EXPERIMENTAL STUDIES OF STRENGTH AND DURABILITY ANALYSIS OF CONCRETE INCORPORATING ULTRAFINE SLAG

Thesis submitted in fulfillment of the requirements for the Degree of

DOCTOR OF PHILOSOPHY

By

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FEB, 2018

DECLARATION BY THE SCHOLAR

I hereby declare that the work reported in the Ph.D. thesis entitled "**Experimental studies of strength and durability analysis of concrete incorporating ultrafine slag**", submitted at **Jaypee University of Information Technology, Waknaghat, India**, is an authentic record of my work carried out under the supervision of **Dr. Ashok Kumar Gupta (Professor and Head)**. I have not submitted this work elsewhere for any other degree or diploma. I am fully responsible for the contents of my Ph.D. Thesis

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SUPERVISOR'S CERTIFICATE

This is to certify that the work reported in the Ph.D. thesis entitled "**Experimental studies of strength and durability analysis of concrete incorporating ultrafine slag**", submitted by **Saurav** at **Jaypee University of Information Technology, Waknaghat, India**, is a bonafide record of his original work carried out under my supervision. This work has not been submitted elsewhere for any other degree or diploma.

Dr. Ashok Kumar Gupta

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Date:

ACKNOWLEDGEMENTS

Firstly I must express my very profound gratitude to the all mighty GOD, my parents and my spouse, for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them.

I would like to thank my Supervisor **Dr. Ashok Kumar Gupta of the (Prof. and Head)** at Jaypee University of Information Technology. The door to Prof. Gupta office was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this paper to be my own work, but steered me in the right the direction whenever he thought I needed it.

I am grateful for the co-operation and constant encouragement from my DPMC members. Their suggestions made my work easy and proficient.

I am also thankful to **Dr. H.P. Sengupta (Prof., Department of Geology, BHU)** and **Dr. P.R. Maiti (Associate Prof., Civil Engineering Department, IITBHU)** for their kind support.

I am also thankful to Mr. Anjani Kumar Shukla (Research scholar IITBHU) and Mr. Pratyush Malviya (Assistant Prof. United College, Allahabad) for his support and help.

I am also very much thankful to lab staff of Civil engineering Department, JUIT for their tired less help throughout my study

ABSTRACT

There have been enormous researches going on the use and utilization of industrial, agricultural and thermoelectric plant residues in the production of concrete. Production of high performance concrete (HPC) plays an important role with different pozzolanic materials like fly ash, condensed silica fume, blast furnace slag, rise husk ash etc. There has been increase in the consumption of mineral admixture by cement and concrete industries. This rate is expected to increase day by day. The presence of mineral admixture in concrete is known to impart significant improvement in workability and durability in concrete. The present study involves the use of mineral admixture 'ultrafine slag" as a cementitous material for cement and to evaluate the threshold limit of replacement of cement. Main aim of this work is to evaluate the flexural strength of High strength concrete by partial replacement of cement (0, 8, 10, 12, and 14%) with ultra-fine slag (Alccofine 1203) for M60 grade of concrete. OPC of 43grade from single source is used in this investigation. The addition of alccofine shows an early strength gaining properties with increase flexural strength of concrete. In the last millennium concrete had demanding requirements both in technical performance wise and economy wise and yet greatly varied in application from architectural masterpieces to the simplest of utilities. This study presents the results of an experimental investigation carried out to evaluate the flexural strength of concrete incorporated with ultrafine slag (alccofine) by studying the effects of different proportions of ultrafine slag in the mix and to find optimum dose of alccofine content in the mix. The concrete specimens were cured on normal moist curing under elevated atmospheric temperature for better heat of hydration. Main aim was confined to find the change of flexural strength of reinforced concrete beams. The flexural strength was determined at 7 ,14 and 28 days and comparisons were made for both plain concrete and reinforced cement concrete (R.C.C). Further experimental investigations were carried out to find the effect of steel fibers embedded in concrete along with ultra fine slag. Different durability analysis of concrete incorporating ultrafine slag was also carried out. The addition of alccofine shows an early strength gaining property. The combination of ordinary Portland cement (OPC) with alccofine was found to increase the compressive strength of concrete on all ages when compared to concrete made with ordinary Portland cement alone and has showed excellent durability characteristic with hydrochloric acid. Alccofine matches the dimensional realms of silica fume as it is finer than GGBS. Silica fume is hard to get hold of as it is imported from outside of India. Based upon the results of this research alccofine - 1203 can be proposed as the substitute for silica fume in partial replacement of concrete. Manufacturing of high performance concrete (HPC), which is majorly used as building material in the major and huge infrastructure projects, is a daunting task. Though the recent advancements have conquered the hurdles of the preparation of high performance concrete, the use of green materials such as Fly Ash and Rice Husk Ash is limited. Apart from the green materials, many conventional and mineral admixtures or micro materials are available in the market, which enhances the quality and performance of concrete such as Metakaoline, Alccofine and Silica Fume etc. The quality of concrete mix is assessed through various mechanical properties like compressive strength, flexural strength and split tensile strength and various durability tests like rapid chloride penetration test (RCPT), sorptivity test, chloride resistance test, accelerated corrosion test and sea water attack test are carried out to analyse the performance of HPC. The objective of this study is to evaluate the structural strength of high performance concrete by utilizing green and pozzolanic material as supplementary cementitious material.

Key words: High performance concrete, alccofine, steel fibers, flexural strength

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LIST OF ABBREVEATION

ASTM	American Society of Testing machines
ACI	American concrete Institute
BIS	Bureau of Indian Standards
CSF	Condensed silica fume
DOE	Departmental of environmental method
FHWA	Federal Highway Administration
FM	Fineness Modulus
FDOT	Florida Department of transport
GGBS	Ground Granulated Blast Furnace slag
HCP	High Performance Concrete
HVFAC	High Volume Fly ash concrete
IS	Indian Standards
MPa	Mega Pascal
OPC	Ordinary Portland Cement
RHA	Rice husk ash
RCP	Rapid chloride penetration
RCC	Reinforced cement concrete
SCMs	Supplementary cementitous materials
SF	Silica fume
SFRC	Steel fiber reinforced concrete
TZ	Transition zone

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CHAPTER 1

INTRODUCTION

1.1 Cement and Concrete

Concrete is a hard material that has cementitious medium within which aggregates are embedded [3,4,135,136,137]. With the development of concrete technology the use of concrete in the construction industries have gained pace. Cement is one of the major constituent of a concrete. Materials other than cement used in the manufacture of concrete are coarse and fine aggregates, admixtures and water. Cement is an extremely important constituent of a concrete as it binds together other materials. The raw materials used for the manufacture of cement consist mainly of lime, silica, alumina and iron oxide [84,136,137,138]. These oxides interact with one another in the kiln at high temperature to form four major complex compounds [137]. Concrete is strong and tough material. Reinforced concrete resists cyclones, earthquakes, blast and fires much better than timber and steel if designed properly [137]. The developments related to the concrete is used extensively in the production of buildings, bridges, harbours, runways, roads, etc. Concrete is an extraordinary and key structural material in the human history. As written by Brunauer and Copeland (1964), Man consumes no material except water in such tremendous quantities. It is no doubt that with the development of human civilization, concrete will continue to be a dominant construction material in the future. However, the development of modern concrete industries also introduce many environmental problems such as pollution, waste dumping, emission of dangerous gases, depletion of natural resources etc. The quality of concrete is determined by its mechanical properties as well as its ability to resist deteriorations. Hardened concrete can be considered to have three distinct phases i.e. the hardened cement paste (HCP) or matrix, the aggregate and the interfacial or transition zone (TZ) between HCP and the aggregate [136]. For optimum performance all the three phases should be considered explicitly. The HCP is about 30% to 40% of the volume of concrete and aggregates constitute 60% to 70% of the volume. Fig.1.1 shows the different constituents of concrete. Concrete also contains air which is also a part of paste phase. Concrete can be classified into various categories depending on its density and strength as recommended by IS 456: 2000 [146]. The aggregates used in making concrete contribute mainly to its density.

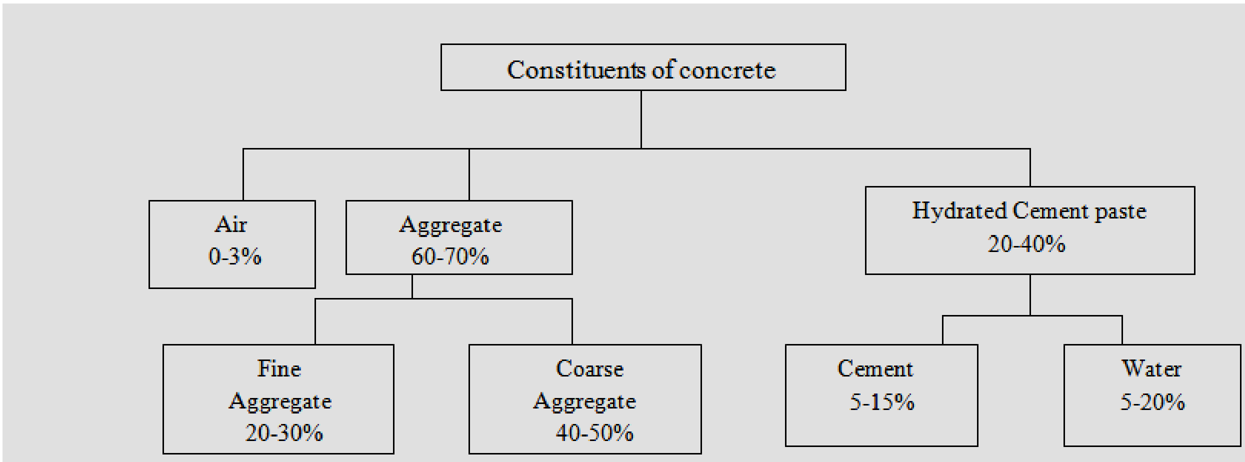


Fig. 1.1: Constituents of Concrete (Source: A.R. Santhakumar [137])

Compressive strength is an important parameter which determines the characteristic of a concrete [4,136,137]. For the construction of high rise buildings and long span bridges the use of high strength concrete (compressive strength 60-100 MPa) were commercially started in the late 70's. This made the concrete technologist to develop high performance concrete (HPC) which not only give high strength but also perform satisfactorily during its service period. The standard code of practice for plain and reinforced concrete IS: 456-2000 [146] has classified concrete on the basis of strength shown in Table 1.1

Table 1.1: Classification of concrete based on strength (Source: IS: 456-2000 [146])

Classification	Maximum Strength (MPa)	Type
Ordinary Concrete	< 20	Low strength
Standard concrete	20-40	Medium strength
High strength Concrete	40-80	High strength

The strength of concrete is the most important characteristic as it has strong relationship with quality. Strength as a parameter is used for controlling as well as evaluating other properties of concrete because of its relationship with durability and dimensional stability [137]. Various parameters that affect the strength of concrete are shown in Fig 1.2. Specimen parameter includes dimension, moisture state and shape of a specimen. Most important factor which affect the strength is the porosity which can result from either the matrix, aggregate, or the interfacial transition zone. Porosity in turn is influenced by w/c ratio, degree of hydration and air content.

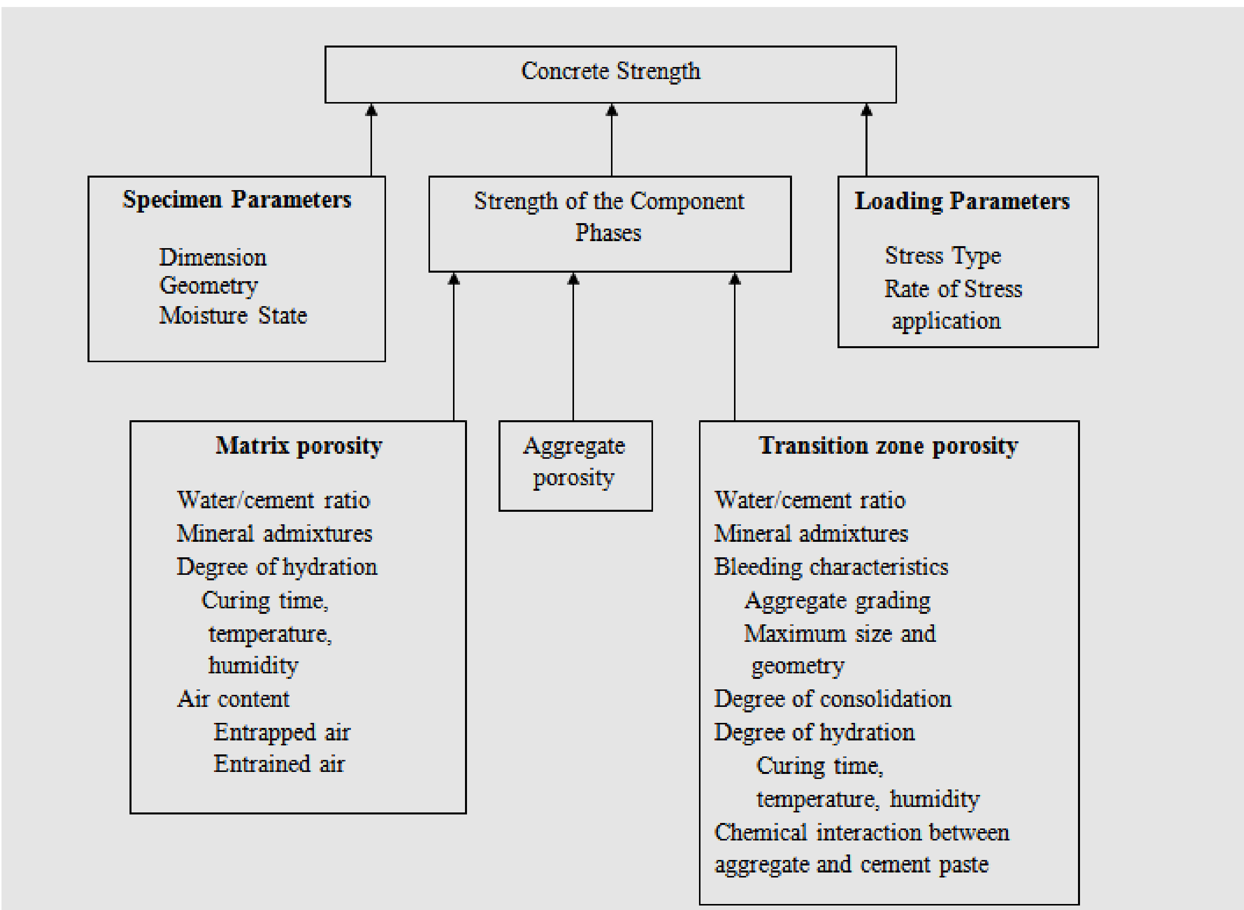


Fig. 1.2: Factors affecting the strength of concrete (Source: A.R. Santhakumar [137])

Small or large all types of construction uses concrete. Though conventional concrete is a widely used construction material, there are other materials that are being increasingly used for special purposes. Depending upon the need one may employed prestressed, self compacting or fiber reinforced concrete. Development in concrete industry can be classified into five major focus areas as shown in the Fig 1.3. Recycling of demolition waste, use of industrial wastes such as fly ash and green building method are developments that have emerged from the need to conserve materials and obtain maximum output from them. Currently a large number of structures are built in very hostile environments to withstand severe and cyclic environmental and weather changes. Therefore durability of concrete is an important parameter in the recent development of concrete. Polymer and co-polymers are added to concrete to impart it new and improved properties in concrete.

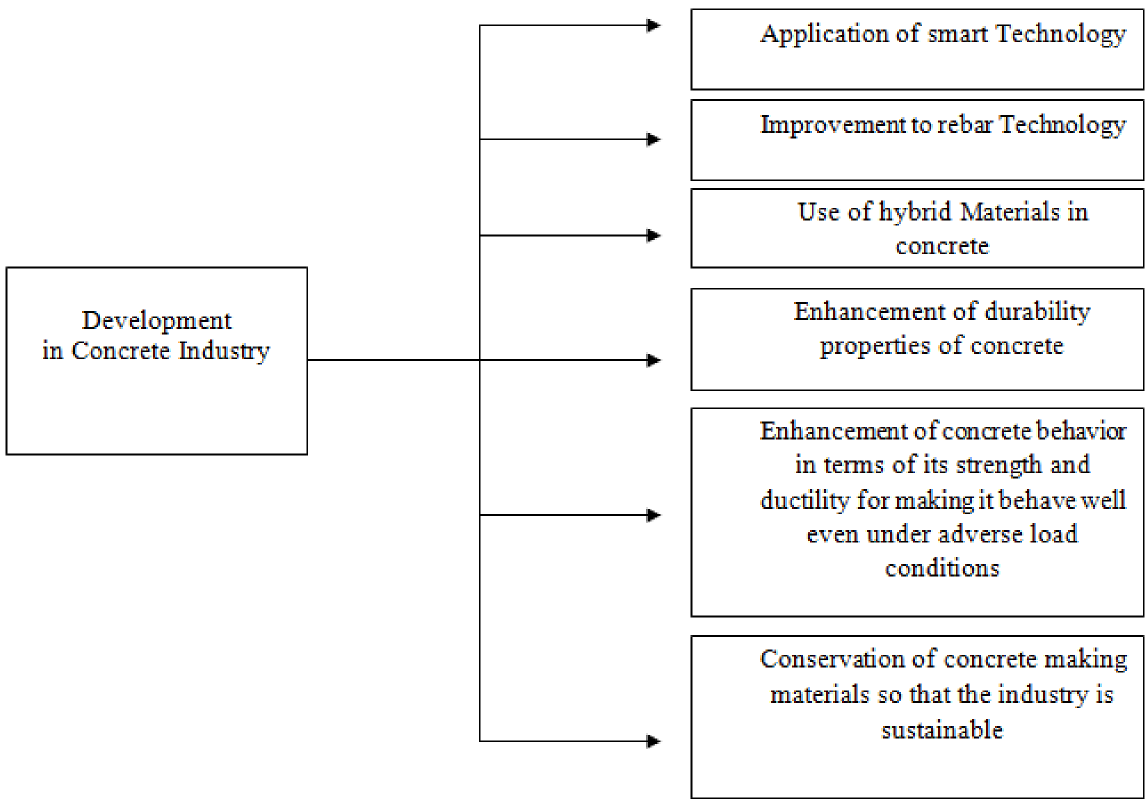


Fig. 1.3: Developments in concrete industry (Source: A.R. Santhakumar [137])

1.2 Environmental concerns

Even though the embodied energy of concrete is among the lowest compared to other engineering materials [72], the concrete industry is still one of the greatest industrial pollutants. The cement industry alone is responsible for approximately 5 to 8% of the world's CO_2 emissions [74]. Other contributing factor is the total amount of materials consumed. A massive use of concrete in the 21st century is inevitable, and an increase in total concrete consumption is projected. In 2015, the main world producers among G20 countries produced approximately 3.5 billion tonne of cement [131], which was used to produce approximately 10 billion m^3 of concrete. The largest portions of the materials used in the concrete industry are still natural and non renewable materials. Therefore, the concrete industry is still very linear, meaning that it uses a huge amount of natural materials and energy and, at the same time, creates significant emissions and waste because at the end of the service life most materials lose their value and are not treated as raw materials. At the same time, the concrete industry has a high potential for a positive shift toward a more sustainable circular production and lower ecological footprint. One strategy is to use waste materials and by-products from other industries as valuable raw materials in the concrete industry. Concrete is an extraordinary and key structural material in the human history. It is no doubt that with the development of human civilization, concrete will continue to be a dominant construction material in the future. However, the development of modern concrete industry also introduces many environmental problems such as pollution, waste dumping, emission of dangerous gases, depletion of natural resources etc. Presently, Portland cement and supplementary cementitious materials are cheapest binders which maintain enhance the performance of concrete. However, out of these binders, production of Portland cement is very energy exhaustive along with CO_2 production. About 1 tonne of CO_2 is produced in manufacturing of each tonne of Portland cement (PC). Thus, cement production accounts for about 5% of total global CO_2 emissions [94]. On the other side of the spectrum, in order to reduce the rate of climate change, a global resolution to an 8% reduction in greenhouse gas emissions by 2010 was set in the Kyoto Protocol in 1997. Developed countries are much aware for its need and a climate change tax was introduced by them. In this connection, UK Government also introduced same kind of tax on 1st April 2001, in order to achieve its target of a 12.5% reduction in greenhouse gas emissions which was the government's domestic goal of a 20% reduction in CO_2 emissions by 2010.

Cement based materials are the most abundant of all manmade materials and are among the most important construction materials and it is most likely that they will continue to have the same importance in 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. However, the development of a sustainable concrete is urgently needed for environmental reasons. It is clear that cement, the key binder ingredient in concrete has a high environmental impact. Presently about 10% of the total anthropogenic CO_2 is due to the cement production solely. Today innovation is leadingly being inspired by nature as a sustainable alternative. The main concern is that concrete is unsustainable due to the painful carbon footprint associated to it. It has been clear that cement, the key binder ingredient in concrete has a high environmental impact. The thumb rule for cement production goes as for every tonne of cement made a tonne of CO_2 is produced. After the Kyoto Protocol, several commitments have been made to reduce this through a series of frameworks-

(i) "Production efficiency,

(ii) Energy efficiency, especially in calcination phase as it accounts for the majority of the Energy consumption; and

(iii) Innovation in CO_2 capture and storage (CCS) technologies.

