powder to keep the filling ability constant, replacement of cement with fly ash would require an increase in water/powder ratio and a reduction in super plasticizer dosage.

Mustafa et al. (2011) developed SCC with spent foundry sand and fly ash for the development of green SCC. In this research, SCC mixes were developed to be even more inexpensive and environmental friendly by incorporating Portland cement with fly ash. In this research 100% sand was replaced with spent foundry sand and up to 70% Portland cement with fly ash enables the manufacture of green, lower cost SCC mixtures with proper fresh, mechanical and durability properties.

Siddique (2011) developed SCC with Class F fly ash. The mixes were prepared with five percentages of class F fly ash ranging from 15% to 35%. Properties investigated were self-compact ability parameters (slump flow, J-ring, V-funnel, L-box and U-box), strength properties (compressive and splitting tensile strength), and durability properties (deicing salt surface scaling, carbonation and rapid chloride penetration resistance). SCC mixes developed 28 days compressive strength between 30 and 35 MPa and splitting tensile strength between 1.5 and 2.4 MPa. SCC mixes made with fly ash exhibited very low chloride permeability resistance (less than 700 and 400 Coulomb) at the age of 90 and 365 days respectively.

Uysal et al. (2011) studied the performance of SCC containing different mineral admixtures. In this research Portland cement (PC) was replaced with fly ash, granulated blast furnace slag, limestone powder, basalt powder and marble powder in various proportioning rates. The influence of mineral admixtures on the workability, compressive strength, ultrasonic pulse velocity, density and sulphate resistance of SCC was investigated. The test results showed that among the mineral admixtures used, fly ash, and granulated blast furnace slag significantly increased the workability and compressive strength of SCC mixtures. Replacing 25% of PC with fly ash resulted in strength of more than 105 MPa at 400 days.

Uysal et al. (2011) used artificial neural network to predict the core compressive strength of the SCC mixtures with mineral additives. This study was based on the determination of the variation of core compressive strength, water absorption and unit weight in curtain wall elements. One conventional vibrated concrete and six different SCC mixtures with mineral additives were prepared. SCC mixtures were produced as control concrete (without mineral additives), moreover fly ash and limestone powder were used with two different replacement ratios (15% and 30%) of cement and marble powder was used with 15% replacement ratio of cement. SCC mixtures were compared to conventional concrete according to the variation of compressive strength, water absorption and unit weight. It could be seen from this study that self-compacting concretes consolidated by their own weight homogeneously in the narrow reinforcement construction elements. Experimental results were also obtained by building models according to artificial neural network (ANN) to predict the core compressive strength. The results showed that

ANN could be an alternative approach for predicting the core compressive strength of the SCC mixtures with mineral additives.

Farediwala et al. (2012) studied the relationship between workability and compressive strength of the SCC. The work of this research focused on concrete mixes having water/binder ratios of 0.40 and 0.50, which contained constant total binder contents of 500 kg/m^3 and 550 kg/m^3, respectively. The concrete mixes contained three different dosages of a super plasticizer based on carboxylic with fly ash. The percentage of fly ash that replaced cement in this research was 15%. The workability tests utilized in this research were the slump flow, V-funnel and L-box which could be used to evaluate the passing ability of the SCC. Based upon the experimental results, there were some linear relationships between compressive strength and each of the workability tests.

Jawahar et al. (2012) reported a simple tool for the SCC mix design. In the mix design of SCC, the relative proportions of key components were generally considered by volume rather than by mass. On the basis of these proportions, a simple tool had been designed for SCC mix design. In this research, this tool had been evaluated with an SCC mix having 28% of coarse aggregate content, 35% replacement of cement with class F fly ash, 0.36 w/c(by weight) and 388 litre/m^3 of paste volume. Crushed granite stones of size 20 mm and 10 mm were used with a blending 60:40 by percentage weight of total coarse aggregate. It was practically seen that this simple tool was very much useful for the mix design of SCC with or without blended cement and with or without coarse aggregate blending.

Kumar et al. (2012) studied the performance of standard and high strength SCC. Medium range (M40) and a higher range (M70 grade) SCC were developed modifying the basic mixes developed using Nan-Su’s method of mix design. The compressive strength tests were conducted to access the strength properties of SCC. Durability properties like resistance to sulphate and the influence of sodium chloride solution were studied. It was concluded that the average compressive strength had decreased after 28 days of immersion in 5% sulphate solution.

Ramakrishna et al. (2012) studied the effect of coarse aggregate size and shape on the strength and flow characteristics of SCC. Two grades of SCC mixes with 60% and 40% replacement of cement with fly ash were used in this study. The results of this study showed that the strength and flow ability of the high volume fly ash SCC mix with 10 mm to 16 mm aggregates was found to be better than the low volume fly ash SCC with 20 mm aggregates.

2.1.2. Literature review on properties of SCC made with silica fume

Farrokhi et al. (2008) formulated an idea of adding coarse aggregate and silica fume to improve the concrete compaction charactertics. The test results showed a good workability and self-compacting ability of the fresh concrete. Test results also showed good shrinkage tendency and the modulus of elasticity.

Ahmed et al. (2011) studied the properties of SCC containing limestone powder and silica fume. The glass powder, ceramic powder and glue were also used as additives in different proportions. The results showed good results of fresh and hardened properties of SCC due to addition of the additives. The best flow ability was obtained by adding glue (4%) in cement. While the glass powder and ceramic powder affected the hardened properties. Adding ceramic powder increased the compressive strength between 10-20% and adding glass powder modified the compressive strength at rates more than 20%.

Lian et al. (2011) studied the relation between porosity and strength for porous concrete by using silica fume. For many porous media, the strength of porous concrete was significantly affected by the porosity of its internal structure. This research described the development of a mathematical model to characterize the relationship between compressive strength and porosity for porous concrete by analyzing empirical results and theoretical derivations. The suitability of existing equations for porous concrete was assessed and a new model was then proposed. The new model, which was derived from Griffith's theory, presents a better agreement with the experimental data for porous concrete. It was demonstrated that the proposed model could provide a better prediction of porous concrete compressive strength based on the material porosity.

Dinakar (2012) studied the remediation of slump flow loss of SCC by overdosing technique. According to the author slump loss of concrete at construction site is a common phenomenon because it results from gradual stiffening and setting of hydrated Portland cement paste, which is associated with the formation of hydration products such as calcium silicate hydrate. In the present investigation a study had been undertaken to study the effectiveness of overdosing the chemical admixtures which was used to provide the initial optimum admixture dosages resulting in suitable SCC for different transportation times. Fly ash and metakoline was used as filler in this research. The test results indicated that the selected overdosing method was successful in producing SCCs with similar unconfined flow ability, stability, and passing ability to those obtained at the control transportation time.

Dubey et al. (2012) developed SCC by use of Portland Pozzolana cement, hydrated lime and silica fume. Lime was used as filler material. Silica fume improved aggregate-matrix bond resulting from the formation of a less porous transition zone in concrete. The test results for acceptance characteristics of SCC such as slump flow; V-funnel and L-box were presented in this research. Further, compressive strength at the ages of 7, 28, and 60 days was also determined and results were included. The authors concluded that with 8% replacement of cement by silica fume had the best effect on compressive strength of SCC. Addition of silica fume and lime developed filling and passing ability of concrete. There was continuous gain of strength up to sixty days due to slow pozzalanic reactions of Portland Pozzolana cement. Different types of SCC having different compressive strength can be prepared by different combinations of cement, lime and silica fume.

2.1.3. Properties of SCC made with lime stone powder

Nagataki and Fujiwara (1992) performed the slump flow test to find out the workability of SCC by using lime stone powder as a filler material. They also performed the segregation test of SCC mix, by using locally available materials. According to the authors the value ranging from 500-700 mm was considered as the slump required for a concrete to be self compacted.

Ozawa et al. (1995) conducted V-shaped funnel test for determining the stability of SCC mixture by using lime stone powder as a filler material and they concluded that the flow time of less than 6 sec was recommended for a concrete to qualify for an SCC.

Okamura and Ozawa (1995) proposed a mix design method. According to this method coarse and fine aggregate content was fixed so that the self-compactability can be achieved easily by simply adjusting the water-powdered ratio and super plasticizer dosage only. Coarse aggregate content in concrete was fixed at 50% of solid volume and fine aggregate content was fixed at 40% of mortar volume. Water powder ratio in volume was assumed as 0.9 to 1.0, depending upon the properties of the powder. The super plasticizer dosage and water powder ratio was determined so as to ensure self compatibility.

Ozkul et al. (1999) investigated the properties of fresh and hardened concrete prepared by new generation super plasticizer and lime stone powder. In this research the effect of cement and admixture dosage on the rheological properties of mortar were investigated by using a coaxial viscometer. Workability properties of concrete were measured by conventional slump flow and also by newely developed slump flow test apparatus. The compressive strength of specimens taken from the concrete mixes and of cores cut of the insitu cast blocks were also presented. The authors concluded that rheological studies on mortar showed that the elapsed time and super plasticizer content affect yield stress more than viscosity.

Sachan et al. (2003) investigated the suitability of crushed stone dust waste as fine aggregate replacement for concrete. Test results indicated that crushed stone dust waste can be efficiently used to replace natural sand in concrete. Concrete made with this replacement can attain the same compressive strength, tensile strength, and modulus of elasticity as control concrete.

Bosiljkov (2003) studied the properties of SCC mixes with poorly graded aggregates and high volume of limestone filler. The author had studied the influence of finely ground limestone and crushed limestone dust on the properties of SCC and their results indicated that with limestone filler compressive strengths developed were between 22.4 and 24.5 MPa, and between 63.6 and 67.6 MPa at 1 and 28 days, respectively.

Persson (2003) reported the results of sulphate resistance of SCC. For this purpose, more than 40 cylinders of concrete were subjected to a solution with sodium sulphate, sea or distilled water during 900 days. The age at the start of testing was either 28 or 90 days. Comparison was done with the corresponding properties of vibrated concrete. When cured in a solution with sodium sulphate, the results showed large loss of mass of SCC than that of vibrated concrete probably due to the limestone filler content in SCC. After curing in water, no such weight difference between the curing types was observed.

Moriconi et al. (2004) examined the work on durable fiber reinforced SCC. Polymer was added into the mixture of cement, limestone and natural sand in order to guarantee very high workability. The authors concluded that the fiber addition proved to be very effective in counteracting drying shrinkage of the SCC.

Zhu et al. (2004) studied the permeation properties (permeability, absorption, diffusivity) to quantify the durability characteristics of SCC. In this research an experimental study on the permeation properties of a range of different SCC mixes in comparisons with those of selected traditional reference concretes of the same strength grade was done. The SCC mixes with characteristic cube strength of 40 and 60 MPa were designed containing either lime stone powder as filler or containing no filler but using a viscosity agent. The results indicated that the SCC mixes had significantly lower oxygen permeability and sorptivity than the vibrated concretes of the same strength grades.

Zhu and Gibbs (2005) carried out an investigation on different types of limestone and chalk powders as filler in SCC and studied their effects on superplastizer demand. It was found that all the different limestone and chalk powders selected could be used successfully for producing SCC mixes, although modest adjustments of super plasticizer dosage were necessary. Generally higher dosage super plasticizers were required for SCC using chalk powder than for that using limestone powder. The compressive strength of SCC mixes containing the limestone and chalk powders was significantly greater than that of the conventional vibrated reference concrete at the same w/c ratio, particularly at early ages.

Almedia et al. (2011) presented a statistical study on the variability of the mechanical properties of hardened SCC, including the compressive strength, splitting tensile strength and modulus of elasticity. The comparison of the experimental results with those derived from several codes and recommendations allowed evaluating if the hardened behaviour of the SCC could be appropriately predicted by the existing formulations. The variables analyzed include the maximum size aggregate, paste and gravel content. Results from the analyzed SCC presented variability measures in the same range than those expected for conventional vibrated concrete, with all the results within a confidence level of 95%.

2.1.4. Properties of SCC using other materials

Ho et al. (2002) used quarry dust in making SCC applications. Results from rheological measurements on pastes and concrete mixes incorporating limestone or quarry dust were compared. It was found that the quarry dust, as supplied, could be used successfully in the production of SCC. However, due to its shape and particle size distribution, mixes with quarry dust required a higher dosage of super plasticizers to achieve similar flow properties.

Sheinn et al. (2002) utilized the granite fines (a part of powder content) referred to as quarry dust. Results from rheological measurements on paste and concrete mixes incorporating limestone or quarry dust were compared and it was found that quarry dust could be used successfully in the production of SCC.

Brouwers and Radix (2005) address the experiments and theories on self-compacting concrete. Before this research the features of ‘Japanese and Chinese Methods’ were discussed, in which the packing of sand and gravel plays a major role. Here, the grading and packing of all solids in the concrete mix serves as the basis for the development of new concrete mixes. Mixes, consisting of slag blended cement, gravel (4-16 mm), three types of sand (0-1, 0-2 and 0-4 mm) and a polycarboxylic ether type super plasticizer, were developed. These mixes were extensively tested, both in fresh and hardened states, and meet all practical and technical requirements such as medium strength and low cost.

Bignozzi et al. (2006) used different kinds of waste as partial substitute of natural aggregates in concrete in their study. The conclusion drawn from this study was that the best results for workability and mechanical strength were obtained when sand fraction was replaced by tyre waste of similar grain size, instead of the substitution of fine fraction with equivalent tyre rubber waste grain size.

Khurana et al. (2009) studied an innovative approach to low fines SCC. In this research concept of low fines content SCC having a total fines content of about 350 kg/m^3, to be used in the ready mixed concrete industry to produce 25 to 35 MPa strength concrete was introduced. It may also be used in the production of precast concrete elements in a more cost effective manner using the state of the art super plasticizers and innovative viscosity modifying admixtures.

Singh et al. (2009) studied the behaviour of confined over-reinforced SCC beams. In the present research, SCC had been used to ensure effective concreting of the over-reinforced beams. The proposed analytical approach based on the moment-curvature characteristics of the over-reinforced section gave a reasonably accurate prediction of the load-displacement behaviour of the over-reinforced beams. The serviceability limit states of cracking and deflection had been examined and the quality of the hardened SCC in the beams had been found to be satisfactory from ultrasonic pulse velocity measurements.

Shutter et al. (2010) carried out the experimental investigation of shear bond strength between steel and SCC. In this research the shear bond strength between steel and SCC without mechanical shear connectors was evaluated by means of push-out tests. The test members differ by steel surface texture, adhesive properties, and SCC mixture. Also the theoretical distribution of the shear bond stress between steel and concrete is examined by means of a finite element analysis (FEA). However, the values were widely scattered and therefore it is difficult to make definite conclusions about the influence of the studied parameters. According to the FEA of the specimens used in this test program, a non-uniform stress distribution between steel and concrete was found and the maximum shear bond stress is 2.98 times higher than the nominal shear stress.

Shutter et al. (2010) carried out the experimental investigation on strain softening behaviour of SCC. Strain-softening is the phenomenon by which the compressive stress-strain curve presents a descending branch after the peak stress has been reached. For high-strength concrete types it is known that failure occurs in a more brittle way, resulting in a steeper descending branch and a smaller area underneath it. Different concrete types, SCC as well as a conventional vibrated concrete was investigated in this study. From the results it could be seen that the peak strain corresponding with the compressive strength of the material was higher for SCC than for conventional vibrated concrete of the same strength. The descending branch of the stress-strain curve appears to be less steep for SCC, resulting in a higher toughness.

Shutter et al. (2010) carried out the investigation on the similarities and differences of pumping conventional vibrated concrete (CVC) and SCC. According to authors, SCC was considered as a simple extension of CVC where pumping was concerned. The same equipment, materials, pumping procedures and guidelines used for CVC was applied when pumping SCC. On the other hand, it had been clearly shown that the rheological properties and the mix design of SCC were different from that of CVC. This research compared some published results of pumping of CVC with those for SCC. From the present research conclusions can be drawn that the difference between pumping of CVC and SCC was only the flow behaviors in the pipes.

Aggarwal et al. (2011) studied prediction of compressive strength of SCC of containing bottom ash using artificial neural networks. This research presented a comparative performance of the models developed to predict 28 days compressive strengths using neural network techniques for the data taken from literature (ANN-I) and the data developed experimentally for SCC containing bottom ash as partial replacement of fine aggregates(ANN-II). The data used in the models were arranged in the format of six and eight input parameters that covered the contents of cement, sand, coarse aggregate, fly ash as partial replacement of cement, bottom ash as partial replacement of sand, water and water/powder ratio, super plasticizer dosage and an output parameter that was 28-days compressive strength and compressive strengths at 7 days, 28 days, 90 days, and 365 days, respectively for ANN-I and ANN-II. The importance of different input parameters was also given for predicting the strengths at various ages using neural network. The model developed from literature data could be easily extended to the experimental data, with bottom ash as partial replacement of sand with some modifications.

Boukendakdji et al. (2012) carried out the investigation on the effect of ground blast furnace slag and super plasticizer type on the fresh properties and compressive strength of SCC. In control SCC, cement was replaced with 10%, 15%, 20%, and 25% of ground blast furnace slag. Results showed that addition of ground blast furnace slag by substitution to cement was found to be very beneficial to fresh properties of concrete, and compressive strength decreased with increase in slag content, as occurs for vibarated concrete, although at later ages the differences were small.

Singh et al. (2012) carried out the investigation on fatigue analysis of plain and fiber reinforced SCC. The results of this research showed significantly improved fatigue performance of self-compacting fiber reinforced concrete with enhanced sensitivity of fatigue lives to the change of applied stress.

Singh et al. (2012) carried out the investigation on flexural fatigue strength and failure probability of self-compacting fibre reinforced concrete beams (SCFRC). The fatigue life data of SCFRC containing 0.5%, 1.0% and 1.5% by volume of steel fibres had been obtained by conducting flexural fatigue tests on approximately 188 beam specimens of size 100 x 100 x 500 mm under third point loading at different stress levels, ranging from 0.90 to 0.70. Approximately 144 complimentary static flexural tests were also carried out
to facilitate fatigue testing. All the static flexural and flexural fatigue tests were conducted on a 100 kN closed loop servo-controlled actuator. The results had been represented in the form of S–N diagrams and to predict the flexural fatigue strength of SCFRC, material coefficients of the fatigue equations had been estimated. Subsequently, family of S–N–Pf curves has been generated from the fatigue test data to graphically represent the relationship between stress level S, fatigue life N, and probability of failure Pf, thus incorporating probability of failure into the fatigue life data of SCFRC. The experimental coefficients of the fatigue equation had also been obtained

from the fatigue test data to represent the S–N–Pf curves analytically. The two-million cycles fatigue strength of SCFRC has been found to be higher than that of normally vibrated fibre reinforced concrete (NVFRC).

2.2. LITERATURE REVIEW OF SCC SUBJECTED TO ELEVATED TEMPERATURE

As the use of SCC becomes common, the risk of exposing it to elevated temperature increases. The behavior of this new material in the case of elevated temperature thus has to be investigated.

2.2.1. Properties of SCC using fly ash

Khatib et al. (2003) investigated the influence of high-temperature and low-humidity curing on chloride penetration in concrete containing cement replacement materials. The results showed that at early periods of exposure, initial curing had a substantial influence on chloride penetration in concrete. Higher chloride penetration resistance was observed when cement was partially replaced with either fly ash or silica fume.

Sivaraja (2010) studied the effect of high temperature on the mechanical properties of five different SCC mixes. These mixes were designed with normal concrete, fly ash, silica fume, rice husk ash, and with quarry dust. All the mixes were satisfied with fresh concrete properties such as filling ability and passing ability. Specimens were subjected to high temperature up to 500°C and 1000°C for 1hour in hot furnace. Mechanical properties such as compressive strength, splitting tensile strength, and modulus of rupture were obtained by conducting tests as per Indian Standards. Results of specimens subjected to high temperature were compared with conventional specimens.

Anand et al. (2011) reviewed the effect of elevated temperature on concrete materials. The compiled test data revealed distinct difference in mechanical properties of normal, high strength and SCC. Shape of the specimens, size of the specimens, magnitude of temperature, load applied on the specimen, time duration maintained for heating, reference on time temperature curve, rate of heating, rate of cooling, time taken for hot test after curing period, time taken for load test after heating, heat test on stressed/unstressed member, type of cooling adopted on heating specimen by natural cooling or cooling by spraying water etc. were the parameters that influenced the test results. According to the authors in order to understand the behaviors of concrete under elevated temperature, it is necessary that several factors be taken into account for each experiment. Strength of concrete, type of cement, type of aggregates, water cement ratio, density of concrete, percentage of reinforcement, cover to the reinforcement etc. are some of the important factors that affect the performance of concrete at elevated temperatures.

Kulkarni et al. (2011) carried out an investigation on comparative study of the effect of sustained high temperature on strength properties of SCC and ordinary conventional concrete. In order to study the effect of sustained elevated temperature on compressive strength, flexural strength, tensile strength and impact strength of SCC and ordinary conventional concrete, the specimens of SCC and ordinary conventional concrete were tested in the lab. For various tests 21 cubes, 21cylinders, 21beams and 21plates were casted and the same for ordinary concrete were also casted. The specimens were kept in the oven at required temperature (28°C, 100°C, 200°C, 300°C, 400°C, 500°C and 600°C) for 5 hours. The results obtained were compared with the corresponding properties of normal concrete with the same w/c ratio and air content.

2.2.2. Properties of SCC using silica fume

Ghandehari et al. (2010) studied the effect of high temperatures on the mechanical properties of high-strength concretes. Mixtures were prepared with water to cementitious material ratios of 0.40, 0.35, and 0.30 containing silica fume at 0, 6, and 10% cement replacement. After heating to 100, 200, 300, and 600°C, the compressive strength, the splitting tensile strength, and the corresponding ultrasonic pulse velocity were measured. A substantial loss of strength was observed for all compositions at 600°C, particularly the silica fume concretes in spite of the superior mechanical properties provided by silica fume at room temperature. The average residual compressive and splitting tensile strengths of the concretes at 600°C were 30 and 25% of the room-temperature strengths, respectively. It was found that the rate of the splitting tensile strength loss is higher than the rate of the compressive strength loss at elevated temperatures and that the ultrasonic pulse velocity measurements slightly underestimate the residual strength of the high strength concretes after exposure to temperature over 200°C.

2.2.3. Properties of SCC using lime stone powder

Reinhardt et al. (2006) carried out an investigation on the influence of heat curing on pore structure and compressive strength of SCC by using lime stone powder and fly ash as filler material. It was found that there was an influence of the composition of the concrete, especially the w/c ratio, on the compressive strength after heat treatment. An empirical formula was presented to calculate the influence of the heat treatment on the compressive strength of the SCC.

Ye et al. (2007) studied the phase distribution and micro structural changes of self-compacting cement paste at elevated temperature by using lime stone powder as a filler material. The experimental results of self-compacting cement paste were compared with those of high performance cement paste and traditional cement paste. It was found that self-compacting cement paste shows a higher change in total porosity in comparison with high performance cement paste. This difference largely depends on the micro structural properties of concrete matrix, i.e. the cement paste, especially on the porosity, pore size distribution and the connectivity of pores in cement pastes.

Anagnostopoulos et al. (2009) carried out an investigation to determine the influence of different fillers on the properties of SCC of different strength classes when exposed to high temperatures. They reported that explosive spalling occurred in both the cases of SCC and NCC when the oven peak temperature of 600°C was maintained. SCC was found to spall more compared to NCC due to lower permeability and higher moisture content. SCC produced with limestone filler was found to have better performance compared to mixtures prepared with different filler materials.

Hanna et al. (2009) studied the physicochemical and mechanical properties of SCC subjected to high temperature. Two SCC mixtures and one vibrated concrete mixture were tested for this purpose. These concrete mixtures come from the French National Project B@P. The specimens of each concrete mixture were heated at a rate of 1°C/min up to different temperatures (150, 300, 450 and 600°C). In order to ensure a uniform temperature throughout the specimens, the temperature was held constant at the maximum temperature for 1 hour before cooling. Thermo gravimetric analysis, thermo differential analysis, X-ray diffraction and SEM observations were made. The aim of these studies was to explain the observed residual compressive strength increase between 150 and 300°C, in particular.

Uygunoglu et al. (2009) studied the effect of aggregate type on the coefficient of thermal expansion of SCC and light weight aggregate at elevated temperature. Two types of aggregates namely crushed lime stone and pumice were used. Thermal test was performed to accurately characterize the coefficient of thermal expansions. Test temperatures were varied from 20 to 1000°C. Test results showed that SCC had higher coefficient of thermal expansions than normal weight concrete and light weight aggregate reduced the coefficient of thermal expansions of SCC due to their porous structure.

Bakhtiyari et al. (2010) carried out an investigation on the fire resistance of SCC containing limestone and quartz powders, with two different compressive strengths, and compared with normal concretes (NC). The residual mechanical strengths of the mixes at different temperatures were measured. The changes in the phase composition of the cement pastes at high temperatures were examined with thermal analysis and X-ray diffractometry methods. The SCC mixes showed a higher susceptibility to spalling at high temperatures but the NC mixes suffered much more from loss of the mechanical strengths. Both the powder types and the compressive strength notably influenced the fire behavior of the SCC. The quartz powder accelerated the hydration of the SCC cement paste at high temperatures, up to 500°C. However, the quartz-contained SCC showed the highest risk of spalling among all the mixes. The results showed that the thermal analysis could be a useful device for evaluating the fire behavior of building materials.

Hanna et al. (2010) carried out an investigation on the performance of SCC subjected to high temperature. Two SCC mixtures and one vibrated concrete were tested for this purpose. These concrete mixes were developed in the French National Project B@P. Mechanical and micro structural properties were studied at ambient temperature and after heating. They studied compressive strength, flexural strength, bulk modulus of elasticity, porosity and permeability. For each test, the specimens were heated at a rate of 1°C/min up to different temperatures (150, 300, 450 and 600°C). The specimen mass was measured before and after heating in order to determine the loss of water during the test. Their results allowed them to analyze the degradation of SCC and vibrated concretes due to heating.

2.2.4. Properties of SCC using other materials

Noumowe and Aggoun (2001) in their research, in order to investigate whether SCC was susceptible to spalling,performed an exploratory research on plain SCC cylinders with different mixture designs for concrete strength up to about 104 Mpa.

Persson (2004) made a comparison between the performance of vibrated concrete and SCC under elevated temperature. Cylinders and columns were tested by compressive loading at elevated temperatures. Polypropylene fibers were used to avoid the spalling of concrete. Specimens were heated in the temperature range of 20 to 800°C. It was observed from the test results that explosive spalling took place for columns with SCC but not for those with vibrated columns.

Noumowe et al. (2006) studied the effect of high strength SCC exposed to fire test. They presented the results of high temperature behavior of conventional vibrated high strength concrete and self-compacting high strength concrete. Their experimental results show that the residual mechanical properties in reference to initial mechanical properties of self-compacting high strength concrete were similar to that of conventional high strength concrete and the risk of spalling for self-compacting high strength concrete was greater than that of conventional high strength concrete.

Jin et al. (2010) reported the results of laboratory investigations carried out to study the compressive strength of SCC during high-temperature exposure ranging from room temperature to 800°C with different w/c ratio. It was found that hot compressive strength of SCC decreases with increasing temperatures. Compared with normal strength SCC, high strength SCC possesses a large compressive strength when exposed to high temperature. Another result of the test was that addition of polypropylene fibers decreased the strength and probability of explosive spalling.

Khaliq et al. (2011) studied the thermal and mechanical properties of fiber reinforced high performance SCC at elevated temperatures. This research presented the effect of temperature on thermal and mechanical properties of SCC and fiber reinforced SCC (FRSCC). For thermal properties, specific heat, thermal conductivity, and thermal expansion were measured, whereas for mechanical properties compressive strength, tensile strength and elastic modulus were measured in the temperature range of 20-800°C. Four SCC mixes, plain SCC, steel, polypropylene, and hybrid fiber reinforced SCC were considered in the test program. Data from mechanical property tests showed that the presence of steel fibers enhances high temperature splitting tensile strength and elastic modulus of SCC. Also the thermal expansion of FRSCC was slightly higher than that of SCC in the temperature range between 20-1000°C.

CHAPTER- 3

EXPERIMENTAL PROGRAM

This chapter deals with the experimental details of the properties of SCC investigated at elevated temperatures up to 300^{o}C. The properties studied were compressive strength, splitting tensile strength, modulus of elasticity, mass loss, porosity, and rapid chloride permeability. It also covers the materials properties of the materials used.

3.1. MATERIALS USED

The details of the materials used along with their properties are presented in the subsequent sections.

3.1.1. Cement

Ordinary Portland cement (Grade 43) was used for all concrete mixes. The cement used was fresh and without any lumps. Testing of cement was done as per *BIS: 8112-1989.* Its physical properties are given in Table 3.1.

Table 3.1: Physical properties of Portland cement

Physical Property	**Value**	**Specifications *(BIS: 8112-1989)***
Fineness retained on 90-µm sieve (%)	1.0	10 mm
Standard Consistency (%)	30	-
Initial setting time (minutes)	65	30 min^{m}
Final setting time (minutes)	215	600 max^{m}
Compressive strength 3-days (MPa)	23.6	22.0 min^{m}
Compressive strength 7-days (MPa)	35.4	33.0 min^{m}
Compressive strength 28-days (MPa)	43.0	44.3
Specific gravity	3.12	3.15
Soundness(mm)	2.50	10 max^{m}

3.1.2. Fly ash

Investigations were made on Class F Fly ash procured from Guru Govind Singh Super Thermal Power Plant, Ropar and Punjab, India. It was tested for physical and chemical properties as per *BIS: 3812-2003*. The physical and chemical properties of fly ash are given in the Tables 3.2 & Table 3.3, respectively.

Table 3.2: Physical properties of fly ash

Physical Properties	Value
Colour	Grey
Specific gravity	2.13
Lime reactivity-average compressive strength after 28 days of mixture (MPa)	4.90

Table 3.3: Chemical properties of fly ash *(BIS: 3812-2003)*

Constituents	% by Weight
Loss on ignition	4.17
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
Total Sulphur (SO_3)	0.07
Insoluble residue	-
Alkalies a) Sodium Oxide (Na_2O) b) Potassium Oxide (K_2O)	 0.58 1.26

3.1.3. Coarse Aggregates

Locally available coarse aggregates having the maximum size of 10 mm were used in the present work. Aggregates used were first sieved through 10 mm sieve and than through 4.75 mm sieve. They were than washed to remove dust and dirt and dried to the saturated surface dry condition. The aggregates were tested as per Indian Standard Specifications *BIS: 383-1970*. The results of various tests conducted on coarse aggregates are tabulated in Tables 3.4 & Table 3.5, respectively

Table 3.4: Properties of coarse aggregates

Characteristics	**Value**
Type	Crushed
Maximum size (mm)	10
Specific gravity	2.66
Water absorption (%)	0.90
Moisture content (%)	0.806
Fineness modulus	6.46

Table 3.5: Sieve analysis of coarse aggregates

Sieve No. (mm)	**Mass Retained (kg)**	**Percentage Retained (%)**	**Percentage Passing (%)**	**Cumulative %age Retained**
80	-	0.00	100	0.00
40	-	0.00	100	0.00
20	-	0 .00	100	0.00
12.50	0.555	18.5	81.5	18.5
10	0.8905	29.68	51.82	48.18
4.75	0.9565	31.88	19.94	80.06
Pan	0.5970	19.90	0.04	99.96
				ΣC =146.74
Fineness modulus of coarse aggregates (10 mm) = (ΣC+500)/100 = (146.74+500)/ 100=6.46.				

3.1.4. Fine aggregates

The sand used for the experimental programme was locally procured and conformed to grading zone III. The sand was first sieved through 4.75 mm sieve to remove any particles greater than 4.75 mm and then washed to remove the dust. The fine aggregates were tested as per Indian Standard Specifications *BIS: 383-1970.* The properties of fine aggregates are given in Table 3.6.