Presently to reach optimal levels of sustainability, several investigations are being made to reduce the environmental impact of concrete. Such as :

(i) Obtaining optimal strengths

(ii) Replacing Portland clinker with alternative cements; and

(iii) Increasing concrete durability.

Another reason for concrete having such an impactful carbon footprint is due to the huge quantities being used. Hence by obtaining optimal strengths the amount of concrete consumed to do the same job can be reduced. To achieve high strengths of concrete the water-cement ratio can be reduced to 0.16, as complete hydration is not needed if admixtures are added and as such attaining higher strengths than completely hydrated concrete. And in terms of threshold of workability due to lowered water amounts can be achieved using additives called plasticizers. However, the workability of the concrete is the only thing preventing from going below this ratio. Replacing Portland clinker, either partially or entirely, with alternative cements is also being investigated as an approach to tackling concrete's CO_2 emissions. Waste materials, such as slag (from blast furnaces) and fly ash (from coal-fired power stations), are already being used as supplementary cementitious materials (SCMs) and have been for some decades. However, with

50% clinker replacement with fly ash, the early strength drops dramatically. Or even if the clinker were to be replaced entirely by slag, an alkali can be added to activate it. However, Alkali-Silica reactions is a more and more of a problem because as time goes by, it is being discovered that more and more aggregates are reactive. Concrete as a material is liable to crack formation and degradation. It has been observed that if 20% of cement content is reduced the durability improves because it is the cement paste that is most porous. So it is the cement that provides a route by which elements of exposure can go in and out, hence the less cement used the better the concrete. Pores in the material allow corrosive materials such as chlorides and sulphates to penetrate the structure and attack the metal reinforcement – the cause of over 90 percent of problems of reinforced concrete durability. However, ultimate strength of concrete is more important than short term CO_2 savings.

The world's yearly cement production of 1.6 billion tons accounts for about 7% of the global loading of carbon dioxide into the atmosphere. Portland cement, the principal hydraulic cement in use today, is not only one of the most energy-intensive materials of construction but also is responsible for a large amount of greenhouse gases. Producing a ton of Portland cement requires about 4 GJ energy, and Portland cement clinker manufacture releases approximately 1 ton of carbon dioxide into the atmosphere. Furthermore, mining large quantities of raw materials such as limestone and clay, and fuel such as coal, often results in extensive deforestation and top-soil loss. Ordinary concrete typically contains about 12% cement and 80% aggregate by mass. This means that globally, for concrete making, we are consuming sand, gravel, and crushed rock at the rate of 10 to 11 billion tons every year. The mining, processing, and transport operations involving such large quantities of aggregate consume considerable amounts of energy, and adversely affect the ecology of forested area and riverbeds. The concrete industry also uses large amounts of fresh water; the mixing water requirement alone is approximately 1 trillion liter every year. Reliable estimates aren't available, but large quantities of fresh water are being used as wash-water by the ready mixed concrete industry and for curing concrete. Besides the three primary components, that is, cement, aggregates, and water, numerous chemical and mineral admixtures are incorporated into concrete mixtures. They too represent huge inputs of energy and materials into the final product. What about batching, mixing, transport, placement, consolidation, and finishing of concrete? All these operations are energy-intensive. Fossil fuels are the primary source of energy today, and the public is seriously debating the environmental costs associated with the use of fossil fuels.

The environmental impact of the concrete industry can be reduced through resource productivity by conserving materials and energy for concrete-making and by improving the durability of concrete products. The task is most challenging but can be accomplished if pursued diligently. To examine how the concrete industry will have to restructure when the business paradigm shifts its emphasis from a culture of acceleration to a culture of resource productivity, I have subdivided the environmental impacts of modern concrete construction practice into several categories that are discussed separately as follows

Cement conservation is the first step in reducing the energy consumption and greenhouse-gas emissions. Resource productivity consideration will require us to minimize portland cement use while meeting the future demands for more concrete. This must be the top priority for a viable concrete industry. Except for blended Portland cements containing mineral additions, no other hydraulic cements seem to satisfy the setting, hardening, and durability characteristics of portland cement-based products. Although there is steady growth in the use of portland cement blends containing cementitious or pozzolanic by-products, such as ground granulated blast-furnace slag and fly ash, vast quantities of these by-products still end up either in low-value applications such as landfills and road sub bases, or are simply disposed by ponding and stockpiling. The world cement consumption rate is expected to reach about 550 million tonne by the year 2020, and there are adequate supplies of pozzolanic and cementitious by-products that can be used as cement substitutes, thus eliminating the need for the production of more portland cement clinker Interestingly, as will be discussed below, Portland cement blends containing 50% or more granulated blast furnace slag or fly ash can yield much more durable concrete products than neat portland cement, and this would also contribute to natural resource conservation. The slower setting and hardening rate of concrete containing a high-volume of a mineral admixture can be compensated for, to some extent, by reducing the water cementitious materials ratio with the help of a superplasticizer. Nevertheless, for most structural applications, somewhat slower construction schedules ought to be acceptable when resource maximization, not labor productivity, becomes the most important industry goal.

1.3 High Performance Concrete

It is important to note the high-strength and high performance concrete are not synonymous. Concrete is defined as high-strength concrete solely on the basis of its compressive strength measured at a given age. In the 1970's, any concrete mixtures that showed 40 MPa or more compressive strength at 28-days were designed as high-strength concrete. Later, 60-100 MPa concrete mixtures were commercially developed and used in the construction of high-rise buildings and long-span bridges in many parts of the world. The definition of high-performance concrete is more controversial. The term, high performance concrete (HPC) was used for the first time for concrete mixtures possessing high workability, high durability and high ultimate strength. ACI defined high-performance concrete as a concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practice. It is mistaken to bestow that supplementary cementitious materials were used in the concrete only because of their availability and just for economic considerations. These materials present some unique desirable properties which cannot be met by using OPC only [135]. For producing high performance concrete (HPC), it is well recognized that the use of supplementary cementitious materials (SCMs), such as Silica Fume (SF), GGBS and Fly Ash (FA) are necessary. The concept of HPC has definitely evolved with time. Initially it was equated to high strength concrete (HSC), which certainly has some merit, but it does not show a complete and true picture. There is a need to consider other properties of the concrete as well which sometimes, may even take priority over the strength criterion. Various authors proposed different definitions for HPC. High Performance Concrete is a concrete which made with appropriate materials, combined according to a selected mix design; properly mixed, transported, placed, consolidated and cured so that the resulting concrete will give an excellent performance in the structure in which it is placed, in the environment to which it is exposed and with the loads to which it will be subjected for its design. Thus, HPC is directly related to durable concretes.

From the general principles behind the design of high-strength concrete mixtures, it is apparent that high strengths are made possible by reducing porosity, In homogeneity, and microcracks in the hydrated cement paste and the transition zone. The utilization of fine pozzolanic materials in high strength concrete leads to a reduction of the size of the crystalline compounds, particularly, calcium hydroxide [137]. Consequently, there is a reduction of the thickness of the interfacial transition zone in high-strength concrete. The densification of the interfacial transition zone allows for efficient load transfer between the cement mortar and the coarse aggregate, contributing to the strength of the concrete. For very high-strength concrete where the matrix is extremely dense, a weak aggregate may become the weak link in concrete strength. Almost any ASTM portland cement type can be used to obtain concrete with adequate rheology and with compressive strength upto 60 MPa. In order to obtain higher strength mixtures while maintaining good workability, it is necessary to study carefully the cement composition and finenesses and its compatibility with the chemical admixtures. Experience has shown that low-C_3A cements generally produce concrete with improved rheology. In high-strength concrete, the aggregate plays an important role on the strength of concrete. The low-water to cement ratio used in high strength concrete causes densification in both the matrix and interfacial transition zone, and the aggregate may become the weak link in the development of the mechanical strength. Extreme care is necessary, therefore, in the selection of aggregate to be used in very high strength concrete. The particle size distribution of fine aggregate that meets the ASTM specifications is adequate for high strength concrete mixtures. If possible, using of fine aggregates with higher fineness modulus is advisable because high-strength concrete mixtures already have large amounts of small particles of cement and pozzolan, therefore fine particles of aggregate will not improve the workability of the mix. The use of coarser fine aggregates requires less water to obtain the same workability; and during the mixing process, the coarser fine aggregates will generate higher shearing stresses that can help prevent flocculation of the cement paste. The higher the targeted compressive strength, the smaller the maximum size of coarse aggregate. Up to 70 MPa compressive strength can be produced with a good coarse aggregate of a maximum size ranging from 20 to 28 mm. To produce 100 MPa compressive strength aggregate with a maximum size of 10 to 20 mm should be used. To date, concretes with compressive strengths of over 125 MPa have been produced, with 10 to 14 mm maximum size coarse aggregate. Using supplementary cementitious materials, such as blast furnace slag, fly ash and natural pozzolans, not only reduces the production cost of concrete, but also addresses the slump loss problem. The optimum substitution level is often determined by the loss in 12hr or 24-hr strength that is considered acceptable, given climatic conditions or the minimum strength required. While silica fume is usually not really necessary for compressive strengths under 70 MPa, most concrete mixtures contain it when higher strengths are specified. The American concrete committee (ACI 1993) includes the following six criteria for material selections, mixing, placing and curing procedures for concrete.

i) Ease of placement

ii) Long term mechanical properties

iii) Early age strength

iv) Toughness

v) Life of severe environment

vi) Volume stability

Though the freezing thawing resistance is indicated as a measure of high performance concrete, the durability with respect to chloride ingress has been a very important parameter for marine exposed structures especially in India. At present there is virtually no structure in coastal regions in India that has achieved its designed life span without repairs. The following eight parameters are used by Federal Highway Administration (FHWA) in USA to grade HPC

i) Compressive strength

ii) Modulus of elasticity

iii) Creep

iv) Shrinkage

v) Freeze- Thaw resistance

vi) Abrasion

vii) Chloride permeability

viii) Scaling Resistance

“Better durability performance can be achieved by using high strength, low w/c ratio concrete. Though in this approach the design is based on strength and durability it is desirable that the high performance is addressed directly by optimizing critical parameters such as the particle size of the required materials. Two approaches to achieve durability through different techniques are shown in Fig 1.4”

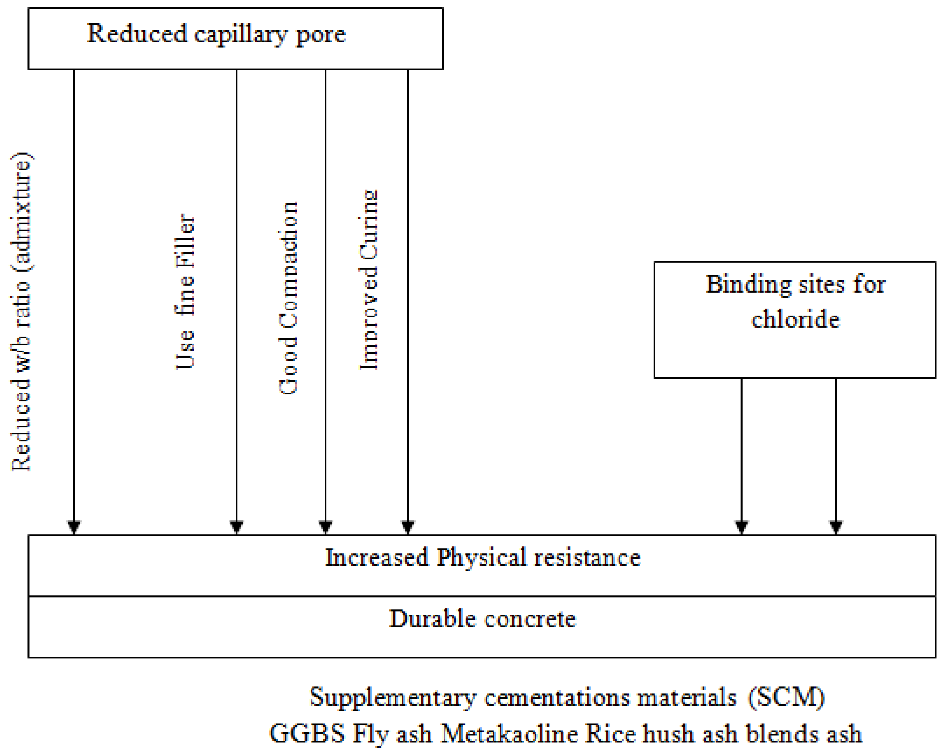


Fig. 1.4: Techniques of production of HPC (Source: A.R. Santhakumar [137])

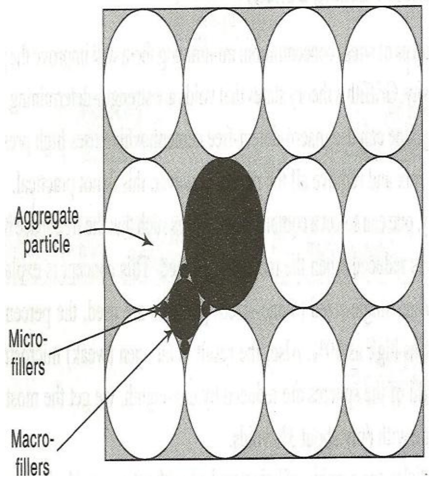
1.4 Need for this Research

Concrete is a commonly used construction material formed by mixing cement (binder), aggregate, water and admixtures in different ratios depending on the function and strengths required. The oldest known surviving concrete is found in the former Yugoslavia and is thought to have been laid in 5600 BC using red lime as the cement. The first major concrete users were the Egyptians around 2500 BC; Egyptians used mud mixed with straw to bind dried bricks. Later the Romans since 300 BC made many developments in concrete technology including the use slaked lime a volcanic ash called pozzolana; animal fat, milk, and blood were used as admixtures; and even built the Pantheon in 200 AD with lightweight aggregates in the roof. Even today this 43.3 m diameter dome is still the world's largest non-reinforced concrete dome. After 400 AD the art of Concrete was lost with the fall of the Roman Empire. It was only in 1824 that modern concrete was developed by Joseph Aspdin. He patented what he called Portland cement which till date remains as the key ingredient in concrete. The work presented here aims at increasing the knowledge on the effect of ultrafine particles in concrete. In the context of this work, ultrafine particles are particles with a grain size finer than cement. These particles may be inert and improve the packing density of the fines in concrete, or they may be pozzolanic and react with hydration products of the cement. The hypothesis of this work is that substantial amounts of cement can be replaced by suitable very fine grained materials without affecting mechanical properties or durability negatively. Cement itself is considered as a fraction of the complete particle mix that builds up the concrete. By application of suitable particle packing models to the entire concrete mix, the particle size distribution (PSD) of the entire mix can be adjusted in order to achieve mobility in the fresh state and adequate properties when hardened. Due to the fact that the ingredients of a concrete mix are particles with continuous size distributions, a model should be based on packing of continuous size distributions. A modification of concrete mixes with ultrafine particles affects the fresh and hardened properties of the concrete. The workability, hardening, mechanical properties and durability may be influenced indifferent ways. Reactive particles like silica fume may have different effects compared to inert particles. Synergy effects from combination of reactive and inert particles can be expected. Therefore, this investigation is done in several steps. First, a literature review on particle packing, cement hydration, load independent deformation and mechanical strength of concrete is done. These issues are considered to be of primary interest for the subject of the work. Particle packing is directly related to the introduction of other fine particles than cement into concrete. It may be used to provide knowledge on how to utilize ultrafine particles in the best way. The hydration of cement is known to be influenced by the presence of other particles. Load-independent deformations of concrete are known to be influenced by the content of fines, the cement content and reactive additives. The mechanical strength of concrete is strongly related to the porosity which in turn is influenced by hydration, particle packing and additives. The experimental section of this work concentrates on concrete experiments. In addition, the influence of the ultrafines on the hydration is examined on paste samples with the help of isothermal calorimetry. In the concrete experiments, different measures are taken in order to isolate the influence of inert and reactive ultrafine particles. First, different inert ultrafine particles are used to replace cement at constant water content and variable water content. Then, mix compositions are optimised towards low cement content with the help of inert ultrafines. The effect of high contents of reactive ultrafine particles on concrete properties is tested, also in combination with inert ultrafines. Then, concrete compositions are optimized towards low binder content. The effect of different ultrafine particles on concrete properties is quantified by tests on compressive strength and calculation of shrinkage, and characterization of the microstructure by microscopy, mercury intrusion Porosimetry (MIP) and capillary suction as well as test of frost resistance. The results of this work shall contribute to an increased understanding of the effects of different very fine particles on concrete properties. Recommendations are given on how to include ultrafine particles in mix design. This work does not concentrate on concrete mixes that comply with recent concrete standards in which concrete properties are mainly related to the water-cement ratio. The results of this work are expected to be more useful for performance based design of concrete or in special applications. Further, it is not primarily the fresh concrete properties that are investigated. Workability of fresh concrete is of course an important issue but within the limitations of this work, super plasticizers were used to achieve workable mixes when necessary. The fine aggregate (0-8 mm) used in this work is of natural origin with well rounded particle shape. Crushed fine aggregate is not tested but it is likely that some adjustments are necessary when using this type of fine aggregate. There are other properties of hardened concrete, e.g. creep, E-modulus, chloride diffusion and carbonation which can be influenced by ultrafine particles but it is not possible to test all of them within this work. Neither is cost efficiency of the resulting mixes considered, at present time the cost of the used ultrafines may exceed the cost of the replaced cement. Additionally, many concrete plants may have problems handling ultrafines. However, the findings of this work can contribute to increased use of ultrafines in concrete and intensified research on suitable byproducts. In that way, cost efficiency can be achieved in the future.

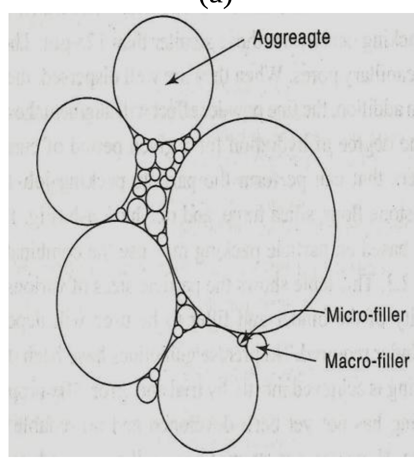
1.4.1 Particle Packing Theory

Particle packing is fundamental to concrete. The better the packing of the particle system, the less binder is required in the concrete. The problem with concrete is, however, that concrete must flow and be compactable in the fresh state which stands in conflict with optimal packing. Introduction of large amounts of fine particles, in size of cement and below, into a concrete mix can solve this problem. Then, the particle size distribution of the whole mix composition, including cement, pozzolanas and/or fillers, should be taken into account when calculating the packing density. Particle packing is an important issue not only for concrete materials. Ceramics, geotechnology, food processing industry and others do benefit from densely packed systems. The first investigations concerning particle packing were done more than 200years ago. One of the most important properties of a particle system is its packing density; the volume percentage of solids for each volume unit. Looking into a certain system, the particle packing of this system is a function of particle size distribution, particle shape, and particle surface, ratio between system size and maximum grain size and presence of liquids, if any. In order to understand the existing theories and models for systems with multiple grain sizes, one ought to look into systems with only one grain size first. Systems consisting of only one grain size are called mono-dispersions; they are useful for modelling but rarely seen in reality. If perfect spherical particles of only one size are assumed, the packing density of the system depends on which structure is formed by the spheres. Practically one can select a combination of sizes such that the free space between the particles is reduced when the material is mixed. Fig. 1.5 explains the concept behind particle packing. Cubical particles are capable of being packed without any voids, but this is not possible for wet concrete in a colloidal suspension. Generally the key particle sizes affecting packing density are those smaller than 125 μm. These particles are smaller than the capillary pores. When they are well dispersed they will block the capillary pores. In addition the fine powder effect will augment the cement reaction. This increases the degree of hydration for a given period of curing. There are number of binders that can perform the particle packing job viz fly ash, GGBS, metakaoline, lime stone flour, silica fume and rice husk ash.

Let us consider a concrete mix composed of a single-sized aggregate and cement paste only. In order to fill up all the gaps between the aggregate particles so as to drive away the air voids in the concrete mix, the volume of cement paste must be larger than the volume of gaps within the aggregate skeleton. If, instead of a single-sized aggregate, a multi-sized aggregate is used, the smaller size aggregate particles would fill up the gaps between the larger size aggregate particles, leading to a smaller volume of gaps within the aggregate skeleton. This has two implications. Firstly, with a multi-sized aggregate used, the volume of cement paste needed to fill up the gaps within the aggregate skeleton would be reduced. Secondly, if the volume of cement paste is kept the same, the use of a multi-sized aggregate



(a)



(b)

Fig. 1.5: (a) Concept of particle packing, (b) effect of fillers between aggregate particles (Source: A.R. Santhakumar [137])

would increase the volume of the excess paste (the portion of paste in excess of that needed to fill up the gaps within the aggregate skeleton), which disperses the aggregate particles, provides a coating of paste for each aggregate particle and renders workability to the concrete mix. Hence, the size distribution, or grading, of the aggregate has an important bearing on the paste demand and the workability of a concrete mix. That the grading of the aggregate can have a great influence on the performance of the concrete mix is actually well known long time ago. It is only that many parameters (the various size fractions of the aggregate) are needed to describe the grading and the effects of the various parameters are often blurred by the interaction between the various parameters involved. Nevertheless, it is nowadays very clear that the single most important parameter influencing the performance of concrete is the packing density of the aggregate. The packing density of a given aggregate or a given lump of solid particles is the ratio of the volume of solids to the bulk volume of the solid particles. Since the bulk volume is equal to the volume of solids plus the volume of voids, a higher packing density means a smaller volume of voids to be filled and vice versa. The single-sized aggregate can be packed together to occupy only limited space, i.e. can achieve only a relatively low packing density. The multi-sized aggregate can be packed together much more effectively to achieve a much higher packing density. With the paste volume fixed, the increase in packing density of the aggregate could be employed to increase the workability of the concrete at the same water/cementitious ratio or increase the strength of the concrete by reducing the water/cementitious ratio while maintaining the same workability. Apart from increasing the excess paste at a given paste volume to improve the workability and/or strength of the concrete, the increase in packing density of the aggregate could also be employed to improve the dimensional stability of the concrete. In a concrete mix, it is the cement paste that generates heat of hydration causing thermal expansion/contraction during the early age and shrinks when subjected to drying in the longer term. Hence, the larger the paste volume is, the larger would be the changes in dimension of the hardened concrete due to early thermal expansion or contraction and long term drying shrinkage. The heat of hydration and drying shrinkage of the concrete are dependent also on the water/cementitious ratio, both being larger at higher water/cementitious ratio. The reduction in paste demand due to a higher packing density of the aggregate would for the same workability allow the use of a smaller paste volume at a fixed water/cementitious ratio or a lower water/cementitious ratio at the same paste volume, either of which would significantly improve the dimensional stability of the concrete. The concept of packing density can be extended to apply also to the cementitious materials, which may include cement and other supplementary cementitious materials, such as pulverized fuel ash (PFA), ground granulated blast-furnace slag (GGBS) and condensed silica fume (CSF) etc. Drawing analogy to the previous case of packing aggregate particles, the packing density of the cementitious materials should have similar effect on the water demand and the flow ability of the cement paste. The different types of cementitious materials are generally of different sizes. By mixing appropriate proportions of different cementitious materials together, the medium size particles would fill up the gaps between the larger size particles and the smaller size particles would fill up the gaps between the medium size particles and so forth. Hence, blending cementitious materials of different sizes together could increase the packing density of the cementitious materials and reduce the water demand. Recent research findings have provided positive support to the above theory. Further in the presence of a super plasticizer, the addition of GGBS, which has a higher fineness than cement, has shown improvement in the fluidity of cement paste through its filling effect. Research shows that during the development of high strength self-consolidating concrete that at a ratio lower than 0.28, the addition of CSF, which has a mean particle size of about 0.1 μm, could substantially increase the workability of the concrete mix, despite large increase in surface area of the cementitious materials. Such increase in workability may be explained by the ultra-high fineness of the CSF, which allowed the CSF particles to fill up the gaps between the cement grains thereby freeing more mixing water to lubricate the concrete mix. Study has showed that blending cement with an ultra-fine PFA, which has a mean particle size of about 3 μm, would reduce the water demand of the cementitious system, due most probably to the increase in packing density after adding the ultra-fine PFA. More recently, many authors have directly measured the packing density of blended cementitious materials and confirmed that the addition of CSF could significantly increase the packing density of the cementitious system. They have also demonstrated that at a water/cementitious ratio of 0.2, the increase in flow ability of the cement paste after addition of CSF could be quite dramatic. The packing density of the cementitious materials has great impact on the strength of the concrete produced. First of all, the reduction in water demand due to a higher packing density would allow the use of a lower water/cementitious ratio for achieving higher strength. Secondly, better packing would reduce the permeability of the bulk of cementitious materials and thus bleeding of the fresh cement paste. Thirdly, better packing would reduce the porosity of the transition zone by filling up the voids formed as a result of the wall effect of the aggregate with very fine particles. Both the reduced bleeding of the cement paste and the reduced porosity of the transition zone would substantially improve the quality of the transition zone, which, as the weakest link in concrete, has dominant effect on the strength of concrete. This phenomenon is often manifested by having trans granular failure (failure with fracture planes cutting through the aggregate particles) instead of transition zone failure (deboning failure at the transition zone) in high strength concrete made with densely packed cementitious materials containing CSF. More recent research has demonstrated that due to improved packing, blending cement with a rice husk ash can lead to an increase in strength of the concrete and that because of the more significant improvement in packing density, the increase in strength is larger when the cement is 12 gap-graded. Apart from strength, an increase in packing density of the cementitious materials would also improve the overall performance of the concrete. For instance, at the same water/cementitious ratio, the flow ability of the cement paste and the workability of the concrete mix would be improved. Furthermore, with increased packing density, the cement paste would be more cohesive and the concrete mix would be less likely to segregate during placing. With the water demand reduced, the water content of the concrete mix might also be adjusted downwards to limit the drying shrinkage and improve the dimensional stability of the concrete. Lastly, with better packing, the permeability of the bulk of cementitious materials, both in fresh state and in hardened state, would be dramatically reduced leading to a much higher durability of the concrete. Summing up the above discussions, many authors are of the view that the packing density of the solid particles in the concrete mix is the key concept in the design of HPC mixes. Both the packing of the aggregate and the packing of the cementitious materials need to be considered. In fact, it is the grading or packing of the whole range of particles from the coarse aggregate to fine aggregate, to cement grains, and to fine and ultra-fine cementitious materials that determines the overall performance of a concrete mix.

1.5 Application of Ultrafine slag

As a result of growth in advance technology in concrete, high performance concrete (HPC) has gained worldwide popularity in the construction industry since 1990. In practice, high performance concrete, are generally characterized by high cement factors and very low W/C ratios. Such concrete suffer from two major weaknesses. It is extremely difficult to obtained proper workability, and to retain the workability for sufficiently long period of time with such concrete mixes. High dosage of high range water reducing agents (HRWR) then become a necessity, and resulting cohesive and thixotropic, sticky mixes are equally difficult to place and compact fully and efficiently. These problem indicate that there is probably a critical limit for the water content below which high HRWR dosage become not only essential but also unhelpful and undesirable, and often even harmful from a durability point of view. In high performance concrete applications, Silica Fume is generally proposed as the appropriate cement extender where high strength, low permeability are the prime requirements. Though silica fume is known to improve durability, its addition in concrete is often negated by the increase water and/or admixture dosage required to improve the workability and handling properties of the fresh concrete. Ultra fine slag Alccofine 1203 is a specially processed product based on slag of high glass content with high reactivity obtained through the process of controlled granulation. The raw materials are composed primary of low calcium silicates. The processing with other select ingredients results in controlled particle size distribution (PSD). The computed blain value based on PSD is around 12000cm^2/gm and is truly ultra fine. Due to its unique chemistry and ultra fine particle size, Alccofine 1203 provides reduced water demand for a given workability, even up to 70% replacement level as per requirement. The quality and impermeability of high performance concrete are determined by the amount of water utilized in mix design i.e. the water/binder ratio. High range water reducers (HRWR) are extensively used to ensure placement with low water contents. The presence of extremely fine particles decreases the permeability and improves durability. In order to measure the effect of Alccofine 1203 on the workability, water requirement and HRWR dosages and based on past research concrete mixes were prepared.

CHAPTER 2
LITERATURE REVIEW

2.1 General

A brief review of literature about the influence of mineral admixtures (fly ash, GGBS and silica fume), chemical admixtures on the fresh concrete, and their effect on strength and durability behaviour of concrete is reported and discussed in this chapter. Literature regarding mix proportioning of HPC is also discussed. This chapter discusses the past research conducted by various researchers to study the applications & different methodology used in understanding of tests and findings due to the above said along with behavior of Alccofine 1203 as an admixture to concrete. This chapter gives a comprehensive review of the findings along with directions for future explorations.

2.2 Fly Ash used as partial replacement for cement

Fly ash is a waste by-product from thermal power plants that use coal as fuel. It's calculable that concerning a hundred twenty five million tones of ash is being made from completely different thermal power plants in Asian country [7]. In spite of continuous efforts created and incentives offered by the govt., hardly only a few share of the fly ash is being employed for profitable functions like brick creating, cement manufacture, soil stabilization and fill material. The two general classes of fly ash can be defined: low-calcium fly ash (LCFA: ASTM Class F) produced by burning anthracite or bituminous coal; and high calcium fly ash (HCFA: ASTM Class C) produced by burning lignite or sub bituminous [135,136,104]. At early stages of ageing, the strength of concrete containing a high volume of fly ash as a partial cement replacement is much lower than that of control concrete, due to the slow pozzolanic reactivity of fly ash coal. There are two ways in which the ash is used: one way is to intergrind bound proportion of ash with cement clinker at the manufacturing plant to supply Portland pozzolana cement (PPC) and the second way is to use the ash as a mineral admixture at the time of preparing concrete directly at the site. The latter technique offers freedom and adaptability to the user concerning the share addition of ash. There are more than seventy five thermal power plants in India. The quality of ash generated in different plants varies from each other to an outsized extent and thus they're not in an exceedingly able to use condition. To create ash of consistent quality, create it appropriate to be used in concrete, the ash is needed to be any processed. Such processing arrangements are not available in India. The standard of ash is ruled by IS: 3812-1: 2003 [150]. High fineness, low carbon content, sensible reactivity area unit the essence of excellent ash. Since ash is made by fast cooling and activity of liquified ash, an outsized portion of parts comprising ash particles area unit in amorphous state. The amorphous characteristics greatly contribute to the pozzolanic reaction between cement and ash. One amongst the necessary characteristics of ash is that the spherical sort of the particles. This form of particle improves the flow ability and reduces the water demand. The suitableness of ash can is determined by finding the dry density of absolutely compacted sample. ASTM classifies ash into 2 categories. Category F: ash unremarkably made by burning anthracite coal or soft coal, sometimes has not up to 55% CaO. Category F ash has pozzolanic properties solely. Category C: ash unremarkably made by burning humate or sub-bituminous coal. Some category C ash might have CaO content in more than 10%. Additionally to pozzolanic properties, category C ash additionally possesses cementitious properties.

G. Venkatesan et al [19] studied the flexural behavior of RCC beam using high volume fly ash concrete confinement in compression zone. For the study M40 grade of concrete was taken with fly ash replaced as 0%, 50%, 55% and 60 %. They compared the results of modulus of rapture for both the cases. On comparison it was noted that for both conventional and high volume fly ash concrete, 0.375d spacing of stirrups gives better result for confinements and regarding economy about 50% savings in cement and 13% in steel is saved. The value of modulus of rupture (extreme fibre stress in bending) depends on the dimension of the beam and manner of loading. Concrete cubes were casted for a size of 15cm x 15cm x15cm for both conventional concrete and high volume fly ash concrete. Compressive strength between them was analysed.

Table 2.1: Compressive strength for conventional concrete (Source: G. Venkatesan et al [19])

Compressive Strength for conventional Concrete			
Cube Mark	Curing period	Ultimate load (KN)	Comp. stgth(N/mm^2)
A	7 days	74.50	32.48
A	7 days	75.50	32.92
A	7 days	77.00	33.57
A	28 days	130.00	56.68
A	28 days	126.50	55.15
A	28 days	125.00	54.50

Table 2.2: Compressive strength for high volume fly ash concrete (Source: G. Venkatesan et al [19])

Compressive Strength for High Volume Fly Ash Concrete			
Cube Mark	Curing period	Ultimate load (kN)	Comp. strength (N/mm^2)
B	7 days	72.50	31.61
B	7 days	71.50	31.17
B	7 days	73.00	31.83
B	28 days	109.00	47.52
B	28 days	109.00	47.52
B	28 days	111.50	48.61

For the determination of flexural strength beams were casted using conventional concrete and high volume fly ash concrete (HVFAC). For the test 2 Nos of 12mm dia rods were taken as main reinforcement and 2 Nos of 12mm dia rods as hanger rods were used. 8mm dia rods are used as stirrups. Stirrups were arranged in such a manner so that spacing of 0.375d and 0.75d for full effective depth and half the effective depth to the required beams." Table. 2.1 shows the compressive strength of conventional concrete. At 28 days the compressive strength of HVFAC is lower than conventional concrete (Table. 2.2).

Table 2.3: Flexural behavior of conventional concrete (Source: G. Venkatesan et al [19])

Flexural Behaviour for conventional Concrete (0.75d)						
No of days	Depth of stirrup	Load at failure (kg)	Distance (in cm)			Modulus of rupture (fb) MPa
			a	b	d	
7	Full depth	4600.00	19.0	15.0	13.0	103.44
7	Half depth	4300.00	17.2	15.0	12.2	99.38
28	Full depth	6600.00	19.5	15.0	12.5	164.74
28	Half depth	6200.00	18.0	15.0	12.1	152.45

Table 2.4: Flexural behavior of HVFA concrete (Source: G. Venkatesan et al [19])

Flexural Behaviour for High volume fly ash Concrete (0.75d)						
No of days	Depth of stirrup	Load at failure (kg)	Distance (in cm)			Modulus of rupture (f_b)
			a	b	d	
7	Full depth	4000.00	18.4	15.0	12.7	91.26
7	Half depth	3700.00	18.4	15.0	12.5	88.56
28	Full depth	4500.00	19.1	15.0	12.7	106.58
28	Half depth	4200.00	18.9	15.0	12.6	100.00

It was found that for both 0.75d and 0.375d spacing of full depth stirrups, the flexural strength for high volume fly ash concrete was lower than the conventional concrete as shown in Table. 2.4. Similarly, for half depth stirrups also there was reduction in flexural strength in high volume fly ash concrete. This is due to alternate half depth stirrups. But for 28 days curing, the flexural strength is increased to certain extent than 7 days strength. It is noted that the high volume fly ash concrete gain strength at later stages. It was found that the flexural strength of concrete for 0.75d and 0.375d spacing of half depth stirrups to 7 and 28 days curing period is more than the high volume fly ash concrete. This was due to 50% replacement of cement with fly ash. However, the flexural strength of beams in high volume fly ash concrete increased at later stages. It was found that the value of flexural strength to half depth stirrups came lower than full depth stirrups spacing due to alternate half depth stirrups spacing. Comparison of flexural strength of conventional concrete and HVFAC is given in Table. 2.3 and Table. 2.4

S. J. Choi et al [25] investigated the effects of the fineness and replacement ratio of fly ash on temperature rise and setting time and compressive, tensile and flexural strength of mortar mixtures. Fly ash with Blaine fineness 4125 cm^2/gm, 6686 cm^2/gm and 9632 cm^2/gm were used to replacement ratios of 0,15,30,45 and 60%. Table 2.5 shows the different mixture proportions of mortar used for a constant w/b ratio of 0.4

Styrofoam boxes of cubical size 220mm and thickness 100mm were used to measure the heat of hydration. Temperature change was measured with help of a thermocouple placed at middle point of insulator Styrofoam box as shown in the Fig 2.1. It was found that after using fly ash

Table 2.5: Mixture proportion of mortar (Source: Se Jin choi et al [25])

Mixture No.	Cement (kg/m^3)	Fly ash (%)	Fly ash (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	w/b
Control	534	0	0	214	1,603	0.4
R15	454	15	80	214	1,603	0.4
R30	374	30	160	214	1,603	0.4
R45	294	45	240	214	1,603	0.4
R60	214	60	320	214	1,603	0.4

“

Fig. 2.1: Test of measuring temperature change of mortars (Source: S. J. Choi et al [25])

as replacement of cement temperature of mortar decreases. The R60 mortar showed the lowest peak temperature at about 34ºC when compared to controlled concrete as shown in Fig. 2.2. There was reduction in temperature of mortar regardless of fineness of fly ash.

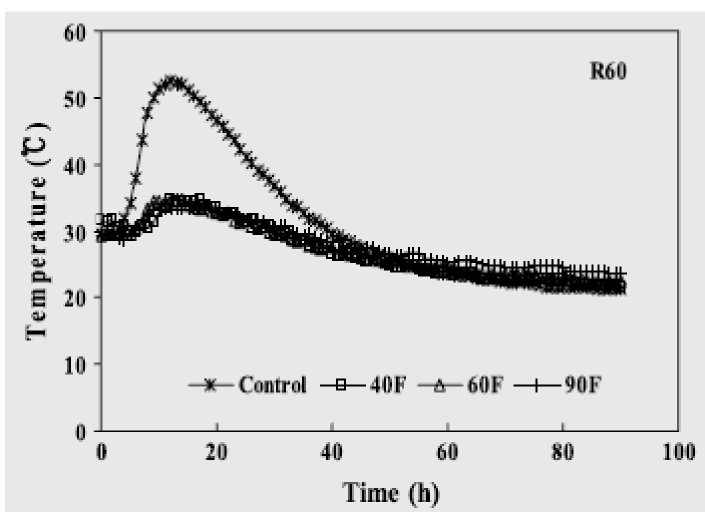


Fig. 2.2: Variation of temperature rise with fly ash (Source: Se Jin choi et al [25])

It was also observed that with increase in fly ash percentage higher reduction in temperature was observed. Compressive strength of mortar mixes were determined after 3,7,14,28 and 56 days of curing. Fig. 2.3 shows the variation of compressive strength ratio with different fly ash percentages at 28 days of curing. It can be observed that with increase in fineness of fly ash

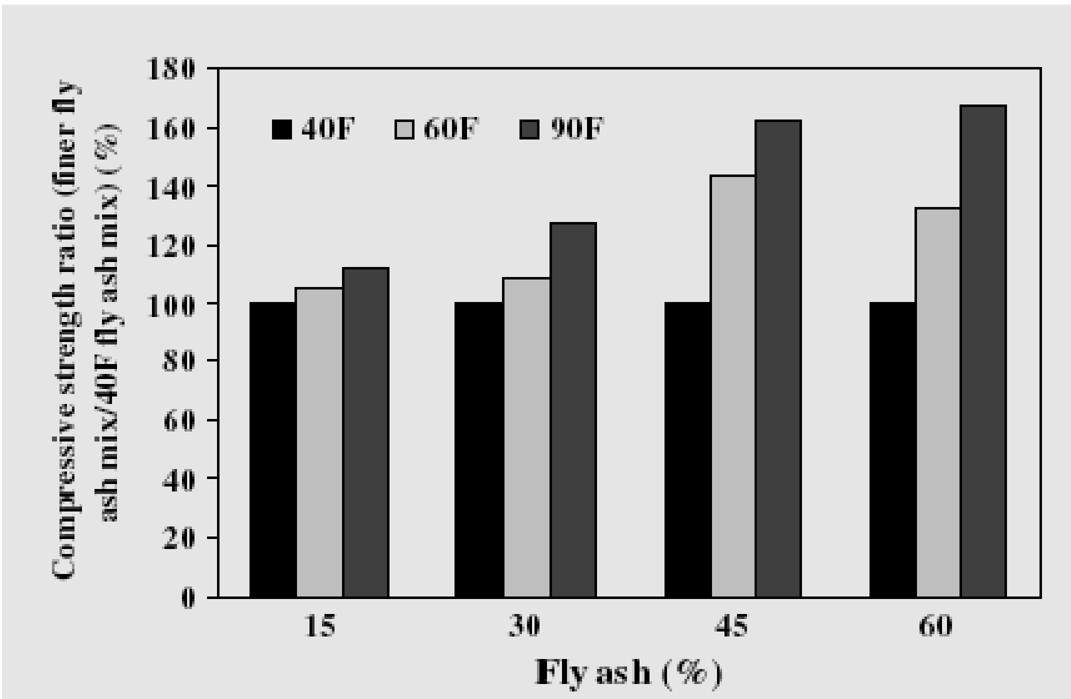


Fig. 2.3: Compressive strength ratio with fly ash fineness at 28 days (Source: Se Jin choi et al [25])

Strength development of mortar mixes using 60F and 90F fly ashes improved when compared to 40F although there is overall decrease in compressive strength with increase in replacement ratio of fly ash. Compressive strength of fly ash mortar with increases with 15, 30 and 45 % cement replacement with 90F fly ash was greater than that of controlled mix after 28 days. Reason may be due to the effect of particle packing with small voids in the mortar [25]. Tensile strength and flexural strength of mortar mixes using 90F fly ash was greater than that of 40F and 60F with same % of fly ash. Fig. 2.4 relation between compressive strength and tensile strength is shown.

W. Tangchirapat et al [12] investigated the effects of fineness and replacement of fly ash on the fresh and hardened properties of recycled aggregates concrete. Study was focused on two groups of recycled aggregates and results were compared with conventional concrete. In first group 100% coarse recycled concrete aggregate was used which was denoted by AF series and in second group crushed lime stone and river sand were fully replaced by coarse and fine recycled concrete aggregate denoted by BF series.