Table 3.6: Properties of fine aggregates

Characteristics	Value
Type	Uncrushed (natural)
Specific gravity	2.65
Moisture content (%)	0.16
Water absorption (%)	0.98
Fineness modulus	2.51
Grading zone	III

Table 3.7: Sieve analysis of fine aggregates

Sieve No.	Mass Retained (gms)	Percentage Retained (%)	Percentage Passing (%)	Cumulative %age Retained
4.75mm	95.0	9.5	90.5	9.5
2.36mm	42.5	4.25	86.25	13.75
1.18mm	110.5	11.05	75.2	24.8
600µm	128.5	12.85	62.35	37.65
300µm	308.0	30.80	31.55	68.45
150µm	281.0	28.10	3.45	96.55
Pan	34.5	3.45	-	-
				ΣF =250.7
Fineness modulus of fine aggregates=250.7/100=2.507				

3.1.5 Foundry sand

Investigations were made on foundry sand procured from Janta Foundries, Mandi Gobindgarh, Punjab. The physical and chemical properties of foundry sand are given in Tables 3.8 and Table 3.9. Table 3.10 gives the sieve analysis of 10% replacement level of sand with foundry sand.

Table 3.8: Physical properties of foundry sand

Property	**Value**
Specific gravity	2.64
Bulk relative density (kg/m^3)	1775
Absorption (%)	0.45
Moisture content (%)	0.1-10.1
Clay lumps and friable particles	1- 44
Coefficient of permeability (cm/sec)	10^{-3}-10^{-6}
Plastic limit/Plastic Index	Nonplastic

Table 3.9: Chemical composition of foundry sand

Constituent	**Value (%)**
Silica (SiO_2)	83.81
Iron Oxide (Fe_2O_3)	5.38
Alumina(Al_2O_3)	0.82
Calcium Oxide (CaO)	1.42
Magnesium Oxide (MgO)	0.86
Sulphur Trioxide (SO_3)	0.21
Sodium Oxide (Na_2O)	0.87
Potassium Oxide (K_2O)	1.14
Titanium Dioxide (TiO_2)	0.22
Manganese Oxide (Mn_2O_3)	0.047
Strontium Oxide (SrO)	0.03
Loss of Ignition (LOI)	5.15
TOTAL	99.95

Table 3.10: Sieve analysis of fine aggregates at 10% replacement level

Sieve No.	Mass Retained (gms)	Percentage Retained (%)	Percentage Passing (%)	Cumulative, %age Retained
4.75mm	37.00	3.70	96.30	3.70
2.36mm	10.50	1.05	95.25	4.75
1.18mm	43.00	4.30	90.95	9.05
600μm	67.50	6.75	84.20	15.80
300μm	23.90	2.39	60.30	39.70
150μm	54.90	5.49	5.40	94.60
Pan	5.15	0.51	0.25	99.75
				ΣF =267.35
Fineness modulus of fine aggregates with 10% foundry sand=ΣF/100=267.35/100=2.67				

Table 3.11: Physical properties of coarse aggregates, fine aggregates and foundry sand

Properties	Coarse aggregates	Fine aggregates	Foundry sand
Specific gravity	2.66	2.65	2.64
Fineness modulus	6.46	2.507	2.67
Bulk density (kg/m^3)	1545	1781	1775
Water absorption (%)	0.90	0.98	0.97

3.1.6. Water

Potable tap water was used for casting and for curing of concrete specimens conforming to the requirements of *BIS: 456-2000*. Properties of water are given in Table 3.12.

Table 3.12: Properties of water

Properties	Value
pH	8.0
Dissolved Solids(mg/l)	290
Suspended Solids	Nil
Chlorides (mg/l)	20

Sulphates (mg/l)	74
MPN Value/100ml	Nil

3.1.7. Admixtures

Super plasticizer: Super plasticizer (SP) is an essential component of SCC. In SCC it is generally necessary to use chemical admixtures in order to increase the workability and to reduce the problem of segregation. Adding a large volume of powdered material or viscosity modifying admixture can eliminate segregation. The incorporation of fly ash reduces the need of super plasticizer necessary to obtain a similar slump flow compared with the concrete containing only cement as binder *(Khatib, 2007).* Polycarboxylic ether based super plasticizer complying with *BIS: 9103:1999, ASTMC-494 type F, BS 5057 part III* with density approximately 1.10 and pH approximately 5.0 was used in this research. Super plasticizer was used to produce high workability in concrete and to reduce the water/binder ratio. It was used as a water reducing admixture and to improve the workability of concrete containing fly ash and foundry sand. It was specially formulated to give water reduction up to 25% without loss of workability or to produce high quality concrete of reduced permeability. The dosage of super plasticizer varied between 1% to 2% by weight of cement. If the super plasticizer content is higher than 2% then the compressive strength decreases because of bleeding. The technical data of super plasticizer is given in Table 3.13.

Table 3.13: Data of super plasticizer

Characteristics	**Value**
Colour	Dark brown liquid
Specific gravity	1.22 to 1.225
Air entrainment	Maximum 1%
Chloride content	Nil

3.2. MIX DESIGN

Mix design is a process of selecting suitable ingredients for concrete and determining their proportions which would produce, as economically as possible, a concrete that satisfies the job requirements. The proportioning of the ingredients of concrete is an important phase of concrete technology as it ensures quality and economy.

Since self-compactibility is largely affected by the characteristics of materials and the mix proportions, it becomes necessary to evolve a procedure for mix design of SCC. *Okamura and Ozawa (1995)* have proposed a mix proportioning system for SCC which is based on the Japanese concept. In this method the coarse and fine aggregate contents are fixed so that self-compactability is to be achieved easily by adjusting the water/binder ratio and super plasticizer dosage only. The proposed mixed design is:

- Coarse aggregate content in concrete is generally fixed at 50% of the total solid volume;
- Fine aggregate content is fixed at 40% of the mortar volume;
- Water/binder ratio in volume is assumed to be 0.9 to 1.0 depending on the properties of the powder; and

Super plasticizer dosage and the final water/binder ratio are determined so as to ensure self-compactability. In the mix proportioning of conventional concrete, the water/cement ratio is fixed at first from the view point of obtaining the required strength. In SCC, the water/binder ratio has to be decided taking into account self-compactability, because self-compactability is very sensitive to this ratio. The required water/binder ratio is determined by conducting a number of trials. One of the limitations of SCC is that there is no established mix design procedure yet.

The procedure adopted for the mix design of the present work was as follows:

- Using Japanese method of mix design as reference, initial mix design for the proposed study was carried out at coarse aggregate content of 50% by volume of concrete (all particles larger than 4 mm and smaller than 10 mm) and fine aggregate content of 40% by volume of mortar in concrete (all particles larger than 0.125 mm and smaller than 4 mm). Initial trial was stated with w/b ratio of 0.36 and 1% super plasticizer dose. Lots of trial mixes were prepared and tests were carried out on the basis of these trial mixes, so that the mix satisfies the fresh properties i.e. slump flow for workability and U-box for passing ability and hardened properties i.e. compressive strength. But it did not satisfy even the fresh properties.

- To proceed towards achieving satisfactory fresh as well as hardened SCC properties, the coarse aggregate content was increased from 50% to 51% by volume of concrete and thereby kept constant. Fine aggregate content was increased from 40% to 49% and kept constant at 49% by volume of mortar in concrete. The w/b ratio was varied from 0.36 to 0.42 for all mixes i.e. (cement and filler having particles smaller than 0.125 mm).

- By increasing the contents of coarse aggregate from 50% to 51% and increasing fine aggregate contents from 40% to 49%, required results in all the fresh properties i.e. slump flow and U-box were obtained. The super plasticizer dosage was varied from 1%-2% of powder content i.e. cement and fly ash. Final super plasticizer dosage was determined through trial mixes so as to ensure self-compatibility by using U-box and slump-flow tests. For each trial, tests were carried out so that the mix satisfied fresh properties. Target value for U-box was 0 to 30 mm and for slump-flow was 500 mm to 750 mm. By increasing the content of coarse aggregate from 50% to 51% and fine aggregates from 40% to 49%, required results in all the tests i.e., slump flow and U-box were obtained.

3.2.1. Mix proportions

There are some guidelines for mixture proportioning of SCC, which include i) reducing the volume ratio of aggregate to cementitious material; (ii) increasing the paste volume and water-cement ratio (w/c); (iii) carefully controlling the maximum coarse aggregate particle size and total volume; and (iv) using various viscosity enhancing admixtures. On the bases of these guidelines, four concrete mixes were finalized, which had total powder content of 500kg/m^3 (cement + fly ash). Coarse aggregate content was maintained at 51% by volume of concrete and fine aggregate content at 49% by volume of mortar in concrete, the w/b ratio was varied from 0.36-0.42 by weight with air content being assumed to be 2%. In this work, one control mix (SCC1) was designed with Ordinary Portland Cement and the other three concrete mixes (SCC2, SCC3, and SCC4) were made by replacing cement with 30%, 40%, and 50% of Class F fly ash by weight of total powder content. The mix proportions for various mixes are given in Table 3.14.

Table 3.14: Mix proportions and fresh concrete properties of SCC mixes

Mix	Cement (kg/m^3)	FA (%)	FS (%)	Fine Aggregate (kg/m^3)	CA (kg/m^3)	W/b	SP (%)	Slump (mm)	U-box (mm)	Room temp. (°C)	Conc. temp. (°C)
SCC 1	500	-	-	830	876	0.38	2.00	627	13	34	33
SCC 2	500	30	10	830	876	0.38	1.82	640	12	35	32
SCC 3	500	40	10	845	860	0.40	1.80	659	10	37	35
SCC 4	500	50	10	856	856	0.42	1.72	678	08	35	34
FS-Foundry sand, FA-Fly ash, CA-Coarse aggregates, SP-Super plasticizer											

3.3. PREPARATION, CASTING, AND TESTING OF SPECIMENS

For the mix proportions given in Table 3.14, required quantities of materials were weighted. A careful procedure was adopted in the batching, mixing and casting operation. The mixing procedure adopted was as follows:

- Ordinary Portland Cement (OPC) having 43 grades was used in casting. Cement and fly ash were mixed in dry state for about five minutes until uniform colour was obtained without any clusters of cement and fly ash.

- The coarse aggregates and fine aggregates were then weighted with an accuracy of 0.5 grams and then mixed in dry state. One proportion of fine aggregate was replaced with foundry sand and then thoroughly mixed.

- All the ingredients were then mixed together thoroughly, until a homogeneous mix was obtained. The concrete mix was prepared by hand mixing on a water tight platform.

- Water was then added gradually. 50% of water was added during mixing, which was continued for five minutes. Super plasticizer as per requirement of the test was added with 40% of water. Remaining 10% of water was sprinkled on the above mix and additional mixing for two minutes was carried out to obtain a homogeneous mix.

The fresh concrete was tested for its rheological properties. Once various criteria of self-compatibility were satisfied, final casting of the mix was done immediately. All the specimens were prepared in accordance with Indian Standard Specifications *IS: 516-1959.* After casting, test specimens were allowed to remain in the steel mould and left in the casting room for 24 hours at ambient condition. Specimens were demoulded after 24 hours with care so that no edges were broken and were placed into the water-curing tank at the ambient temperature for curing until the time of the test or as per requirement of the test. The ambient temperature for curing was 27 ± 2^{o}C. Table 3.15 gives the various properties studied in this research with sizes of specimens and the age of testing. Besides measuring the fresh properties (workability, unit weight, temperature of concrete, and air content) hardened concretes were tested on various properties given in Table 3.15.

Table 3.15: Various properties with size of specimens and age of testing

Property	**Size of specimens**	**Age of testing**
Compressive strength	150 mm size cubes (*BIS: 516-1959)*	28, 91, and 365 days
Splitting tensile strength	150 mm x 300 mm cylinders (*BIS: 516-1959)*	28, 91, and 365 days
Modulus of elasticity	150 mm x 300 mm cylinders (*BIS: 516-1959)*	28, 91, and 365 days
Rapid chloride permeability	100 mm x 200 mm cylinders *(ASTM C1202)*	28, 91, and 365 days
Porosity	100 mm x 50 mm cylinders *(RILEM, 1994)*	28, 91, and 365 days

3.4. FRESH CONCRETE PROPERTIES

Workability of SCC is provided by the binding paste in fresh state. Fresh concrete properties, such as slump flow, U-box, unit weight, temperature of concrete, and air content, were determined. SCC is characterized by filling ability, passing ability and resistance to segregation.

Many different methods had been developed to characterize the properties of SCC. No single method has been found till date, which characterizes all the relevant workability aspects, and hence, each mix had been tested by more than one test method for different workability parameters.

For determining the self-compactibility properties, slump flow test and U-box (difference in height) tests were performed. According to *Nagataki and Fujiware (1995)*, a slump flow ranging from 500 to 750 mm is considered as the slump required for a concrete to be self-compacted. If the slump flow is greater than 750 mm the concrete might segregate and if it is less than 500 mm the concrete is considered to have insufficient flow to pass through highly congested reinforcement. U-box test gives us the filling and passing ability of SCC.

3.4.1 Slump Flow Test

The slump flow test is the most common method used for assessing the flowing/ filling ability of SCC mixes in the laboratories or on site. The basic equipment used for slump flow test of SCC is the same as for the conventional slump test (Fig. 2). The test method differs from the conventional test in the way that the concrete sample placed into the mould has no reinforcement rod. The slump cone is filled with the concrete mixture without rodding, and then lifted up vertically. When the slump cone has been lifted up and the sample has collapsed, the diameter of the spread is measured rather than the vertical distance of the collapse as measured in the conventional test The slump flow represents the mean diameter of the mass of concrete after release of a standard slump cone; the diameter of the spread of the sample is measured in two perpendicular directions i.e., a horizontal distance is measured. While measuring the diameter of the spread, the time that the sample takes to reach a diameter of 500 mm (T50) is also sometimes measured. The slump flow test can give an indication about the filling ability of SCC. The viscosity of the SCC mixtures can also be evaluated through the slump flow test.

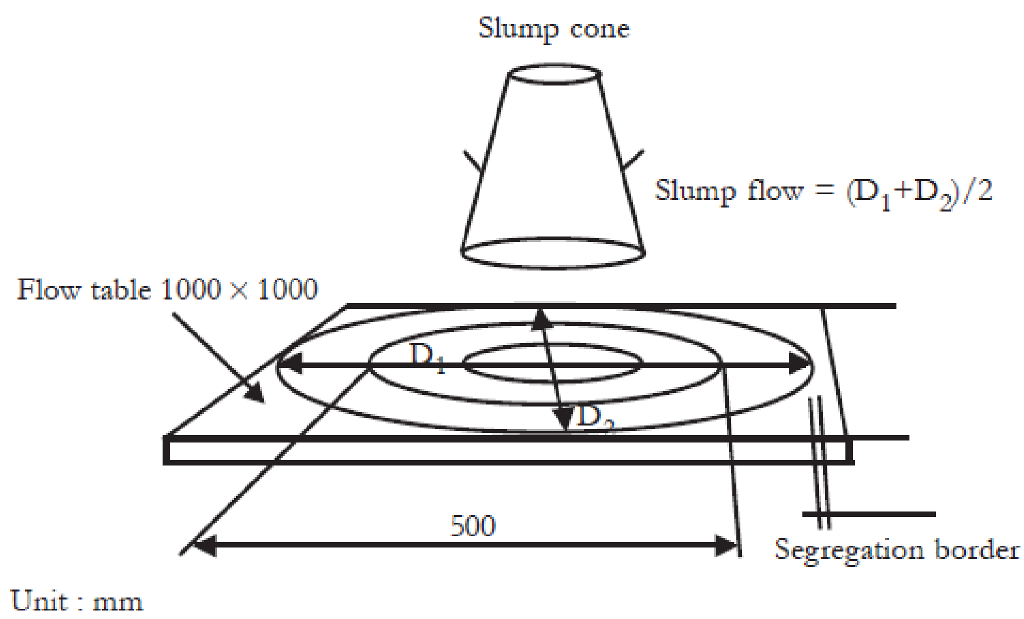


Fig. 3.1: Slump flow test

Slump test is a measure indicating the workability of cement concrete. Slump flow test is the most commonly used test for finding out the workability of SCC, and it gives good assessment of filling ability. It gives no indication of the ability of the concrete to pass between reinforcement without blocking, but may give some indication of resistance to segregation. The higher the slump flow value, the greater is its ability to fill formwork under its own weight. The slump flow test was used in the present research to assess the horizontal free flow of SCC in the absence of obstructions. The test method was based on the conventional slump test. The diameter of the concrete circle was measured for the filling ability of the concrete. Fig. 3.2 shows the slump flow test for this research. The results of slump flow test for this research are presented in Table 3.14.

Fig. 3.2: Slump-flow test

Table 3.16 gives the recommended values for different tests given by different researchers for mix to be characterized as SCC mix.

Table 3.16: Recommended limits for different properties

Property	**Range**
Slump flow diameter	500-750 mm
T_{50cm}	2-5 sec
U-box	0-30 mm

3.4.2. U-box test

This test is used for measuring the flow ability of SCC through an obstacle with coarse aggregates having the maximum size of less than 25 mm. The time and height to be filled in the chamber band and the amount of aggregate passing through the obstacles are measured for self-compactability. The apparatus consists of a vessel that is divided by a middle wall into two compartments (as shown in Fig. 3.3). It provides a good direct assessment of filling ability. For conducting the U-box test, one of the compartments of the apparatus was filled with the concrete sample and the filled concrete was left to stand for one minute. Then the sliding gate was lifted to allow the concrete to flow out into the other compartment. After the concrete comes to rest, the height of the concrete in the compartment that had been filled was measured in two places and the mean height (H1) was calculated. Also the height in the other compartment (H2) was measured. The filling height was then calculated as H1-H2. The whole test had to be performed within five minutes. If the concrete flows as freely as water, at rest it will be horizontal, so H1-H2 = 0. Therefore, the nearer this test value, i.e., the 'filling height', is zero, the better the flow ability and passing ability of SCC (*EFNARC, 2002*). The results of U-box test for this research are presented in Table 3.14.

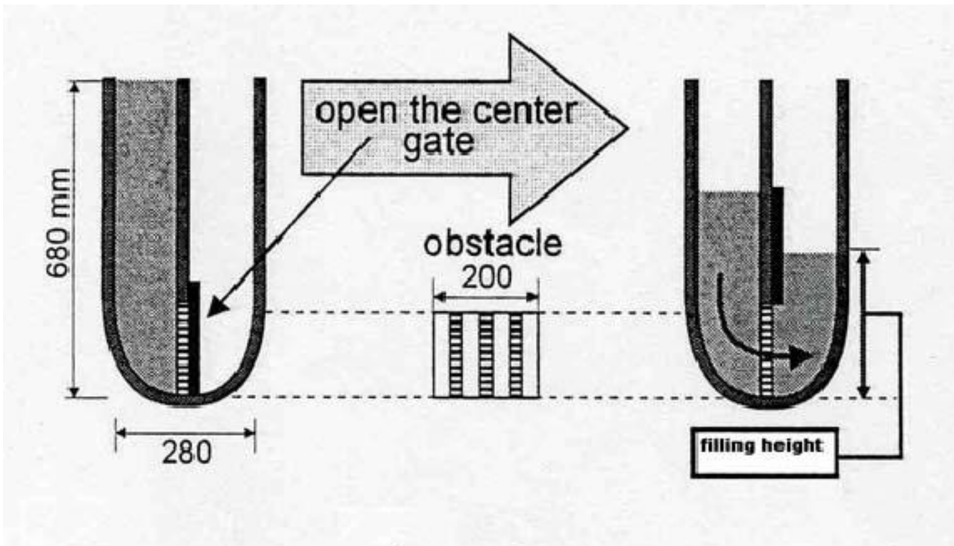


Fig. 3.3: U-box test

3.5. MEASUREMENTS OF PROPERTIES

After the required curing period, the specimens were taken out of the curing tank and their surfaces were wiped off. The specimens of each concrete mixture were heated at a rate of 1°C/min up to different temperatures i.e.100^{o}C, 200^{o}C, and 300^{o}C in an electric oven. In order to ensure a uniform temperature throughout the specimens, the temperature was held constant at the maximum for one hour before cooling to achieve the thermal steady state. The specimens were allowed to cool naturally to room temperature.

The rate of heating refers to the recommendations of the *RILEM Technical Committee TC-129.* The changes in the mechanical properties of SCC due to elevated temperature were examined. The strength of SCC was provided by the aggregates binding by the paste at hardened state.

Compressive strength, splitting tensile strength, modulus of elasticity, porosity, and mass loss were determined at the age of 28, 91, and 365 days, as per *BIS: 516:1959*.

3.5.1. Compressive strength

All the cube specimens of size 150 mm were tested in an automated CTM as shown in Fig. 3.4. The compressive strength was than calculated according to the formula:

$$C_s = P / A \qquad \text{---------(3.1)}$$

C_s = Compressive Strength (N/mm^2)

P = Maximum load (N), A = Cross sectional area of cube (mm^2)

Fig. 3.4: Compression failure of cube without fly ash

3.5.2. Splitting tensile strength

Splitting tensile strength test is a well known indirect test used for determining the tensile strength of concrete. This test consists of applying compressive line loads along the opposite sides of a concrete cylinder placed with its axis in a horizontal position between the plates, as shown in Fig. 3.5. Due to the applied line loading a fairly uniform tensile stress is introduced over nearly two third of the loaded diameter as obtained from an elastic analysis. The magnitude of this tensile stress acting in a direction perpendicular to the line of action of applied compression is given by:

$$T_s = 2P/ \pi DL \qquad \text{--------- (3.2)}$$

T_s = Tensile Stress (N/mm^2)

P = Applied load at failure (N)

D = Diameter of cylinder (mm)

L = Length of cylinder (mm)

Fig. 3.5: Splitting tensile strength testing machine

3.5.3. Modulus of elasticity

Elastic modulus of concrete is a very important parameter reflecting the ability of the concrete to deform elasticity. The modulus of elasticity or Young's modulus is defined as the slope of the stress-strain curve with the proportional limit of a material. Before performing the modulus of elasticity test, three cubic specimens were broken first to determine the compressive strength of concrete. Extensometer was used for determining the change in length of specimens on compressive loading. The extensometer consists of two frames for clamping the specimens by means of five tightening screws with a hardened and tapered end. The spacers hold the two frames in position. The dial gauge was attached with the compressometer. Least count of dial gauge was 0.025 mm. On the specimens, load was applied according to *IS 516:1959.* The rate of loading was 14N/mm^2/min. The modulus of elasticity was calculated according to the following formula:

C_s = P/A, A = $\pi / 4\, d^2$, $\epsilon = \Delta L / L$, $E = C_s / \epsilon$ ---------- (3.3)

C_s = Compressive stress (N/mm^2)

P = Compressive load (N),

A = Area of cylindrical specimen (mm^2)

D = Diameter of cylinder (mm)

ϵ = strain,

ΔL = Change in length (mm)

L = Length of cylinder,

E = Modulus of elasticity (N/mm^2)

Fig. 3.6: Modulus of elasticity testing machine

3.5.4. Concrete mass loss

The mass of each specimen was measured before and after each temperature cycle. Weight change of concrete was mainly due to dehydration of cement paste. This allows us to quantify the dehydration of concrete after each heating. Mass loss was determined at the ages of 28, 91, and 365 days.

Concrete mass loss = $W_1 - W_2$ ---------- (3.4)

W_1 = Weight of the sample before heating (gm)

W_2 = Weight of the sample after heating (gm)

3.5.5. Porosity

Total porosity of the different mixes was studied. These properties were measured before and after each temperature cycle. Five samples were tested for each concrete and each temperature cycle. ASTM vacuum saturation technique was used to measure the porosity of concrete. ASTM standard procedures were employed using 100 x 50 mm cylinder specimens. The specimens were dried in the oven at 100°C for more than 48 hours and then specimens were removed from the oven, cooled in dry air to a room temperature of 27°C and then weighted to obtain the oven dry mass. After that the specimens were vacuum saturated. Porosity of concrete was calculated based on the concept of weight gain due to water absorption and weight loss because of buoyancy. The amount of water penetrated into the sample was a measure of porosity and it was calculated as follows:

$$\text{Porosity} = (W_s - W_d) / (W_s - W_b) \times 100\% \qquad \text{---------} \ (3.5)$$

(RILEM recommendation, 1994)

Where, $W_s =$ saturated surface dry weight (in air), W_d = oven dried sample weight (in air), and $W_b =$ saturated submerged weight (in water).

3.5.6. Rapid chloride permeability

Permeability is one of the main characteristics influencing the durability of concrete to the ingress of chloride ions. Corrosion of reinforcing steel is the largest durability problem worldwide in concrete structures. Engineers have been specifying high strength/low permeability in recent years in an effort to reduce concrete chloride diffusion and to increase the service life of structures. The chloride ion present in the concrete can have harmful affect on concrete as well as on the reinforcement. Swelling of concrete due to chloride ion penetration is 2 to 2.5 times larger than that observed with water penetration. Thus the ability of concrete to resist the penetration of chloride ions is a critical parameter in determining the service life of steel-reinforced concrete structures exposed to deicing salts or marine environments. The measurement concerns the chloride ions that come into the contact of concrete and also those flowing through the samples.

The chloride permeability test for the present research was conducted to assess the concrete quality as per *ASTM C 1202-97* at the ages of 28, 91, and 365 days. To measure the permeability, cylindrical specimens of size 100 mm dia and 50 mm length were cut from the cylinders of size 100 mm dia and 200 mm length. Only the central part of the cylinders was kept for the measures. The specimens were placed in the vacuum desiccator's bowl with the set up of vacuum pump, desiccators with stopcock, vacuum gauge and valve and the deaerated water container after the water had filled the desiccators as shown in Fig. 3.7. The vacuum was maintained in the desiccator bowl for 3 hours. The de-aerated water was allowed to flow into the desiccator, so that it completely covered the specimens and air was allowed to enter. Again the vacuum was maintained for another one hour. Then the specimens were left for another 18 hours. The specimens were removed from the dessicator, dried and placed in gasket. In this test one end of the specimen was placed in contact with a 0.3 N NaOH (sodium hydroxide) solution, and the other with a 3.0% NACl (sodium chloride) solution. The total charge passed during 6 hours was measured, indicating the degree of resistance of the specimen to chloride ion penetration. A potential difference of 60V applied DC voltage for 6 hours was maintained across the specimen using the apparatus and the cell arrangement as shown in Fig. 3.8. Fig. 3.9 shows the top view of RCPT test set up. Heated specimens were tested 24 hours after cooling in order to maintain the same hydric conditions for all the specimens. The residual permeability obtained after each temperature cycle was determined. The chloride ion permeability was decided on the basis of charge passed according to Table 3.17.

Table 3.17: Chloride ion penetrability based on charge passed *(ASTM C 1202-97)*

Charge passed (Coulomb)	Chloride ion penetrability
>4000	High
2000–4000	Moderate
1000–2000	Low
100–1000	Very low
<100	Negligible

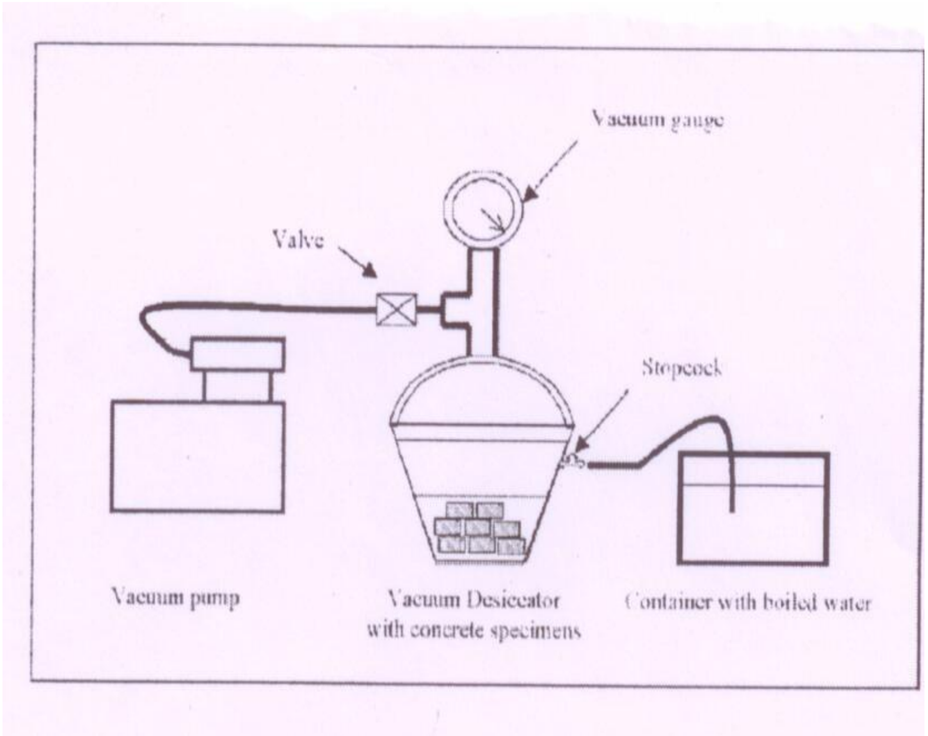


Fig. 3.7: Vacuum pump, desiccator and a container with de-aerated water

The procedure of this test method for measuring the resistance of concrete to chloride ion penetration had no bias because the value of this resistance was defined only in terms of a test method. The interpretation was that the larger the Coulomb number or the charge transferred during the test, the greater the permeability of the sample. The more permeable the concrete, the higher the coulombs, the less permeable the concrete, the lower the coulombs. The following formula, based on the trapezoidal rule was used to calculate the average current flowing through one cell.

$$Q = 900\ (I_0+2I_{30}+2I_{60}+2I_{90}+2I_{120}+\ldots+2I_{300}+2I_{330}+I_t) \qquad \text{------ (3.7)}$$

Where, Q = current flowing through one cell (coulombs)

I_0 = Current reading in amperes immediately after voltage was applied,

I_{30} = Current reading in amperes after 30 minutes voltage was applied, and

I_t = Current reading in amperes at t minutes after voltage was applied

. **Fig. 3.8: Rapid chloride permeability test set up**

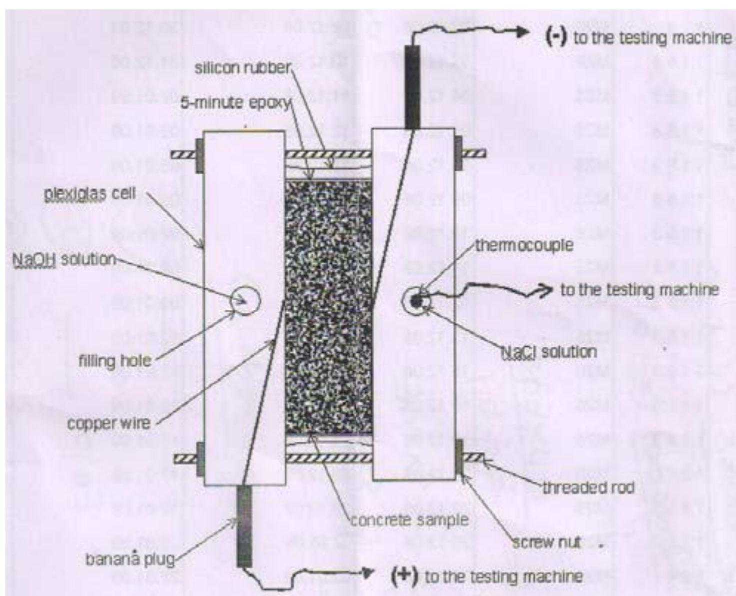


Fig. 3.9: Top view of RCPT test set up (*ASTM C1202-97*)

3.6 MICROSCOPIC OBSERVATIONS (SEM-SCANNING ELECTRON MICROSCOPY)

Scanning electron microscope (SEM) plays an important role for the analysis of rough as well as smooth surfaces. The SEM images provide the information regarding the grain size, shape, porosity, and agglomeration of the powder. SEM exhibits properties of high resolution, extensive magnification range and high depth of field. The sample for SEM analysis is mounted on a conductive substrate such as aluminum stub and gold plated in vacuum. The gold coated samples are kept at the sample stage of the microscope. The samples can be moved in X, Y, and Z directions, tilted as well as rotated. Further, the data signal is released due to interaction between bombarding electrons and atoms of the specimens. These data signal arise due to elastic or inelastic collisions of beam electrons with the atoms of the specimens. The elastic (electron-nucleus) collisions produce back scattered electrons (BSE) and inelastic (electron-electron) produce secondary electrons. The back scattered electrons provide topographic as well as compositional information about the specimens. In other words, SEM micrographs could be taken in two modes i.e., secondary emission and back scattered. In the present study secondary emission mode was used. Mechanical tests were performed at normal temperature and after exposure to elevated temperature in order to determine the residual compressive strength, splitting tensile strength and modulus of elasticity. After each mechanical test, concrete samples were taken and put into plastic bags in order to carry out microscopic observations. Samples of size 3 or 4 cm had been drilled out from concrete without coarse aggregates. Scanning electron microscope (SEM) measurement was done on samples with fly ash and without fly ash. The samples used for SEM observations were dried at 70°C. The samples were observed at different magnification using JEOL JSM-6510 LV microscope. Before examination, these samples were gold sputtered, to make the surface conductive for surface topography examination. Fig. 3.10 shows the equipment used for scanning electron microscope.