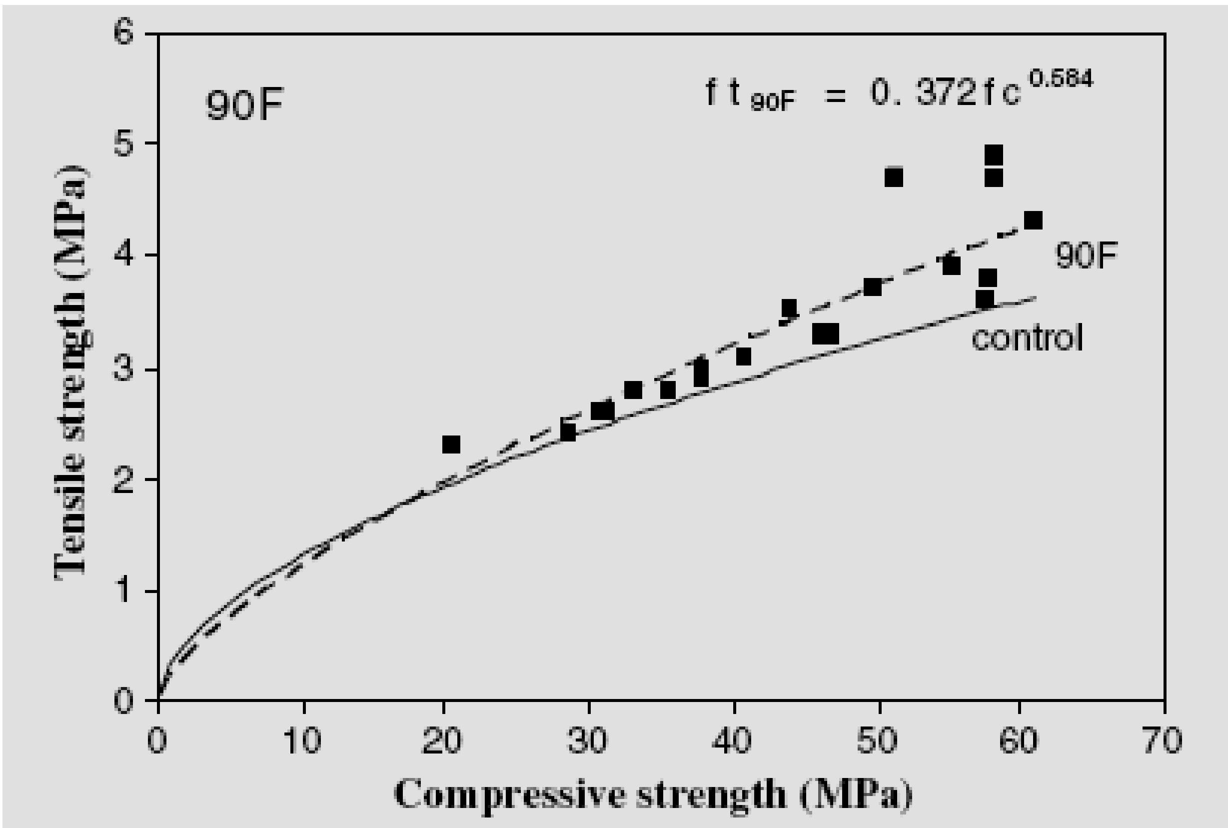


Fig. 2.4: Relation between compressive strength and tensile strength (Source: S. J. Choi et al [25])

Table 2.6 shows the physical properties of natural and recycled concrete aggregates used in their study. Fly ash was used as a pozzolanic material to partially replace cement at replacement level of 20, 35 and 50% by weight of binder for recycled aggregates concrete. It was found that the recycled aggregates concrete requires more mixing water than conventional concrete due to very high water absorption which is 12 to 13 times greater than conventional concrete.

Table 2.6: Physical properties of natural and recylcled concrete aggregates (Source: W. Tangchirapat et al [12])

Properties	Natural aggregates		Recycled concrete aggregates	
	River sand	Limestone	Fine	Coarse
Fineness modulus	3.04	6.79	3.55	6.40
Specific gravity (SSD)	2.60	2.67	2.31	2.45
Absorption (%)	0.94	0.46	11.91	5.61
Los Angeles abrasion loss (%)	N/A	21.70	N/A	33.08

The recycled aggregates concrete with original and ground fly ash require almost the same amount of mixing water as the recycled aggregates without fly ash. Due to the use of fly ash increase in slump was observed in fresh concrete aggregates with fly ash. The slump loss of the conventional concrete reached zero at approximately 105 min after mixing while AF and BF concerts had zero slump loss values at 90 and 60 min as shown in Fig. 2.5.

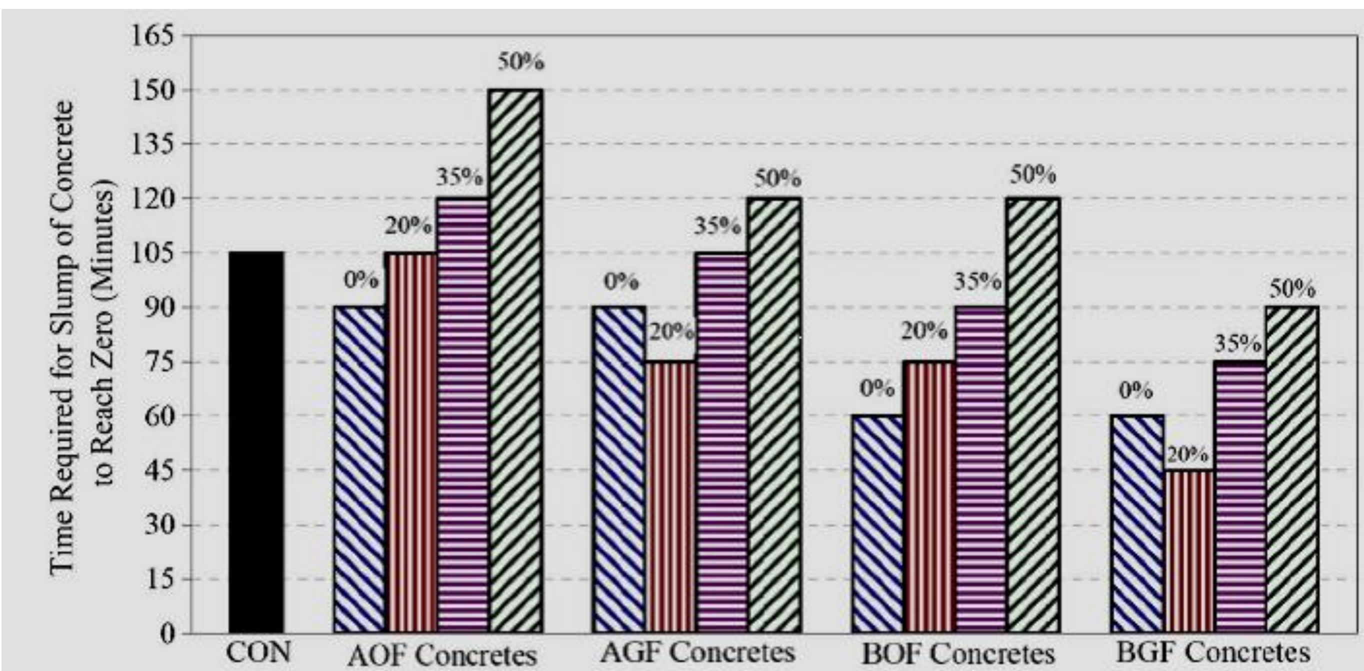


Fig. 2.5: Slump loss concrete containing recycled aggregates (Source: W. Tangchirapat et al [12])

There was increase in slump loss after adding fly ash. The compressive strength of recycled aggregates concrete with and without fly ash was also compared with that of conventional concrete. With use of original fly ash (OF) and ground fly ash (GF) increase in compressive strength of recycled aggregates concrete was observed. The effect of fineness of fly ash and its replacement ratio on the splitting tensile strength of recycled aggregate concrete was also studied. It was found that recycled aggregates concrete with OF and GF has maximum and minimum ratio values of 8.1% and 8.5 % respectively which shows that use of either OF and GF did not have a great effect on the splitting tensile strength of recycled aggregates concrete. Failure of the recycled aggregate concrete after splitting tensile strength testing occurred through the old cement paste or mortar adhering to the recycled concrete aggregate as shown in Fig. 2.6

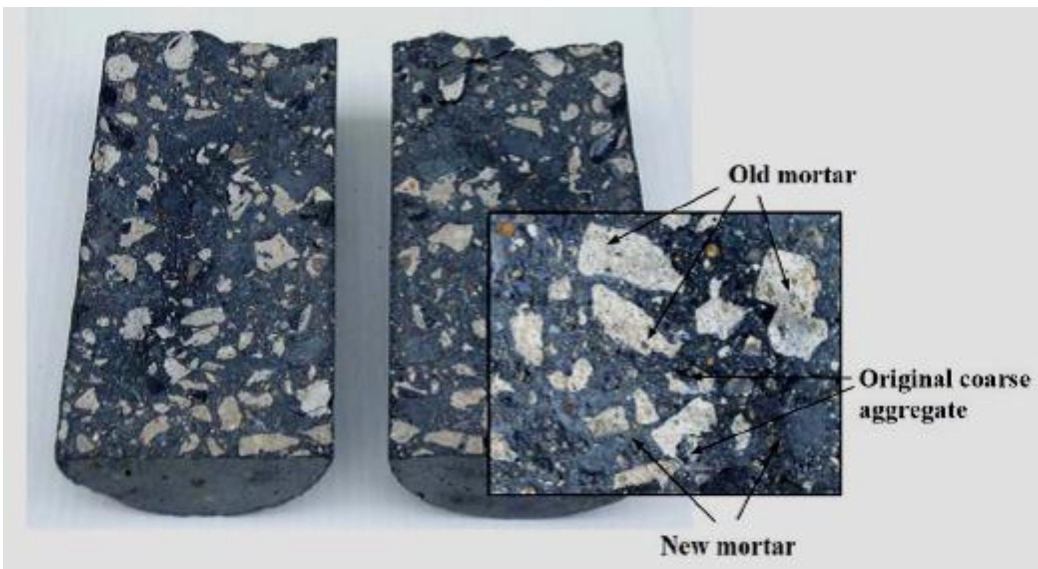


Fig. 2.6: Failure of recycled aggregate concrete after Splitting tensile test (Source: W. Tangchirapat et al [12])

M. Arezoumandi et al [21] conducted an experimental investigation to study the shear strength of concrete beams constructed with 50% replacement of cement with fly ash (HVFAC) and controlled concrete (CC) in which no fly ash was added. They prepared 16 beams of size 305 mm ×457 mm in which 12 beams were without shear reinforcement and 4 beams were with shear reinforcement in forms of vertical stirrups. Fresh and hardened properties were determined as shown in Table. 2.7. Linear variable differential transformers (LVDTs) strain gauges were used to measure the deflection of beam center and strain in the reinforcement as shown in Fig. 2.7

Table. 2.7: Fresh and hardened concrete properties (Source: M. Arezoumandi et al [21])

Property	CC	HVFAC
Slump (mm)	114	139
Air content (%)	5.5	3.5
Unit weight (kg/m^3)	2,306	2,451
Split cylinder strength[a] (MPa)	2.9	2.8
Compressive strength[a] (MPa)	29.0	30.7

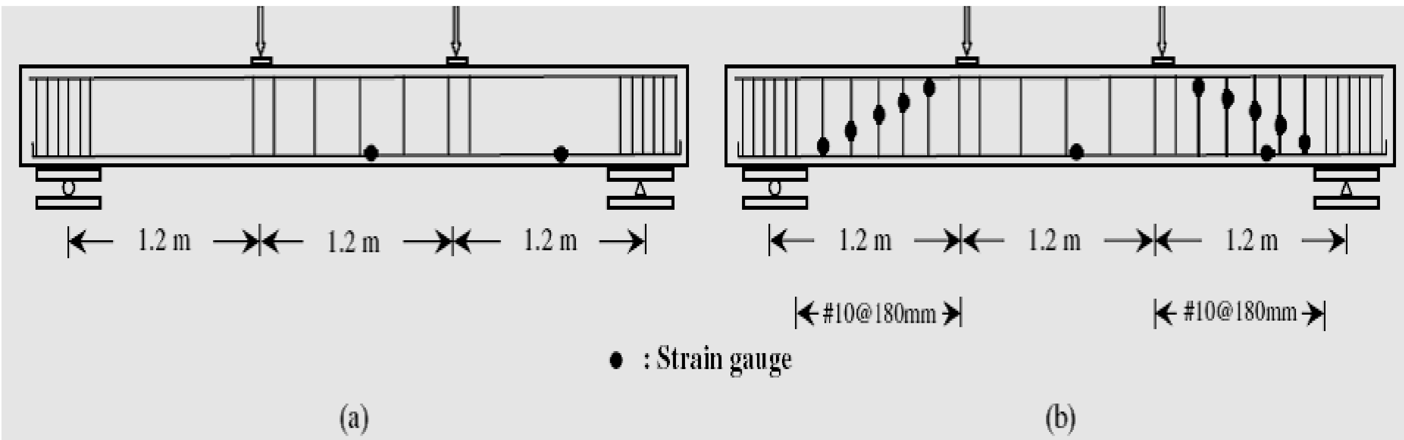


Fig. 2.7: Location of strain gauges on the test beams (a) Without stirrups on test region (b) with stirrups on test region (Source: M. Arezoumandi et al [21])

The results were compared with ACI 318 and AASHTHO LFRD. No significant difference was observed when concrete with 50% replacement of cement with fly ash were compared with controlled concrete in terms of crack patterns and failure mode. The load vs deflection behavior for beams with different longitudinal reinforcement is shown in Fig. 2.8. Section with a higher percentage of longitudinal reinforcement had a higher shear capacity. The HVFAC beams have higher V_{test}/V_{code} ratio when compared with controlled concrete (CC) beams.

J. Solanki and J. Pitroda [13] investigated the feasibility of using fly ash and hypo sludge cement (Fig. 2.9) in concrete. They studied the flexural strength of beams by partial replacement of cement with fly ash and hypo sludge in concrete. Two test groups were constituted with the replacement percentages of 0%, 10%, 20% and 30%. M20 grade of concrete was prepared as per IS 10262: 2009 [142].

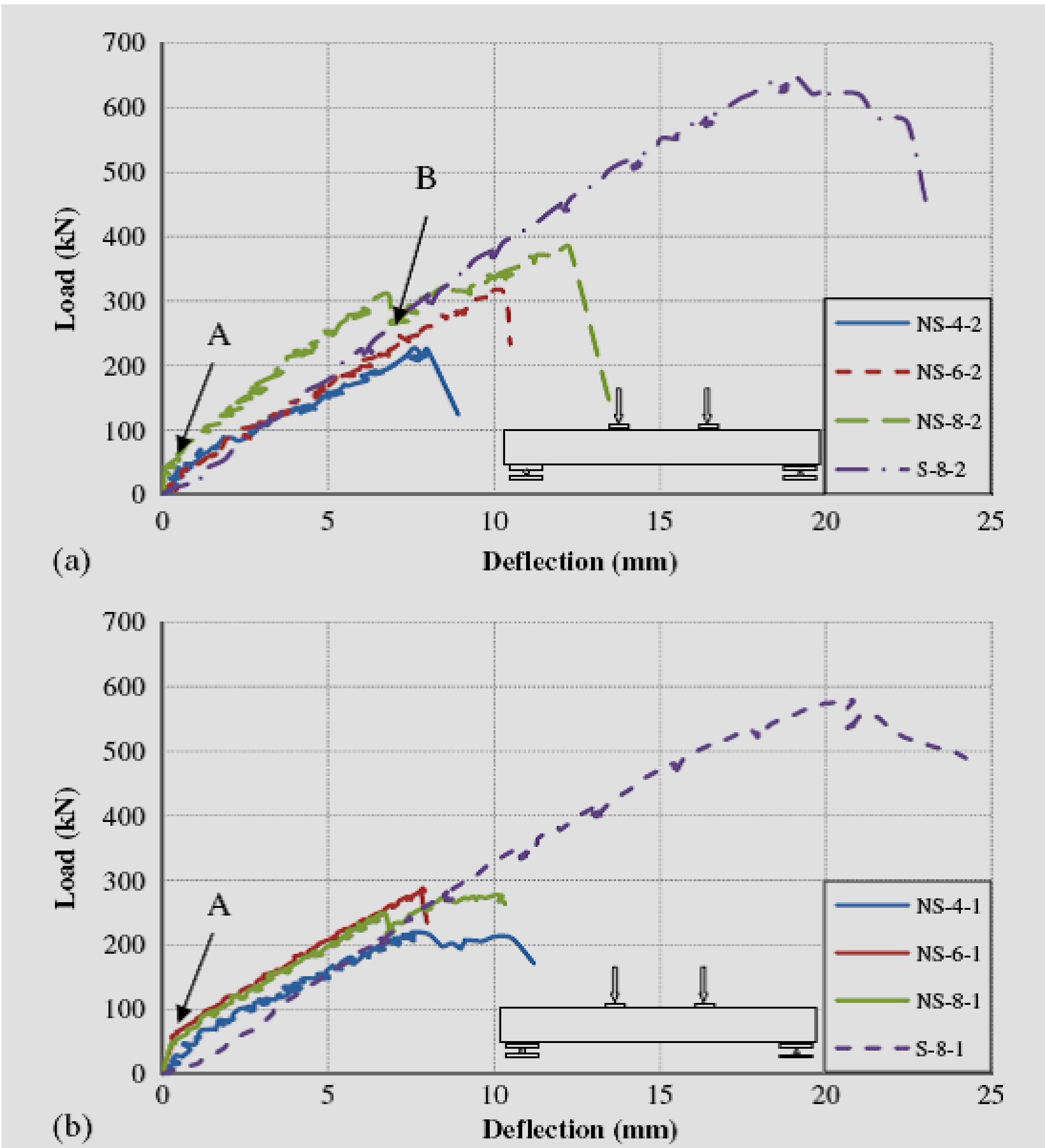


Fig. 2.8: Load-deflections of the beams: (a) HVFAC; (b) CC (Source: M. Arezoumandi et al [21])

Fig. 2.9: Hypo sludge (Source: J. Solanki and J. Pitroda [13])

The results showed that the use of effect of fly ash and hypo sludge on concrete beams increases the flexural strength by a considerable amount. Flexural strength of the concrete was found to be increased by 11.08% when 20% replacement of cement by fly ash was done. Flexural strength of the concrete was also increased when the 10% replacement of cement by hypo sludge was done and was increased up to 8.91%.

J. Pitroda et al [34] investigated on partial replacement of cement with fly ash in design mix concrete. Their work explores the feasibility of using the fly ash which is a thermal industry waste in concrete production as partial replacement of cement. The cement was replaced by fly ash in variations of 0%,10%,20%,30% and 40% by weight of cement for M-25 and M-40 mix. Comparisons were made in terms of compressive and split tensile strength with the conventional concretes so as to evaluate the mechanical properties for the test results for compressive strength of aging upto 28 days and split tensile strength at 56 days. They concluded that compressive strength was reduced when cement was replaced by fly ash and as fly ash percentage was increased the compressive and split tensile strength decreased. Utilization of fly ash in concrete will save the coal & thermal industry disposal costs and shall produce a 'greener' concrete for construction. The cost analysis indicated that cement reduction by flyash decreased the cost of concrete, but at the same time strength was also decreases.

P. K. Mehta [87] took Class F Fly Ash and Ordinary Portland cement for determination of mechanical properties of concrete. He replaced cement with fly ash of replacement of 16% to 60%. Water binder ratio was varied from 0.3 to 0.4. from his study it was found that at the age of 28 days of curing with 25 to 30 replacement achieved good compressive strength, thermal cracking & salt resistant. Use of more than 50% FA for sustainable development was recommended.

S. Gopalakrishnan et al [79] investigated M30 grade concrete using fly ash at 50% cement replacement level. A slump of 100mm was to be achieved for the workability. The strength values were nearly similar at the age of 28 days and HVFAC exhibited higher strength at later ages. The flexural strength was found to be higher for HVFAC. HVFAC showed terribly low chloride porosity and water absorption and reduced water permeability compared to it of OPC primarily based concrete. The abrasion resistance of HVFAC was found to be marginally higher compared to OPC primarily based concrete.

L.Yijin et al [68] used the Fly Ashes collected by electro-static precipitators and airflow classing technology. Due to their spherical shape and smooth surface features, the Fly Ash demonstrated improved water reduction effect with increased fineness. The incorporation of ultra-fine C Fly Ash may increase the setting time of cement paste. The water demand ratio of UFA decrease with the increasing of fineness. The water reducing rate of 30% ultra-fine C Fly Ash reach 10%. Ultra-fine C Fly Ash is a kind of good mineral water reducer. Ultra-fine C Fly Ash has significantly increased the slump and reduced the slump loss of concrete.

V. Agarwal [52] found that the proportions of fly ash in concrete would vary from 30% to 80% for numerous grades of concrete. It had been ascertained that the later age strength of concretes having more than 40% replacement of cement by fly ash suffers adversely through water/ binder quantitative relation is step by step reduced. For concretes with lower than four-hundredth replacement of cement, the characteristic strength at twenty eight days is on higher side. Whereas for concrete with less than 40% replacement of cement, the twenty eight days compressive strength is on higher side when compared with plain concrete.

A.D. Pofale and S.V. Deo [51] in their research found that the compressive strength and flexure strength of concrete mixes increases when sand was replaced by Fly ash. There was 34% increase in compressive strength and 24% increase in flexural strength was observed. It has been found that by replacing sand with fly ash strength increases. Workability of concrete using Fly Ash was higher than to control concrete and density was decreased by replacing sand with Fly Ash. It was also concluded that there is significant reduction in cost when sand is replaced with Fly ash.

C.F. Christy and D. Tensing [53] explored the use of fly ash in replacement of cement in mix of proportions of 1:3, 1:4.5 and 1:6. Replacement of fly ash was 10%, 20%, 25% and 30% by weight of cement. Higher compressive strength was observed with increase in the richness of the mix. Study was concluded in improvement in the strength of the mortar containing fly ash as partial replacement replaced of fine aggregate and cement in the cement mortar 1:6.

Md. M. Islam and S. Islam [50] studied the strength behaviour of mortar with fly ash as partial replacement of cement. Cement was partly varied in six percentages (10%, 20%, 30%, 40%, 50% and 60%) of class F fly ash by weight. Ordinary Portland cement mortar was additionally prepared as referral mortar. Compressive in addition to tensile strengths of the mortar specimens were determined at 3, 7, 14, 28, 60 and 90 days of curing. Taking a look at results exhibited that strength increased with the rise of fly ash up to an optimum value, on the far side that, strength values started decreasing with more addition of fly ash. Among the six completely different percentages of ash mortars, the optimum quantity of cement replacement in mortar was concerning 40% that gave 14% higher compressive strength and 8% higher tensile strength when compared to OPC mortar.