Fig. 3.10: Scanning electron microscope (SEM)

3.7. X-RAY DIFFRACTION

X-ray diffraction is one powerful technique to obtain crystallographic information about a sample. X-ray diffraction technique is the most prominent technique used for unraveling the structure of the materials in thin film forms. When an electron moving at high speed is directed to a targeted metal, then a small percentage of its kinetic energy is converted into X-rays. It is a non-destructive technique used to determine the elements present in any particular substance. X-ray diffraction is based on the fact that in a mixture the measured intensity of a diffraction peak is directly proportional to the content of the substance producing it.

The X-ray diffraction study of the mortar samples was done to identify crystalline phases. Mortar samples were taken from concrete specimens subjected to elevated temperature and stored in watertight bags. Then, they were crushed into the powder form and sieved to achieve a proper specimen for XRD. The concrete sample for X-ray diffraction analysis was taken from the inner core of the matrix. X-ray diffraction analysis was conducted, in order to identify the crystal phases in the different samples, using copper radiations.

X-ray diffraction analyses (XRD) of the samples were performed using Rigaku model Geiger diffractogram operated at 45 KV, 40mA using CuKα radiation (λ = 1.5418 A°) obtained from copper target using an in-built Ni filter. X-ray diffraction of some of the samples was performed using XPert Pan analytical with CuKα radiation. Fig.3.11 shows the X-ray diffractometer (XRD**).** For the given samples, XRD graphs were obtained with intensities on Y-axis and 2θ on x-axis.

The Bragg condition for reflection of X-rays by the atomic planes is given by:

$$2d \sin \theta = n \lambda \qquad \text{------------ (3.6)}$$

Where d = interplaner spacing;

λ = wavelength of incident x-ray;

θ = diffraction angle;

n = integer;

Fig. 3.11 : X**-ray diffractometer (XRD)**

CHAPTER- 4

RESULTS AND DISCUSSION

This chapter deals with the findings of experimental investigations. Various tests were conducted to evaluate the effect of elevated temperatures on compressive strength, splitting tensile strength, modulus of elasticity, mass loss, porosity and rapid chloride permeability of the SCC designed mixes containing various percentages of fly ash (30%, 40%, and 50%) and 10% replacement of fine aggregate with foundry sand.

4.1. COMPRESSIVE STRENGTH

4.1.1. Effect of temperature on compressive strength of the SCC mixes made with fly ash and foundry sand

The results of compressive strength test for different fly ash contents (0%, 30%, 40%, and 50%) and foundry sand incorporating different temperatures (27^{o}C, 100^{o}C, 200^{o}C, and 300^{o}C) at the end of different curing periods (28, 91, and 365 days) are given in Table 4.1. The results have also been plotted in Figs. 4.1 to 4.11.

The behavior of SCC and vibrated concrete differs significantly between 27°C and 300°C. As can be seen from Figs. 4.1 to 4.7, compressive strength increased with the decrease in fly ash content at different temperatures, as compared with the SCC mix prepared without fly ash and foundry sand. On the other hand compressive strength decreased with the increase in temperature up to 200^{o}C and after that little improvement in strength was observed. The compressive strength was calculated as the average of five tested cubes. At normal temperature (27°C), with the increase in fly ash content from 30-50%, the SCC mixes developed compressive strengths between 30.67 and 21.43 MPa, 39.50 and 30.40 MPa, and between 42.25 and 33.64 MPa. Strength values were 40.68, 48.90, and 51.20 MPa at 28, 91, and 365 days respectively, for the control mix. An increase of approximately 24%, 20% and 16% strength was observed at 28, 91, and 365 days respectively, with the decrease of fly ash content from 50-30% (SCC4, SCC3, and SCC2) and with 10% replacement of fine aggregate with foundry sand as compared with the control mix (SCC1).

Table 4.1: Compressive strength of the SCC mixes

Mix	Temperature(°C)	Fly Ash (%)	Compressive strength(MPa)		
			28 days	**91 days**	**365 days**
SCC1	Normal	0	40.68	48.90	51.20
SCC1	100	0	39.26	47.65	49.75
SCC1	200	0	39.09	47.07	49.08
SCC1	300	0	41.24	48.25	50.84
SCC2	Normal	30	30.67	39.50	42.25
SCC2	100	30	29.56	38.00	40.50
SCC2	200	30	29.00	37.90	40.26
SCC2	300	30	31.45	39.00	41.70
SCC3	Normal	40	26.22	35.00	38.10
SCC3	100	40	25.13	33.91	36.91
SCC3	200	40	24.60	33.26	36.26
SCC3	300	40	25.98	34.85	37.90
SCC4	Normal	50	21.43	30.40	33.64
SCC4	100	50	19.96	29.25	32.02
SCC4	200	50	19.25	29.12	31.75
SCC4	300	50	21.20	30.20	33.16

After heating at 100°C and subsequent cooling, the SCC mixes (SCC2, SCC3, and SCC4) developed compressive strength ranged between 29.56 and 19.96 MPa, 38.00 and 29.45 MPa, and between 40.50 and 32.80 MPa. For the control mix (SCC1), the values of strength were 39.26, 47.65, and 49.75 MPa at 28, 91, and 365 days respectively. An increase of approximately 24.50%, 19% and 14% was observed at 28, 91, and 365 days respectively; with the decrease of fly ash content from 50-30% (SCC4, SCC3, and SCC2) as compared with the control mix (SCC1).

With the increase in temperature from 100°C to 200°C, compressive strength varied between 29.00 and 19.25 MPa (SCC2), 37.90 and 29.12 MPa (SCC3), and between 40.26 and 31.75 MPa (SCC3). Strength values were 39.09, 47.07, and 49.08 MPa at 28, 91, and 365 days respectively, for the control mix. With the decrease in fly ash content from 50-30% (SCC4, SCC3, and SCC2) and with 10% replacement of fine aggregate with foundry sand, the strength increased approximately 25%, 18% and 13% at 28, 91, and 365 days.

With further increase in temperature from 200°C to 300°C, compressive strength ranged between 31.45 and 21.20, 39.00 and 30.20 MPa, and between 41.70 and 33.16 MPa at 28, 91, and 365 days. Strength values were 41.24, 48.25, and 50.84 MPa for the control mix (SCC1). The mix SCC4, SCC3, and SCC2 exhibited increase in compressive strength by approximately 25.50%, 17.00% and 12.00% at 28, 91, and 365 days respectively, as compared with the SCC1.

Strength loss with fly ash and foundry sand in the temperature range of 27°C to 100°C was about 2.10%. Between 100-200°C, there was little reduction in strength. With further increase in temperature from 200°C to 300°C, there was little improvement in strength (about 1%), as compared with the control mix (SCC1). Strength loss with 30-40% fly ash between 27°C to 100°C was about 1%. Strength loss with 50% fly ash between 27°C to 100°C was about 2.50%. Between 100-200°C, there was about 0.90% loss of strength and after that stabilizing and regaining stage between 200°C and 300°C.

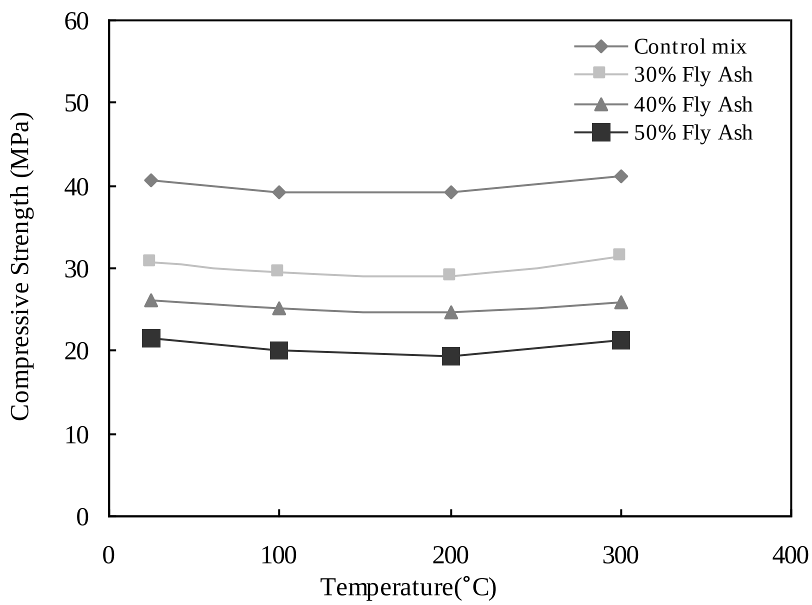


Fig. 4.1: Compressive Strength verses Temperature (28 days)

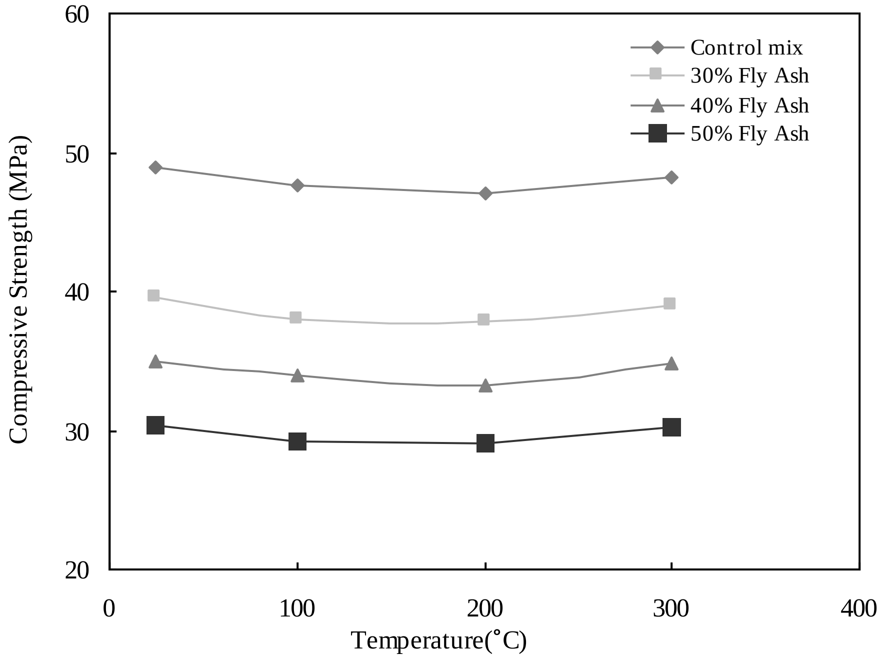


Fig.4.2: Compressive Strength verses Temperature (91 days)

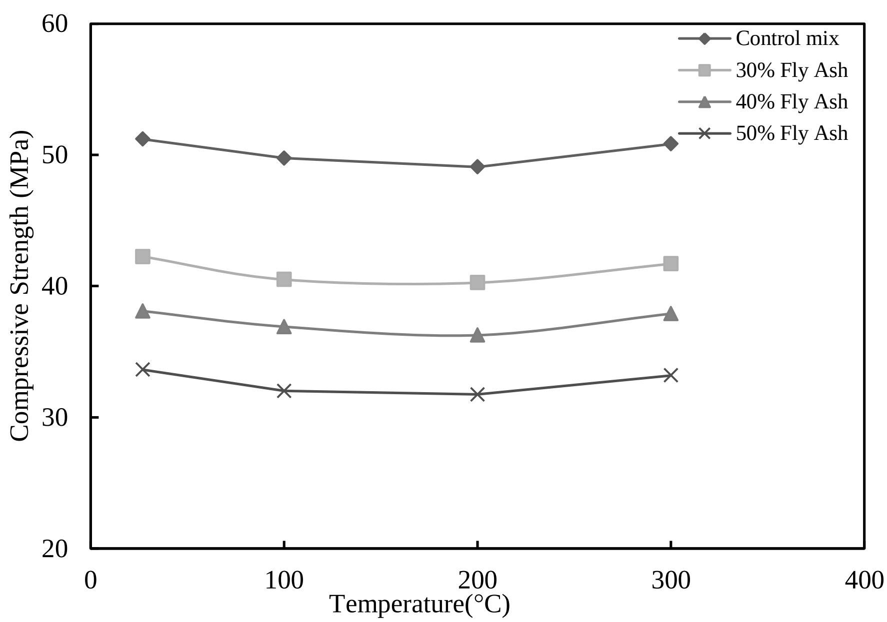


Fig. 4.3: Compressive Strength verses Temperature (365 days)

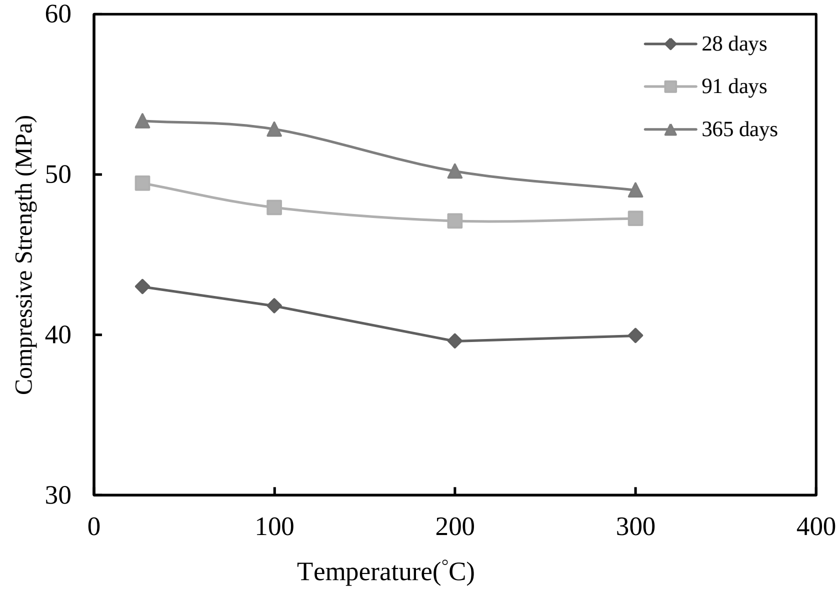


Fig. 4.4: Compressive Strength verses Temperature (without fly ash)

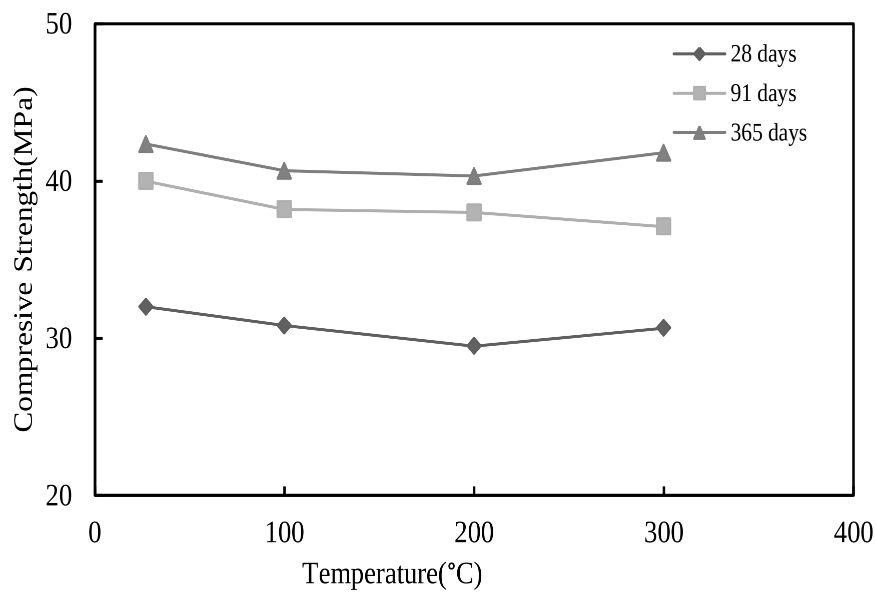


Fig. 4.5: Compressive Strength verses Temperature (with 30% fly ash)

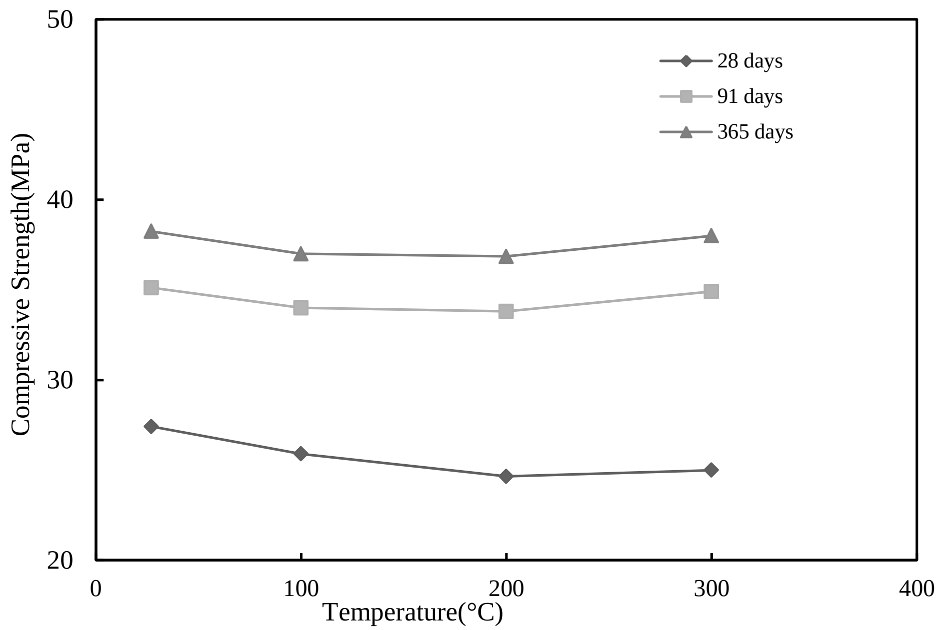


Fig. 4.6: Compressive Strength verses Temperature (with 40% fly ash)

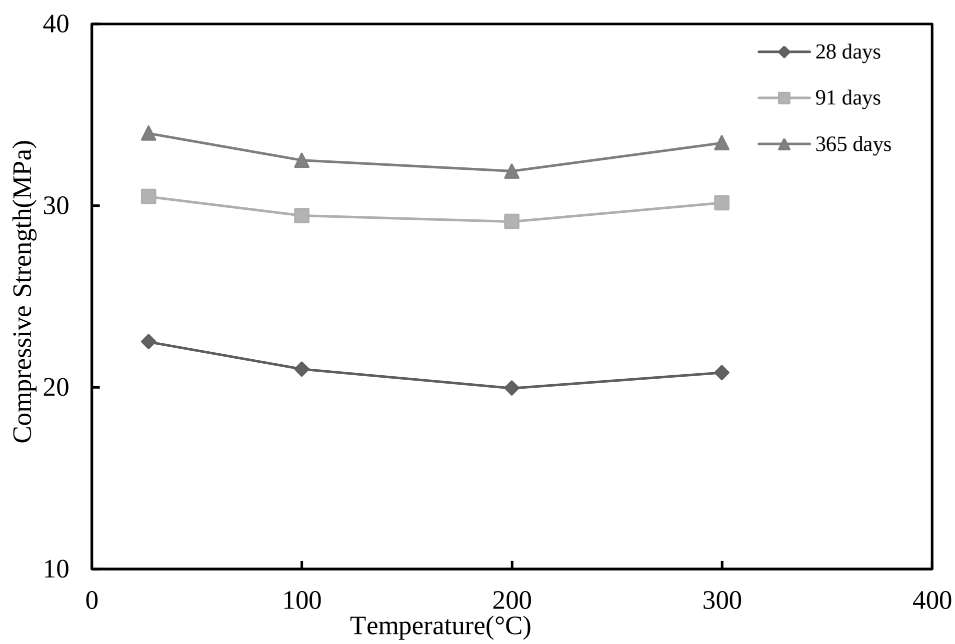


Fig. 4.7: Compressive Strength verses Temperature (with 50% fly ash)

4.1.2. Effect of age on compressive strength of the SCC mixes made with fly ash and foundry sand at varying temperatures

Effects of age on compressive strength of the SCC mixes made with and without fly ash and foundry sand at varying temperatures are shown in Figs. 4.8, 4.9, 4.10, and 4.11. It is evident from Figs. 4.9 to 4.11 that compressive strength of concrete mixes made with 30%, 40%, and 50% of fly ash SCC is lower than that of the control mix (Fig. 4.8) at all ages and that the strength of all mixtures continued to increase with age. Compressive strength increased with the decrease in fly ash content at different temperatures, as compared with the SCC mix prepared without fly ash and foundry sand (Fig.4.1 to 4.7).

For the SCC mix without fly ash (SCC1), at 91 days, an increase of about 13%, 12%, 15%, and 15.50% strength was observed at 27°C, 100°C, 200°C, and 300°C as compared with its strength at 28 days (Fig. 4.8). At 365 days, the strength increased by about 19%, 20%, 21%, and 18.50% at 27°C, 100°C, 200°C, and 300°C as compared with 28 days.

With 30% fly ash SCC mix (SCC2), increase of about 20%, 19.37%, 22.36%, and 17.38% strength was observed at 27°C, 100°C, 200°C, and 300°C at 91 days as compared with 28 days. An increase of about 24.43%, 24.23%, 26.86%, and 26.67% strength was observed at 27°C, 100°C, 200°C, and 300°C at 365 days as compared with 28 days (Fig. 4.9).

When the fly ash content increased from 30% to 40% (SCC3), it can be observed from Fig. 4.10, that the strength increased by 21.90%, 23.82%, 27.07% and 28.36% at 91 days, and 28.31%, 30%, 33.12%, and 34.21% at 365 days as compared to 28 days, with the increase in temperature from 27°C to 300°C.

With the further increase in fly ash content from 40% to 50% (SCC4), an increase of about 26.22%, 28.69%, 31.49% and 31.01% strength was observed at 91 days, when compared with 28 days strength at 27°C, 100°C, 200°C, and 300°C. An increase of about 33.78%, 39%, 37.46%, and 37.83% strength was observed at 365 days, with the increase in temperature from 27°C to 300°C (Fig. 4.11).

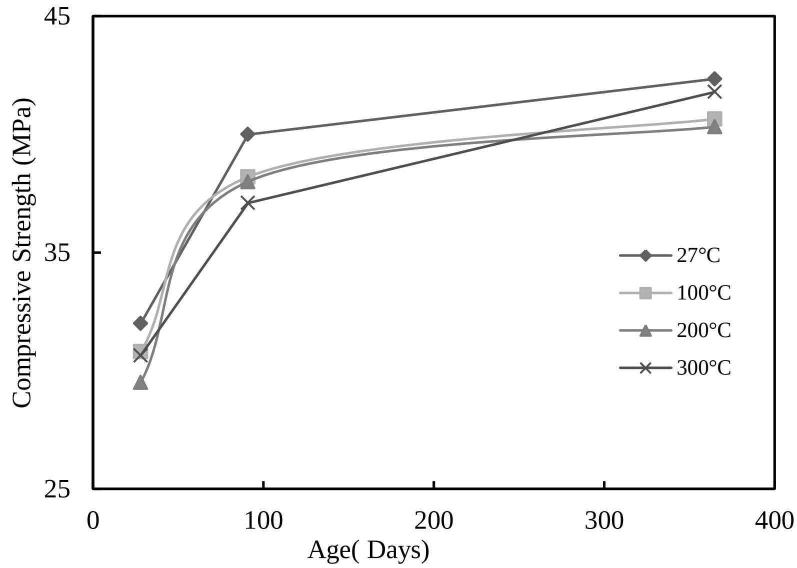


Fig. 4.8: Compressive Strength verses Age (without fly ash)

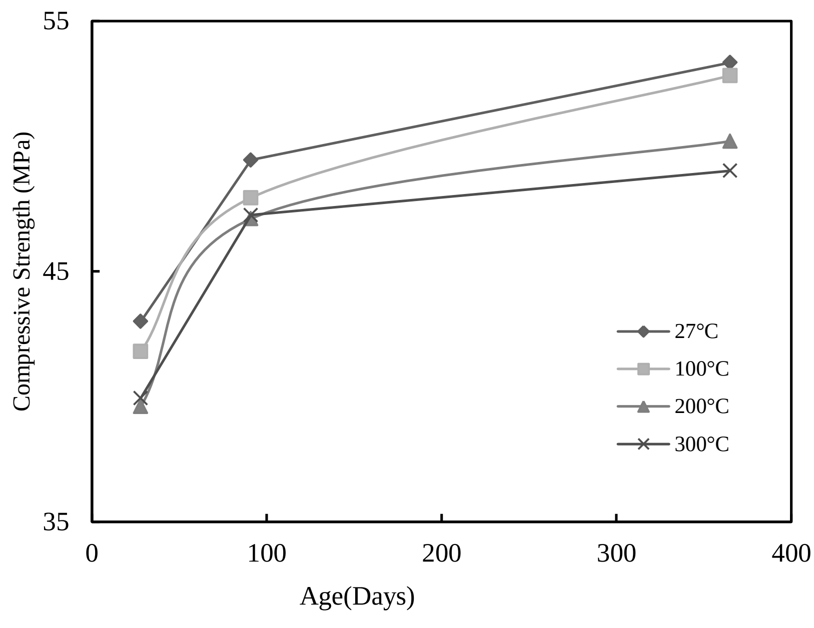


Fig. 4.9: Compressive Strength verses Age (with 30% fly ash)

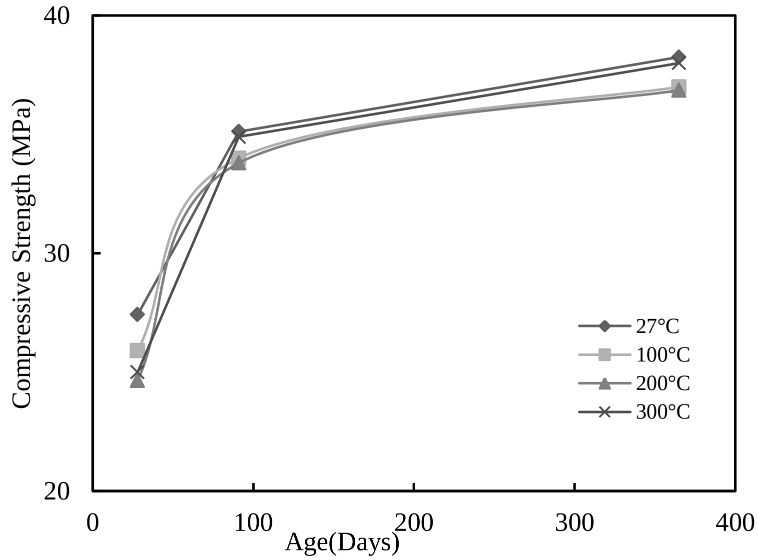


Fig. 4.10: Compressive Strength verses Age (with 40% fly ash)

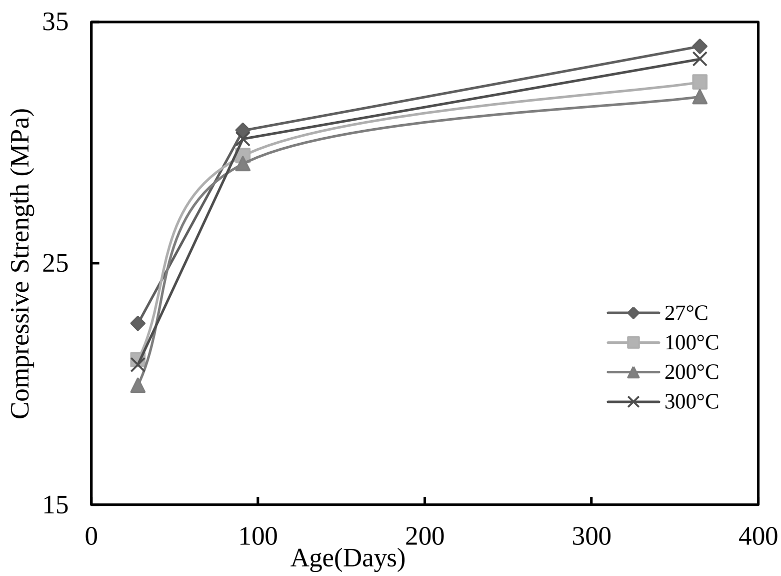


Fig. 4.11: Compressive Strength verses Age (with 50% fly ash)

It has been well documented that the moisture content has a significant effect on the strength of concrete at temperatures ranging from 27°C to 200°C. For all of the mixtures, a small improvement occurred in the residual strength at 200°C when compared with 100°C. The increase in strength associated with this increase in temperature was attributed to the increase in surface forces between gel particles (Vander Waal Forces) due to the removal of moisture content. This was most likely due to the compact microstructure, which results in a buildup vapor pressure formed by the evaporation of physically and chemically bound water. Therefore, concretes with higher strength grade are more sensitive to elevated temperatures. Such response is most likely due to the reduced porosity in high-strength concrete with smaller and less interconnected pores favoring buildup of vapor pressure and reducing thermal diffusivity.

The strength values of this research were comparable with those reported by *Hanaa et al. (2009), Khoury et al. (1992), and Dias et al. (1990).* The authors observed the increase in compressive strength between 150°C and 300°C, after decrease in compressive strength between 27°C and 150°C. The strength loss in this research at elevated temperature was much less than that reported by previous researchers, and this is because of incorporation of fly ash and spent foundry sand. The reduction in compressive strength of the SCC mixes when exposed to elevated temperatures can be attributed to the dehydration of concrete by driving out of free water and fraction water of hydration of concrete due to elevated temperature. According to *Khoury (1992)* the decrease in strength corresponds to a reduction of the cohesion of Vander Waal forces between the C-S-H layers. This reduces the surface energy of C-S-H and leads to the formation of silanol groups (Si-OH: OH-Si) that presents weaker bonding strength. Several hypotheses had been proposed in the literature to explain the increase in strength between 150°C and 300°C. *Khoury (1992)* assumed that the silanol groups lose a part of their bonds with water, which induces the creation of shorter and stronger siloxane elements (Si-O-Si) with probably larger surface energies that contribute to the increase in strength. *Dias et al. (1990)* attributed it to a rehydration of the paste due to the migration of water in the pores. This increase in strength was also observed by *Xu et al. (2001)* who carried out micro hardness tests on hardened cement paste and interfacial transition zone. The results of this research clearly showed that the evolution of residual compressive strength between 200°C and 300°C was due to the hydration of anhydrous cement which leads to the formation of hydrates having better bonding properties. These results confirm the hypothesis of *Dias et al. (1990)* i.e. the increase in strength was also due to an increase in the bonding properties of hydrates (a larger compressive strength was obtained for a larger porosity of the material). There appeared to be slight increase in strength by replacing 10% of fine aggregate with foundry sand as compared with the control mix. This increase in strength by using recycled aggregate or pozzolanic addition was also observed by *Paulo cachim (2009)* and *Paula et.al (2009).* Therefore these results are in line with the published literature.

4.2. SPLITTING TENSILE STRENGTH

4.2.1. Effect of temperature on splitting tensile strength of the SCC mixes made with fly ash and foundry sand

The results of splitting tensile strength test for different fly ash contents (0%, 30%, 40%, and 50%) and foundry sand incorporating different temperatures (27^{o}C, 100^{o}C, 200^{o}C, and 300^{o}C) at the end of different curing periods (28, 91, and 365 days) are given in Table 4.2. The splitting tensile strength test results of SCC mixes at various temperatures have also been plotted in Figs. 4.12 to 4.22.

It was found that the splitting tensile strength of class F fly ash concrete (using 30%, 40%, and 50% fly ash) at different temperature depends on the percentage of fly ash used and temperature exposure. At normal temperature (27°C), with the increase in fly ash content from 30-50%, the SCC mixes (SCC2, SCC3, and SCC4) developed splitting tensile strength between 2.00 and 1.35 MPa, 2.24 and 1.54 MPa, and between 2.28 and 1.76 MPa at 28, 91, and 365 days respectively. Strength values were 3.56, 3.78, and 3.98 MPa at 28, 91, and 365 days, for the control mix (SCC1). An increase of about 21.00%, 18.00%, and 13% strength was observed at 28, 91, and 365 days with the decrease of fly ash content from 50-30% and with 10% replacement of fine aggregate with foundry sand (SCC2, SCC3, and SCC4) as compared with the control mix (SCC1), as can be seen from Figs. 4.12, 4.13, and 4.14.

Table 4.2: Splitting tensile strength of the SCC mixes

Mix	Temperature(°C)	Fly Ash (%)	Splitting tensile strength(MPa)		
			28 days	91 days	365 days
SCC1	Normal	0	3.56	3.78	3.98
SCC1	100	0	3.21	3.42	3.75
SCC1	200	0	3.00	3.26	3.54
SCC1	300	0	2.85	3.14	3.26
SCC2	Normal	30	2.00	2.24	2.28
SCC2	100	30	1.84	2.00	2.15
SCC2	200	30	1.62	1.87	1.89
SCC2	300	30	1.56	1.75	1.67
SCC3	Normal	40	1.68	1.80	2.05
SCC3	100	40	1.45	1.62	1.84
SCC3	200	40	1.36	1.56	1.65
SCC3	300	40	1.20	1.45	1.48
SCC4	Normal	50	1.35	1.54	1.76
SCC4	100	50	1.26	1.48	1.42
SCC4	200	50	1.00	1.22	1.35
SCC4	300	50	0.94	1.14	1.28

After heating to 100°C and subsequent cooling, the SCC mixes (SCC2, SCC3, and SCC4) developed splitting tensile strength ranged between 1.84 and 1.26 MPa, 2.00 and 1.48 MPa, and between 2.15 and 1.42 MPa at 28, 91, and 365 days. For the control mix (SCC1), the values of strength were 3.21, 3.42, and 3.75 MPa respectively. Strength increased by about 18.80%, 15.00%, and 11.00% at 28, 91, and 365 days with the decrease of fly ash content from 50-30%, and with 10% replacement of fine aggregate with foundry sand (SCC2, SCC3, and SCC4) as compared with control mix (SCC1).

With the increase in temperature from 100°C to 200°C, splitting tensile strength varied between 1.62 and 1.00 MPa, 1.87 and 1.22 MPa, and between 1.89 and 1.35 MPa. Strength values were 3.00, 3.26, and 3.54 MPa at 28, 91, and 365 days, for the control mix (SCC1). With the decrease of fly ash content from 50-30%, and with 10% replacement of fine aggregate with foundry sand (SCC2, SCC3, and SCC4), an increase of about 20.00%, 14.00% and 10.00% strength was observed at 28, 91, and 365 days.

With further increase in temperature from 200°C to 300°C, splitting tensile strength ranged between 1.56 and 0.94 MPa, 1.75 and 1.14 MPa, and between 1.87 and 1.28 MPa respectively. Strength values were 2.85, 3.14, and 3.26 MPa at 28, 91, and 365 days, for the control mix (SCC1). With the decrease of fly ash content from 50-30% and with 10% replacement of fine aggregate with foundry sand (SCC2, SCC3, and SCC4), the strength increased by 22.00%, 16.00% and 12.00% at 28, 91, and 365 days) as compared with control mix (SCC1).

Strength loss of the SCC mixes (SCC2, SCC3, and SCC4) in the temperature range of 27°C to 100°C was negligible (0.2%). Between 100°C-200°C, it was about 2.00%.With further increase in temperature from 200°C to 300°C, there was about 2.8% loss, as compared with the SCC1.

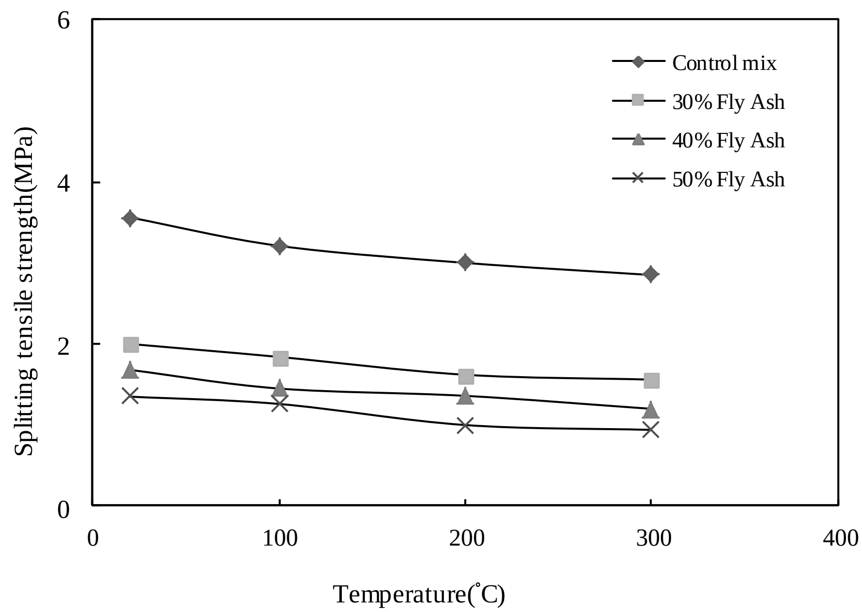


Fig. 4.12: Splitting Tensile Strength verses Temperature (28 days)

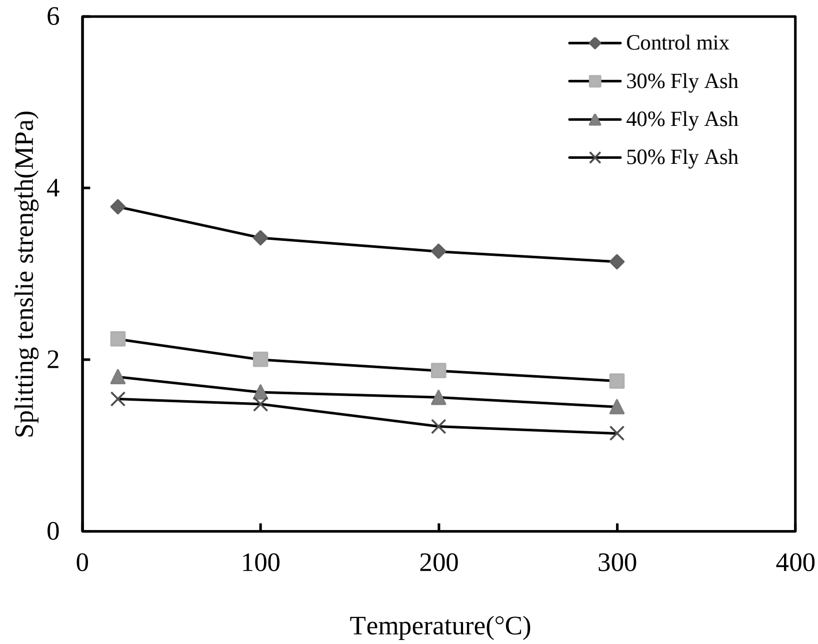


Fig. 4.13: Splitting Tensile Strength verses Temperature (91 days)

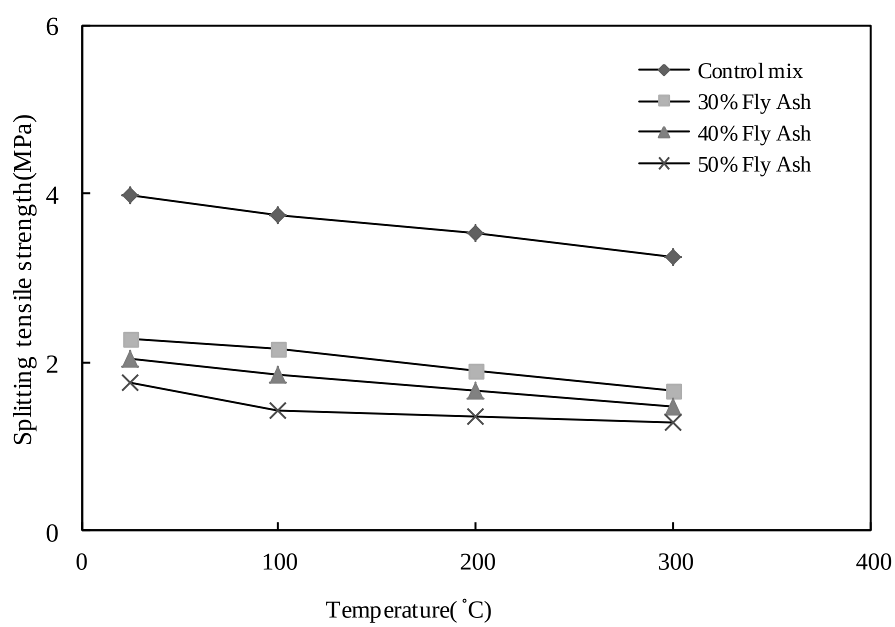


Fig. 4.14: Splitting Tensile Strength verses Temperature (365 days)

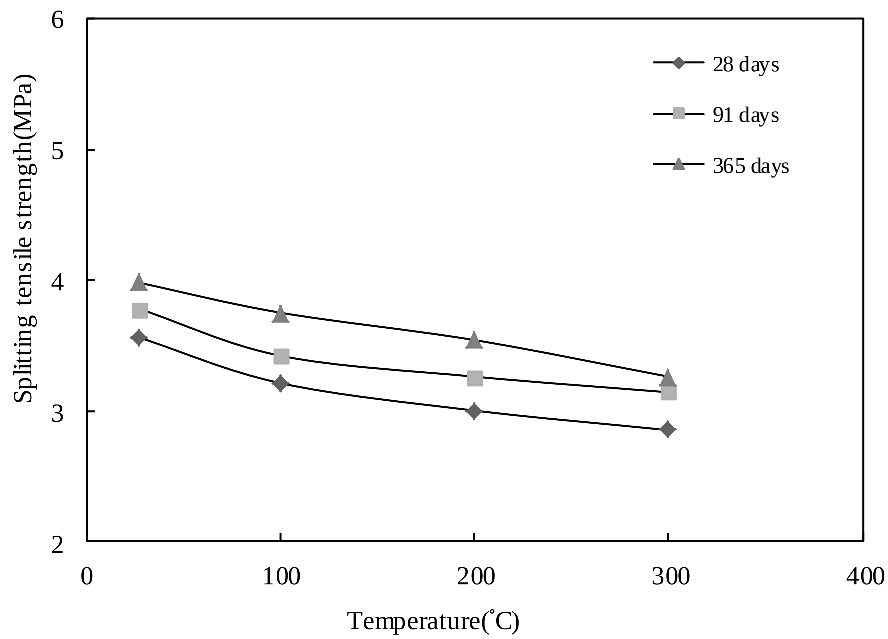


Fig. 4.15: Splitting Tensile Strength verses Temperature (without fly ash)

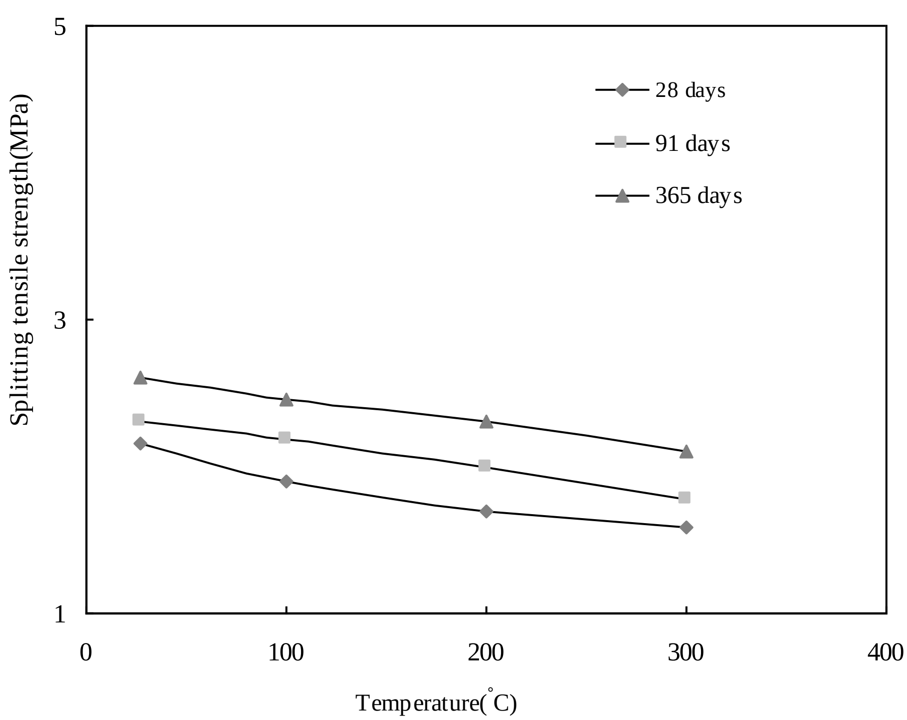


Fig. 4.16: Splitting Tensile Strength verses Temperature (with 30% fly ash

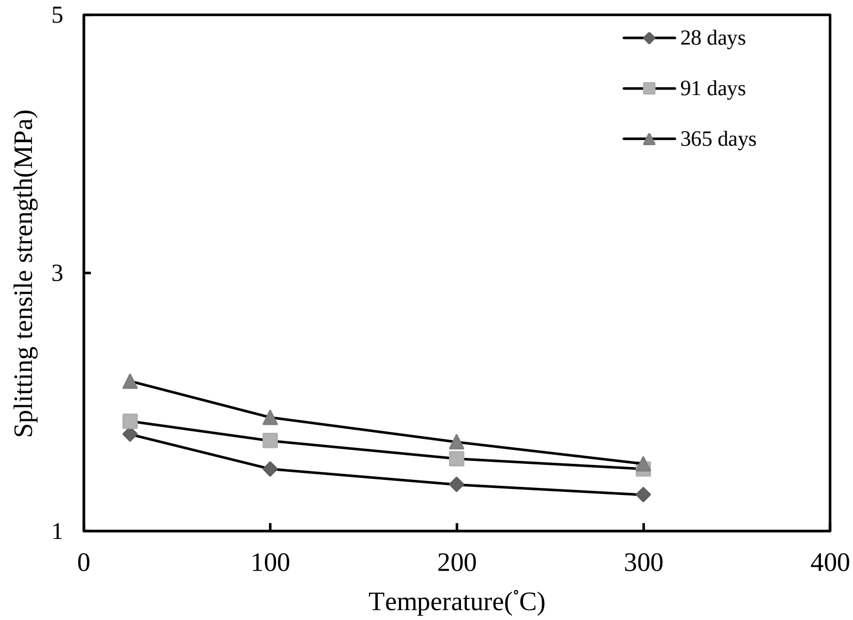


Fig. 4.17: Splitting Tensile Strength verses Temperature (with 40% fly ash)

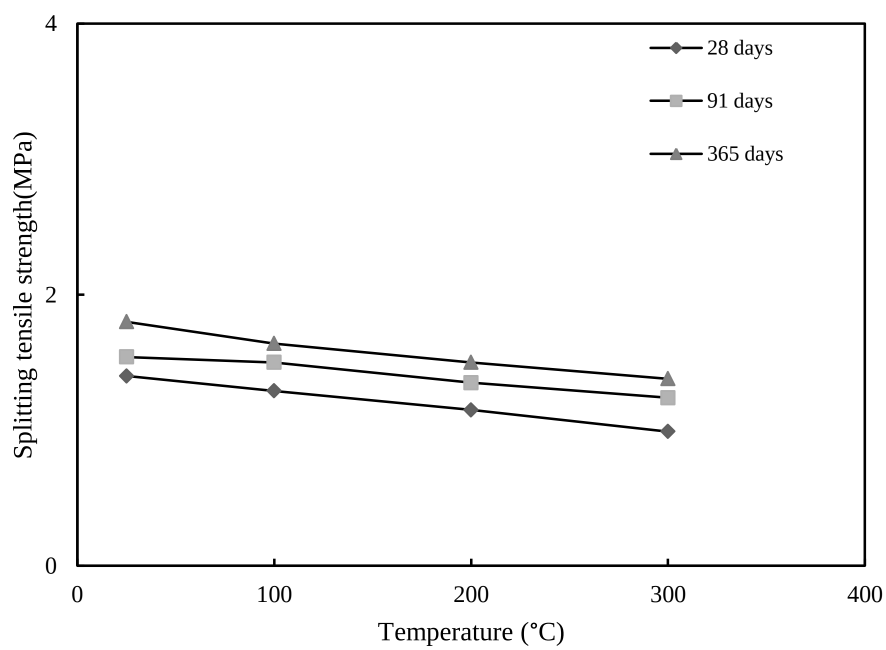


Fig. 4.18: Splitting Tensile Strength verses Temperature (with 50% fly ash)

4.2.2. Effect of age on splitting tensile strength of the SCC mixes made with fly ash and foundry sand at varying temperatures

Effects of age on splitting tensile strength of the SCC mixes made with and without fly ash and foundry sand at varying temperatures are shown in Figs. 4.19 to 4.22. It is evident from the Figs. 4.20 to 4.22 that splitting tensile strength of concrete mixes made with 30%, 40%, and 50% of fly ash SCC is lower than the control mix (Fig.4.19) at all ages and that the strength of all mixtures continued to increase with the age. Splitting tensile strength decreased with increase in temperature, at all ages, as can be seen from Figs. 4.12 to 4.18.

For SCC mix without fly ash (SCC1), at 91 days, an increase of about 4.14%, 7.22%, 7.24%, and 10% strength was observed at 27°C, 100°C, 200°C, and 300°C as compared with its strength at 28 days (Fig.4.19). At 365 days, the strength increased by about 11.90%, 14.16%, 12.08%, and 15.71% at 27°C, 100°C, 200°C, and 300°C as compared with 28 days.

With 30% fly ash (SCC2), increase of about 6%, 12.84%, 15.50%, and 11.23% strength was observed at 27°C, 100°C, 200°C, and 300°C at 91 days as compared with 28 days. An increase of about 16.92%, 25.22%, 26.52%, and 24.76% strength was observed at 27°C, 100°C, 200°C, and 300°C at 365 days as compared with 28 days (Fig. 4.20).

When the fly ash content increased from 30% to 40% (SCC3), it can be observed from Fig. 4.21, that the strength increased by 5.40%, 12.94%, 12.82%, and 13.51% at 91 days, and 18.98%, 21.27%, 19.53%, and 15.78% at 365 days as compared to 28 days, with the increase in temperature from 27°C to 300°C.

With the further increase in fly ash content from 40% to 50% (SCC4), the strength increased by about 9.09%, 14%, 14.81%, and 20.16% at 91 days when compared with 28 days strength at 27°C, 100°C, 200°C, and 300°C. An increase of about 22%, 21.34%, 23.33%, and 28.26% strength was observed at 365 days, when the temperature increased from 27°C to 300°C (Fig. 4.22).

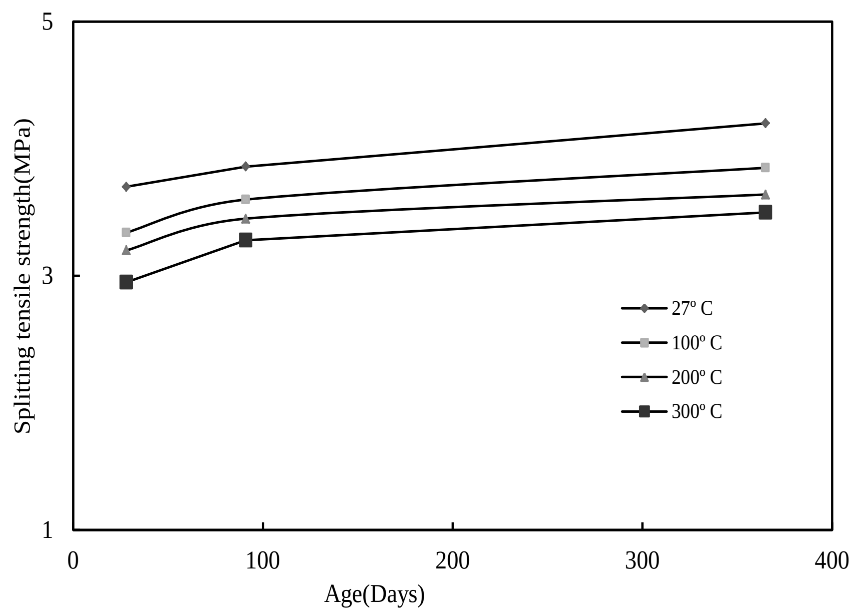


Fig. 4.19: Splitting Tensile Strength verses Age (without fly ash)

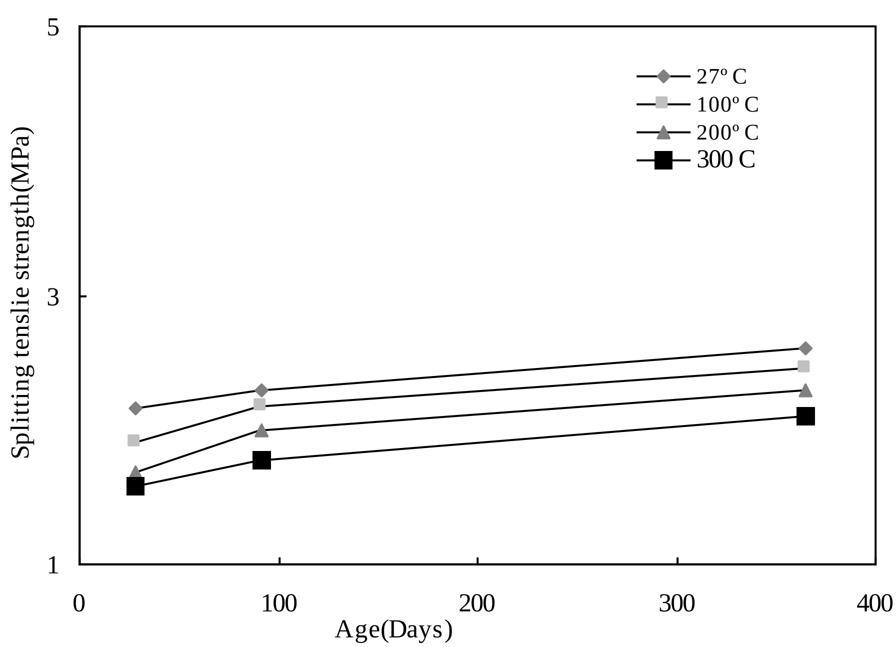


Fig. 4.20: Splitting Tensile Strength verses Age (with 30% fly ash)

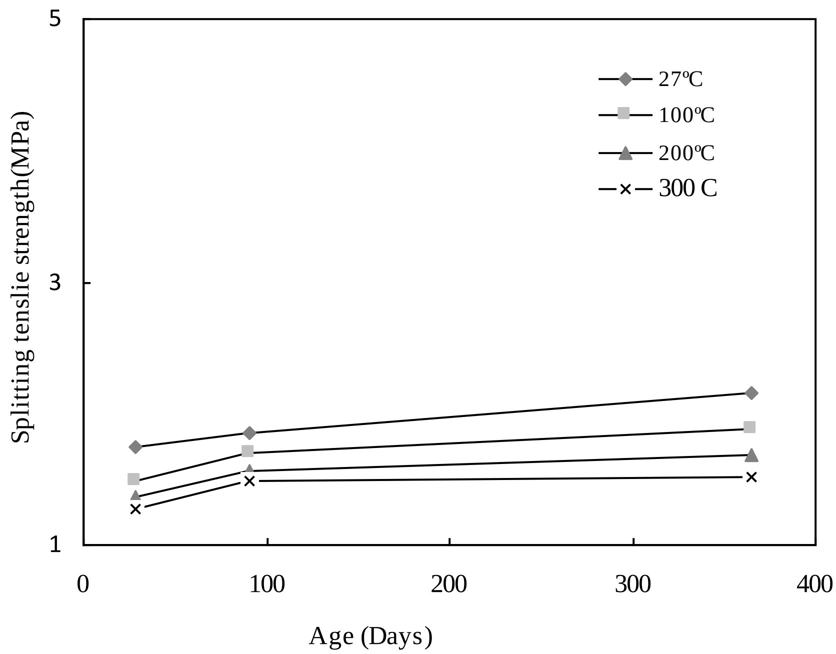


Fig. 4.21: Splitting Tensile Strength verses Age (with 40% fly ash)

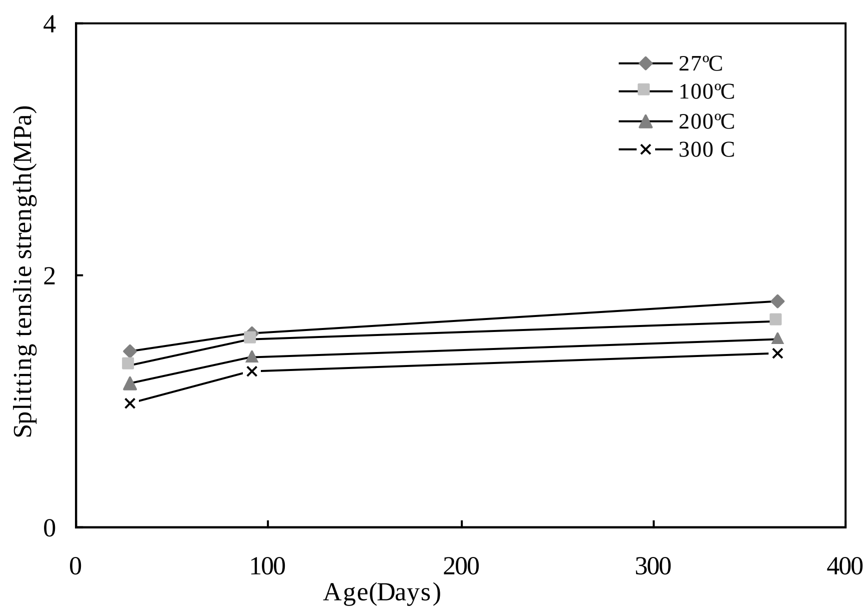


Fig. 4.22: Splitting Tensile Strength verses Age (with 50% fly ash)

Noumowe et al. (2006) reported in their research that splitting tensile strength decreased continuously with increase in temperature. The authors reported the value of splitting tensile strength as 4.8 MPa at ambient temperature and 2.8 MPa after heating to 400°C. In another research *Ghandehari (2010)* reported the reduction from 14.4 to 17.9% after being exposed from 100-600°C. Reduction in splitting tensile strength observed in this research was much less than that already reported in the previous researches. This loss of strength was not only attributed to the decomposition of the hydration products but also due to the thermal incompatibility between aggregates and cement paste. Less reduction in strength was also due to replacement of cement with fly ash and spent foundry sand**.**

4.3. MODULUS OF ELASTICITY

4.3.1. Effect of temperature on modulus of elasticity of the SCC mixes made with fly ash and foundry sand

In this investigation modulus of elasticity which is also called secant modulus, is taken as the slope of chord from the origin to some arbitrary point on the stress-strain curve. The results of modulus of elasticity test for different fly ash contents (0%, 30%, 40%, and 50%) and foundry sand incorporating different temperatures (27^{o}C, 100^{o}C, 200^{o}C, and 300^{o}C) at the end of different curing periods (28, 91, and 365 days) are given in Table 4.3. The modulus of elasticity test results of the SCC mixes at various temperatures have also been plotted in Figs. 4.23 to 4.30.

At normal temperature (27°C), with the increase in fly ash content from 30-50%, the SCC mixes developed modulus of elasticity between 16.00 and 8.50 GPa, 17.00 and 9.00 GPa, and between 19.00 and 14.00 GPa respectively. Modulus of elasticity values were 24.00, 29.00, and 34.00 GPa at 28, 91, and 365 days respectively for the control mix. The increase in modulus of elasticity of about 31.25%, 37%, and 47.70% was observed with the decrease in fly ash content.

After heating to 100°C and subsequent cooling, the SCC mixes developed modulus of elasticity ranged between 9.00 and 5.85 GPa, 13.00 and 6.67 GPa and, between 17.00 and 7.09 GPa at 28, 91, and 365 days respectively. Modulus of elasticity values were 17.00, 19.00, and 24.00 GPa respectively for the control mix. An increase of about 18%, 33%, and 41% in modulus of elasticity was observed with the decrease in fly ash content, at the age of 28, 91, and 365 days respectively.

Table 4.3: Modulus of elasticity of the SCC mixes

Mix	Temperature(°C)	Fly Ash (%)	Modulus of Elasticity (GPa)		
			28 days	91 days	365 days
SCC1	Normal	0	24.00	29.00	34.00
SCC1	100	0	17.00	19.00	24.00
SCC1	200	0	13.00	16.80	20.00
SCC1	300	0	8.50	10.00	14.00
SCC2	Normal	30	16.00	17.00	19.00
SCC2	100	30	9.00	13.00	17.00
SCC2	200	30	6.67	8.50	13.00
SCC2	300	30	4.70	7.62	9.00
SCC3	Normal	40	13.00	14.00	16.00
SCC3	100	40	7.73	8.50	14.00
SCC3	200	40	5.26	5.45	8.50
SCC3	300	40	3.80	4.50	7.62
SCC4	Normal	50	8.50	9.00	14.00
SCC4	100	50	5.85	6.67	7.09
SCC4	200	50	4.49	5.26	6.67
SCC4	300	50	2.90	3.10	5.00

With the increase in temperature from 100°C to 200°C, modulus of elasticity varied between 6.67 and 4.49 GPa, 8.50 and 5.26 GPa, and between 13.00 and 6.67 GPa at 28, 91, and 365 days respectively. Modulus of elasticity values were 13.00, 16.80, and 20.00 GPa respectively for the control mix. The increase in modulus of elasticity of about 32%, 38% and 48% was observed with the decrease in fly ash content, at the age of 28, 91, and 365 days respectively.

With further increase in temperature from 200°C to 300°C, modulus of elasticity ranged between 4.70 and 2.90 GPa, 7.62 and 3.10 GPa, and between 9.00 and 5.00 GPa respectively. For the control mix, modulus of elasticity values was 8.50, 10.00, and 14.00 GPa at 28, 91, and 365 days. It increased by about 38%, 45%, and 51% with the decrease in fly ash content.