T. P. Madhavi et al [20] explored partial replacement of cement and fine aggregates by fly ash and glass mixture. In their investigation they used fly ash as cement replacement material and glass mixture as fine aggregates replacement material in concrete. Natural fine aggregates were substituted by weight by plate glass powder at rates varied from 10, 20, 30, 40 and 50 percentages. Compressive, tensile and flexural strength were measured and compared up to 180 days of curing. Compressive strength of cubes at three days, seven days and twenty eight days of curing period were studied. Fineness modulus, relative density, wetness content, water absorption was additionally determined. They performed experiments on M30 grade of concrete at a constant w/c ratio of 0.5 as per IS 10262: 2009 [142]. Based on the test results, the ideal percentage of mix which shows maximum compressive strength was identified.

S.P. Upadhyay and M.A. Jamnu [8] used ternary blended cement to determine the compressive strength of high performance concrete. Cement was replaced with Alccofine at different replacement percentages of 4,6,8,10 and 12% and fly ash was replaced at 30% by weight of cement. The concrete specimens were cured on traditional wet curing process traditionally under normal atmospheric temperature. The compressive strength was resolute at three, seven and twenty eight days of curing. The addition of Alccofine showed an early strength gaining property which of fly ash showed long term strength. The ternary system of standard portland cement-fly ash-Alccofine concrete was found to extend the compressive strength of concrete on all ages when put next to controlled concrete.

M.I. Khan [92] investigated permeation related properties of high performance concrete in which fly ash and micro silica was used as partial replacement of cement. Concrete with different water-binder ratio was prepared to determine the oxygen permeability, porosity and sorptivity of concrete. The incorporation of fly ash resulted in a marginal reduction in the oxygen permeability, porosity, and sorptivity values, especially at later ages. For low w/b mixes with 10% micro silica, an optimum level of fly ash replacement in the range of 15 to 20% was found to yield the lowest permeability, porosity, and sorptivity values.

2.3 Silica Fume used as replacement of cement

Silica fume is a byproduct of ferro-silicon industries. It is made at a temperature of approx. 2000ºC. Its specific surface area lies between 20-25 m^2/gm and hence it acts a good filler material [29,38,116,136,]. The standard specifications of Silica Fume are defined in ASTM - 1240. It is commonly used at a replacement level of 5% to 12% by mass of total cementitious materials. It can be used successfully for the structures where high strength is needed or significantly reduced permeability to water is the major concern. Extraordinary procedures are required to be adopted for handling, placing and curing concrete with these very fine SF particles. Silica fume, conjointly observed as micro silica or condensed oxide fume, is another material that is used as a synthetic pozzolanic admixture [40,47,74]. It's a product ensuing from reduction of high purity quartz with coal in an electrical arc chamber within the manufacture of Si or ferro silicon alloy. Oxide fume rises as a modify vapour. It cools, condenses and is collected in cotton bags. It is then processed to get rid of impurities and to regulate particle size. Condensed oxide fume is actually silica (more than 90%) in non crystalline form. Since it is an air borne material like fly ash, its shape is spherical. It's very fine with particle size less than 1 micron and with a mean diameter of 0.1 micron, regarding one hundred times smaller than average cement particles. Silica fume has specific surface area of 20000 m^2/kg, as against 230 to 300 m^2/kg. Silica fume as an admixture in concrete has displayed an added chapters on the advancement in concrete technology. The utilization of silica fume in conjunction with super plasticiser has been the backbone of recent High performance concrete. In one article printed in 1998 issue of 'Concrete International' by archangel Shydlowski, President, Master Builder, Twenty five years past nobody within the concrete housing industry may even imagine making and putting concrete mixes that might win in situ compressive strengths as high as 125 MPa. The structures appreciate Key Tower in Cleaveland with design strength of 85 MPa, and Wacker Tower in Chicago with such as concrete strength of 85 MPa, and two Union sq. in metropolis with concrete that achieved 130 MPa strength – square measure testaments to the advantages of silica fume technology in concrete construction.

K. Sakr [73] investigated the effect of silica fume (SF) and rice hush ash (RHA) as a replacement of cement. Physical mechanical and shielding properties of different types of heavy weight concrete were studied. Durability analysis was also investigated. Optimum percentage of Silica fume or rice hush ash (RHA) as a partial replacement of cement for heavy weight concrete properties was determined and compared with ordinary heavy weight concrete. Sulphonated naphthalene formaldehyde condensate was used as super plasticizer to maintain a constant workability. Shielding tests for gamma rays (γ rays) were performed using cobalt 60 and cesium 137 point source of 3.7×10^4 Bq. Different thickness of concrete specimens ranging from 20 to 100 mm cut from specimens of 150×150×150 mm were used. Tests were carried out using a 4 in. diameter NaI detecter connected to a computerized multichannel analyser (MCA) for measuring the gamma counting as shown in Fig 2.10.

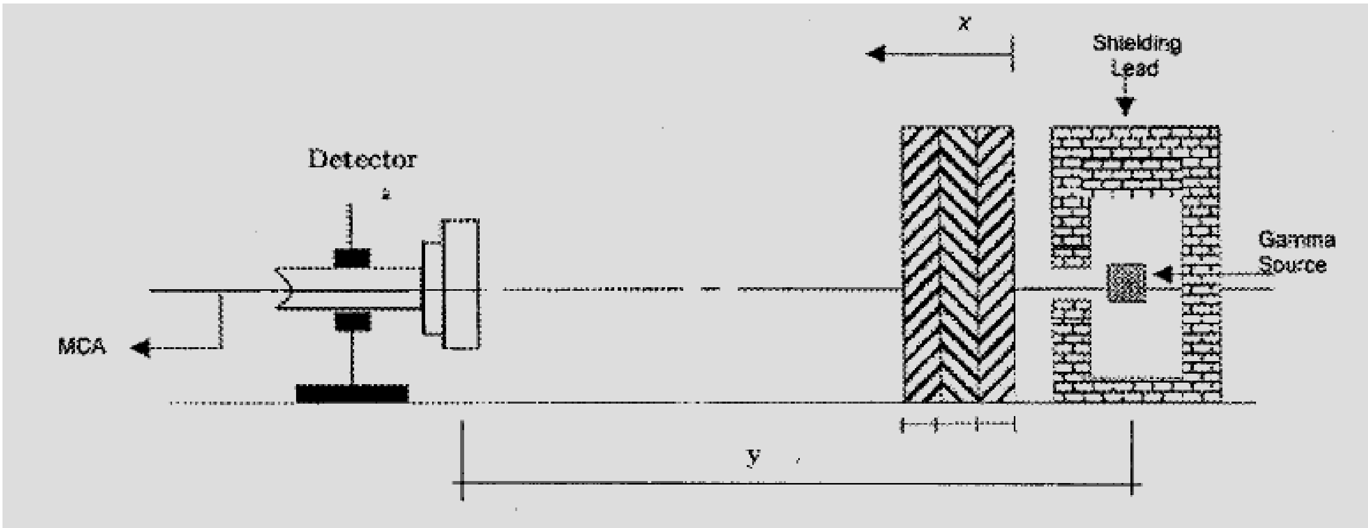
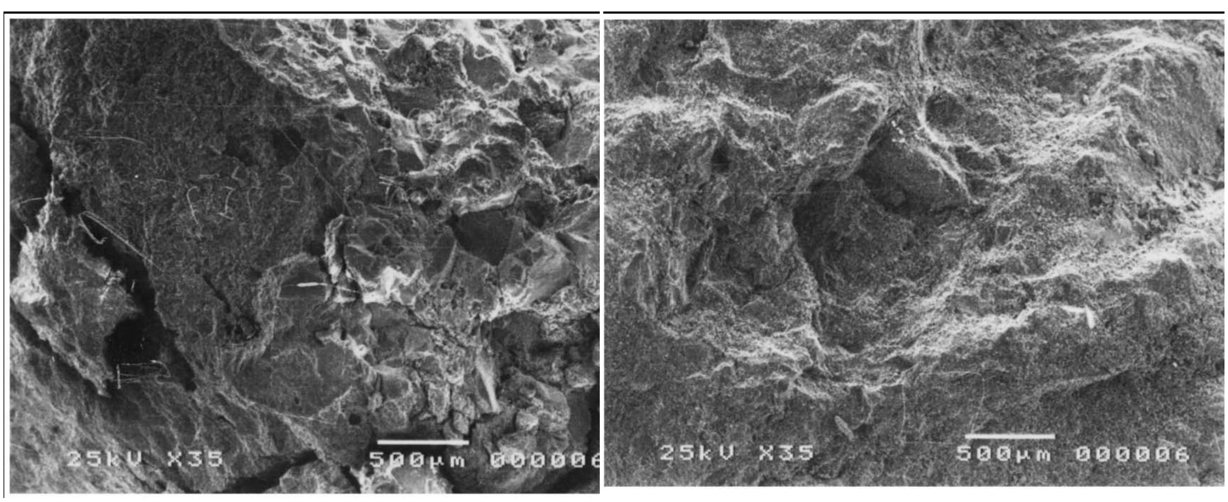


Fig. 2.10: Diagram of shielding properties investigation (Source: K Sakr [73])

It was found that the density of ilmenite concrete was higher than that of the gravel concrete by 45%. Mixing of SF or RHA had no significant effect on density of concrete. The micro structural investigation (Fig. 2.11 (a) and (b)) showed that 15% SF or 15% RHA (optimum dose) as a partial replacement of cement by weight in the case of ilmenite concrete led to an increase in concrete densification and all properties.



(a) (b)

Fig. 2.11: Microstructure investigation of tested concretes (a) ilmenite concrete (b) ilmenite concrete +15% SF (Source: K Sakr [73])

The compressive strength of ilmenite concrete mixed with 15% SF was 23% higher than that of 0% SF while when mixed with 15% RHA it was 21% higher. SF mixed concrete demonstrated better resistance to sulphate attack than RHA. High gamma does have a bad effect on the mechanical properties of all types of concrete and there is no significant effect of the presence of SF or RHA on the compressive strength of irradiated concrete.

N. Yazdami et al [63] studied an experimental investigation to determine the feasibility of steam curing of Florida Department of Transport (FDOT) concrete with silica fume in order to reduce precast turn around time. Concrete mix design used was a FDOT class V (Special) mix design with silica fume as shown in Table 2.8. The FDOT class V are primarily intended for use in structures requiring high performance concrete such as piles. The mix design involved two mineral admixtures, densified silica fume and class F fly ash. A steam curing chamber for the accelerated curing part of the test was constructed with interior of the chamber was water proofed with water sealant and the corners were sealed with silicon caulk and the heaters were placed in three containers capable of holding 16 gallon of water each as shown in Fig. 2.12

Table 2.8: Concrete Mix Design Class Concrete: V Special 41 MPa (Source: N. Yazdami et al [63])

Parameter and properties	Value
Cement [kg (lb)]	251 (553)
Coarse agg. [kg (lb)]	798 (1,760)
Fine agg. [kg (lb)]	488 (1,075)
Air entr. admix [mL (oz)]	166 (5.6)
1st admixture [mL (oz)]	444 (15.0)
2nd admixture [mL (oz)]	1,334 (45.1)
Silica fume [mL (oz)]	43,976 (1,487.0)
Water [kg (lb)]	87 (195.5)
Fly ash	61 (135)
Slump range [mm (in.)]	140–216 (5.5–8.5)
Air content (%)	1.0–5.0
Unit weight (wet) [kg/m^3 (pcf)]	2,275 (142)
W/C ratio (plant) [kg/kg (lb/lb)]	0.35
W/C ratio (field) [kg/kg (lb/lb)]	0.35
Theo yield [m^3 (ft)]	0.78 m^3
Producer test data	
Chloride cont [kg/m^3 (pcf)]	0.002 (0.221)
Slump [mm (in.)]	152.4 (6.00)
Air content (%)	2.75
Temperature [°C (°F)]	38 (100)
Compressive strength [MPa (psi)]	28 -Day- 61 (8,870)

The compressive strength tests were performed as per ASTM C39. At 28 days of curing target strength of 41.37 MPa was reached. Steam curing times of 12, 18 and 24 h did not seem to play a major role in controlling concrete compressive strengths. The surface resistivity of all samples increased significantly with time. Surface resistivity tests was done using wenner array (Fig. 2.13)

Fig. 2.12: Setup of heaters inside steam-curing chamber (Source: N. Yazdami et al [63])

Fig. 2.13: Surface resistivity test using Wenner array (Source: N. Yazdami et al [63])

Chloride ion permeability at 28 and 364 days of age of steam cured specimen was very low. All steam cured and moist cured specimens showed a general increase in shrinkage with time

R.P. Lohtia and R.C. Joshi [111] concluded that partial replacement of cement by silica fume leads to reduction of heat of hydration with no reduction in strength. For a high strength concrete having 540 kg/m^3 cement and ten percentage cement replacement with silica fume, heat was 9% less compared to the mix without silica fume. Addition of silica fume might accelerate the temperature rise throughout the initial two to three days, however a overall decrease in temperature rise of silica fume concrete was ascertained at later stages (7–28 days) in comparison to corresponding plain concrete. At early age, because of quick pozzolanic reaction of silica fume, a larger quantity of heat is liberated when compared to Portland cement. Quantitative relation of heat liberated by pozzolanic activities of silica fume throughout the initial 2 to 3 days per gram of silica fume to it of Portland cement is reported to be of the order of 1–2

B.W. Langan et al [102] studied how the heat of hydration of portland cement is affected by silica fume. Silica fume was used as a partial replacement of cement at ten percentage by weight of the total cementitious material. Measuring instrument tests were performed on these mixtures at water/cementitious ratios (w/cm) of 0.35, 0.40 and 0.50, up to amount of twenty four hours. However, many were carried on for seventy two hours to look at any later reactions. Impact of silica fume on the accumulative heat of hydration is shown in Table 2.9. It's evident that the presence of silica fume increases heat evolution throughout the initial thirty minutes of hydration, and through the amount from eight to twenty four hours no matter the w/cm quantitative relation. Heat evolved throughout the dormant amount remained virtually constant for all mixtures, whereas the heat throughout the amount from two to eight hours was reduced. Heat content evolved at one and three days wasn't affected by the presence of silica fume at w/c quantitative relation of 0.35. Heat content at one day increased with a rise in w/cm.

Table. 2.9: Effect of silica fume on heat evolution of Portland cement hydration (Source: B.W. Lagan et al [102])

Mix type	Heat of hydration (Kcal/kg)						
	w/cm	0.0–0.5 h	0.5–2.0 h	2.0–8.0 h	8.0–24 h	Total at 1 day	Total at 3 days
0% SF	0.35	2.6	0.4	11.7	31.3	45.9	56.9
10% SF	0.35	3.1	0.4	8.7	34.5	46.6	56.1
0% SF	0.40	2.6	0.5	11.8	31.8	46.7	–
10% SF	0.40	3.2	0.4	10.3	33.6	47.4	–
0% SF	0.50	2.6	0.4	10.2	33.3	46.4	–
10% SF	0.50	3.2	0.5	9.7	35.3	48.7	–

H. Uchikawa and S. Uchida [127] reported that addition of silica fume accelerates the hydration reaction of standard Portland cement in any respect stages of hydration. Like a shot when mixture, the saturation factor of $Ca(OH)_2$ indicative of the concentrations of Ca^{2+} and OH^- ions, within the paste containing silica fume was reduced when compared to paste prepared from standard Portland cement. However, the saturation issue sharply inflated to its most sooner than for standard Portland cement paste. Throughout the course of reaction, the accumulative heat evolved due to association of standard Portland cement containing silica fume was invariably above from standard Portland cement paste. However, this trend could also be reversed if water-reducing admixture is supplementary to the blending water. Within the presence of alkali based mostly water reducer, the key reaction peak was accelerated during a silica fume cement paste. The accumulative heat evolved additionally inflated within the presence of silica fume within the paste, and also the higher the number of silica fume within the paste, the more the heat evolved and also the shorter the reaction time

E. H. Kadri and R. Duval [59] investigated how heat of hydration in concrete is influenced by the presence of silica fume. They replaced cement with silica fume in which w/(c+sf) ratios were varied in between 0.25 and 0.45 with replacement ratios of silica fume was taken between 10 to 30% by mass. Semi adiabatic calorimeter was used to determine the continuous heat of hydration. From their study it was found that rate of hydration of concrete incorporating silica fume depends on two factors. Firstly w/(c+sf) ratio and secondly percentage of silica fume. As the ratio of w/(c+sf) reduces the hydration reaction ceases as less water is available for cement hydration. However addition of superplasticizer may extend the dormant period. At 0.45 w/(c+sf) ratio enough water is available to fill the voids and increase the hydration reaction. They also found that hydration process get altered at early ages due to addition of silica fume. Heat of hydration in concrete incorporating silica fume increase in the first hour with three different lower w/(c+sf) ratios. Concrete in which 30% silica fume was used when compared to plain concrete the rate of heat evolution exceeds 50% for 0.25 and 0.35 w/(c+sf) ratios. But when w/(c+sf) ratio was taken equal to 0.45 the rate of heat evolution in plain concrete was more than that of silica fume incorporated concrete. This may be due to the fact that quantity of cement decreases with increase in silica fume contents. Total heat released was lower due to reduction in cement content but pozzolanic reaction enhances the heat evolution. Due to formation of less amount of $Ca(OH)_2$ the hydration rate of cement slows down at later stages and hence total heat of hydration decreases. The amount of $Ca(OH)_2$ and its availability greatly influence the pozzolanic reaction

G.A. Rao [94] studied how the consistency of cement pastes and mortars get affected by use of silica fume. In his study he used silica fume whose specific surface area was 16000m^2/kg and having specific gravity of 2.05. Variation of silica fume from 0 to 30% was made with an increment of 2.5% by weight of cement it was found that with increase in silica fume contents the consistency of cement paste increased. At 0% silica fume standard consistency was found to be 31.5% but when silica fume percentage was made equal to 30% consistency increased to 44.25%.The variation of cement consistency with variable silica fume contents is shown in Fig. 2.14. Cement pastes contents 20 to 30% silica fume requires almost 40% additional water.

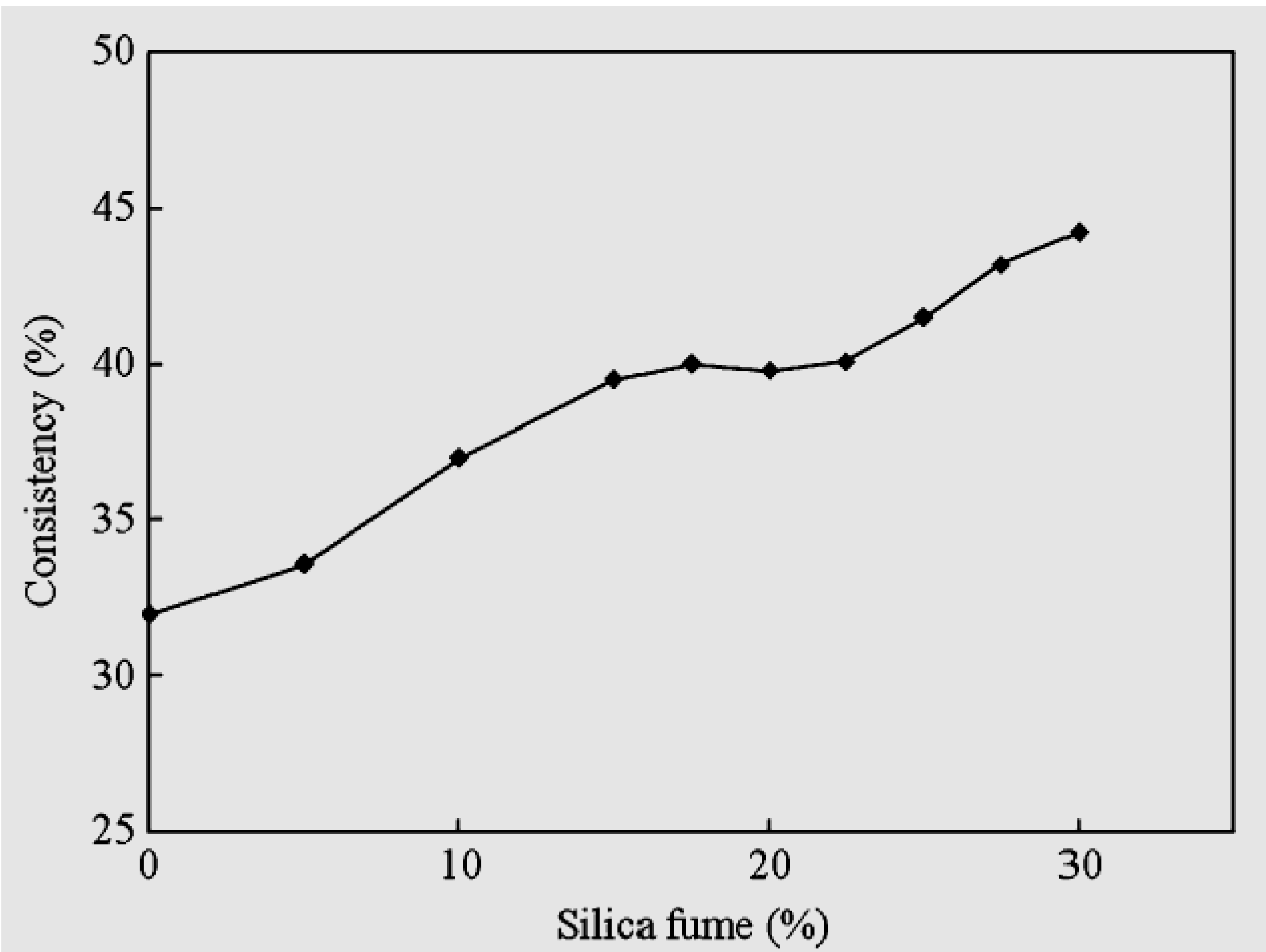


Fig. 2.14: Variation of consistency of cement pastes containing different percentages of silica fume (Source: G.A. Rao [94])

M. Mazloom et al [84] investigated the hardened properties of high performance concrete incorporating silica fume. In their study they varied the replacement ratios of silica fume at 0,6,10,15% at a fixed water cement ratio of 0.35. Table. 2.10 shows the result of their investigation. From the table it can be observed that when compared with controlled concrete having 0% silica fume 28 days compressive strength of concrete incorporating silica fume was 21% stronger. But there is less effect on gain in strength of concrete containing silica fume after 90 days of curing. However gain in strength of controlled concrete after 1 year shows 26% increase in strength when compared to 28 days strength. It was also observed that at 400 days of curing compressive strength of all the samples were nearly same.

Table: 2.10: Development of compressive strength with age in MPa (Source: M. Mazloom et al [84])

Concrete mixes	Silica fume (%)	Compressive strengths (MPa)						
		7 days	14 days	28 days	42 days	90 days	365 days	400 days
OPC	0	46	52	58	62	64	73	74
SF 6	6	50.5	58	65	69	71	73	73
SF 10	10	52	61	67.5	71	74	73	73
SF 15	15	53	63	70	73	76	75	76

H.S. Wong and H.A. Razak [78] prepared concrete mixtures incorporating silica fume at different water/cement ratios and compressive strength was determined. Replacement ratios of silica fume was taken equal to 0,5,10 and 15% at each w/c ratios. Different observations made from their study and tabulated in Table. 2.11 are as follows

(i) use of silica fume does not enhance the strength of concrete at early days. There is gain strength of blended mixtures only after 7 days of curing. Due to dilution effect and slow pozzolanic reaction there is loss in strength at early ages and this loss was nearly proportional to the cement replacement level and

(ii) (ii) at 10% replacement level of silica fume 17% increase in strength was observed at 90days of curing. Form their study it was also concluded that by reducing the w/c ratio from 0.35 to 0.27 does not affect the strength significantly.

A. Behnood and H. Ziari [66] designed concrete mixtures to evaluate the effect of silica fume on the compressive strength of the heated and unheated concrete specimens. Three mixtures were made with a constant water-to-cement ratio (w/c) 0.30. The dosages of replacing cement by silica fume were 0% (W30OPC), 6% (W30SF6) and 10% (W30SF10). One mixture was prepared with w/c of 0.40 without silica fume (W40OPC), whereas other concrete was produced with w/c of 0.35 containing 6% silica fume (W35SF6). The results of the compressive strength are given in Table 2.12. As was expected, the replacement of cement by 6 and 10% silica fume increased the 28-day compressive strength approximately by 19 and 25% respectively. This was due to the reaction of silica fume with calcium hydroxide formed during the hydration of cement that caused the formation of calcium silicate hydrate (C–S–H). It was also due to the filler effect of

Table. 2.11: Cube compressive strength (source: H.S. Wong and H.A. Razak [78])

Mixture	Compressive strength (MPa)						
	1 day	3 days	7 days	28 days	56 days	90 days	180 day
w/cm 0.27	39	68	72.5	84	86.5	87.5	90
SF 5	35	63	75.5	88.5	93	96.5	97.5
SF 10	25	61	79	95.5	100	104	107
SF 15	24.5	59.5	76.5	101	103.5	106	109
w/cm 0.30	48	63.5	72	83.5	84.5	85.5	87.5
SF 5	46	62	81	91	95.5	95.5	97
SF 10	42	61.5	78.5	95	97	99	103
SF 15	38	57.5	74.5	98.5	101.5	104	106.5
w/cm 0.33	41.0	58.0	62.5	75	78	79	81.5
SF 5	35.0	55.0	69.5	83.0	85.0	90.0	90.0
SF 10	32.0	53.0	70.5	89.5	90.5	92.0	93.5
SF 15	31.0	47.5	70.5	88.5	93.0	95.5	100.5

very fine particles of silica fume. Furthermore, concretes containing different levels of silica fume showed lower rates of compressive strength gain in early ages. They concluded that (i) Concrete containing silica fume had significantly higher strength than that of OPC concrete at room temperature. After exposure to 100ºC, significant reductions occurred in the compressive strength of concrete with and without silica fume; (ii) In the range 300ºC to 600ºC, severe strength losses occurred in all three concretes, which were 68.8, 70.9 and 73.2% of the initial values for W30OPC, W30SF6 and W30SF10 concrete respectively. This was because during exposure to high temperatures, cement paste contracts, whereas aggregates expand. Thus, the transition zone and bonding between aggregates and paste are weakened. As a result, this process as well as chemical decomposition of hydration products causes severe deteriorations and strength loses in concrete after subjecting to high temperatures; and (iii) After heating to 600ºC, the residual compressive strength of all three concretes were approximately same, whereas the relative residual compressive strengths of concretes containing 6% and 10% silica fume were 6.7% and 14.1% lower than those of the OPC concretes, respectively, after exposure to 600ºC. Therefore, the rate of strength loss was significantly higher in silica fume concretes. This was attributed to the presence and amount of silica fume in concretes that produced very dense transition zone between aggregate and paste due to ultra fine particles as filler.

Table: 2.12: Results of compressive strength at different temperatures (Source: A. Behnood and H. Ziari [66])

Mixture name	SF (%)	w/c	Compressive strength (MPa)					
			20°C		100°C	200°C	300°C	600°C
			7-day	28-day				
W40OPC	0	0.40	48.3	61.8	53.3	55.5	46.5	20.6
W35SF6	6	0.35	61.5	73.9	62.8	64.7	56.5	21.8
W30OPC	0	0.30	55.3	67.4	57.6	59.7	49.0	21.0
W30SF6	6	0.30	69.1	80.3	68.0	69.0	56.5	23.4
W30SF10	10	0.30	74.1	84.2	70.8	71.7	57.9	22.6

A. Kilic et al [65] examined the influence of aggregate types on the flexural strength characteristics of high-strength silica fume concrete. Five different aggregate types (gabbro, basalt, quartsite, limestone and sandstone) were used to produce high strength concrete containing silica fume. Silica fume replacement ratio with cement was 15% on a mass basis. Water-binder ratio used was 0.35. The amount of super plasticizer was 4% of the binder content by mass. The flexural tensile strengths of concretes were measured at 3, 7, 28 days, and 90days of curing. The results are given in Table 2.13. They showed that (i) flexural tensile strength increased with the increase in curing time; and (ii) sandstone concrete showed the lowest flexural tensile strength, while Gabbro concrete showed the highest flexural tensile strength.

Table: 2.13: Flexural strength of concrete at different curing times (Source: A. Kilic et al [65])

Curing time (days)	Flexural tensile strength (MPa)				
	Gabbro (247)	Basalt (132)	Quartsite (160)	Limestone (110)	Sandstone (52)
3	12.6	11.4	12.9	7.9	3.2
7	16.1	15.4	14.9	12.5	4.5
28	17.3	16.7	16.2	12.8	5.2
90	18.4	17.9	16.9	13.9	5.6

A.K. Mullick [69] Proposed ternary blends of OPC with 10 % Silica Fume and 45% granulated slag gives 69.5 MPa strength at 28 days of curing. A mixture of 32.5% OPC, 60.5% slag and 7% Silica Fume was found to result in compressive strength of 50 MPa at 48 hours, when cured at 38ºC. Addition of 22.5 kg Silica Fume to 300 kg cement + 350 kg Fly Ash mixes of self-compacting concrete (SCC) resulted in high early strength (21 MPa at 3 days and 45 MPa at 28 days) along with increase in cohesiveness was achieved.

S. Bhanja and B. Sengupta [77] suggested that silica fume incorporation in concrete results in significant improvements in the tensile strengths of concrete, along with the compressive strengths. Increase in split tensile strength beyond 15% Silica Fume replacement is almost insignificant, whereas comparable gains in flexural tensile strength have occurred even up to 25% replacements.

Y. Ji and H.C. Jong [91] concluded that Silica Fume agglomeration has been found in blended pastes, which cannot be broken down by normal mixing. The compressive strength of blended cement paste is not significantly increased up to 28 days due to this agglomeration. Pore structure is not sufficiently refined by silica fume replacement.

M.C.G. Juenger and C.P. Ostertag [86] reported that large particles of Silica Fume may either decrease or increase expansion due to alkali–silica reaction in mortar. Under the accelerated testing conditions, agglomerated Silica Fume decreased expansion when used as a 5% replacement of reactive sand. When the same sand was replaced by 5% of sintered Silica Fume aggregates, expansion considerably increased.

J.M. Andrew et al [71] reported that when Silica Fume is alkali silica reactive, there is a pessimism effect with expansion related to the percentage of Silica Fume used; smaller amounts of Silica Fume result in higher expansions than larger amounts. All Silica Fume agglomerates appear to react with pore solution under scanning electron microscopy.

Kulkari et al [151] reported that addition of both silica fume and fly ash resulted in reducing the chloride ion permeability of concrete from "moderate" (2000-4000 coulombs) to "low" (1000-2000 coulomb) level in accordance with ASTM C 1202. The percentage reduction in chloride ion permeability from 28 days to 90 days was found to be highest in case of mixes containing OPC and Fly Ash. Such reduction was however marginal in the case of mixes containing OPC and Silica Fume.

D.K.S. Roy and A. Sil [33] studied the effect of partial replacement of cement by silica fume on hardened concrete. The properties of hardened concrete such as ultimate compressive strength, flexural strength, splitting tensile strength was determined for different mix combinations of materials and these values were compared with the corresponding values of conventional concrete. The maximum 7 days and 28 days cylindrical compressive strength are found to be 4.32% higher and 16.82% higher respectively when cement was replaced by silica fume .As the percentage of silica fume was increased, there was improvement in packing action of it as a filler material resulting in improvement of the interfacial bond between the aggregate and cement matrix resulting in a sharp increase in tensile strength. The maximum 28 days flexural strength of SF concrete was found to be 21.13% higher with respect to that of the normal concrete for 10% cement replaced by silica fume. This value was far more than the value calculated from the expression $0.7\sqrt{fck}$.

K. Perumal and R. Sundararajan [89] evaluated the performance of high performance concrete trial mixes having different replacement levels of cement with silica fume. The strength and durability characteristics of these mixes were compared with the mixes without silica fume. Compressive strengths of 60 MPa, 70 MPa and 110 MPa at 28 days were obtained by using only 10 percent replacement of cement with Silica fume. The use of SF and low w/c ratio resulted in practically impermeable concrete. The compression failure pattern of concrete was due to the crushing of coarse aggregate and was not due to bond failure. Concrete mixes containing silica fume showed higher values of acid resistance, sea water resistance, abrasion resistance and impact resistance. The results of the strength and durability related tests demonstrated superior strength and durability characteristics of high performance mixes containing Silica fumes. This is due to the improvement in the microstructure due to pozzolanic action and filler effects of SF, resulting in fine and discontinuous pore structure.

D. Pradhan and D. Dutta [18] explored the influence of silica fume on normal concrete. These experiments were carried out by the authors by replacing cement with different percentages of silica fume at a single constant water-cementitious materials ratio while keeping other mix design variables constant. The silica fume was replaced by 0%, 5%, 10%, 15% and 20% for water-cementitious materials w/c ratio for 0.40. For all mixes compressive strengths were determined at 24 hours, 7 and 28 days for 100 mm and 150 mm cubes. Other properties like compacting factor and slump were also determined for five mixes of concrete. The compressive strength was increased by 13.9 % for the replacement of cement by 10% fly ash and 5% silica fume mix. Split tensile strength is increased by 12.15% for the replacement of cement by 15% fly ash and 7.5% silica fume mix. Flexural strength increased by 16% for the replacement of cement by 15% fly ash and 7.5% silica fume mix.

A. Hassan and Mohamadien [32] investigated the effect of marble powder and silica fume as partial replacement for cement on mortar which resulted in the compressive strength increased by 31.4%, 48.3% at 7 and 28 days respectively at 15% replacement ratio of silica fume with cement content and in case of replacement marble powder with cement content the compressive strength increased by 22.7%, 27.8% at 7, and 28 days at 15% replacement ratio of marble powder with cement content respectively.

A.A. Elsayed [42] performed the effect of mineral admixtures on water permeability and compressive strength of concretes containing silica fume, fly ash and super plasticizer. The main objective of this research was to determine the water permeability and compressive strength of concrete containing silica fume, fly ash, super plasticizer and high slag cement to achieve the best concrete mixture having lowest permeability. The results were compared to those of the control concrete; ordinary Portland cement concrete without admixtures. The optimum cement replacement by fly ash, super plasticizer and Silica fume in this experiment was 10% super plasticizer. The knowledge on the strength and permeability of concrete containing silica fume, fly ash, super plasticizer and high slag cement could be beneficial in the utilization of these waste materials in concrete work, especially on the topic of durability.

E.J. Sellevold et al [126] examined the effect of addition of silica fume on the water demand and strength development of concrete and concluded that the addition of silica fume to a concrete mix will increase the strength of that mix by 30-100 percent depending on the type of mix, type of cement, amount of silica fume, use of plasticizers, aggregate types and curing regimes. Silica fume concrete is very susceptible to temperature variations during the hardening process. The optimum silica fume content to achieve higher strengths seems to range between 15% and 20%.

R.F. Feldman and H. Cheng-yi [123] studied the effect of addition of silica fume on the micro structural development in cement mortar and arrived at the following conclusions. The silica fume reacts with most $Ca(OH)_2$ produced in hydrated cement-silica fume mortars within 28 days. The addition of silica fume to mortars resulted in an improved bond between the hydrated cement matrix and the sand. Silica fume affects the pore distribution of mortars by reacting with the $Ca(OH)_2$ formed around the sand grains as well as with the $Ca(OH)_2$ dispersed throughout the cement paste.

K.H. Khayat and P.C. Aitcin [114] found that there is some small retrogression in strength due to the drying of a very thin layer of the skin of the HPC. This strength retrogression of HPC is due to severe drying conditions. Hence it is emphasized that proper early water curing is much more important for HPC, especially when most of the hydration reactions are taking place. He found that some HPC laboratory specimens experienced a slight decrease in compressive strength after a long period of curing in air, particularly that containing silica fume.

D.P. Bentz et al [115] conducted experiments on silica fume concrete and developed a model for simulating the development of microstructure in the interfacial transition zone region in concrete. Based on the simulation and experimental results, they revealed that the strength development is much earlier than with Portland cement alone. The contribution of silica fume to the early strength development up to 7 days is probably through improvement in packing, that is, acting as filler and improvement of the interface zone with the aggregate.

Z. Bayasi and J. Zhou [113] investigated the early age properties of concrete and mortar incorporating silica fume and reported that the addition of silica fume enhances the rate of cement hydration at early hours due to release of OH^- ion and alkalis in the pore fluids. Silica fume accelerates both C3S and C3A hydration during the first few hours. Calcium silicate hydrates (C-S-H) play a vital role in influencing the characteristics of cement paste. The hydration process proceeds faster in pastes with silica fume, due to both CH and non-evaporable water contents at the early ages of 3-7 days. However, the hydration reactions in mortar terminate earlier. After 28 days, the non-evaporable water content continues to increase significantly in plain cement concrete.

V.M. Malhotra and P.K. Mehta [88] observed that the use of blended cements or supplementary cementing materials improves the strength, decreases the permeability of concrete, thereby increasing the resistance of concrete deterioration in aggressive environments". "Hence, the incorporation of pozzolanic material is inevitable to make HPC. For silica fume concrete, the incorporation of superplasticizer is essential for maintaining high workability, but this normally results in an increase in the cost of production. Fly ash or GGBS can be used to reduce cost, conserve energy and resources, reduce environmental impact and enhance workability.

G.M. Gao et al [81] investigated the Interfacial Transition Zone (ITZ) microstructure of concrete containing GGBS using X-Ray Diffraction (XRD), Scanning Electron Microscope (SEM) and micro-hardness measurements. The experimental results demonstrated that the GGBS significantly decreases both the quantity and the orienting arrangements of CH crystal at the ITZ. The weak ITZ between aggregates and cement paste was strengthened as the result of the pozzolanic reaction of GGBS. The pozzolanic reaction rate is in direct proportion to the specific surface area of GGBS. The weak zone at the ITZ almost vanishes when 40 percent cement is replaced by GGBS with a specific surface area of 425m^2/kg and the weak zone completely vanishes when GGBS with a specific surface area of 600 m^2/kg replace 20 percent of cement.

H.N. Hani and S. Nakin [82] examined the elastic modulus of HPC made from mixes using various percentages of fly ash, silica fume and GGBS, and pointed out that the rate of increase of elastic modulus is less than that of the compressive strength. The addition of silica fume and fly ash seems to reduce the rate of increase of the modulus of elasticity with age. The elastic modulus of HPC using GGBS and silica fume increases with age, and the rate of increase becomes less as the concrete approaches 28 days.

2.4 Ground granulated blast furnace slag used as replacement of cement

Ground Granulated Blast Furnace is a byproduct from the Blast furnace slag is a solid waste discharged in large quantities by the iron and steel industry in India. These operate at a temperature of about 1500 degree centigrade and are fed with a carefully controlled mixture of iron – ore, coke and limestone [11,23,30,83]. The iron ore is reduced to iron and remaining materials from slag that floats on top of the iron. This slag is periodically tapped off as a molten liquid and if it is to be used for the manufacture of GGBS it has been rapidly quenched in large volumes of water. The quenching optimizes the cementitious properties and produces granules similar to coarse sand [45,46,72,107]. This granulated slag is then dried and ground to a fine powder.

B.S. Divsholi et al [5] conducted an experimental investigation on concrete incorporating GGBS to find the compressive strength, electrical resistivity and chloride permeability and carbonation tests. The moisture loss and micro structure of concrete were studied. The characteristics of GGBS were examined using particle size analyzer, X-ray diffraction and chemical analysis tests are shown in Fig. 2.15 (a) and Fig. 2.15 (b) respectively. RPC test was performed to study the resistance of concrete against chloride penetration. Increased slump and fluidity was measured with increase in GGBS replacement %. Compressive strength development for control mix and mixes with 10,30,50% GGBS are shown in Fig. 2.16.