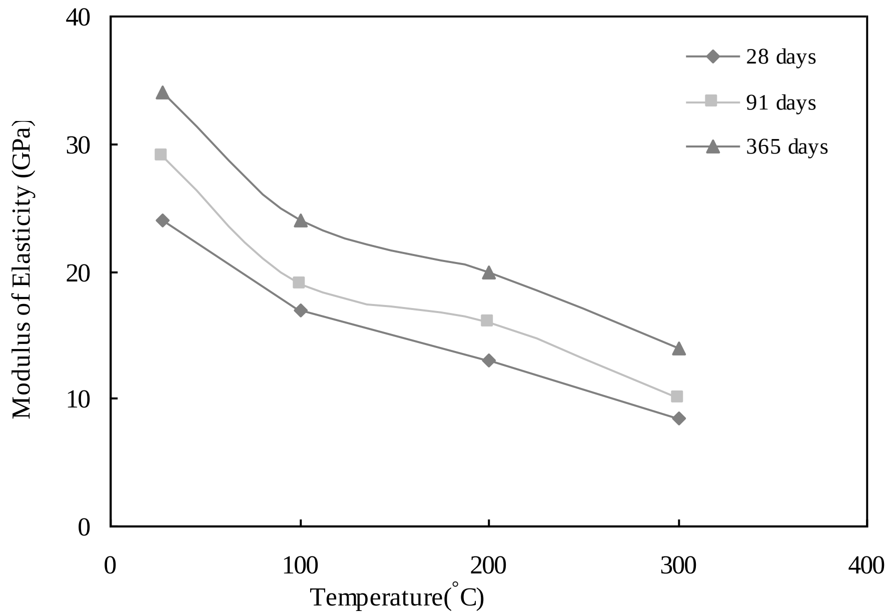


Fig. 4.23: Modulus of Elasticity verses Temperature (without fly ash)

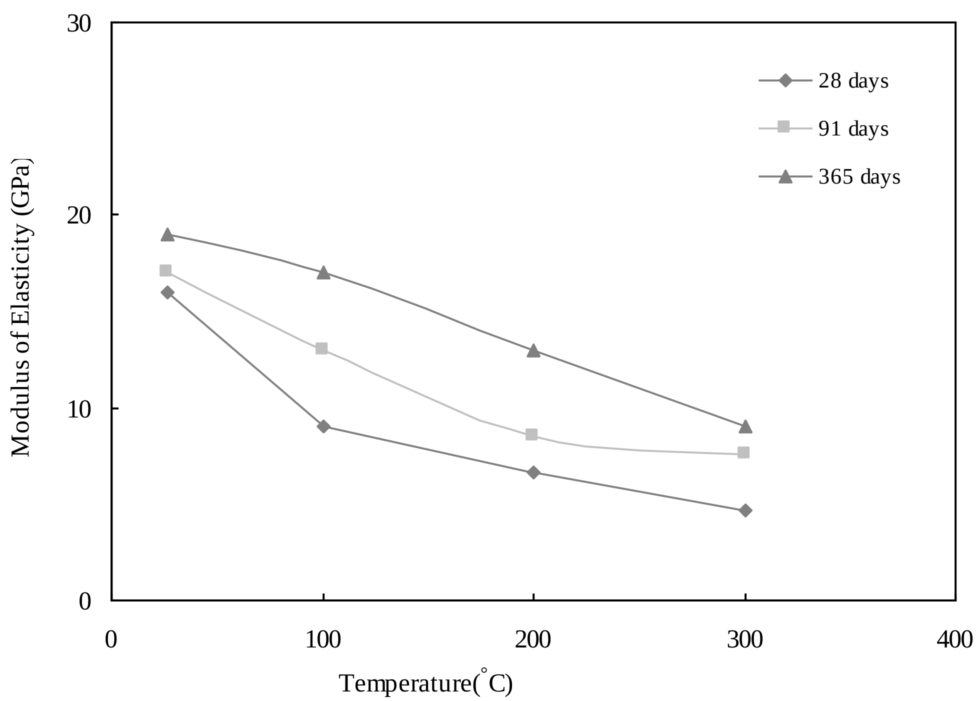


Fig. 4.24: Modulus of Elasticity verses Temperature (with 30% fly ash)

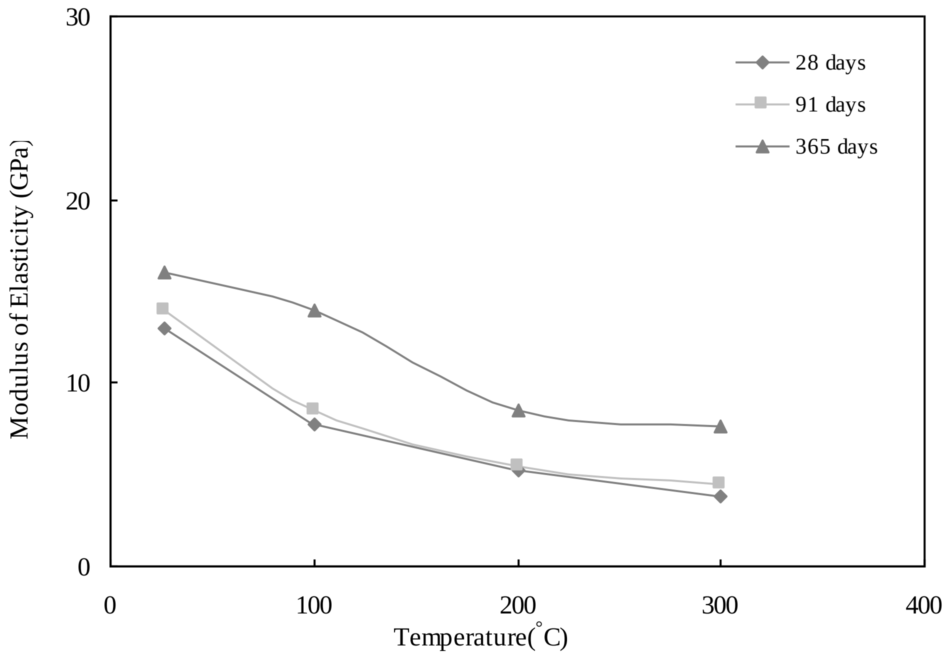


Fig. 4.25: Modulus of Elasticity verses Temperature (with 40% fly ash)

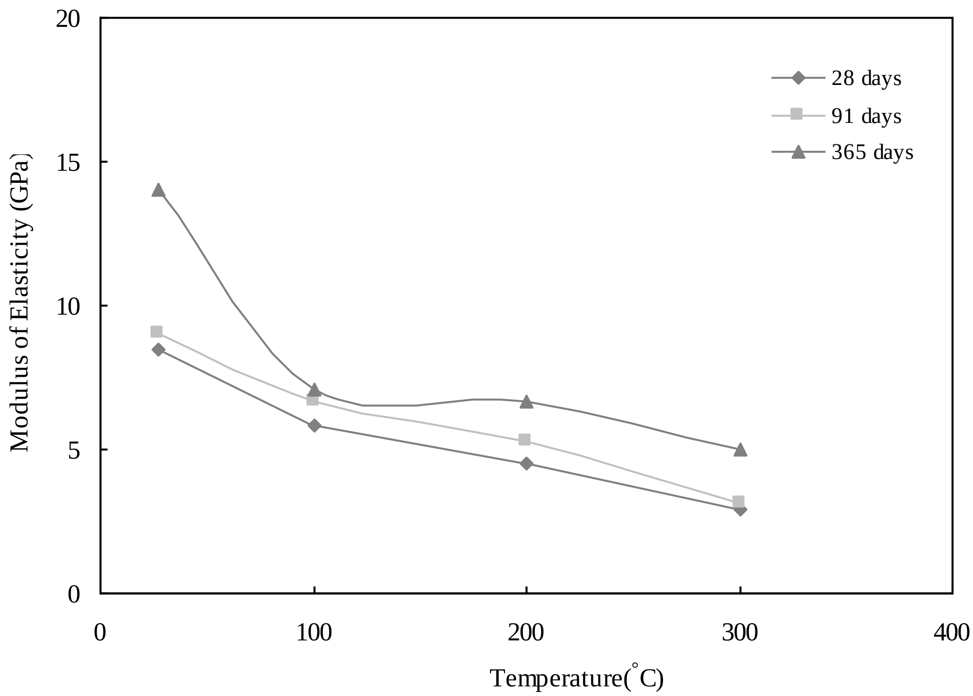


Fig. 4.26: Modulus of Elasticity verses Temperature (with 50% fly ash)

4.3.2. Effect of age on modulus of elasticity of the SCC mixes made with fly ash and foundry sand at varying temperatures

The effects of age on modulus of elasticity of the SCC mixes made with and without fly and foundry sand at varying temperatures are shown in Fig.4.27 to 4.30. It is evident from these figures that modulus of elasticity increased with decrease in percentage of fly ash and decrease in temperature, at all ages. Modulus of elasticity also increased with age.

For the SCC mix without fly ash (SCC1) at 91 days, an increase of about 17.24%, 10.52%, 22.62%, and 15% in modulus of elasticity was observed at 27°C, 100°C, 200°C, and 300°C as compared with 28 days (Fig. 4.27). At 365 days, it increased by about 29.41%, 20.83%, 35%, and 28.57% at 27°C, 100°C, 200°C, and 300°C as compared with 28 days.

With 30% fly ash (SCC2), percentage increase of about 5.88%, 30.76%, 21.52%, and 38.32% was observed at 27°C, 100°C, 200°C, and 300°C at 91 days as compared with 28 days. An increase of about 15.80%, 4.70%, 48.69%, and 47.78% in modulus of elasticity was observed at 27°C, 100°C, 200°C, and 300°C at 365 days as compared with 28 days (Fig. 4.28).

When the fly ash content increased from 30% to 40% (SCC3), it can be observed from Fig. 4.29, that the modulus of elasticity increased by 7.14%, 9%, 3.50%, and 15.56%, and 18.75%, 4.47%, 38%, and 50.13% at 91, and 365 days as compared to 28 days, with the increase in temperature from 27°C to 300°C.

With further increase in fly ash content from 40% to 50% (SCC4), and increase in temperature from 27°C to 300°C, an increase of about 5.88%, 12.29%, 14.63%, and 16.45% was observed at 91 days, as compared with 28 days elastic modulus. An increase of about 33.78%, 39%, 37.46%, and 37.83% was observed at 365 days (Fig. 4.30).

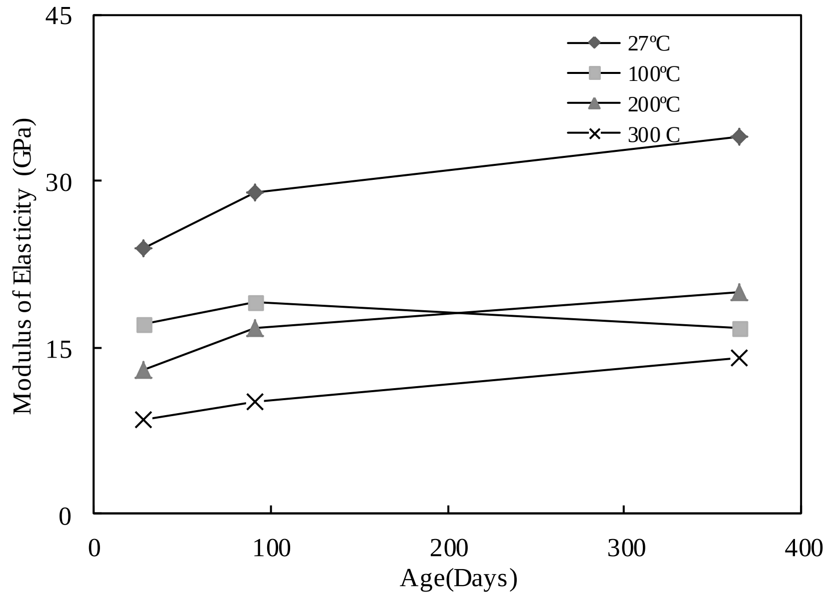


Fig. 4.27: Modulus of Elasticity verses Age (without fly ash)

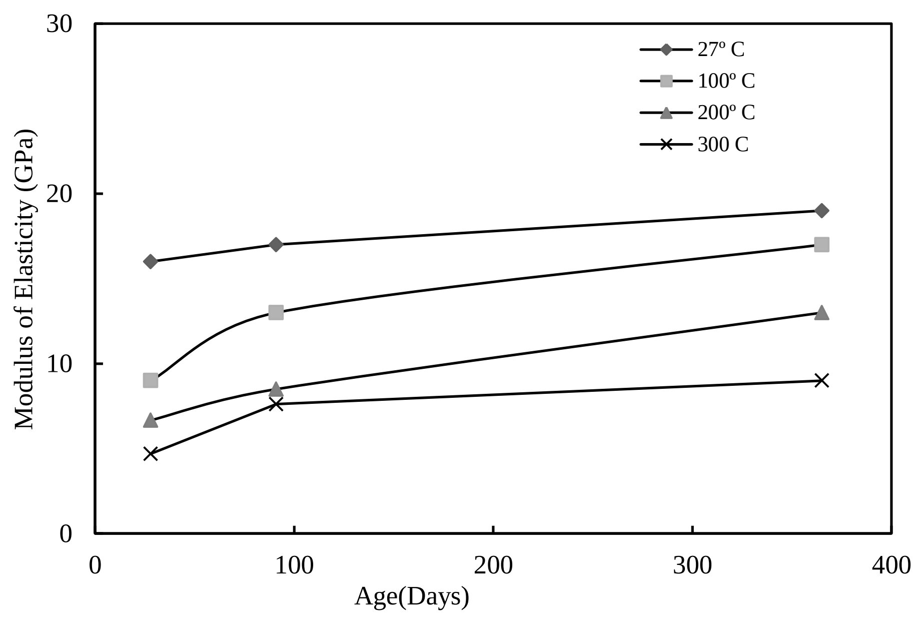


Fig. 4.28: Modulus of Elasticity verses Age (with 30% fly ash)

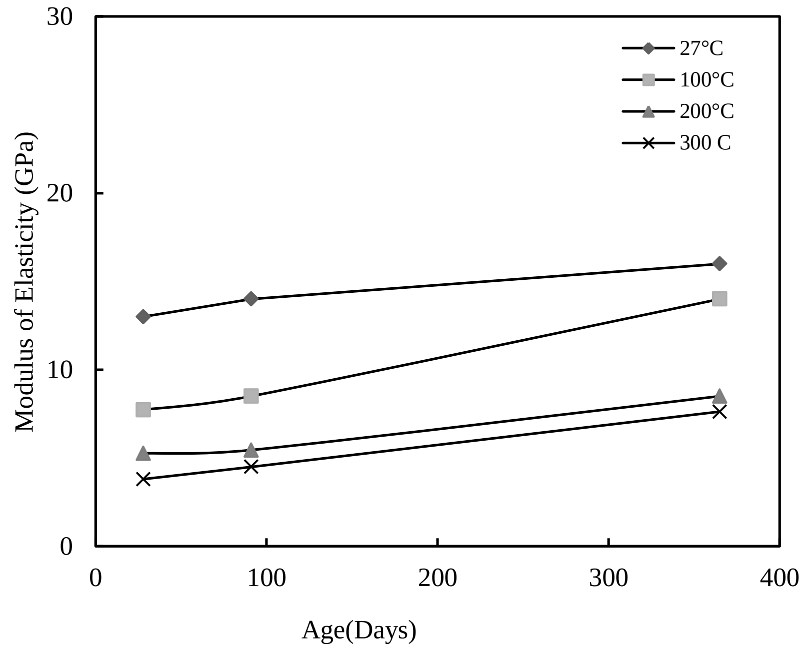


Fig. 4.29: Modulus of Elasticity verses Age (with 40% fly ash)

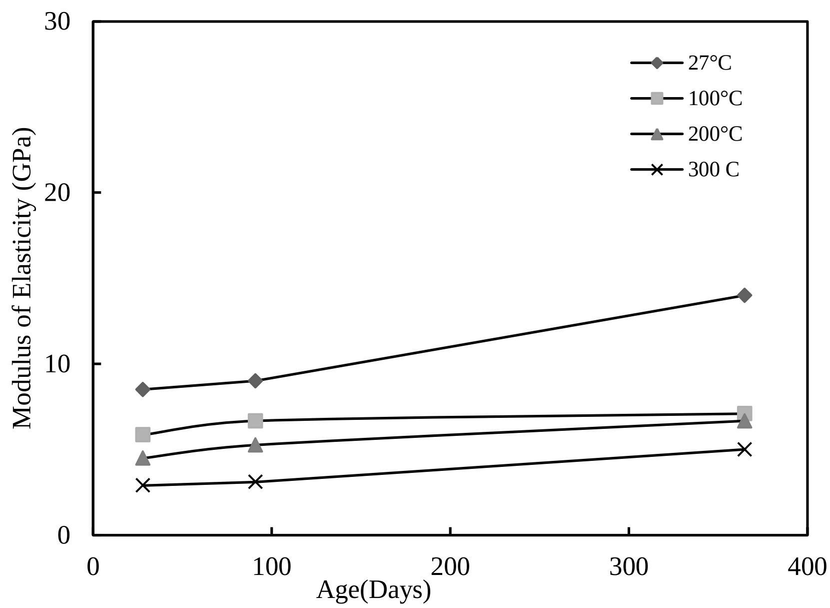


Fig. 4.30: Modulus of Elasticity verses Age (with 50% fly ash)

As can be seen from the Table 4.3, and from Figs. 4.23 to 4.30 when the temperature increased from normal (27°C) to 100°C, 200°C, and 300°C, elastic modulus decreased monotonically, unlike the behaviour of compressive strength. Modulus of elasticity also decreased with the increase in fly ash content as compared with the control mix. On the other hand modulus of elasticity increased with age, as can be seen from Figs. 4.23 to 4.30. In this research, loss of modulus of elasticity of around 70% was observed with the increase in temperature and fly ash content. And this decrease is due to the increase in porous volume of concretes and also to the cracking of the interfacial transition zone. Similar results were observed by *Phan (2002).* The author had observed a loss of modulus of elasticity around 70% beyond 300°C. *Hanna et al. (2009)* had observed the decrease in modulus of elasticity of about 90% by heating from 20°C to 450°C. So the results of this research are in line with the published literature.

4.4. CONCRETE MASS LOSS

4.4.1. Effect of temperature on mass loss of the SCC mixes made with fly ash and foundry sand

The results of concrete mass loss for different fly ash contents (0%, 30%, 40%, and 50%) and foundry sand incorporating different temperatures (27°C, 100°C, 200°C, and 300°C) at the end of different curing periods (28, 91, and 365 days) are given in Table 4.4. Mass loss test results of the SCC mixes at various temperatures have also been plotted in Figs. 4.31 to 4.38.

At 100°C, with the increase in fly ash content from 30-50%, mass loss of the SCC mixes (SCC2, SCC3, and SCC4) varied between 168 and 186 gm, 112 and 130 gm, and between 95 and 112 gm at 28, 91, and 365 days respectively. Mass loss values were 225, 124, and 100 gm at 28, 91, and 365 days, for the control mix (SCC1). An increase of about 8%, 5.10%, 5.70% was observed at 28, 91, and 365 days with the decrease of fly ash content from 50-30% and with 10% replacement of fine aggregate with foundry sand (SCC2, SCC3, and SCC4) as compared with the control mix (Figs. 4.31 to 4.34).

Table 4.4: Mass loss of the SCC mixes

Mix	Temperature(°C)	Fly Ash(%)	Mass loss(gm)		
			28 days	**91 days**	**365 days**
SCC1	100	0	225	124	100
SCC1	200	0	242	139	112
SCC1	300	0	285	155	137
SCC2	100	30	168	112	95
SCC2	200	30	190	125	98
SCC2	300	30	234	143	121
SCC3	100	40	180	150	103
SCC3	200	40	211	175	105
SCC3	300	40	240	210	120
SCC4	100	50	186	130	112
SCC4	200	50	220	146	118
SCC4	300	50	245	170	135

With increase in temperature from 100°C to 200°C, and fly ash content from 30-50%, mass loss of the SCC mixes (SCC2, SCC3, and SCC4) varied between 190 and 220 gm, 125 and 146 gm, and between 98 and 118 gm respectively. Mass loss values were 242, 139, and 112 gm at 28, 91, and 365 days, for the control mix (SCC1). The percentage increase of approximately 12.50%, 15.20%, and 17.85% was noticed at 28, 91, and 365 days.

When the temperature further increased from 200°C to 300°C, mass loss ranged between 234 and 245 gm, 143 and 170 gm, and between 121 and 135 gm respectively, with the increase in fly ash content for the SCC mixes (SCC2, SCC3, and SCC4). For the control mix (SCC1), mass loss values were 285, 155, and 137 gm at 28, 91, and 365 days. Weight of the specimens reduced by 3.85%, 17.41%, and 10.21% at 28, 91, and 365 days with the increase of fly ash content from 30-50% and with 10% replacement of fine aggregate with foundry sand (SCC2, SCC3, and SCC4) as compared with the control mix (SCC1), as can be seen from Figs. 4.31 to 4.34.

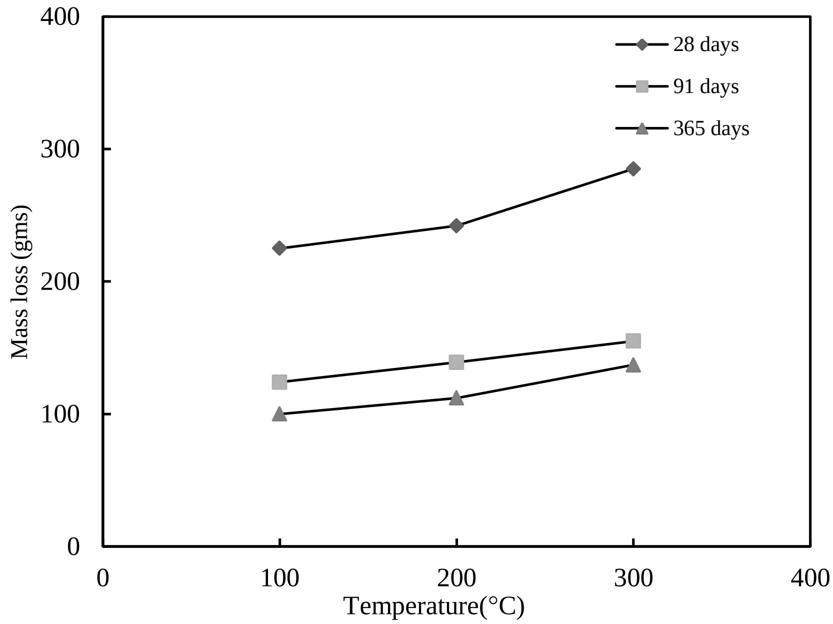


Fig. 4.31: Mass Loss verses Temperature (without fly ash)

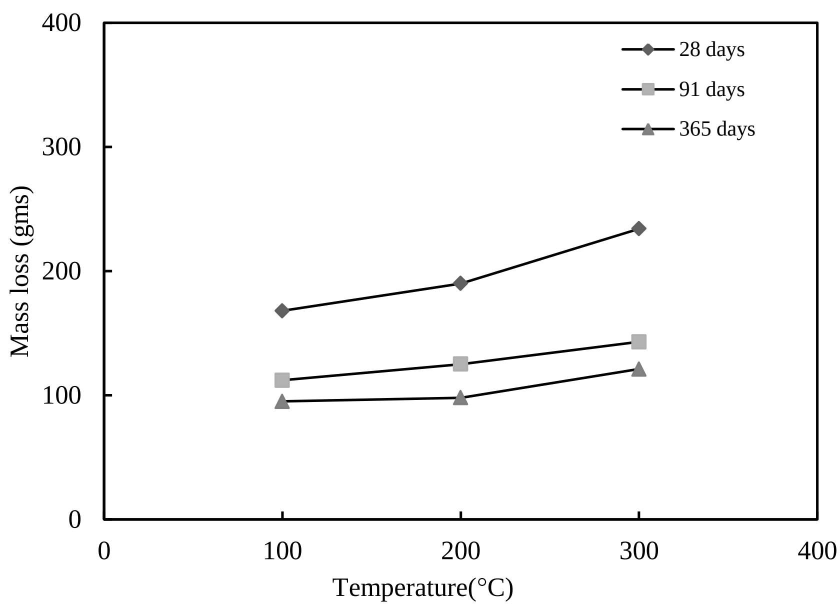


Fig. 4.32: Mass Loss verses Temperature (with 30% fly ash)

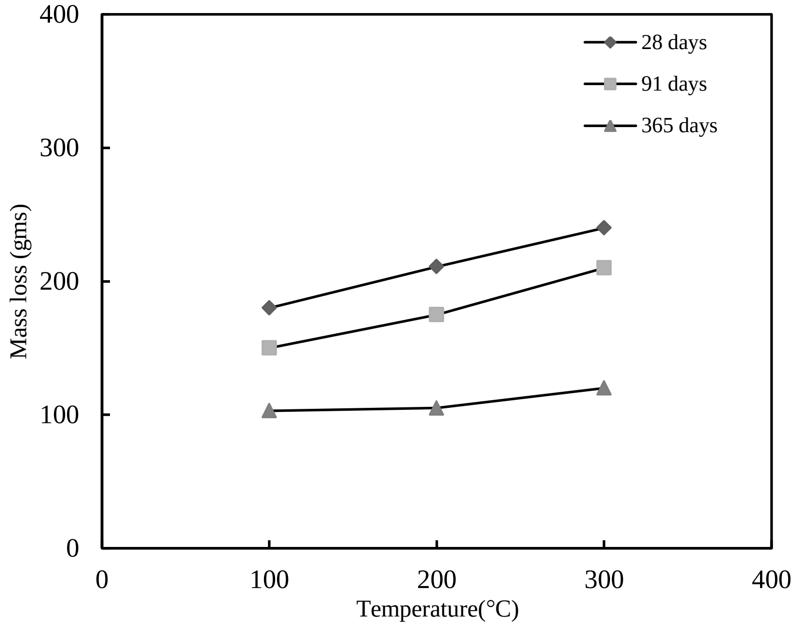


Fig. 4.33: Mass Loss verses Temperature (with 40% fly ash)

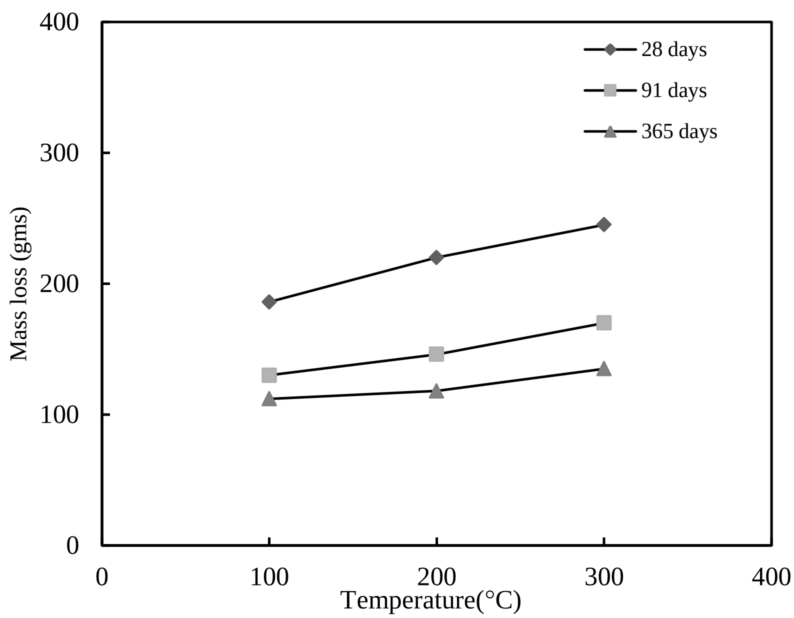


Fig. 4.34: Mass Loss verses Temperature (with 50% fly ash)

4.4.2. Effect of age on mass loss of the SCC mixes made with fly ash and foundry sand at varying temperatures

The effects of age on mass loss of the SCC mixes made with and without fly ash and foundry sand at varying temperatures are shown in Fig. 4.35 to 4.38. Mass loss increased with the increase in percentage of fly ash (SCC2, SCC3, and SCC4) as seen from Figs. 4.36, 4.37, and 4.38, as compared with the SCC mix without fly ash (SCC1) (Fig.4.35). Mass loss also increased with increase in temperature. But loss of mass decreased with age.

For SCC mix without fly ash (SCC1) at 91 days, mass loss decreased by about 42.66%, 42.56%, and 45.61% at 100°C, 200°C, and 300°C (Fig. 4.35). At 365 days, the decrease of about 55.55%, 53.72%, and 51.92% was noticed at 100°C, 200°C, and 300°C as compared with 28 days.

With 30% fly ash (SCC2), percentage decrease of about 33.33%, 34.21%, and 38.89% was observed at 100°C, 200°C, and 300°C at 91 days as compared with 28 days. The decrease of about 24.43%, 24.23%, 26.86%, and 26.67% was observed at 100°C, 200°C, and 300°C at 365 days (Fig. 4.36).

When the fly ash content increased from 30% to 40% (SCC3), it can be observed from Fig. 4.36, that the decrease in mass loss of about 16.67%, 17.06%, and 12.50% at 91 days, and 43.33%, 48.42%, and 48.29% at 365 days was noticed, as compared to 28 days, with the increase in temperature from 100°C to 300°C.

With further increase in fly ash content from 40% to 50% (SCC4), decrease of about 30.10%, 33.64%, and 30.61% was observed at 91 days, when compared with 28 days. The decrease of about 39.78%, 46.34%, and 44.89% was observed at 365 days, with the increase in temperature from 100°C to 300°C (Fig. 4.37).