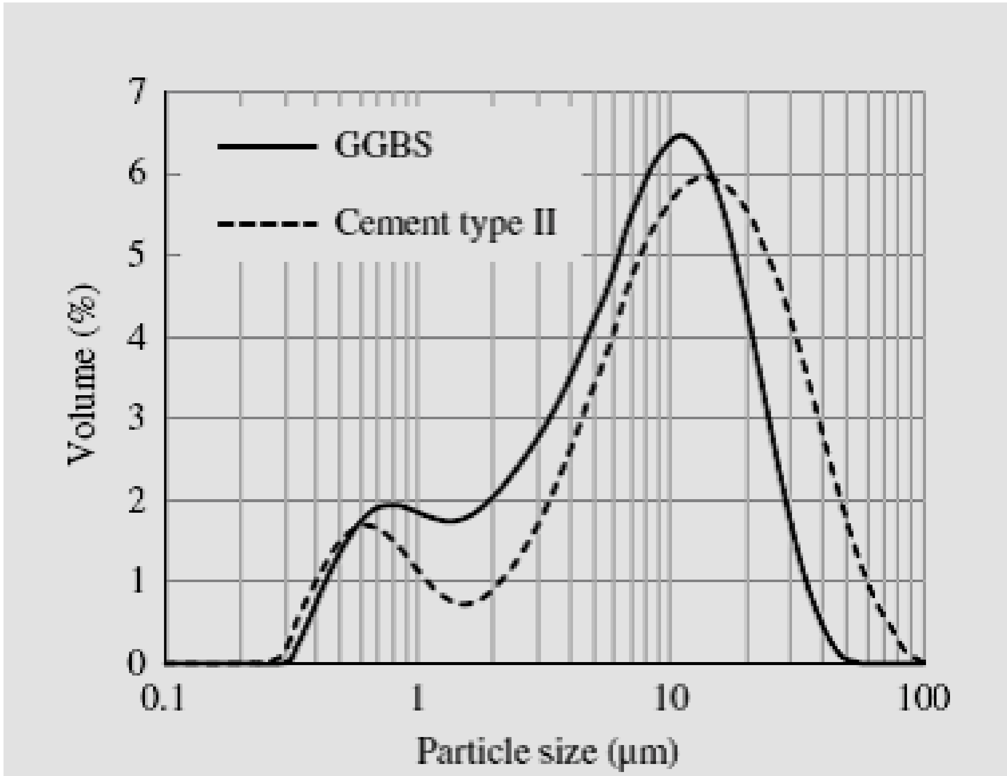


Fig. 2.15: (a) Particle size distribution of GGBS and cement
(Source: B.S. Divsholi et al [5])

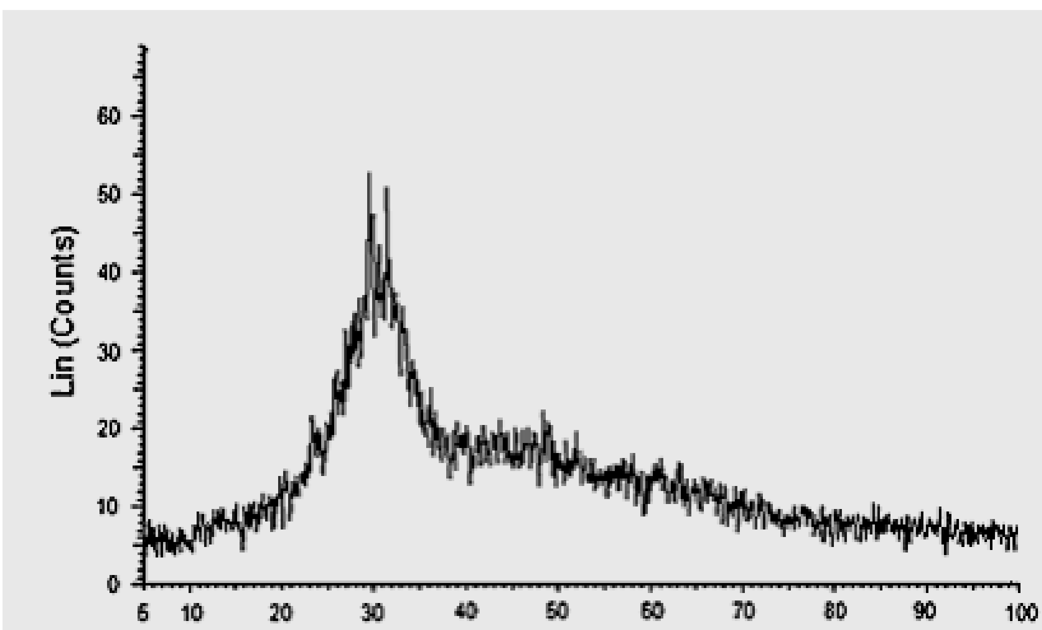


Fig. 2.15: (b) X-ray diffraction test on GGBS.
(Source: B.S. Divsholi et al [5])

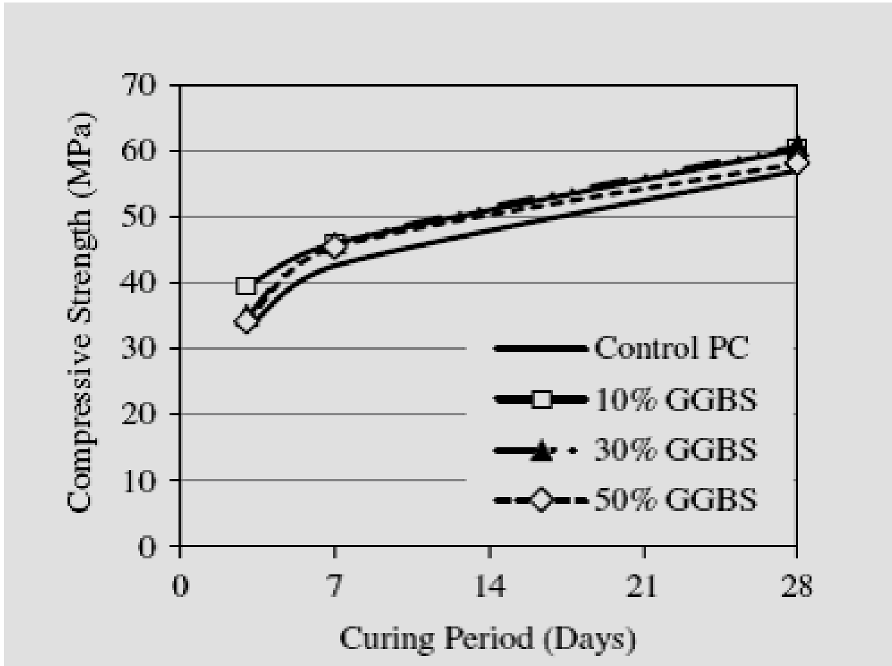


Fig. 2.16: Effect of GGBS replacement on compressive strength (Source: B.S. Divsholi et al [5])

Average pore size diameter decreases by 15, 30 and 47% while increasing the GGBS for 10, 30, 50% respectively. The average pore size GGBS blended cement significantly reduced with increase in the water curing duration to secondary pozzolanic reaction.

H.L. Chaithra et al [2] conducted experimental investigation on M40 grade of concrete in which GGBS was used as partial replacement of cement. The Cement has been replaced by GGBS in the range of 30%, 40%, and 50% by weight of cement. It is found that by the partial replacement of cement with GGBS and sand with quarry sand helped in improving the strength of the concrete substantially when compared to normal mix concrete. Compressive strength test was carried out for 7, 28 and 56 days while flexural and split tensile strength test was carried out at 28 days curing period.

S.K. Karri et al [1] studied on the characteristics of M20 and M40 grade of concrete with partial replacement of cement with GGBS. They performed experiments on the concrete incorporating GGBS to find the hardened properties of concrete i.e compressive strength, split tensile strength and flexural strength. They also performed durability analysis on the same concrete. From the study they concluded that there is increase in workability of concrete with increase in GGBS replacement". "At 40% replacement maximum gain in compressive strength, split tensile strength and flexural strength was observed. Form durability analysis they concluded that there is less effect of HCl on strength of concrete when compared with H_2SO_4.

S. Arivalagan [10] studied the effect of GGBS on the hardened properties of based concrete. He worked on M35 Grade of concrete with partially replacing cement by various percentages of GGBS. From his study it was found that GGBS based concrete showed increase in compressive and flexural strength. Maximum increase in strengths was observed at 20% replacement of GGBS.

M. Shariq et al [67] studied the effect of curing procedure on the compressive strength development of cement mortar and concrete incorporating ground granulated blast furnace slag. The compressive strength development of cement mortar incorporating 20, 40 and 60 percent replacement of GGBFS for different types of sand and strength development of concrete with 20, 40 and 60 percent replacement of GGBFS on two grades of concrete were investigated. Tests results showed that the incorporating 20% and 40% GGBFS is highly significant to increase the compressive strength of mortar after 28 days and 150 days, respectively.

A.A. Elsayed [42] investigated experimentally in his study the effects of mineral admixtures on water permeability and compressive strength of concretes containing silica fume (SF) and fly ash (FA). The results were compared to the control concrete, ordinary Portland cement concrete without admixtures. The optimum cement replacement by FA and SF in this experiment was 10%. The strength and permeability of concrete containing silica fume, fly ash and high slag cement could be beneficial in the utilization of these waste materials in concrete work, especially in terms of durability.

R.B. Kogbara and A. Al-Tabba [41] investigated the potential of GGBS activated by cement and lime for stabilization/solidification (S/S) treatment of a mixed contaminated soil. The results showed that GGBS activated by cement and lime would be effective in reducing the leachability of contaminants in contaminated soils.

A. Chanakya [31] reported that GGBS concrete is expected to show a higher surface concentration than OPC concrete due to its greater binding capacity. The Silica Fume concrete also has a smaller effective porosity than the OPC concrete. Replacing 50% of OPC with GGBS slightly increases weight sorptivity yet effective porosity is smaller than for OPC concrete.

2.5 Rice husk ash used as replacement of cement

Rice Husk Ash (RHA) which is an agricultural by-product has been reported to be a good pozzolan by numerous researchers. Rice Husk is one of the waste materials in the rice growing regions. This not only makes the purposeful utilization of agricultural waste but it will also reduce the consumption of energy used in the production of cement. Therefore Rice Husk is an agro based product which can be used as a substitute of cement without sacrificing the strength and durability [43]. Each tone of paddy can generate 0.2 tonne of husk. It is highly reactive pozzolonic admixture and produced by controlled combustion of husk retaining silica in the non crystalline form with cellular structure. The fineness of husk is found to be in the order of 50- 60 m^2/gm. Rice husk ash has been effectively used as simple cementitious coatings for concrete surfaces to act as a waterproofing barrier coupled with higher chemical resistance [152]. Fig. 2.17 shows a typical coating application of RHA in a water-treatment plant. Fig. 2.18 shows application of RHA in repair of RCC beams.

Fig. 2.17: Concreting Water Treatment Plant with Hyper 2000 (Source: R.N. Krishna [152])

Fig. 2.18: Repair of RCC Beams with Hyper 2000 (Source: R.N. Krishna [152])

Scanning Electron Micrographs (SEM) of OPC and RHA cement concrete samples were taken for manification of 2000 X. The samples were prepared out of hardened cement paste. Fig. 2.19 and Fig. 2.20 show Scanning Electron Micrograph of OPC and RHA respectively. SEM of rice husk ash blended concrete clearly shows large number of silicon fibers in concrete [152]. These silicon fibers are seen to be very effective in substantial resistance to corrosion of RHA blended cement concrete. Earlier experiments combined with SEM observations suggest that the structure of rice husk ash is similar to the composite material with silica fibers filled with cellulose material with the matrix consisting of lignin. These silica fibers constitute the greatest advantage when using rice husk ash in concrete and are responsible for its impressive performance in corrosive environments.

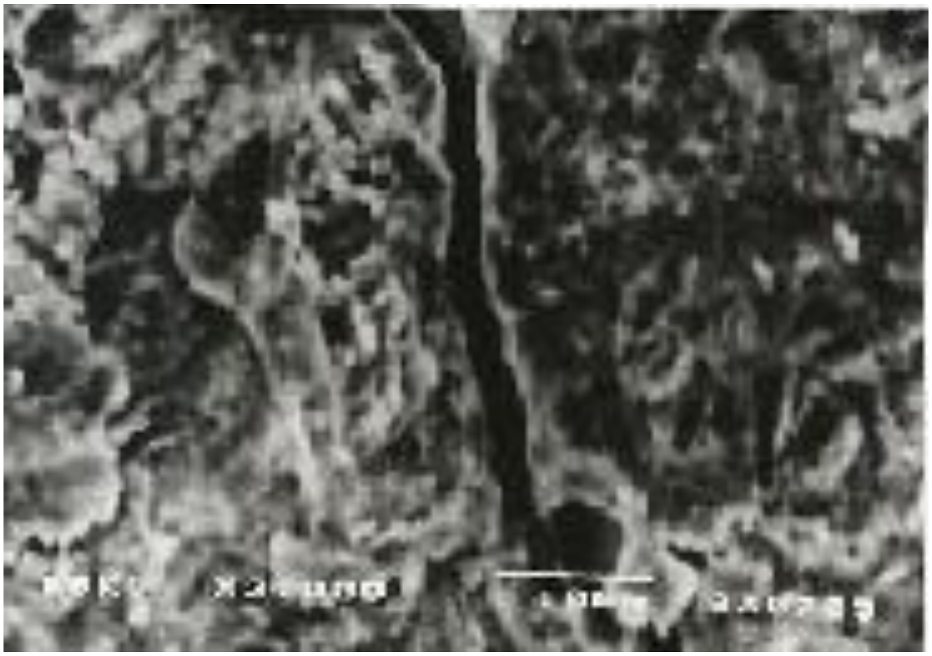


Fig. 2.19: SEM of OPC Concrete (Source: R.N. Krishna [152])

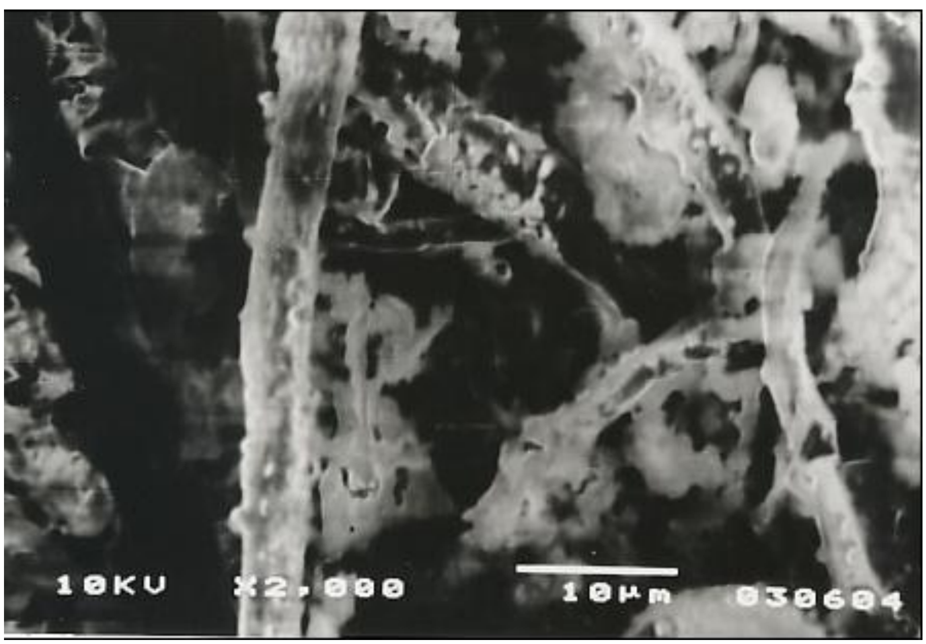


Fig. 2.20: SEM of Concrete with Hyper 2000 (Source: R.N. Krishna [152])

A. Shukla et al [43] investigated one type of commercially available RHA as supplementary cementitious material for cement and evaluated the threshold limit of cement replacement. They conducted experiments on two different grades of concrete i.e M30 and M60 which were designed as per IS 10262: 1982 [142]. Replacement of cement by rice husk ash showed in M30 grade of concrete compressive strength improvement upto the replacement of 10% in all ages. Both concrete mixes at 10 % rice husk ash level showed an increase in 3 to 10% compressive strength as shown in Table. 2.14 and Table. 2.15. There was so significant increase in flexural strength of concrete with rice hush ash content of 10% for grade M30 and M60. There was reduction in split tensile strength as the percentages of rice husk ash increased. Use of rice husk does not affect the tensile strength of concrete.

Table. 2.14: % change in compressive strength of M30 grade of concrete (Source: A. Shukla et al [43]))

Mix	7 days	28 days
BC	-	-
BC1	4.68	3.37
BC2	10.93	6.74
BC3	-6.25	13.48
BC4	-14.06	-17.97

Note- Negative sign shows decrease in strength.

Table. 2.15: % change in compressive strength of M60 grade of concrete (Source: A. Shukla et al [43])

Mix	7 days	28 days
CC	-	-
CC1	2.88	4.87
CC2	4.23	6.50
CC3	-4.80	0.80
CC4	-8.65	-5.69

Note- Negative sign shows decrease in strength.

R. Kishore et al [153] investigated the mechanical properties of high strength concrete with different replacement levels of OPC by RHA. Concrete cubes of size 150mm×150mm×150mm and cylinders of size 150mm×300mm and beam of size 500mm×100mm×100mm were casted to study the mechanical properties of M40 and M50 grades of concrete. It was found that as the replacement of cement by RHA in concrete increases, the decreases in workability was reported.

From Table. 2.16 it can be observed that for M40 grade of concrete with 0% RHA the slump reported was 40 mm. At 15 % replacement level for M40 the slump reduced to 32mm. Percentage loss in slump was reported to be 20% for M40 and 22% for M50 grade of concrete. The optimum replacement level of RHA was found to be 10% as shown in Table. 2.17

Table. 2.16: Slump and Compaction factor values of M40 and M50 grades concrete (Source. R. Kishore et al [153])

Rice Husk Ash %	M40		M50	
	Slump (mm)	Compaction Factor	Slump (mm)	Compaction Factor
0	40	0.87	35	0.87
5	37	0.86	32	0.83
10	35	0.82	29	0.81
15	32	0.80	27	0.80

Table. 2.17: Compressive strength for M50 grade at different ages of curing (Source. R. Kishore et al [153])

Rice Husk Ash %	Compressive strength (MPa) of M50		
	7 days	28 days	90 days
0	48.31	59.37	62.50
5	42.00	56.40	58.36
10	38.40	53.43	56.40
15	37.37	50.46	52.50

2.6 Ultra fine slag used as replacement of cement

Ultra fine slag is more advanced form of GGBS in which slag is further ground to less than 20 micron [1,4]. As a result its specific surface area is increased dramatically to 3000-5000m^2/kg (Bet Analysis). Particle shape of ultrafine slag is spherical (Scanning electron microscope) which due to ball bearing effect gives increased workability at much reduced water content. Ultra fine slag is produced in India by a joint venture with Ambuja cement Ltd and Alcon developers with a brand name Alccofine. One of the unique properties of Alccofine is its optimized particle size distribution as it is manufactured with special equipments in a controlled manner. Alccofine are available in market as per different percentages of calcium silicate. Alccofine 1203 has low calcium silicate and Alccofine 1101 has high calcium silicate. Alccofine 1203 is generally used as supplementary cementing material due to its fineness and particle size whereas Alccofine 1101 is used for soil stabilization purposes as a grouting material. Study Counto microfine products pvt. Ltd. was conducted by Ambuja cements in India which presented the results of examination carried out on Alccofine 1203 in comparison with Silica Fume in concrete, and the effect it has on workability, water requirement, admixture requirement, strength and durability were discussed. Thus, obtained results confirm that properly designed mixes with judicious use of Alccofine 1203 exhibits superior properties than Silica Fume. The mix deigns containing Alccofine 1203 were prepared to give optimum advantages in terms of technical as well as economical benefits. The obtained comparative results clearly confirm the superior performance of Alccofine 1203 over Silica Fume. As per the methodologies carried out, in first case with equal amount of water/binder ratio and HRWR in concrete specimen the comparative results of Alccofine 1203 was better than the silica fume. The results are similar even in other two methodologies. Increase in strength & workability and decreased HRWR ratio is mainly due to the optimized Particle Size Distribution and proper chemical composition of Alccofine 1203. It facilitates to reduce water content and/or HRWR dosage to provide superior performance of concrete in terms of workability and compressive strength over Silica Fume. Long term pozzolanic activity of Alccofine 1203 can be observed as a function of its particle size distribution and chemical composition. Alccofine 1203 results in to formation of dense pore structure and inbuilt CaO provides increased secondary hydrated products because of which improved strength gain at early as well as later ages are observed. Secondary hydrated products formed due to pozzolanic and cementitious hydration reaction fills the pores. This reduces the permeability of hydrated products to great extent and protects concrete from chemical attack.

S.P. Upadhyaya and M.A. Jamnu [8] investigated effect on Compressive strength of High Performance Concrete (HPC) incorporating Alccofine and Fly Ash and concluded that the addition of Alccofine shows an early strength gaining property and that of Fly ash shows long term strength. The combination of Ordinary Portland cement-fly ash-Alccofine concrete was found to increase the compressive strength of concrete on all ages when compared to concrete made with fly ash and Alccofine alone.

D. Soni et al [17] investigated the Strength of concrete of grade M80 with locally available ingredients and then to study the effects of different proportions of Alccofine and fly ash in the mix and to find optimum range of Alccofine and fly ash content in the mix. The Alccofine and fly ash is added by weight of cement as a replacement. The Concrete specimens were tested at different age level for mechanical properties of concrete, namely, cube compressive strength, flexural Strength. Perfect proportion of replacing cement material as Alccofine and fly ash was obtained without losing its strength. Alccofine performed better when compared to other slag materials and microsilica. It helps to make concrete workable. Perfect dosages of Alccofine and fly ash proportion was concluded as 8% of Alccofine and 16% of fly ash. From their study it was found that Alccofine helps to increase strength in both compressive and flexural strength upto certain limit.

S.B. Suthar and B.K. Parekh [16] studied the strength development of high strength concrete containing alccofine and fly-Ash in which the compressive strength was determined at 56 days of curing. The results indicated that the concrete made with varying proportions generally show excellent fresh and hardened properties since the combination is somewhat synergistic. The addition of Alccofine shows an early strength gaining property and that of fly ash shows long term strength. The ternary system that is ordinary Portland cement-fly ash-alccofine concrete was found to increase the compressive strength of concrete on all age when compared to concrete made with fly ash and Alccofine alone.

Y.H. Patel et al [15] studied the durability of high performance concrete incorporating alccofine and flyash. The study investigates the performance of concrete mixture in terms of Compressive strength, Chloride Attack tests, Sea water test and Accelerated corrosion test at age of 28 and 56 days. In addition the optimum dosage of Alccofine and fly ash from given mix proportion was determined. Result showed that concrete incorporating Alccofine and fly ash has higher compressive strength and Alccofine enhanced the durability of concretes and reduced the chloride diffusion. An exponential relationship between chloride permeability and compressive strength of concrete was exhibited.

M.S. Pawar and A.C. Saoji [14] studied the effect of alccofine on self compacting concrete. The study explores the use of the Alccofine powder to increase the amount of the fines and hence achieve self compatibility. The study focuses on comparison of the properties of SCC with fly ash and Alccofine to that of standard one with fly ash. Properties of SCC with fly ash and Alccofine were evaluated and compared with those of SCC with fly ash. From the experimental investigations, following conclusions were established that the addition of Alccofine in SCC mixes increases the self compatibility characteristic like filling ability, passing ability and resistance to segregation and the fresh properties and harden properties of SCCs with 10% Alccofine were superior than SCCs with 5% and 15% of Alccofine.

A. Pathik et al [49] reported that replacing 10% cement by Alccofine improves workability, workability retention and permits additional strength gains. Alccofine strength gains are at both early and later ages. This makes it a preferred material for use in high performance concrete.