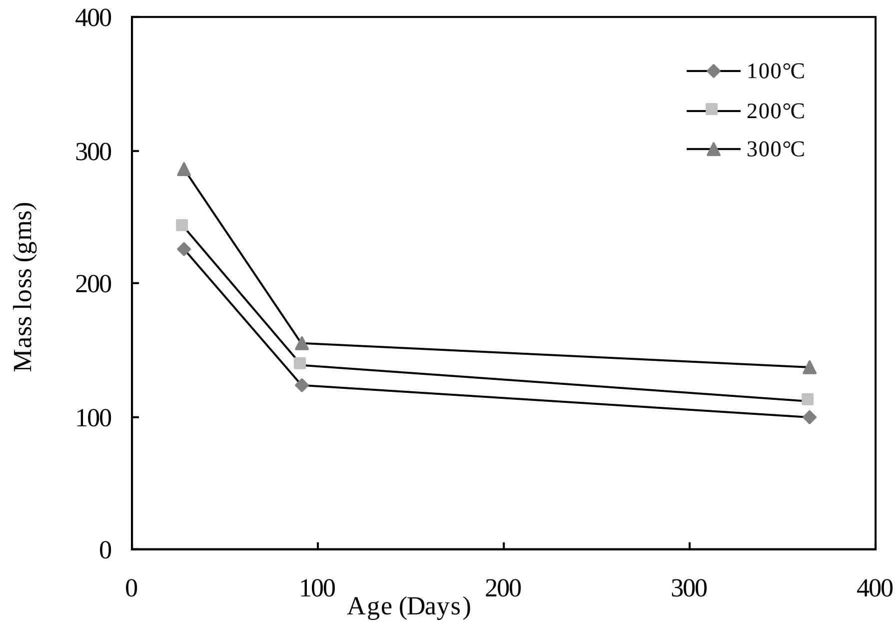


Fig. 4.35: Mass Loss verses Age (without fly ash)

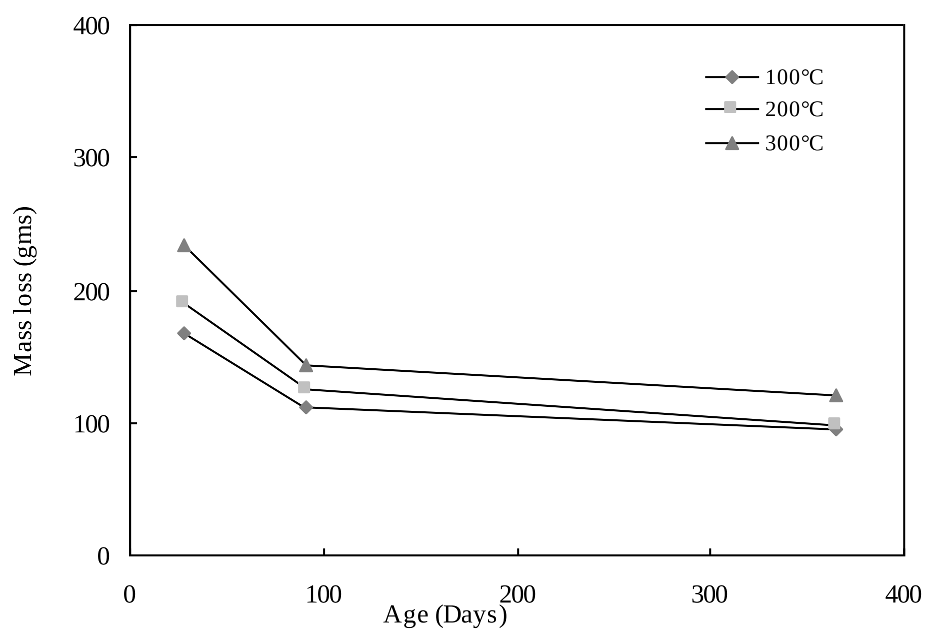


Fig. 4.36: Mass Loss verses Age (with 30% fly ash)

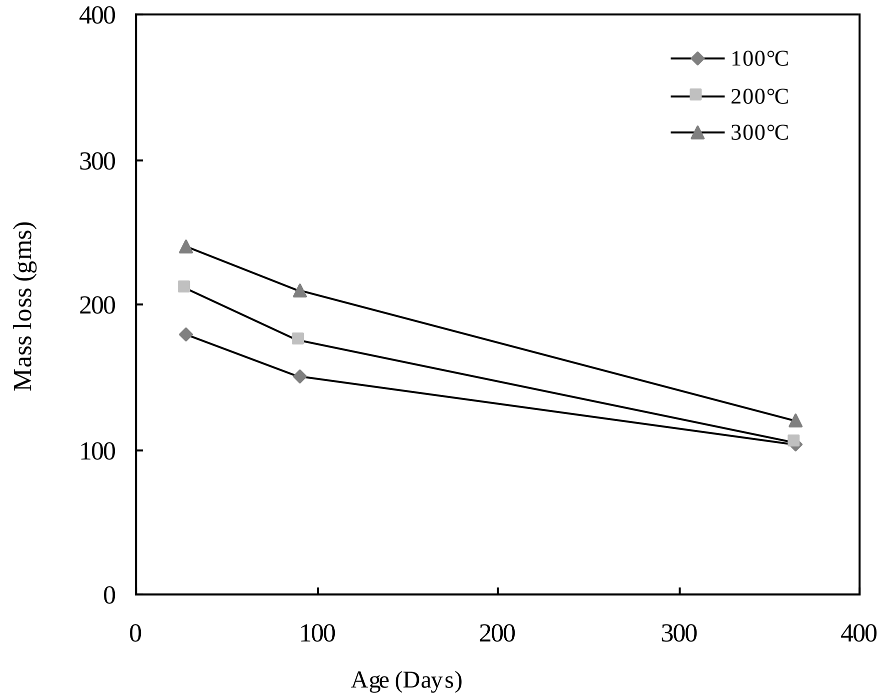


Fig. 4.37: Mass Loss verses Age (with 40% fly ash)

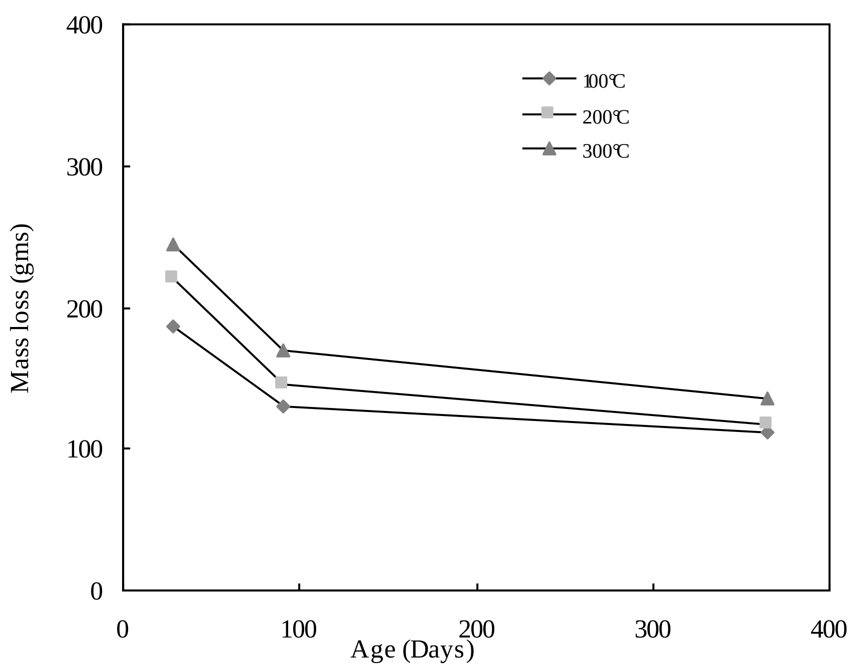


Fig. 4.38: Mass Loss verses Age (with 50% fly ash)

The weight of concrete specimens reduced significantly as the temperature increased. It was observed that the evolution of mass loss versus temperature was very close to five studied concrete samples. Between 100°C and 200°C, less increase in the mass loss was observed. The mass loss in this domain corresponds to the departure of free water contained in the capillary pores. Between 200°C and 300°C, increase in mass loss was more as compared to 100°C and 200°C. This was because of loss of chemically bound water from the decomposition of the C-S-H gel, and the dehydration of calcium silicate hydroxide.

In the literature *Hanna et al. (2009)* observed that about 70% of the water contained in the concretes had evaporated at 300°C. Therefore the results of this research are in line with the published literature.

4.5. POROSITY

4.5.1. Effect of temperature on porosity of the SCC mixes made with fly ash and foundry sand

The results of porosity test for different fly ash contents (0%, 30%, 40%, and 50%) and foundry sand incorporating different temperatures (100^{o}C, 200^{o}C, and 300^{o}C) at the end of different curing periods (28, 91, and 365 days) are given in Table 4.5. The porosity test results of the SCC mixes at various temperatures have also been plotted in Figs. 4.39 to 4.46.

At 100°C, with the increase in fly ash content from 30-50%, porosity of the SCC mixes (SCC2, SCC3, and SCC4) varied between 1.20 and 1.88%, 1.00 and 1.67%, and between 0.80, and 1.52% at 28, 91, and 365 days respectively. Porosity values were 0.77, 0.55, and 0.26% at 28, 91, and 365 days, for the control mix (SCC1). The decrease of about 23.21%, 22.00%, and 15.39% was observed at 28, 91, and 365 days with the decrease of fly ash content from 50-30% and with 10% replacement of fine aggregate with foundry sand (SCC2, SCC3, and SCC4) as compared with the control mix (SCC1).

Table 4.5: Porosity of the SCC mixes

Mix	Temperature(°C)	Fly Ash (%)	Porosity(%)		
			28 days	**91 days**	**365 days**
SCC1	100	0	0.77	0.55	0.26
SCC1	200	0	0.86	0.64	0.34
SCC1	300	0	0.95	0.79	0.61
SCC2	100	30	1.20	1.00	0.80
SCC2	200	30	1.36	1.12	0.97
SCC2	300	30	1.54	1.36	1.14
SCC3	100	40	1.50	1.40	1.28
SCC3	200	40	1.67	1.52	1.32
SCC3	300	40	1.73	1.60	1.44
SCC4	100	50	1.88	1.67	1.52
SCC4	200	50	2.13	1.74	1.64
SCC4	300	50	2.40	1.95	1.76

With increase in temperature from 100°C to 200°C, and increase in fly ash content from 30-50%, porosity of the SCC mixes (SCC2, SCC3, and SCC4) varied between 1.36 and 2.13%, 1.12 and 1.74%, and between 0.97 and 1.64% at 28, 91, and 365 days respectively. For the SCC mix without fly ash, the values of porosity were 0.86, 0.64, and 0.34%. It decreased by 22.86%, 20.36%, and 14.32% at 28, 91, and 365 days.

When the temperature further increases from 200°C to 300°C, and fly ash content increases from 30-50%, the SCC mixes (SCC2, SCC3, and SCC4) developed porosity between 1.54 and 2.40%, 1.36 and 1.94%, and between 1.14, and 1.76% at 28, 91, and 365 days respectively. For the control mix (SCC1), the values of porosity were 0.95, 0.79, and 0.61% at 28, 91, and 365 days respectively. The decrease of about 22.10%, 17.58%, and 16.85% was observed with the decrease in fly ash content.

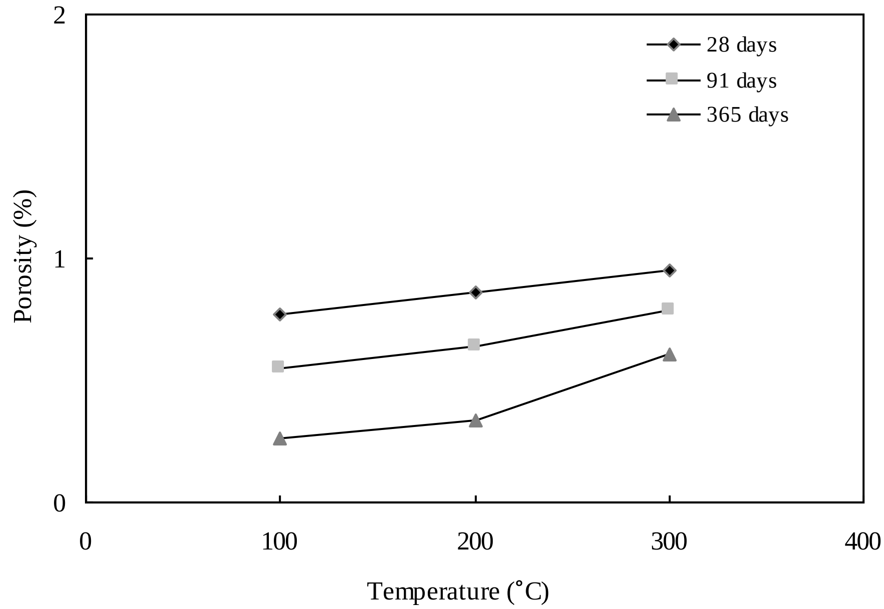


Fig. 4.39: Porosity verses Temperature (without fly ash)

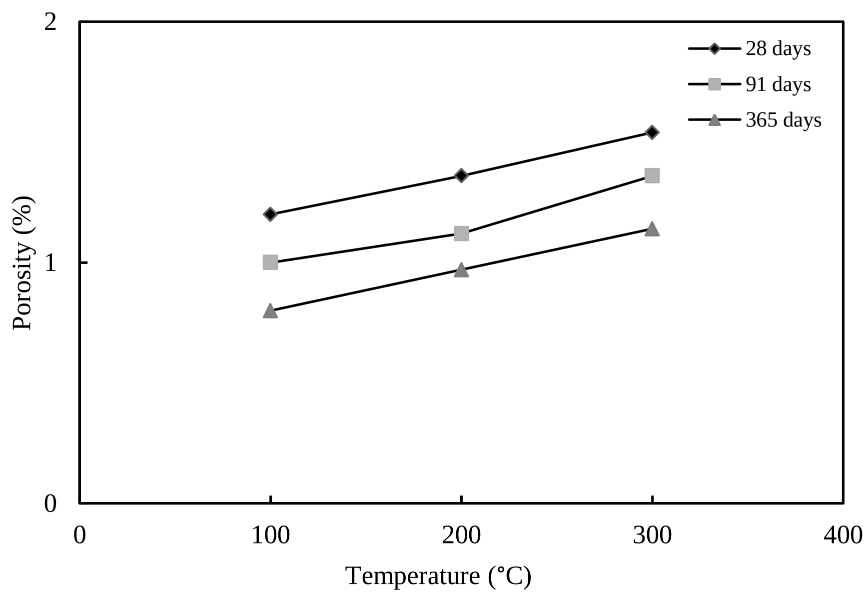


Fig. 4.40: Porosity verses Temperature (with 30% fly ash)

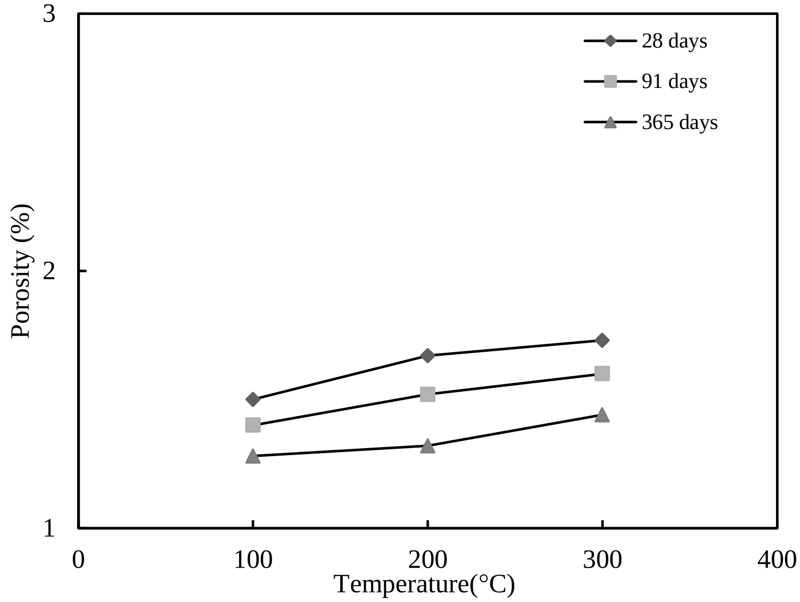


Fig. 4.41: Porosity verses Temperature (with 40% fly ash)

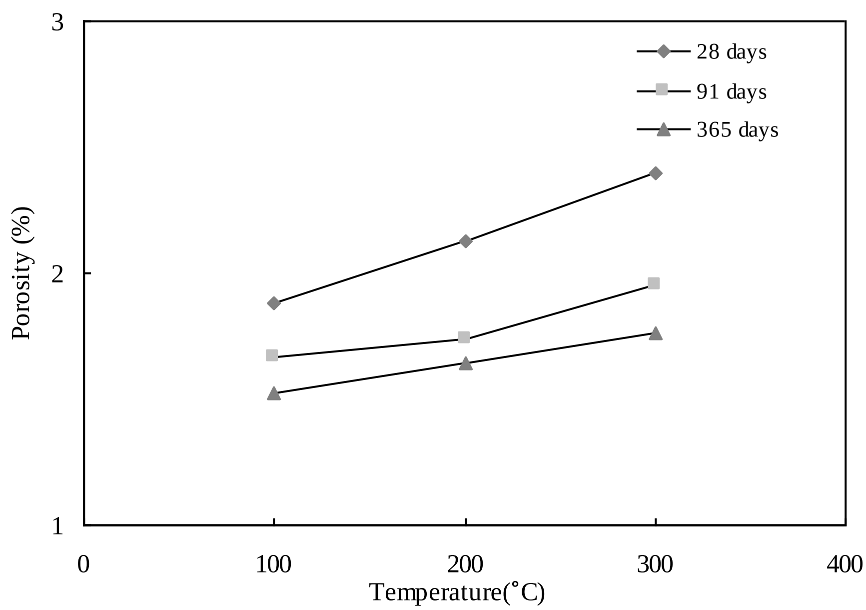


Fig. 4.42: Porosity verses Temperature (with 50% fly ash)

4.5.2. Effect of age on porosity of the SCC mixes made with fly ash and foundry sand at varying temperatures

Effect of age on porosity of the SCC mixes made with and with out fly ash and foundry sand at varying temperatures has been shown in Figs. 4.43 to 4.46. Porosity increased with the increase in percentage of fly ash and increase in temperature (Figs. 4.44, 4.45, and 4.46) as compared with control mix (Fig. 4.43). But porosity decreased with age.

For the SCC mix without fly ash (SCC1) at 91 days, the decrease of about 29.33%, 25.58%, and 16.84% was observed at 100°C, 200°C, and 300°C as compared with 28 days (Fig. 4.43). At 365 days, the porosity decreased by about 66.28%, 60.40%, and 35.79% at 27°C, 100°C, 200°C, and 300°C as compared with 28 days.

With 30% fly ash the SCC mix (SCC2), percentage decrease of about 16.67%, 17.65%, and 11.69% in porosity was observed at 27°C, 100°C, 200°C, and 300°C at 91 days as compared with 28 days. The decrease of about 33.33%, 28.67%, and 25.97% was observed at 27°C, 100°C, 200°C, and 300°C at 365 days as compared with 28 days (Fig. 4.44).

When the fly ash content increased from 30% to 40% (SCC3), it can be observed from Fig. 4.45, that the decrease of about 6.67%, 8.90%, and 7.50% at 91 days, and the decrease of about 14.67%, 20.95%, and 16.76% at 365 days was noticed as compared to 28 days, with the increase in temperature from 27°C to 300°C.

With further increase in fly ash content from 40% to 50% (SCC4), and increase in temperature from 27°C to 300°C, the approximate decrease in porosity observed was 11.17%, 18.30%, and 18.75%, and about 19.14%, 29.87%, and 26.67% at 91, and 365 days respectively (Fig. 4.46).

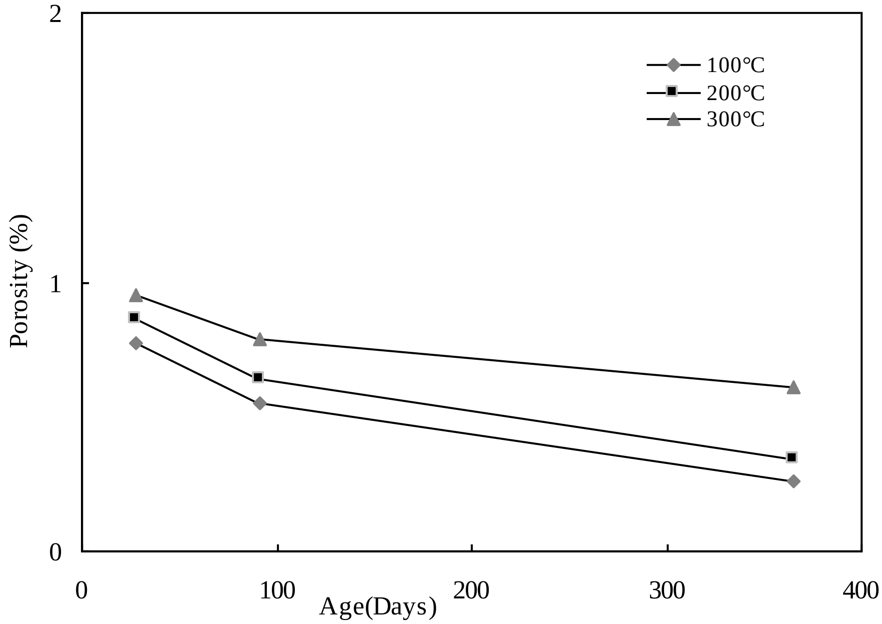


Fig. 4.43: Porosity verses Age (without fly ash)

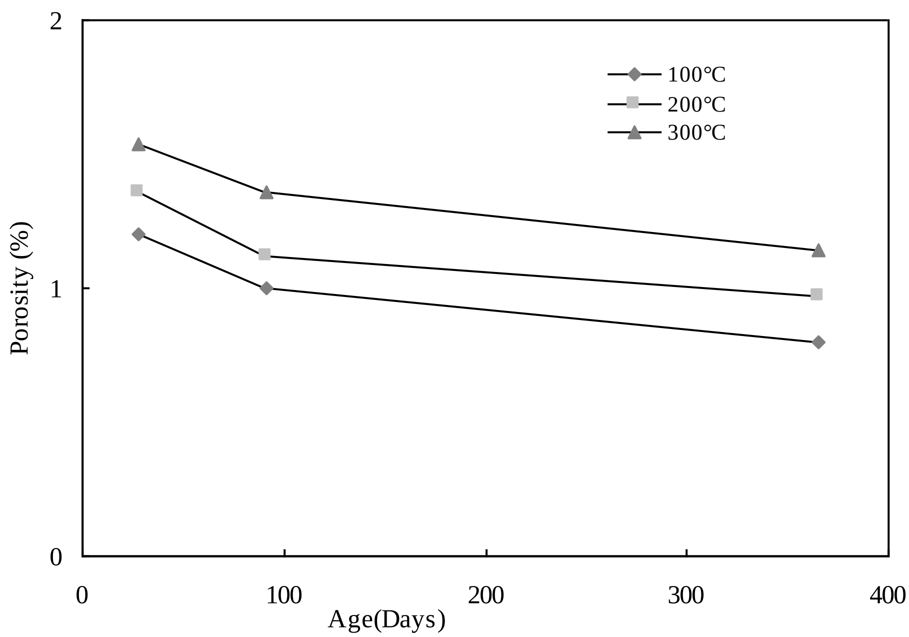


Fig. 4.44: Porosity verses Age (with 30% fly ash)

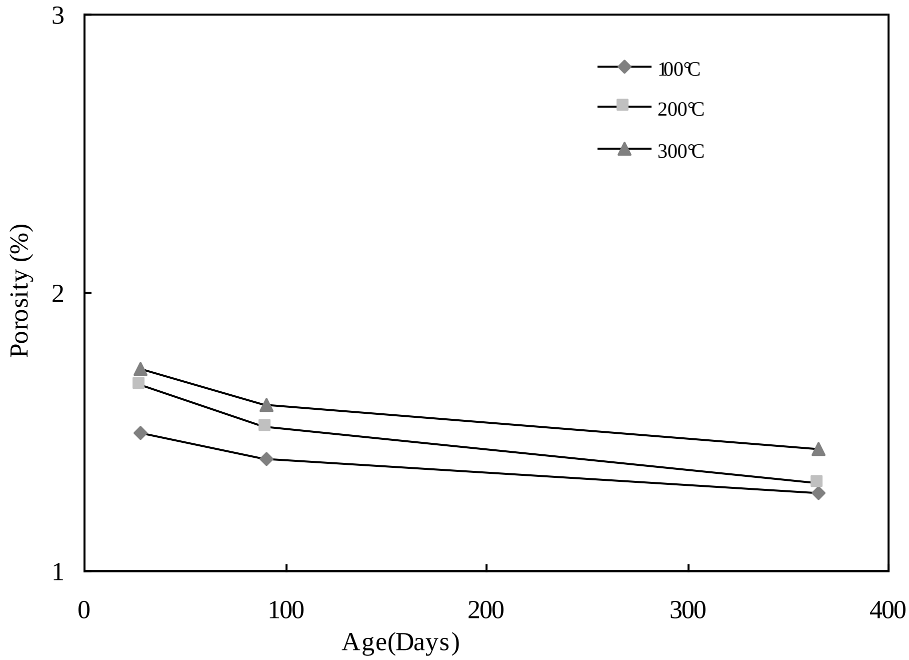


Fig. 4.45: Porosity verses Age (with 40% fly ash)

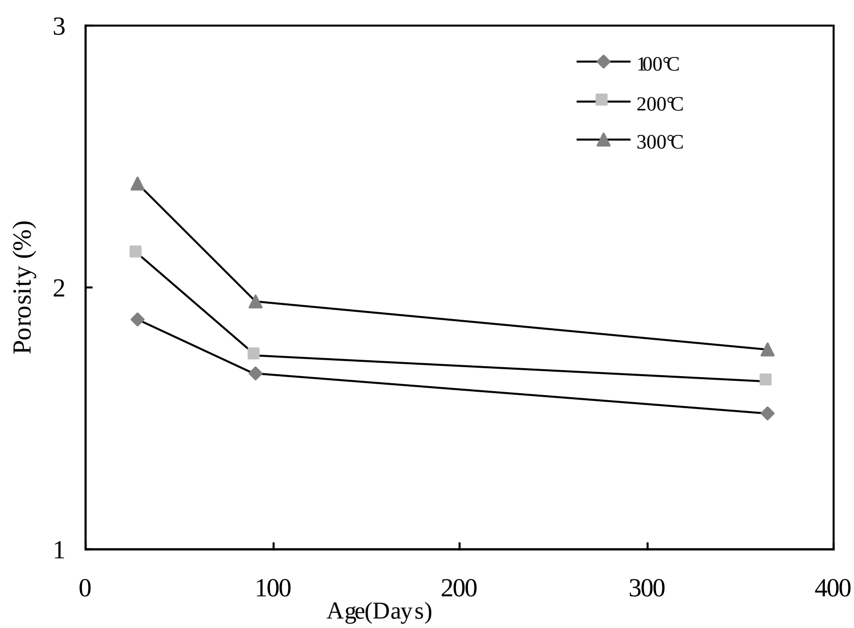


Fig. 4.46: Porosity verses Age (with 50% fly ash)

For the initial stage of heating, the porosity was nearly stable up to 100°C. By increasing the temperature from 100°C-300°C porosity increases. When the percentage of fly ash increased porosity also increased but it decreased with age. The increase in porosity values was attributed to the change in SCC from impermeable to permeable material due to losses and pruned of fine, super fine and organic materials.

The increase in porosity with increase in fly ash content was also observed by *Jiang et al. (1999)*. According to *Gupta et al. (2003)* mineral admixtures, such as fly ash and silica fume in concrete tend to refine the pore structure towards a finer microstructure. In the cement mortar containing class F fly ash, the function of fly ash is mainly to act as a dilutent at early ages and therefore porosity is higher and coarser at early ages. On the other hand *Hanna et al. (2009)* attributed the increase in porosity with temperature to the departure of bound water and to the micro cracking generated by differential expansion between the paste and aggregates. *Kalifa et al. (2000)* attributed the increase in porosity with temperature to the departure of bound water and to the micro cracking generated by differential expansion between the paste and aggregates. *Noumowé et al. (2006)* showed by mercury intrusion porosimetry an increase in the pores sizes beyond 120°C. *Ye et al. (2007)* attributed the increase in porosity to the decomposition of C-S-H and CH (main hydration products). These transformations create an additional void space in the heated concretes. *Galle et al. (2001)* attributed the evolution of porosity to the generation of large capillary pores. Their appearance is due to the release of adsorbed water of capillary pores and release of bound water in cement paste hydrates. They observed macro pores correlated to micro cracks observed at the surface of specimens heated beyond 250°C. If the comparison of the evolution of compressive strength with that of porosity was done, both an increase in strength and an increase in porosity for the SCC between 200°C and 300°C was observed. The increase in strength can therefore not be attributed to a decrease in porosity but rather to a modification of the bonding properties of the hydrates of cement paste. The experimental results are therefore in line with *Hanna and Khoury's (2009, 1992)* hypothesis concerning the creation of shorter and stronger siloxane elements by the loss of a part of the bonds with water in silanol groups.

4.6. RAPID CHLORIDE PERMEABILITY

4.6.1. Effect of temperature on permeability of the SCC mixes made with fly ash and foundry sand

The results of rapid chloride permeability test for different fly ash contents (0%, 30%, 40%, and 50%) and foundry sand incorporating different temperatures (27^{o}C, 100^{o}C, 200^{o}C, and 300^{o}C) at the end of different curing periods (28, 91, and 365 days) are given in Table 4.6 and plotted in Figs. 4.47 to 4.53.

At normal temperature (27°C), with the increase in fly ash content from 30-50%, the Coulomb charge of fly ash SCC mixes (SCC2, SCC3, and SCC4) varied between 1240 and 1155 Coulomb, 1038 and 865 Coulomb, and between 567 and 410 Coulomb respectively. Rapid chloride permeability values were 1410, 1195, and 698 Coulomb at 28, 91, and 365 days respectively for the control mix (SCC1). The decrease of about 6.03%, 14.47%, and 22.50% in permeability was observed at 28, 91, and 365 days with the increase of fly ash content from 30-50% and with 10% replacement of fine aggregate with foundry sand, indicating high chloride penetration resistance.

With the increase in temperature from normal (27°C) to 100°C, and increase in fly ash content from 30-50%, the Coulomb charge of fly ash mixes (SCC2, SCC3, and SCC4) varied between 1282 and 1172 Coulomb, 1125 and 887 Coulomb, and between 592 and 424 Coulomb respectively. The values of rapid chloride permeability were 1495, 1278, and 715 Coulomb respectively for the control mix (SCC1), at the age of 28, 91, and 365 days. It increased by approximately 7.35%, 18.62%, and 23.49% with the decrease of fly ash content from 50-30% and with 10% replacement of fine aggregate with foundry sand as compared with the SCC mix without fly ash (SCC1).

At 200°C, the Coulomb charge of fly ash SCC mixes (SCC2, SCC3, and SCC4) varied between 1290 and 1220 Coulomb, 1190 and 912 Coulomb, and between 619 and 447 Coulomb at 28, 91, and 365 days respectively. Rapid chloride permeability values were 1520, 1370, and 736 Coulomb for the control mix (SCC1). An increase of about 4.61%, 20.21%, and 23.38% in penetration resistance was observed, with the increase in fly ash content and with 10%

replacement of fine aggregate with foundry sand (SCC2, SCC3, and SCC4) as compared with the control mix (SCC1), as can be seen from Figs. 4.47 to 4.53.

Table 4.6: Rapid chloride permeability of the SCC mixes

Mix	Temperature(°C)	Fly Ash (%)	Rapid chloride permeability(Coulombs)		
			28 days	91 days	365 days
SCC1	Normal	0	1410	1195	698
SCC1	100	0	1495	1278	715
SCC1	200	0	1520	1376	736
SCC1	300	0	1538	1442	784
SCC2	Normal	30	1240	1038	567
SCC2	100	30	1282	1125	592
SCC2	200	30	1290	1190	619
SCC2	300	30	1370	1245	642
SCC3	Normal	40	1215	1100	535
SCC3	100	40	1242	1025	567
SCC3	200	40	1259	1054	598
SCC3	300	40	1325	1087	615
SCC4	Normal	50	1155	865	410
SCC4	100	50	1172	887	424
SCC4	200	50	1220	912	447
SCC4	300	50	1255	945	465

With further increase in temperature from 200°C to 300°C, and increase in fly ash content from 30-50%, the Coulomb charge of fly ash mixes (SCC2, SCC3, and SCC4) ranged from 1370 to 1255 Coulomb, 1245 to 923 Coulomb, and between 642 and 465 Coulomb respectively. Coulomb charge passed were 1538, 1442, and 784 for the control mix (SCC1) at 28, 91, and 365 days of age. Percentage increase observed in rapid chloride permeability was 7.48%, 20.80%, and 22.58% with the decrease of fly ash content from 50-30% and with 10% replacement of fine aggregate with foundry sand (SCC2, SCC3, and SCC4) as compared with the SCC mix without fly ash. In no case the value of the charges passed was greater than 1538 Coulomb implying dense SCC mix structure.

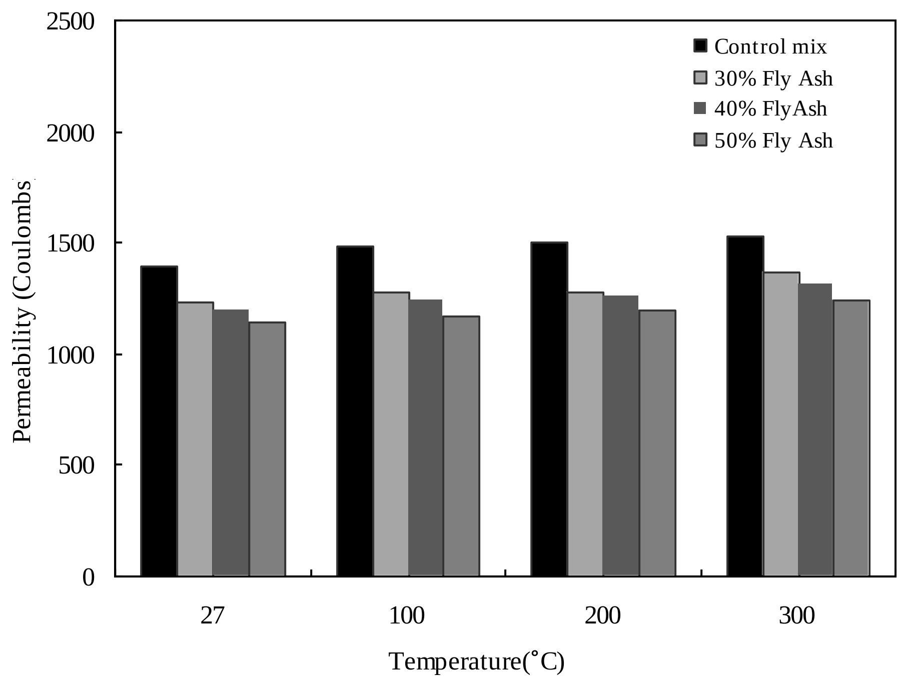


Fig. 4.47: Rapid Chloride Permeability of SCC mixes (28 days)

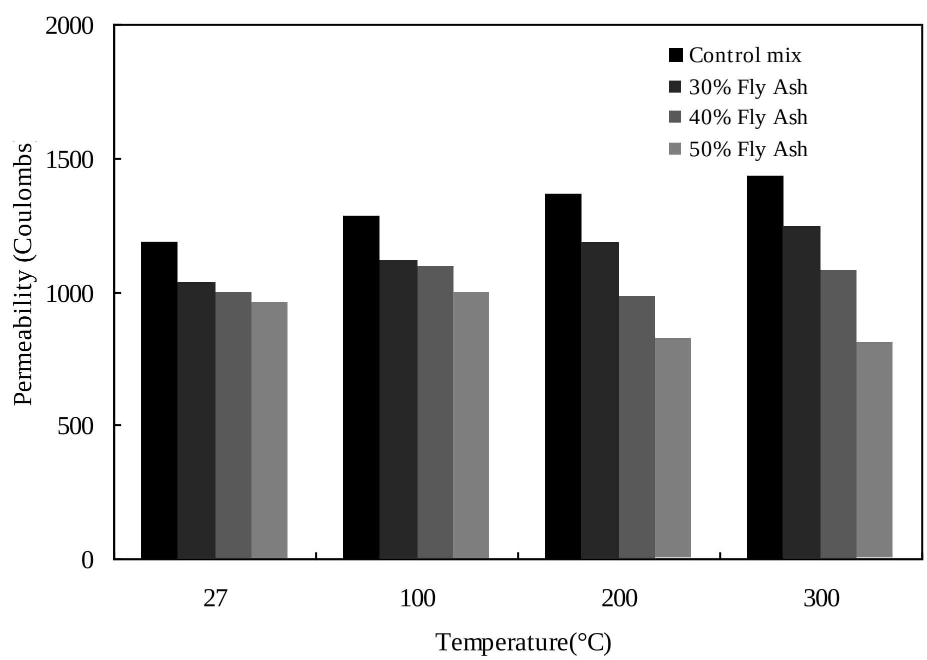


Fig. 4.48: Rapid Chloride Permeability of SCC mixes (91 days)

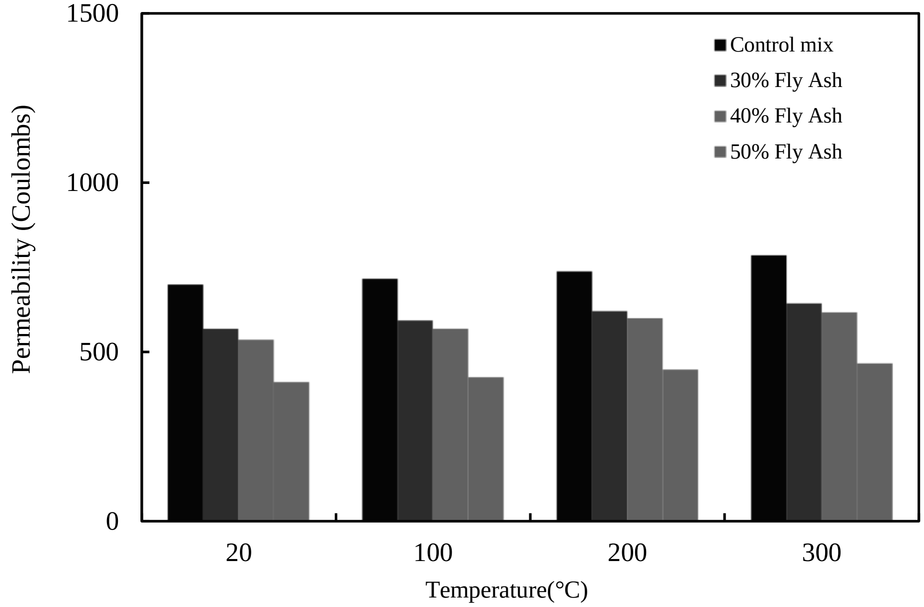


Fig. 4.49: Rapid Chloride Permeability of SCC mixes (365 days)

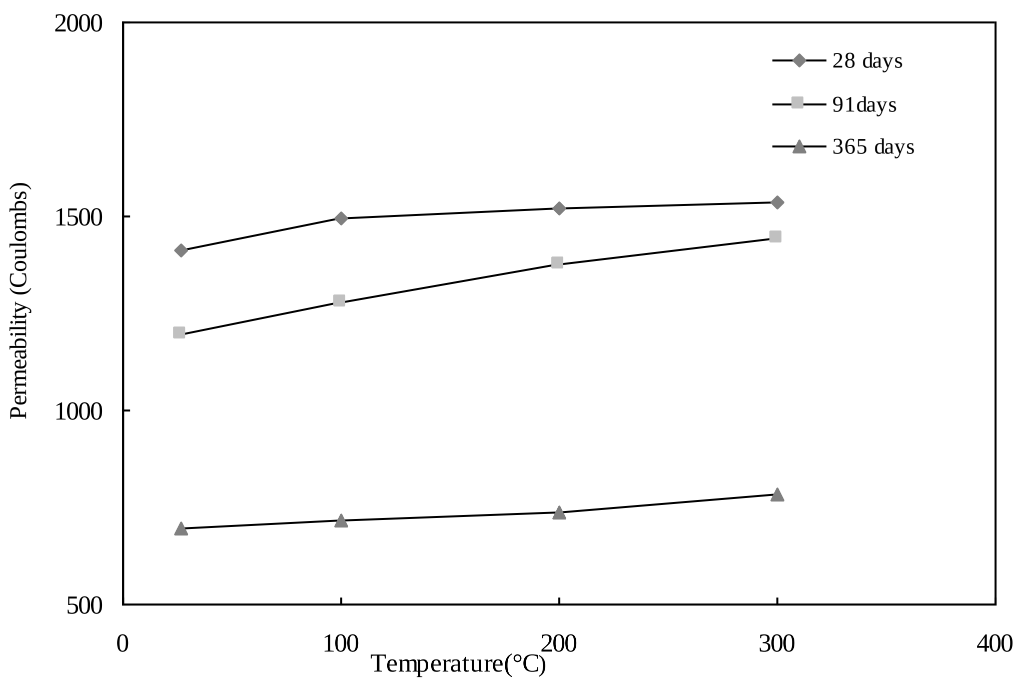


Fig. 4.50: Permeability verses Temperature (without fly ash)

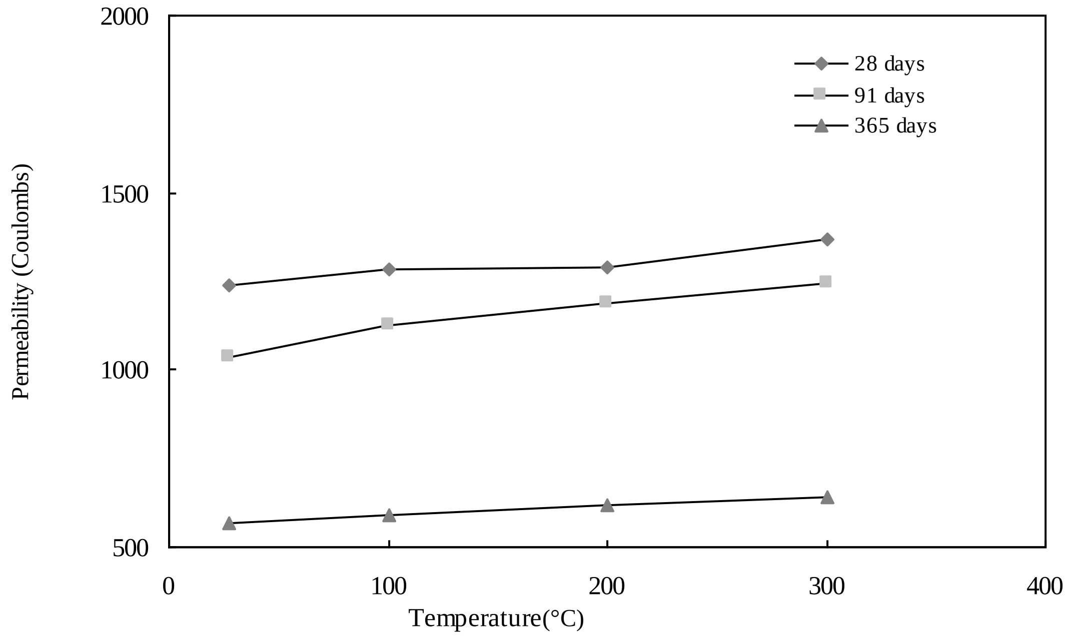


Fig. 4.51: Permeability verses Temperature (with 30% fly ash)

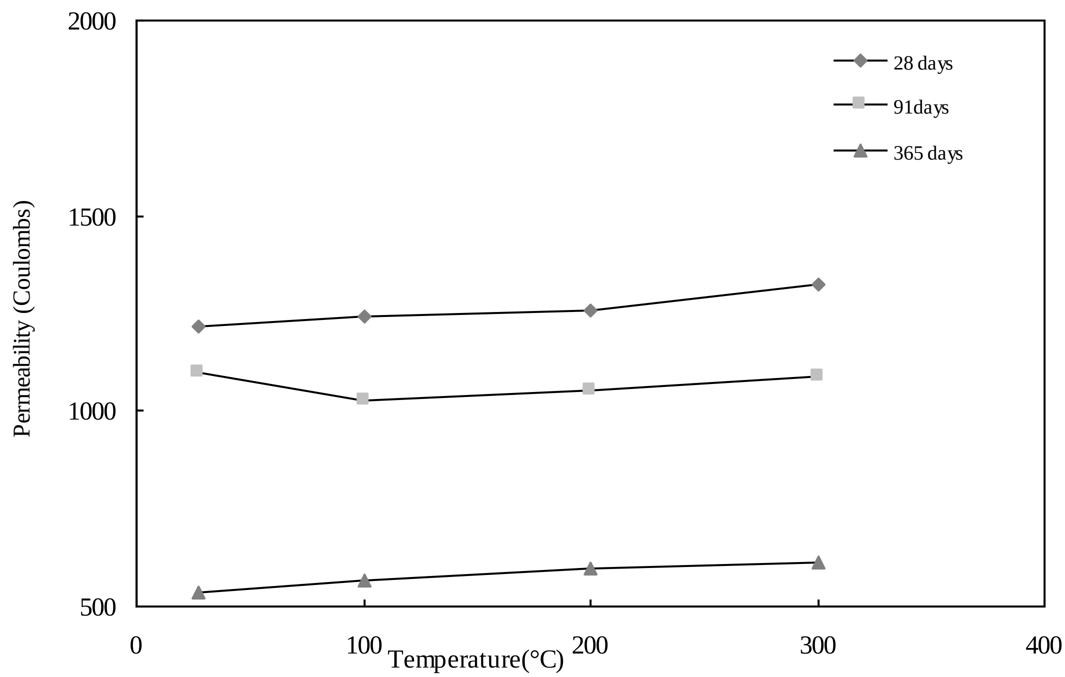


Fig. 4.52: Permeability verses Temperature (with 40% fly ash)

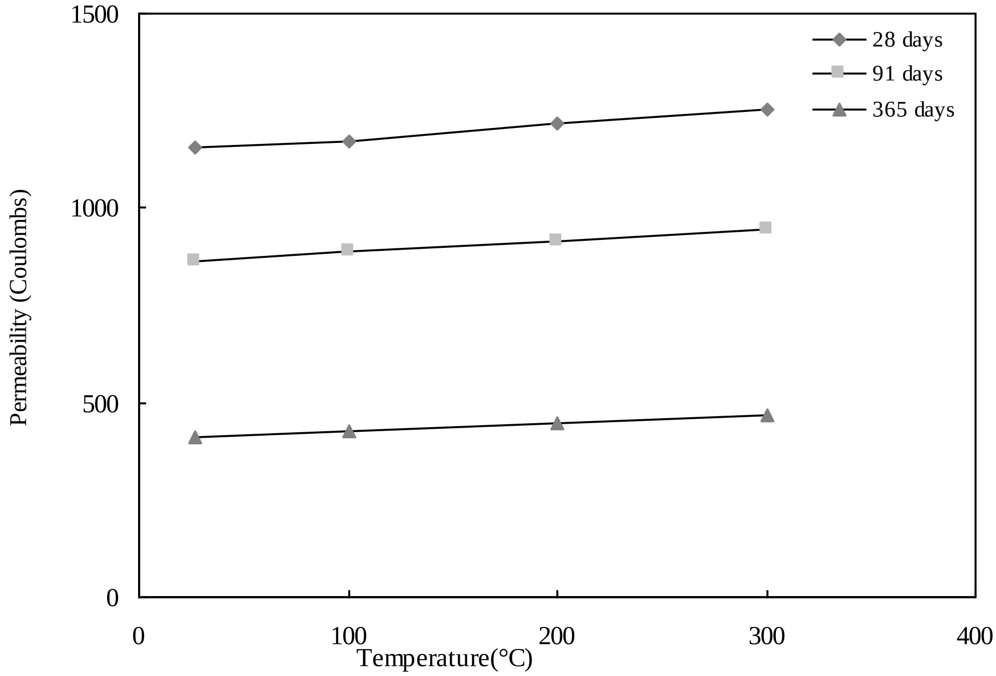


Fig. 4.53: Permeability verses Temperature (with 50% fly ash)

4.6.2. Effect of age on rapid chloride permeability of the SCC mixes made with fly ash and foundry sand at varying temperatures

Effects of age on rapid chloride permeability of the SCC mixes made with and without fly ash and foundry sand at varying temperatures have been shown in Figs. 4.54 to 4.57.

Rapid chloride permeability decreased with the increase in percentage of fly ash content and increased with increase in temperature at all ages.

For the SCC mix without fly ash (SCC1) at 91 days, the decrease of about 15.25%, 14.52%, 9.47%, and 6.24% in permeability was observed at 27°C, 100°C, 200°C, and 300°C (Fig. 4.54). At 365 days of age, the permeability decreased by about 50.49%, 52.17%, 51.57%, and 49% at 27°C, 100°C, 200°C, and 300°C as compared with 28 days.

With 30% fly ash SCC mix (SCC2), percentage decrease of about 16.29%, 12.25%, 7.75%, and 9.12% was observed at 27°C, 100°C, 200°C, and 300°C at 91 days as compared with 28 days. The decrease of approximately 54.27%, 53.82%, 52.01% and 53.14% in chloride permeability was observed at 27°C, 100°C, 200°C, and 300°C at 365 days as compared with 28 days (Fig. 4.55).

When the fly ash content increased from 30% to 40% (SCC3), it can be observed from Fig. 4.56, that the chloride penetration decreased by 9.46%, 17.47%, 16.28%, and 17.96% at 91 days, and about 55.96%, 54.34%, 52.50% and 53.58% at 365 days as compared to 28 days, with the increase in temperature from 27°C to 300°C.

With further increase in fly ash content from 40% to 50% (SCC4), and increase in temperature from 27°C to 300°C, the approximate decrease of 25.10%, 24.32%, 25.24%, and 24.70%, and decrease of about 64.50%, 63.82%, 63.36% and 62.94% was observed at 91, and 365 days respectively (Fig. 4.57).

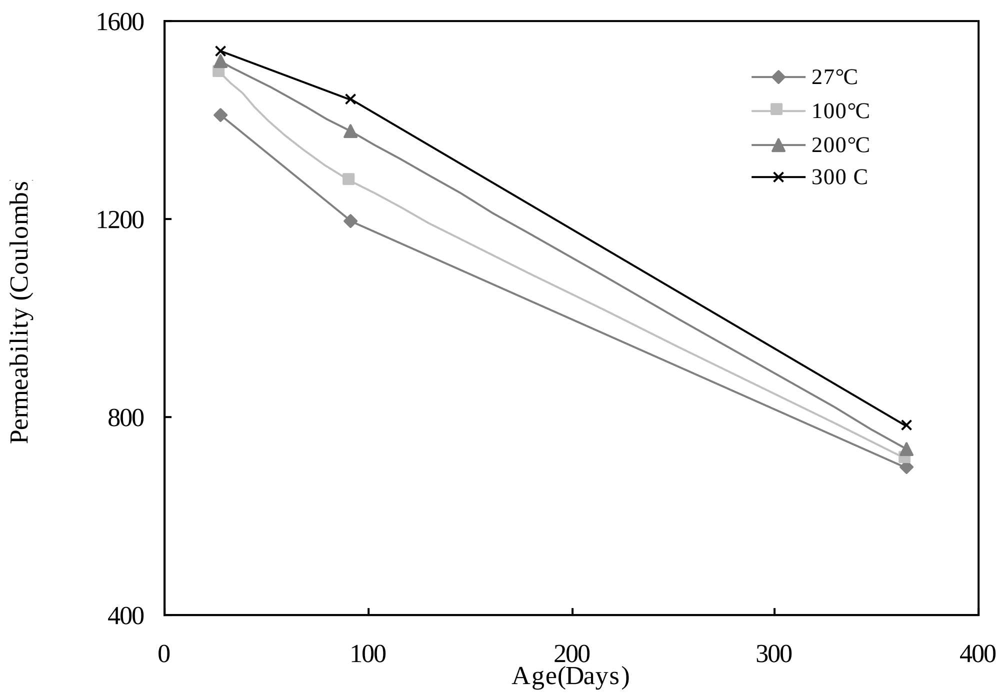


Fig. 4.54: Permeability verses Age (without fly ash)

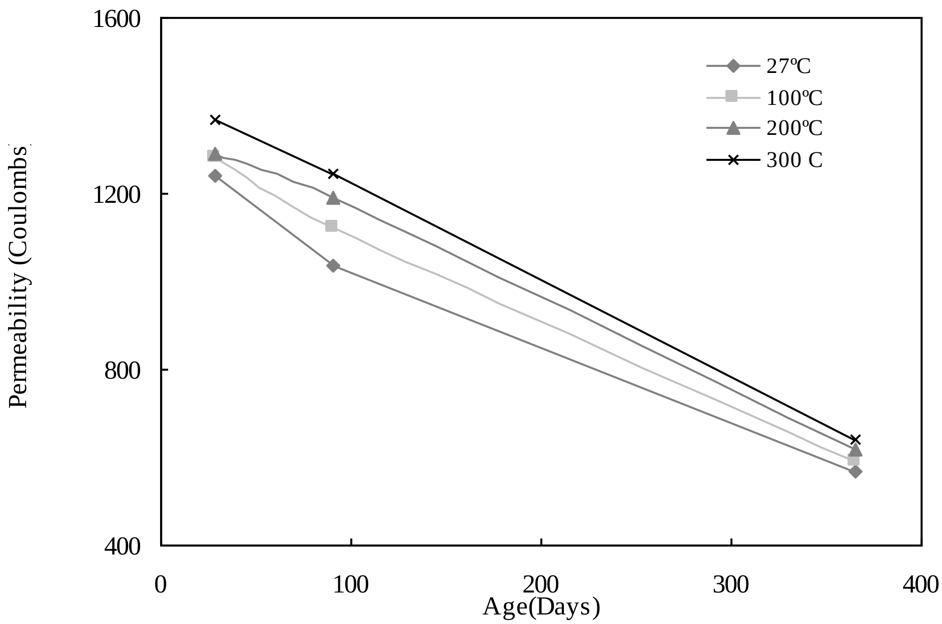


Fig. 4.55: Permeability verses Age (with 30% fly ash)

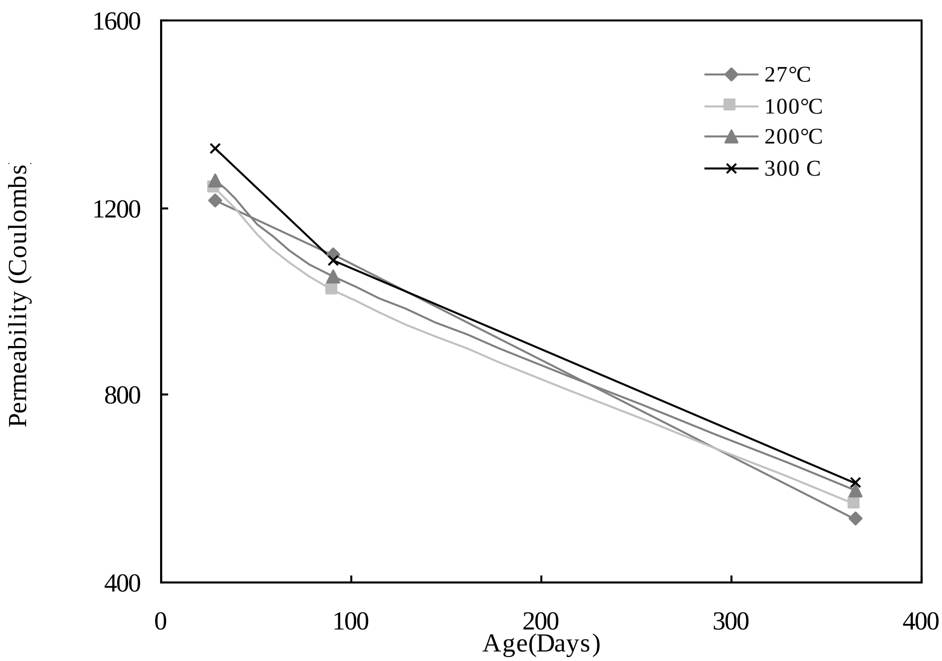


Fig. 4.56: Permeability verses Age (with 40% fly ash)

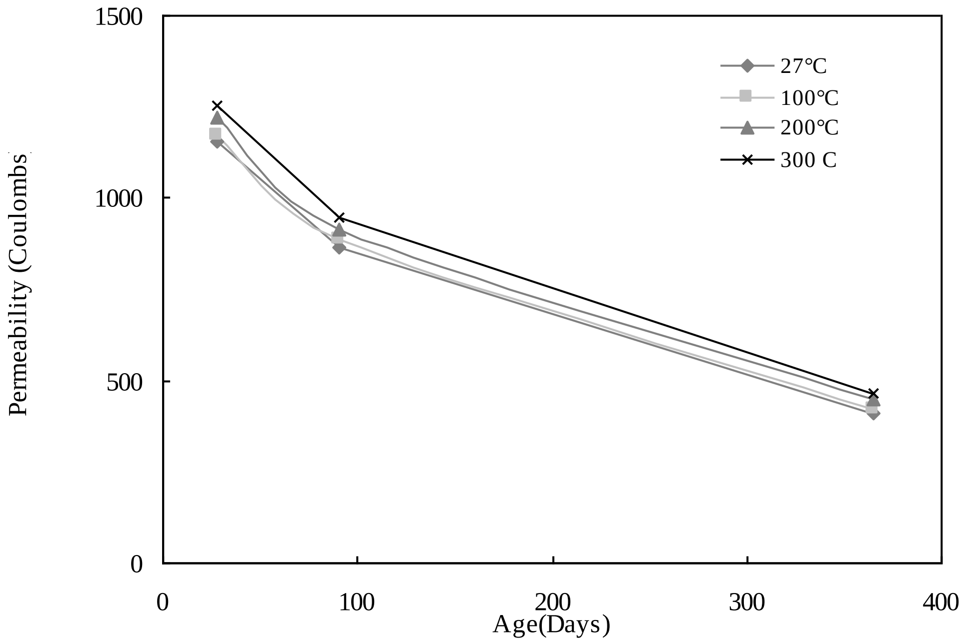


Fig. 4.57: Permeability verses Age (with 50% fly ash)

These figures showed that the use of fly ash and foundry sand significantly reduced the chloride permeability of hardened SCC mixtures when compared with control mix. The chloride ion penetrability limits suggested by ASTM C1202 (Table 3.17) were compared with the results. It was reported in the literature that the use of fly ash decreased the rapid chloride penetration. Coulomb value of concrete and the presence of fly ash could improve the permeability of concrete due to its capability to transform large pores of concrete into small pores and reducing micro cracking in the transition zone. The reduction of chloride migration due to presence of fly ash can be explained partially by the fact that spherical particles of fly ash could improve the particle density in the matrix and the interface zone between aggregates and paste.

This view is well supported by the data in Figs. 4.47, 4.48, and 4.49 that the use of fly ash significantly reduced the chloride permeability of hardened SCC mixtures when compared to the control concretes. It can be clearly observed that the alumina content has a significant influence on the total column charge passed of the concrete. As the alumina (Al_2O_3) content increased the total charge passed decreased, indicating increased resistance against chloride ion penetration and hence corrosion. The SCC with high volume replacements of fly ash (with high amounts of alumina contents) resulted in increased resistance against chloride ion penetration.

On the other hand permeability increased with the increase in temperature, like previous research by *Hanna et al. (2009).* But this increase in permeability was reduced by simultaneous use of fly ash and spent foundry sand. It is evident from the results of this research that the SCC mixes (SCC2, SCC3, and SCC4) made with fly ash reduced the rapid chloride ion penetrability to the low range (1000-2000 Coulomb) at the age of 28 days (Fig.47), between low range to very low range (<1000 Coulomb) at the age of 91 days (Fig.48), and very low at the age of 365 days (Fig.49). The incorporation of fly ash and foundry sand resulted in a reduction in Coulomb charges. The reduction was higher as the fly ash content increased, as can be seen from these figures.

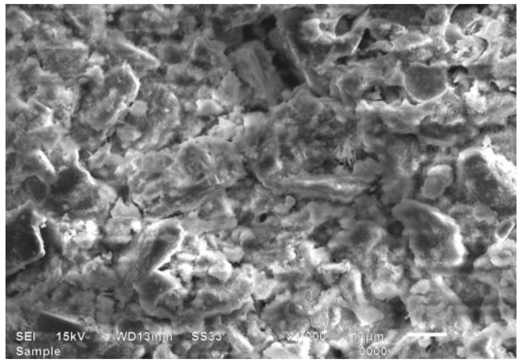
In the present research, it was observed that permeability was lower at 365 days, as compared with 28 and 91 days, as expected due to the hydration of Portland cement and pozzolanic reactions of fly ash. Lower rapid chloride permeability of fly ash concretes can be attributed to more compact structure of the paste, which was a result of fine fly ash particles than Portland cement (filler effect) and pozzolanic reactions of fly ash. These effects reduced the pore size and the thickness of transition zone between the aggregate and surrounding cementitious matrix, resulted in lower permeability. One of the most important factors that affected the permeability of concrete was the internal pore structure, which in turn was dependent on the extent of hydration of the cementitious materials. Basically the chloride ion penetration depends on the chloride binding capacity of the constituent materials. Usually chlorides penetrate in concrete by diffusion along with water paths or open pores. Some of these chlorides can react with the cement compounds, mainly tricalcium-aluminates (C_3A), forming stable chloride complexes. The excess of chloride is free and leads to the initiation of the corrosion process. The presence of fly ash leads to an increase in the amount of C_3A due to the higher amount of alumina present in the mix and to an increase in the content of calcium silicate hydrate that is formed in the pozzolanic reactions. Thus, the chloride binding capacity of concrete tends to increase with fly ash addition and consequently less free chloride is available to initiate the corrosion process. The curing conditions and the age of concrete thus largely determine the ease with which chloride ions can move into a concrete. From the test results it was observed that most concretes become significantly less permeable with increase in curing time. Therefore, it is important to specify the age at which the permeability is measured.

The implications of such substantial decreases in chloride ion penetrability should be seriously considered in the design of offshore structures, bridge decks, parking garages and other structures that are vulnerable to corrosion of reinforcing steel under chloride ion attack. Not only would SCC made with high-volume replacement composite cements provide excellent workability at a competitive cost, but the repair, maintenance and overall life cycle costs would make such a material more appealing. The results showed that at an early age, chloride permeability is most influenced by the water/binder ratio. However, at later ages the beneficial effect of fly ash is apparent and is the governing parameter in reducing permeability. Thus, in aggressive chloride environment, such as sea coast or structures where deicing salts are used, the increased addition of fly ash in SCC mixes will prove beneficial.

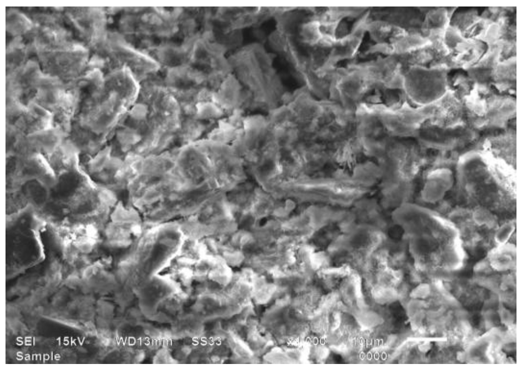
Significant reduction of chloride diffusivity of the SCC with fly ash was also reported earlier by *Zhu and Bartos (2003)* and *Nayak et al. (2011). Shi (2004)* states that the use of supplementary cementing material such as fly ash may have a significant effect on the chloride migration of concrete as measured by the RCPT effect. It was already found by *Rajamane et al. (2011)* that addition of pozzolanic mineral admixture refines the matrix of hydrated Portland cement due to its reaction with free lime formed during cement hydration, improving the penetration resistance against chlorides, sulphates, and oxygen. The reason for the lower chloride ion penetration of concrete with fly ash may be attributed to the presence of fly ash. The use of fly ash probably resulted in dense microstructure, by reducing the pore size and thickness of transition zone between aggregate and surrounding cementitious matrix. It should also be noted that the RCPT results depend on the electrical conductivity of pore solution, which is determined by the composition of pour solution. The experimental results of this research are in line with the published literature.

4.7 MICROSCOPIC OBSERVATIONS (SEM-SCANNING ELECTRON MICROSCOPY)

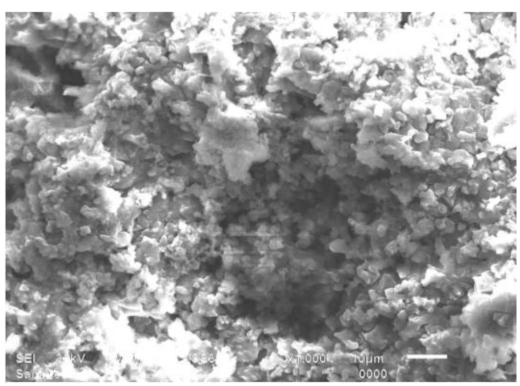
SEM micrographs of samples without heat treated and heat treated at 100°C, and 300°C are shown in Fig. 4.58 (a, b, and c) respectively. It clearly indicates that, the exposed (300°C) sample, exhibit coarsening and non uniform distribution of the grains, as compared to unexposed samples. It is well reported in the literature by *Peng (2008)* that grain coarsening leads to lowering of the mechanical strength and increase the grain size. It is well supported by the XRD results and compressive strength measurements as given in the Fig. 4.60 and Table 4.1. Basically, bigger grains are responsible for forming the pores, which ultimately leads to crack formation in the samples. On the other hand fly ash containing samples as shown in Fig. 4.59 (a, b and c), lead to non-uniformity with increased content of fly ash. However, in case of 30% fly ash sample, two types of grains are observed i.e. faceted and needle shaped grains. As the fly ash content increased in the samples, the fly ash distribution becomes more uniform among the original components of cement. Additionally the needle shaped grains reduced as shown in Fig. 4.59 (b) with increased fly ash content. Contrary to this, 50% fly ash content in the sample shows the uniform distribution of the grains. However, the size of the grain is larger than in any other studied samples. The larger grain size may be responsible for decrease in the compressive strength of the sample.



(a) 27°C

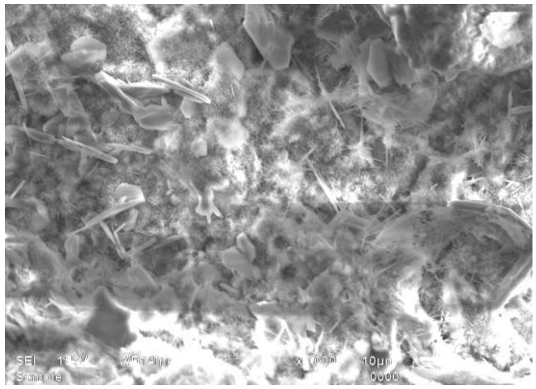


(b) 100°C

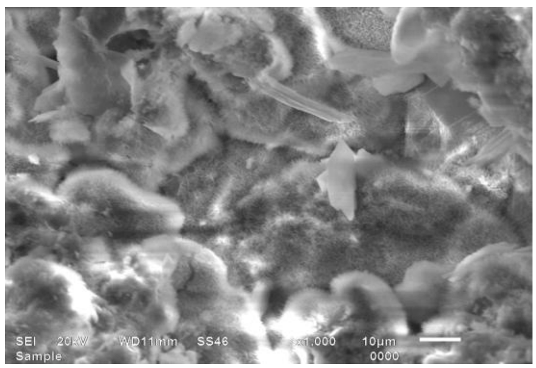


(c) 300°C

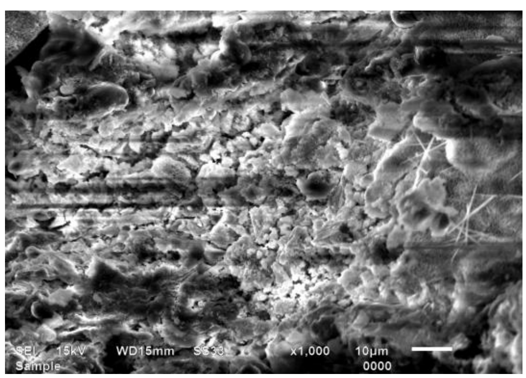
Fig. 4.58: SEM images of SCC1 (27°C, 100°C, 300°C)



(a) 30% Fly Ash



(b) 40% Fly Ash

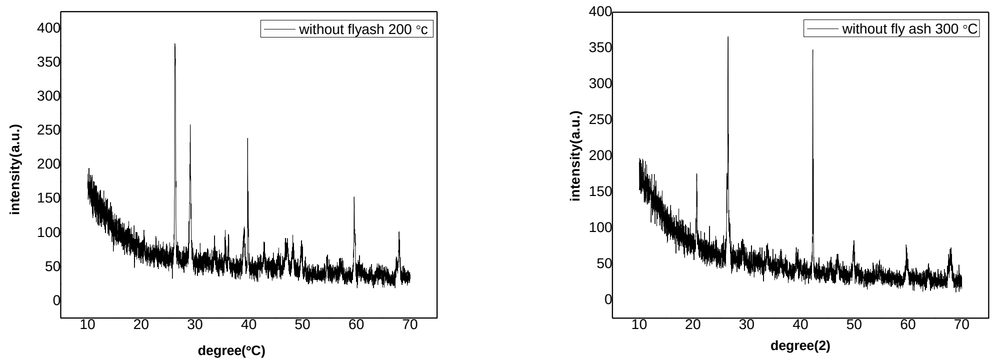


(c) 50% Fly Ash

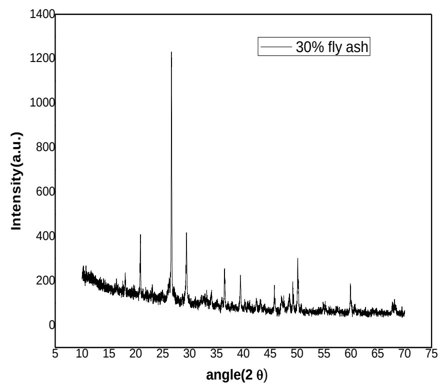
Fig. 4.59: SEM images of SCC2, SCC3 and SCC4

4.8. X-RAY DIFFRACTION

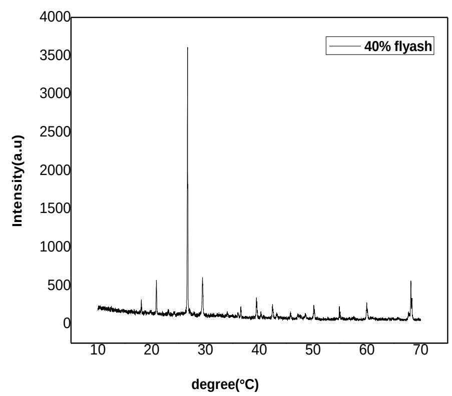
The XRD patterns of samples without fly ash and foundry sand heat treated at 100°C, 200°C and 300°C are shown in Fig. 4.60. As evident from full width at half maximum (FWHM) of XRD peaks, the peak width increases with increasing heat treatment temperature in all the samples. However, the change in peak width is more pronounced in higher temperature heat treated sample i.e. 300°C. It clearly indicates that the samples heat treated at 300°C had higher disorder due to presence of porosity as compared to samples heat treated at 100°C and 200°C. It may be possible due to higher rate of decomposition of C-S-H gel, which is the main component of hydration products that leads to large porosity in this particular sample. The mass loss of this sample is also supportive of the XRD results, since this sample shows highest mass loss during heat treatment. Ultimately dehydration leads to some cracks in the sample, since pores in the specimen work as the stress raiser centers. In addition to this, the XRD pattern did not show any new crystalline phase formation, except peak broadening and shifting of the XRD peak. *Hanaa et al. (2009)* also reported similar results. On the other hand, the replacement of cement with different percentages of fly ash, and fly ash contents leads to increase in the porosity by filling the gaps and cracks within the samples. These proportions lead to create during hydration. The XRD patterns of these three samples with fly ash (SCC2, SCC3, and SCC4) again indicate the higher ordering as fly ash contents increase in these samples. Since porosity and ordering increases, with increasing content of fly ash leading to decrease in the compressive strength in these samples. The sharpness of the XRD peaks in fly ash contained samples shows less disordering as compared to the samples without fly ash.



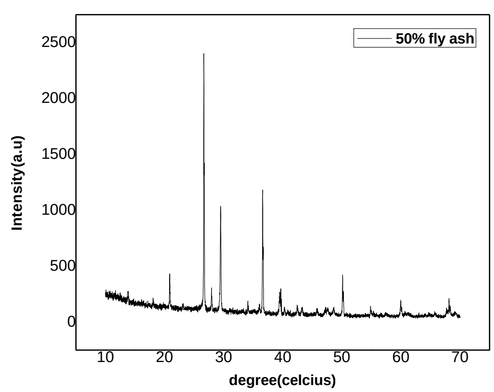
(a) SCC1



(b) SCC2



(c) SCC3



(d) SCC4

Fig. 4.60: XRD images of SCC1, SCC2, SCC3 and SCC4

4.9. STATISTICAL ANALYSIS OF THE RESULTS

The correlation analysis of the results of various properties of the present research, like compressive strength, splitting tensile strength, modulus of elasticity, mass loss, porosity, and rapid chloride permeability was carried out using support vector machine approach. Support vector machines are classification and regression methods which had been derived from statistical learning theory (*Vapnik 1995).* The support vector machines classification methods are based on the principal of optimal separation of classes. If the classes are separable - this method selects, from among the infinite number of linear classifier the one that minimize the generalization error, or at least an upper bound on this error, derived from structural risk minimization. The formulation of support vector machine so that it can be applied to regression problems can be as given by Vapnik *(1995)* for '€' for support vector regression. The purpose of support vector regression is to find a function having the most '€' deviation from the actual target vectors for all given training data and have to be as flat as possible *(Smola 1996).*

In the situation with non-linear decision surfaces, support vector machines use a mapping to project the data in a higher dimensional feature space. To make computation simpler, the concept of the kernel was introduced. A number of kernels were discussed in the literature (linear kernel, polynomial kernel, radial basis kernel), but it is difficult to choose one, which gives the best generalization with a given data set. As the choice of kernel may influence the prediction capabilities of the support vector machines, the present study uses a linear kernel, after a lot of trials with other kernels also. In this research statistical analysis of the data is going to be carried out using support vector machine approach.

The use of support vector machines requires setting of user-defined parameters such as regularization parameter (C), type of kernel, kernel specified parameters and error-insensitive zone (€). Variation in error-insensitive zone found to have no effect on the predicted strength. The optimum values of parameters were obtained after a large number of trials by varying these values for different data sets used in the present study. The correlation coefficients and root mean square error (RMSE) values were compared to reach at a suitable choice of these parameters. Cross validation is used to generate the model with SVMs on the input data set and predicting the 28, 91, and 365 days compressive strength, splitting tensile strength, modulus of elasticity, rapid chloride permeability, mass loss, and porosity of the data set used in the present research. The cross validation is the method of estimating the accuracy of a classification or regression model. It required a small computational time to reach at a suitable choice of user defined parameter with used data set. SVM software used in the present research is based on sequential minimization optimization.

The model success in predicting the behavior of SCC mixtures depends on comprehensiveness of the training data. Availability of large variety of experimental data is required to develop the relationship between mixture variables of SCC and its measured properties. The basic parameters considered in this study were cement content, fine aggregate content, coarse aggregate content, foundry sand, fly ash, water/binder ratio and super plasticizer dosage added and elevated temperatures. The response was derived for compressive strength, splitting tensile strength, modulus of elasticity, and rapid chloride permeability.

The training of support vector machines was carried out using pair of input vector and output vector. Support Vector Machines was designed using data taken from the present research for compressive strength, splitting tensile strength, modulus of elasticity, rapid chloride permeability, mass loss, and porosity prediction. The input vector consisted of mixture variables and an output vector of one element i.e. compressive strength, splitting tensile strength, modulus of elasticity, mass loss, porosity and rapid chloride permeability. For compressive strength, splitting tensile strength, modulus of elasticity, and rapid chloride permeability input parameters were the weight of cement (kg/m^3), fine aggregate content (kg/m^3), coarse aggregate content (kg/m^3), foundry sand (kg/m^3), fly ash (%), water/binder ratio, and super plasticizer(%).

The acceptance and rejection of the model developed was determined by its ability to predict the compressive strength, splitting tensile strength, modulus of elasticity, rapid chloride permeability, mass loss, and porosity of SCC. Also a successfully trained model is characterized by its ability to predict the values of various properties for the data it was trained on. Several trials were carried out to find the suitable choice of parameter C and kernel specified parameters in predicting the strength of concrete data. Tables 4.7, 4.8, and 4.9 give the values of user-defined parameters for linear kernel in predicting the various properties for different ages. A 10-

fold cross validation was used to predict the various properties for the data set used in this research. The cross-validation is the method of accuracy of a classification or regression model. The input data set is divided into several parts (a number defined by the user), with each part intern used to test a model fitted to the remaining part. The correlation coefficient and root mean square error was used to judge the performance of support vector machine in predicting the various properties.

Tables 4.10, 4.11, and 4.12 provides the correlation coefficient and root mean square error obtained with the data using support vector machines to predict the strength and permeability for 28, 91, and 365 days of age respectively. To compare the performance of support vector machines, graphs between actual and predicted strength were plotted. The performance of support vector machines approach in predicting the strength is shown in Fig. 4.61 to 4.66 for SVM linear kernel. The result of compressive strength suggests that most of the points are lying within ± 10% of the line of perfect agreement. For splitting tensile strength most of the points are lying within ±20% of the line of perfect agreement. For modulus of elasticity most of the points are lying within ±20% of the line of perfect agreement. For mass loss most of the points are lying within ±20% of the line of perfect agreement. For RCPT most of the points are lying within ±10% of the line of perfect agreement. For porosity most of the points are lying within ±10% of the line of perfect agreement.

For predicting the 28 days strength and permeability, a correlation coefficient of 0.99, 0.98, 0.94, 0.98, 0.97, and 0.99 and a root mean square error of 0.92, 11.68, 3.88, 1848.11, 244.07, and 0.06 were achieved with support vector machines linear based kernel approach

A correlation coefficient of 0.99, 0.98, 0.94, 0.93, 0.84, and 0.99 and a root mean square error of 5.69, 11.95, 2812.30, 315.45, and 0.01 were obtained for predicting the various properties at the age of 91 days.

For predicting the various properties, a correlation coefficient of 0.90, 0.96, 0.95, 0.93, 0.99, and 0.99 and a root mean square error of 149.58, 0.28, 5.99, 10.97, 169.67, and 17.92 were achieved with support vector machines linear based kernel approach at the age of 365 days.

The values of correlation coefficient value near to one in most of the cases. It means that the inclusion of fly ash and foundry sand in SCC at elevated temperatures gives better affect to its strength and permeability properties. The results suggested a better performance by support vector machines for predicting the strength and permeability for all the properties for the data set used in the present study.

Table 4.7: Values for various parameters of Support Vector Machines by linear kernel (28 days)

Parameters	Regularization parameter(C)	Error-insensitive zone (€)
Compressive strength	10.00	0.10
Splitting tensile strength	10.00	0.10
Modulus of elasticity	2.00	0.30
Rapid Chloride permeability	10.00	0.10
Mass loss	10.00	0.10
Porosity	1.00	0.50

Table 4.8: Values for various parameters of Support Vector Machines by linear kernel (91 days)

Parameters	Regularization parameter(C)	Error-insensitive zone (€)
Compressive strength	10.00	0.10
Splitting tensile strength	10.00	0.10
Rapid chloride permeability	1.00	0.50
Mass loss	10.00	0.10
Porosity	4.00	0.10

Table 4.9: Values for various parameters of Support Vector Machines by linear kernel (365 days)

Parameters	Regularization parameter(C)	Error-insensitive zone (€)
Compressive strength	1.00	0.50
Splitting tensile strength	1.00	0.50
Modulus of elasticity	6.00	0.10
Rapid chloride permeability	3.00	0.10
Mass loss	4.00	0.20
Porosity	3.00	0.10

Table 4.10: Summary of coefficients of Support Vector Machines (28 days)

Property	Correlation Coefficient	Mean Absolute Error	Root Mean Square Error
Compressive strength	0.99	1.11	0.92
Splitting tensile strength	0.98	3.64	11.68
Modulus of elasticity	0.94	1.56	3.88
Rapid chloride permeability	0.98	36.52	1848.11
Mass loss	0.97	15.76	244.07
Porosity	0.99	0.19	0.06

Table 4.11: Summary of coefficients of Support Vector Machines (91 days)

Property	Correlation Coefficient	Mean Absolute Error	Root Mean Square Error
Compressive strength	0.99	2.34	5.69
Splitting tensile strength	0.98	3.62	11.95
Rapid chloride permeability	0.93	9.05	2812.30
Mass loss	0.84	18.15	315.45
Porosity	0.99	0.12	0.01

Table 4.12: Summary of coefficients of Support Vector Machines (365 days)

Property	Correlation Coefficient	Mean Absolute Error	Root Mean Square Error
Compressive strength	0.90	11.49	149.58
Splitting tensile strength	0.96	0.527	0.28
Modulus of elasticity	0.95	2.51	5.99
Rapid chloride permeability	0.93	2.61	10.97
Mass loss	0.99	11.62	169.67
Porosity	0.99	4.20	17.92

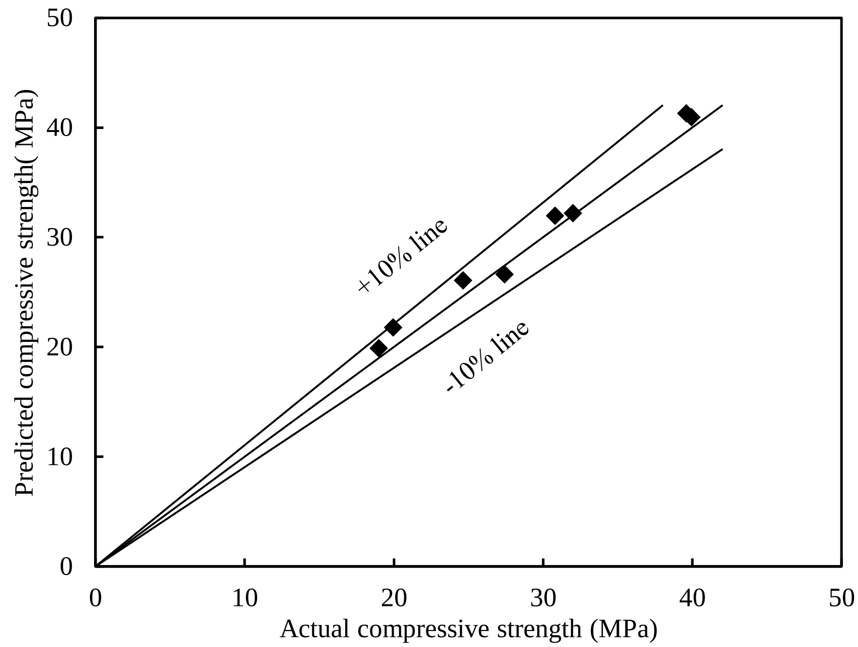


Fig. 4.61: Actual Compressive Strength verses Predicted Compressive Strength

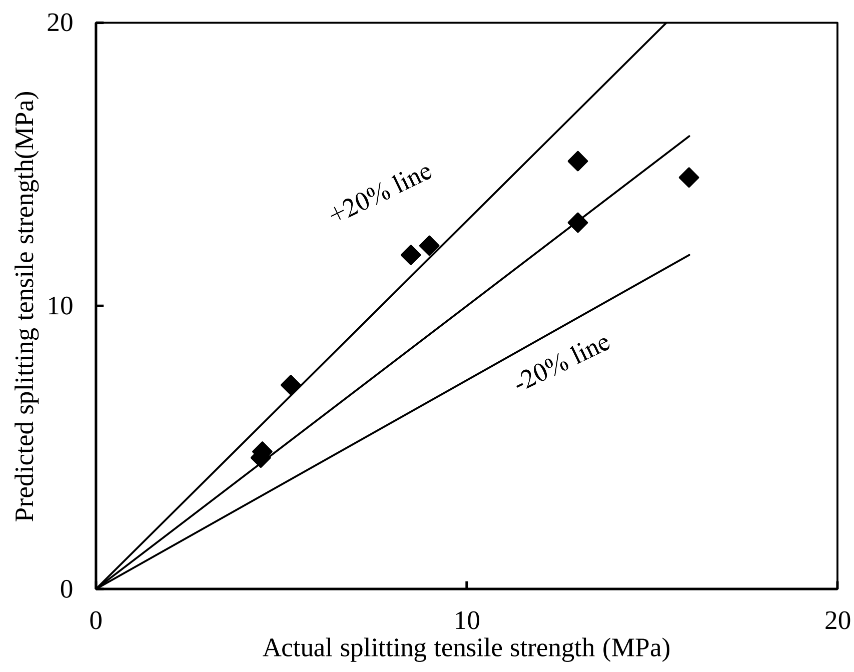


Fig. 4.62: Actual Splitting Tensile Strength verses Predicted Splitting Tensile Strength

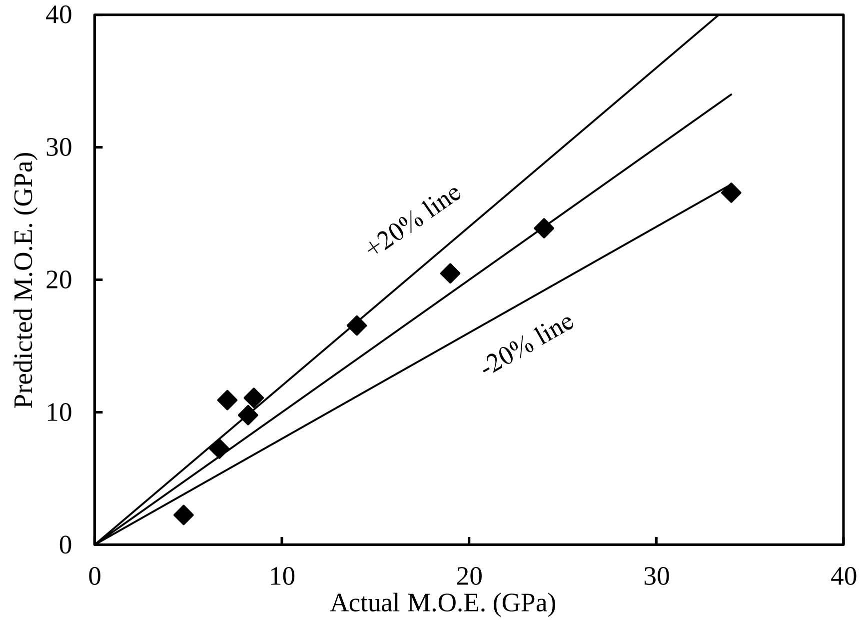


Fig. 4.63: Actual Modulus of Elasticity verses Predicted Modulus of Elasticity

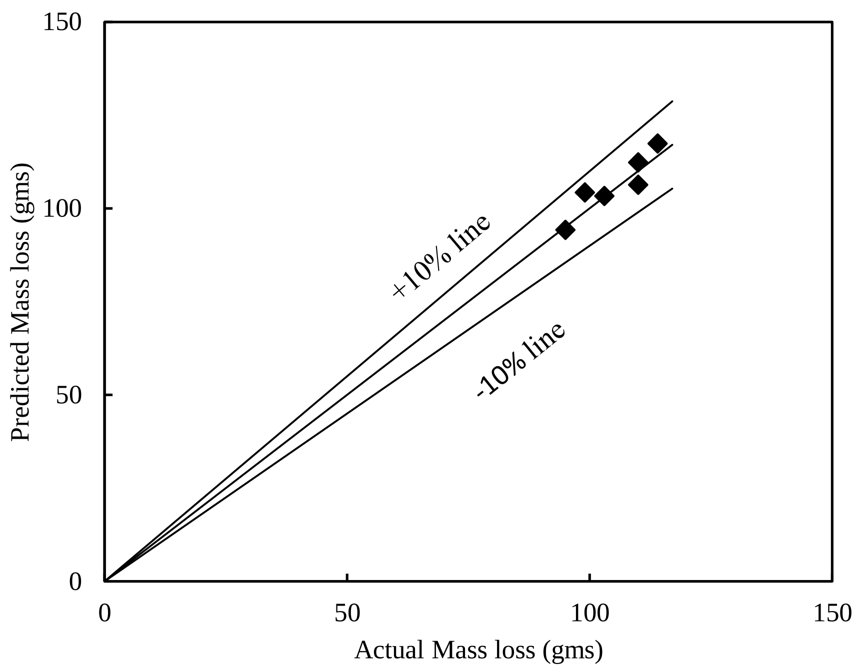


Fig. 4.64: Actual Mass Loss verses Predicted Mass Loss

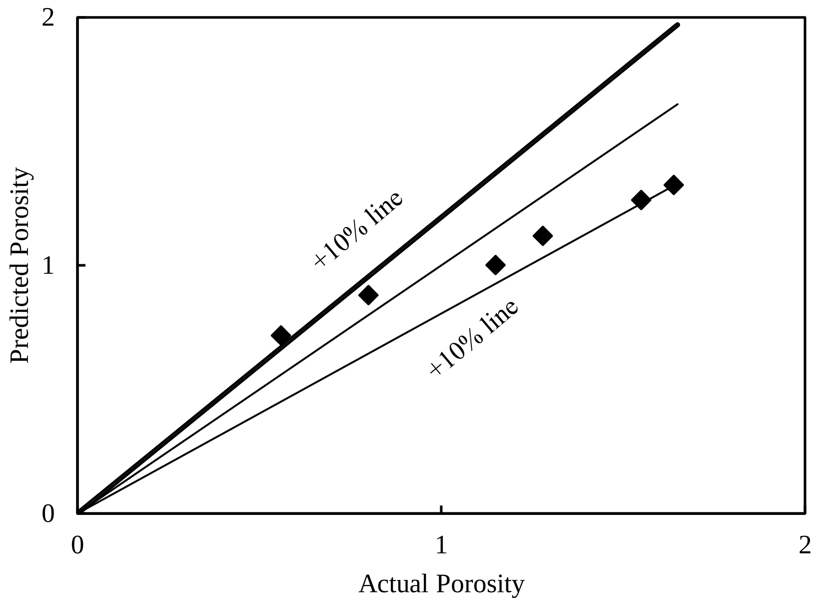


Fig. 4.65: Actual Porosity verses Predicted Porosity

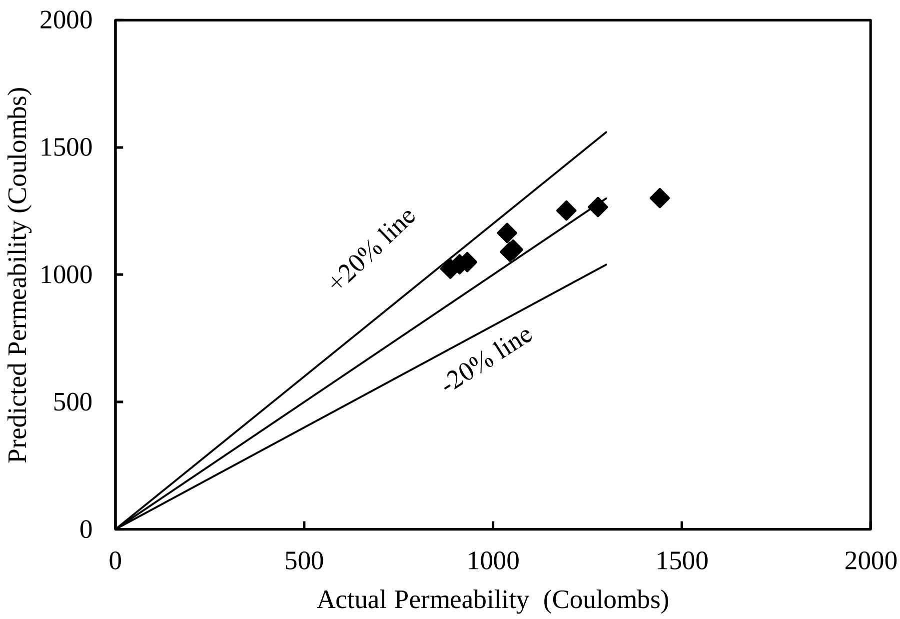


Fig. 4.66: Actual Permeability verses Predicted Permeability

These results clearly indicates that the proposed model is quite accurate in predicting the compressive strength, splitting tensile strength, modulus of elasticity, mass loss, porosity, and rapid chloride permeability of the designed SCC mixes at elevated temperatures.

CHAPTER – 5

CONCLUSIONS

The present work investigated the influence of fly ash as replacement of cement, and influence of foundry sand as a partial replacement of fine aggregate on the various strength and permeability properties of SCC at elevated temperatures. On the basis of the results of present study, the following conclusions are drawn:

5.1. COMPRESSIVE STRENGTH

- High volume replacement of Ordinary Portland Cement with fly ash generally leads to lower early age strength. However this strength decrease was minimized by carefully selecting the material i.e. by replacing 10% of fine aggregate with foundry sand.

- At the w/b ratio of 0.36 to 0.42, all the SCC mixes (SCC1-SCC4) can be produced with adequate fresh properties such as slump flow test and U-box test were found to be satisfactory, i.e. passing ability, filling ability and segregation resistance are within the specified range when sand is replaced with foundry sand and cement with high volume fly ash.

- Although fly ash reduces the strength, it is still possible to produce SCC with compressive strengths ranging from 30.67 to 19.25 MPa, 39.50 to 29.00 MPa, and 42.25 to 31.75 MPa at 28, 91 and 365 days respectively at elevated temperatures. High volume fly ash SCCs with different compressive strength can be selected for use in different applications.

- Compressive strength increased with a decrease in the percentage of the fly ash and the water-to-cementitious materials ratio at all ages.

- Compressive strength decreased with the increasing temperature, except between 200-300°C. Between 200°C and 300°C, the compressive strengths of most of the concrete specimens slightly improved as compared to strength at 100°C. The increase in strength could be attributed to a modification of the bonding properties of the cement paste hydrates i.e. rehydration of the paste due to the migration of water in the pores. The increase in strength can be explained by the hydration of anhydrous cement due to water movement, leading to the formation of hydrates.

- Higher percentage replacement of cement with fly ash can be used to produce SCC with an adequate strength. The strength of concrete with 30%, 40% & 50% fly ash content at 28 days is sufficiently enough for use in reinforced concrete construction.

- SCC can be made economical with up to 50% replacement of Ordinary Portland Cement with fly ash while achieving good workability and adequate compressive strength values.

- Compressive strength of all SCC mixes was found to increase with increase in age.

- SCC can be made cost effective by replacing high proportions of Ordinary Portland Cement by cementatious materials and low cost micro fillers and by reducing the dosage of chemical admixture and viscosity modifying admixtures. In this study SCC was developed without using viscosity modifying admixtures.

5.2. SPLITTING TENSILE STRENGTH

- The splitting tensile strengths developed were from 0.94 to 2.00, 1.14 to 2.24 and 1.28 to 2.28 MPa at 28, 91 and 365 days respectively. The splitting tensile strength continued to decrease in a similar way as was observed between 27°C and 200°C, due to the departure of bound water, corresponding to a large mass loss.

- Splitting tensile strength increased with a decrease in the percentage of the fly ash and the water-to-cementitious materials ratio at all ages.

- Splitting tensile strengths of all SCC mixes was found to increase with increase in age.

- At elevated temperatures, the rate of splitting tensile strength loss is higher than the rate of compressive strength loss. Thus it can be concluded that the splitting tensile strength is more sensitive to elevated temperatures.

5.3. MODULUS OF ELASTICITY

- Modulus of elasticity ranged between 16 and 2.90 GPa, 17.00 and 3.10 GPa, and 19.00 and 5.00 GPa at 28, 91 and 365 days respectively, at elevated temperatures.

- Modulus of elasticity increased with a decrease in the percentage of the fly ash and the water-to-cementitious materials ratio at all ages.

- Modulus of elasticity continued to decrease in a similar way as was observed between 27°C and 200°C, due to the departure of bound water, corresponding to a large mass loss.

- Modulus of elasticity of all SCC mixes was found to increase with increase in age.

5.4. MASS LOSS

- The weight of the concrete specimens reduced significantly as the temperature increased and with the increase in fly ash content. Mass loss of the concrete specimens increased with the increase in temperature.

- Mass loss of all SCC mixes was found to decrease with increase in age.

5.5. POROSITY

- Porosity of the concrete specimens increased with increase in temperature and increase in fly ash content. This increase in porosity is due to expansion of the pore diameters which therefore leads to an increase in permeability. The physical property changes were due to the alteration of the porous network (departure of bound water and decomposition of hydrates) and to the micro cracking. The connectivity of the pores and micro cracks increased, thus increasing the concrete permeability.

- Between 27°C and 200°C, a small loss of strength was observed. The departure of bound water contained in C-S-H gel, and of free water contained in the concrete was also observed. This departure of water leads to a slight modification of porosity.

- Porosity of all SCC mixes was found to decrease with increase in age.

5.6. PERMEABILITY

- An increase in permeability of the tested concretes was measured with increase in temperature.

- The high volume fly ash SCC mixes showed significantly lower chloride ion permeability than control mix. Most of the SCC mixes were assessed as ‘‘low” chloride permeability concretes as per ASTM C1202-94 assessment criteria, with less than 1000 coulombs of total charge passing. From the test results of this research, it was concluded that most concretes become significantly less permeable with increase in time.

- Rapid chloride permeability of all SCC mixes was found to decrease with increase in age.

5.7. STATISTICAL ANALYSIS

In this analysis, correlation between strength and permeability properties was investigated. The value of correlation coefficient ranging from 0.90 to 0.99 was obtained. It means that inclusion of fly ash and foundry sand in the SCC led to increase the chloride penetration resistance, and there is a good correlation between actual and predicted properties. Results obtained from this study suggested that Support Vector Machines modeling approach performed well in predicting the various properties of SCC for the data set used in the present study and the Support Vector Machines based approach can be effectively used to analyze the complex relationship between various parameters used in predicting various properties.

LIST OF PUBLICATIONS FROM PRESENT WORK

- Pathak, N., Siddique, R. Properties of self-compacting concrete containing fly ash subjected to elevated temperatures. Construction and Building Materials, Vol.30, May 2012, pp.274-280. (Elsevier, Impact factor-1.84)

- Pathak, N., Siddique, R. Effect of elevated temperatures on properties of self-compacting concrete containing fly ash and spent foundary sand. Construction and Building Materials, Vol.34, September 2012, pp.512-521. (Elsevier, Impact factor-1.84)

- Pathak, N., Siddique, R. Study of self-compacting concrete using waste foundary sand and high volume fly ash. Proceedings of UKERI Concrete Congress on Innovations in Concrete Construction, NIT Jalandhar, 5-8th March, 2013,pp.209-219

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