M. Venu and P.N. Rao [154] investigated that the percentage increase of compressive strength of concrete was 11.06 and 17.6% at the age of 7 and 28 days by replacing 50% of cement with GGBS and 25% of sand with ROBO sand The percentage of increase in the compressive strength were 19.64 and 8.03% at the age of 7 and 28 days and the percentage of increase in the split tensile strength was 1.83% at the age of 28 days, by replacing 30% of sand with ROBO sand with 1.5% admixture.

K. Pazhani and R. Jeyaraj [48] reported that the water absorption for 30% replacement of cement with GGBS decreases by 4.58%. Also, the water absorption for 100% replacement of fine aggregate with copper slag decreases by 33.59%. The chloride ion penetrability for 30% replacement of cement with GGBS decreases by 29.90%. Also, the 100% replacement of fine aggregate with copper slag decreases by 77.32%. The pH value for 30% replacement of cement with GGBS decreases by 0.39%. Also, for 100% replacement of fine aggregate with copper slag decreases by 3.04%.

Saurav and A.K.Gupta [4] investigated the study of strength relationship of concrete cube and concrete cylinder using ultrafine slag alccofine and concluded that the hardened properties of concrete with alccofine were enhanced at the optimum alccofine percentage. After 12% replacement of alccofine there was very significant change in the strength of conventional concrete. The cylindrical strength of concrete increased after addition of alccofine but was always less than its cubical counterpart.

2.7 Steel fiber reinforced concrete

Advancement cement based materials and improved concrete construction techniques provide opportunities for the design of structures to resist severe loads resulting from earthquakes, impact, fatique and blast environments [137]. Conventional concrete cracks easily. When concrete is reinforced with random dispersed fibers, we get favorable behavior for repeated loads. Fibers prevent micro cracks from widening and hence make the components ductile and tough [95,117,137]. Researches carried out have established that addition of fibers improves the static flexural strength, fatigue, ductility and fracture toughness of the material [26,39,54,103,107]. Typical ranges of the application of fiber reinforced material are shown in Table. 2.18. The durability of concrete when reinforced with conventional rebars is a major concern in aggressive environments. To address this there have been efforts in recent years to develop alternatives to conventional rebars. Fibers reinforced plastics and fiber reinforced concrete have shown better behavior because of their inherent ability to stop or delay crack propagation. Fig. 2.21 shows a four phase representation which defines fiber reinforced mortar and concrete.

Table. 2.18: Typical ranges of application of fiber reinforced concrete (Source: A. R. Shantakumar [137])

Volume fraction (%)	Matrix	Application
$V_f < 0.5$	Concrete	Pilecaps members
$0.5 < V_f < 3$	Concrete	Pavements, joints, machine foundation
$3 < V_f < 8$	Mortar	Cement sheets, repair works
$8 < V_f < 20$	Paste/slurry	Asbestos cement

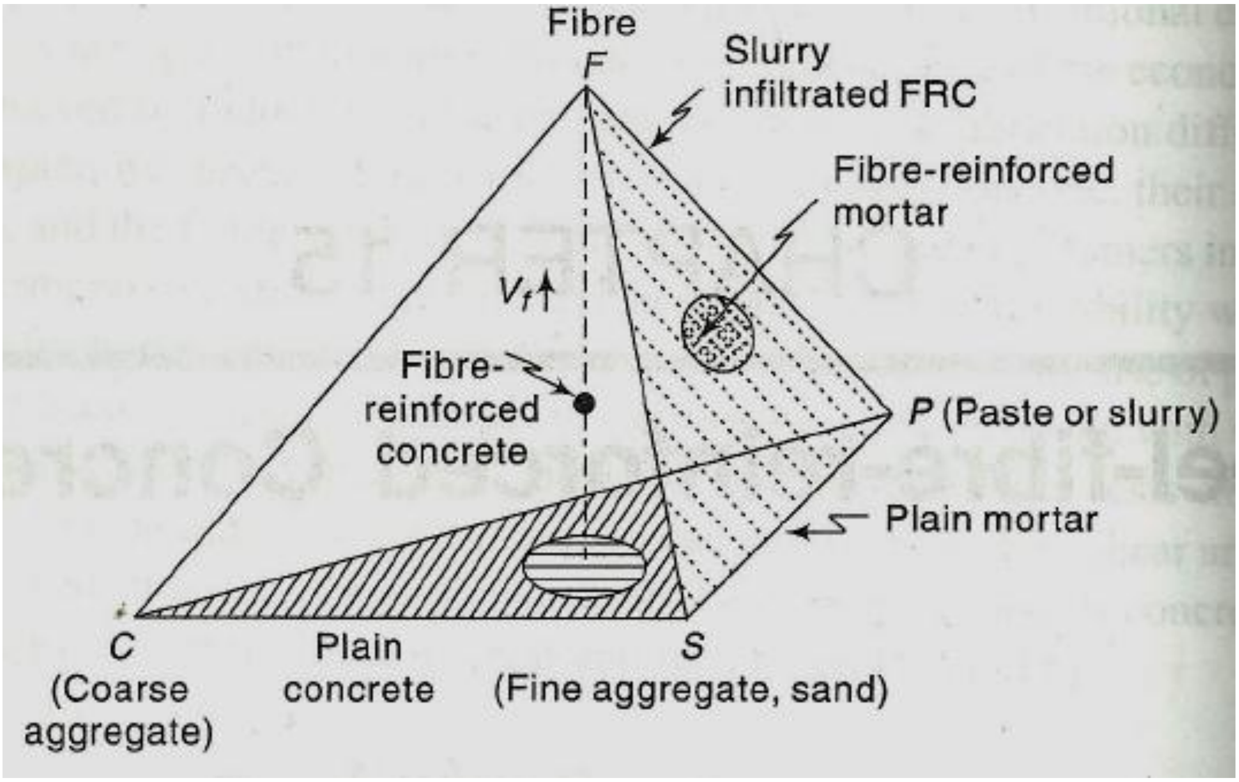


Fig. 2.21: Four phase representation of FRC (Source: A. R. Shantakumar [137])

Reinforcing fibers stretch more than concrete under loading. Materials used in fiber reinforcing include acrylic, asbestos, cotton, glass, steel, etc. Acid resistive glass and steel are common. The percentage of fibers in concrete mix is based on volume and is expressed as a percentage of mix. 1% to 2% of fibers are common [55,64,70,98,137]. The main properties of FRC in tension, compression and shear are influenced by the type of fiber, volume fraction fibers aspect ratio and orientation of fibers in the matrix. The fiber and the matrix share the tensile load until the matrix cracks and then almost full load gets transferred to the fiber. This predominant feature of FRC gives rise to favourable dynamic properties such as energy absorption and fracture toughness which distinguish FRC from conventional concrete [115,137].

Studies on the tensile strength of fibrous composites have been reported by P. S. Mangat [129]. The effects of fibers in a cementitous material are principally to cause relief of tensile stress at the crack tip and prevent unstable crack propagation.

A. Kelly [130] investigated the mechanism of fiber pull out test as shown in Fig. 2.22. Debonding of fiber characterizes the straight portion of the curve OA. In the case of short fibers the debonding occurs at short maximum load. The debonding energy per unit area is obtained by dividing the area OAB under the stress strain curve by the surface area of the fiber.

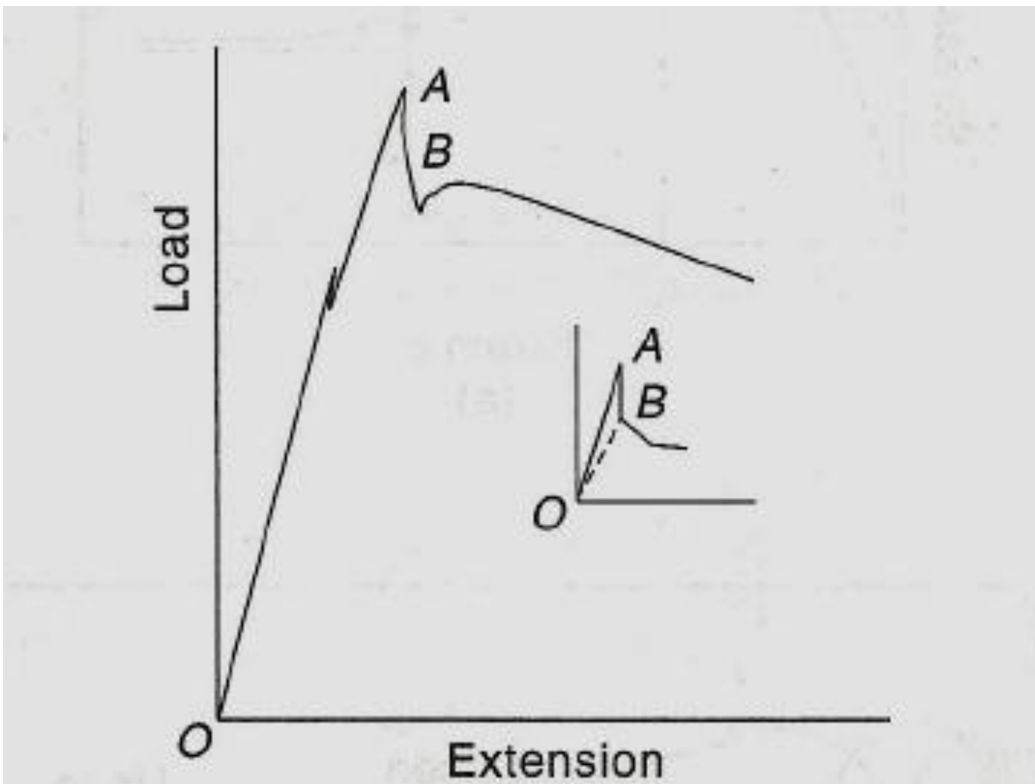


Fig. 2.22: Typical load extension curve for fiber pull out test (Source: A. Kelly [130])

Though the increase in the compressive strength of FRC is marginal and ranges from 0% to 20%, the post cracking compressive stress strain response changes substantially. This change is generally characterized by a noticeable increase in strain at peak load and a significant increase in ductility beyond ultimate load, resulting in substantially higher toughness. This increased toughness is advantageous in preventing sudden failures such as earthquake and blast type of loading as proposed by V. Ramakrishnan [120]. The typical increase in the toughness index varies between 200% to 300%. The improvements in ductility and energy absorption capacity resulting from the increase in fiber volume fraction are comparable to those improvements due to the effect of confining steel of conventional concrete by transverse as shown in Fig. 2.23 (a) and (b). Since confinement by transverse steel produces improvements of the same nature as fiber reinforcement in the compressive behavior of concrete for a certain reinforcement index of each fiber type, there exists a confinement condition which results in comparable compressive stress-strain relationship of fiber reinforced concrete. Thus the characteristic model of FRC consists of two curvilinear ascending and descending branches similar to confined concrete as shown in Fig. 2.24. It is evident that the improvement in material toughness can be assessed as the ratio of total area (A_1+A_2) under stress –strain curve up to a strain limit beyond the peak stress to the area up to its peak (A_1). Thus the benefits of confining steel in the conventional earthquake resistance design can also be attained by suitable inclusion of fibers.

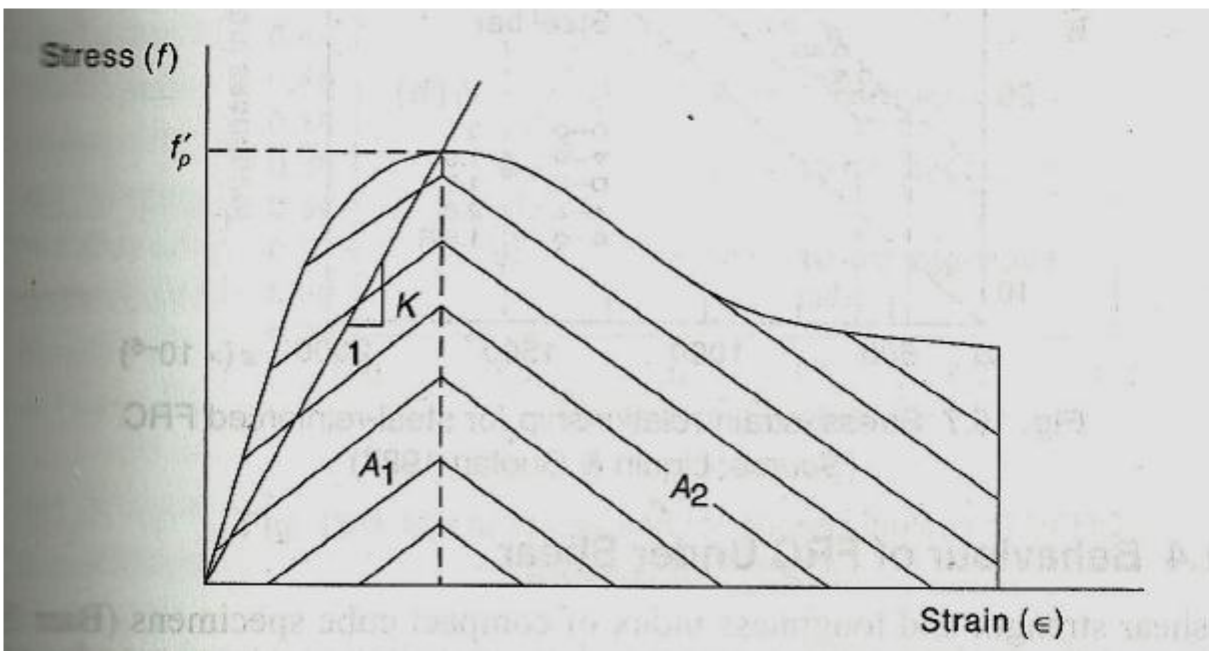


Fig. 2.24: Characteristics of compressive stress strain relationship of concrete and fiber reinforced concrete (Source: V. Ramkrishna [120])

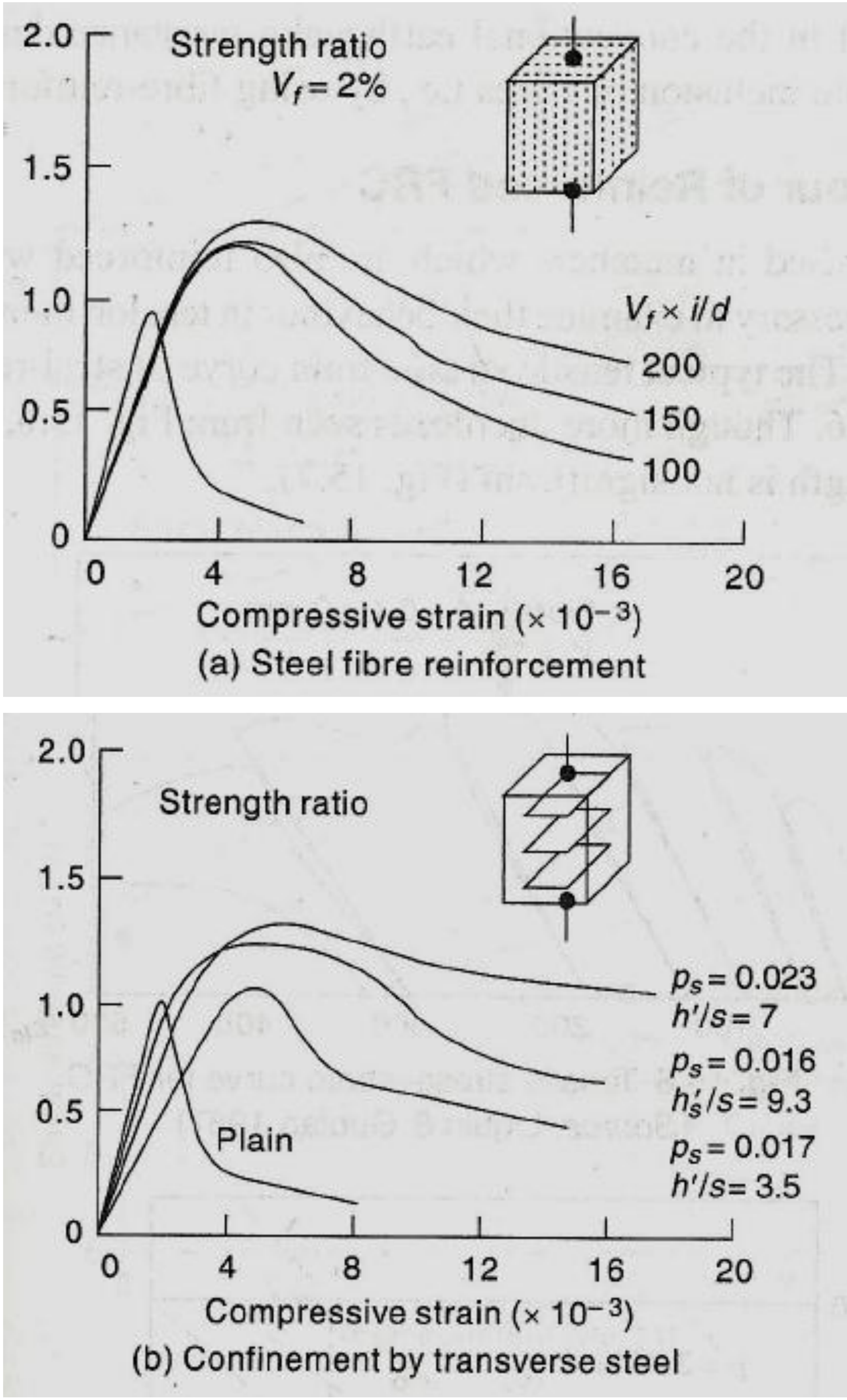


Fig. 2.23: Effect of fiber reinforcement and containment by transverse steel on compressive behavior of concrete (Source: V. Ramkrishna [120])

B. Barr [121] investigated the shear strength and toughness index of compact cube specimens as shown in Fig. 2.25 and Fig. 2.26. It can be observed that shear strength was not affected by fiber volume. However the post cracking toughness increased uniformly with increases in fiber content. This again shows a favourable FRC behavior in earthquake and blast prone areas.

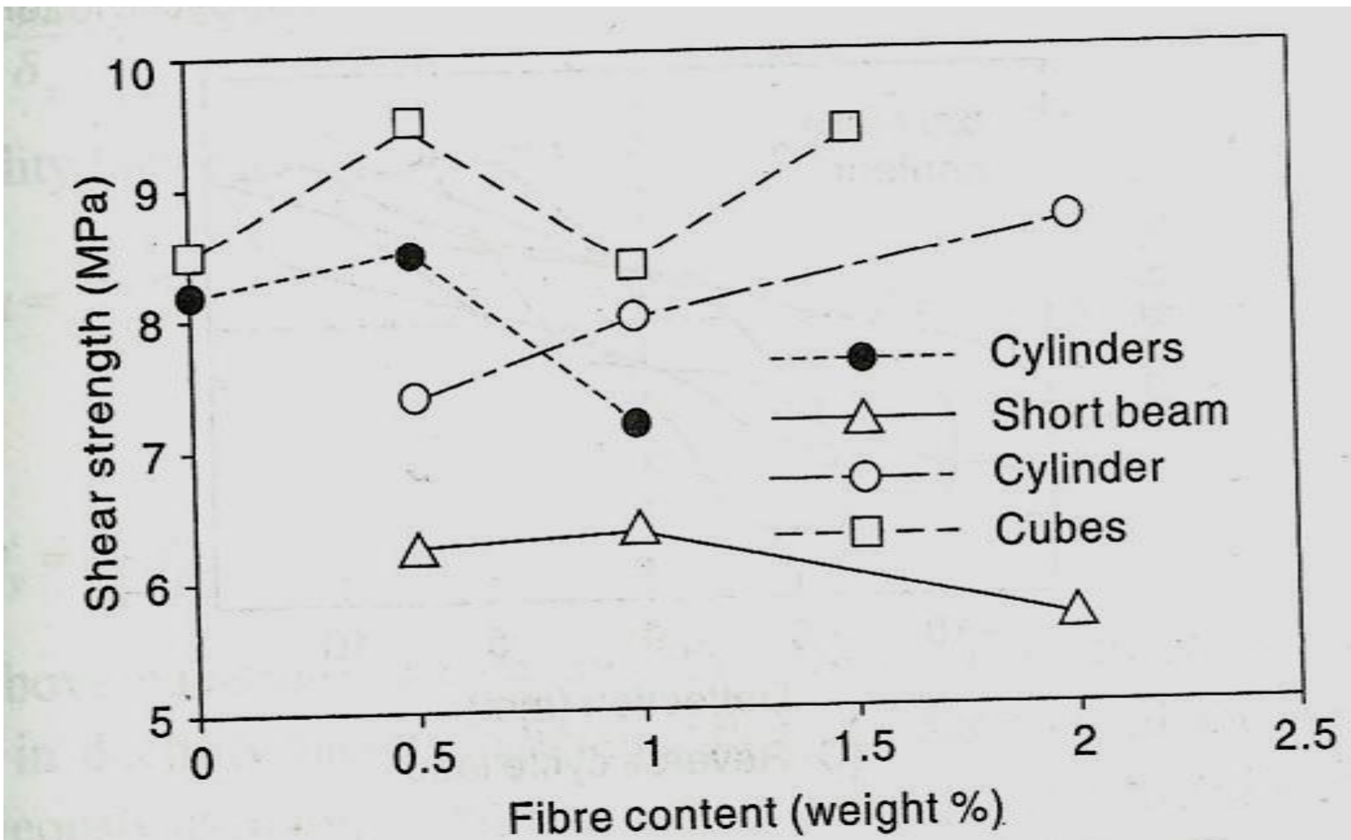


Fig. 2.25: Shear strength of SFRC (Source: B. Barr [121])

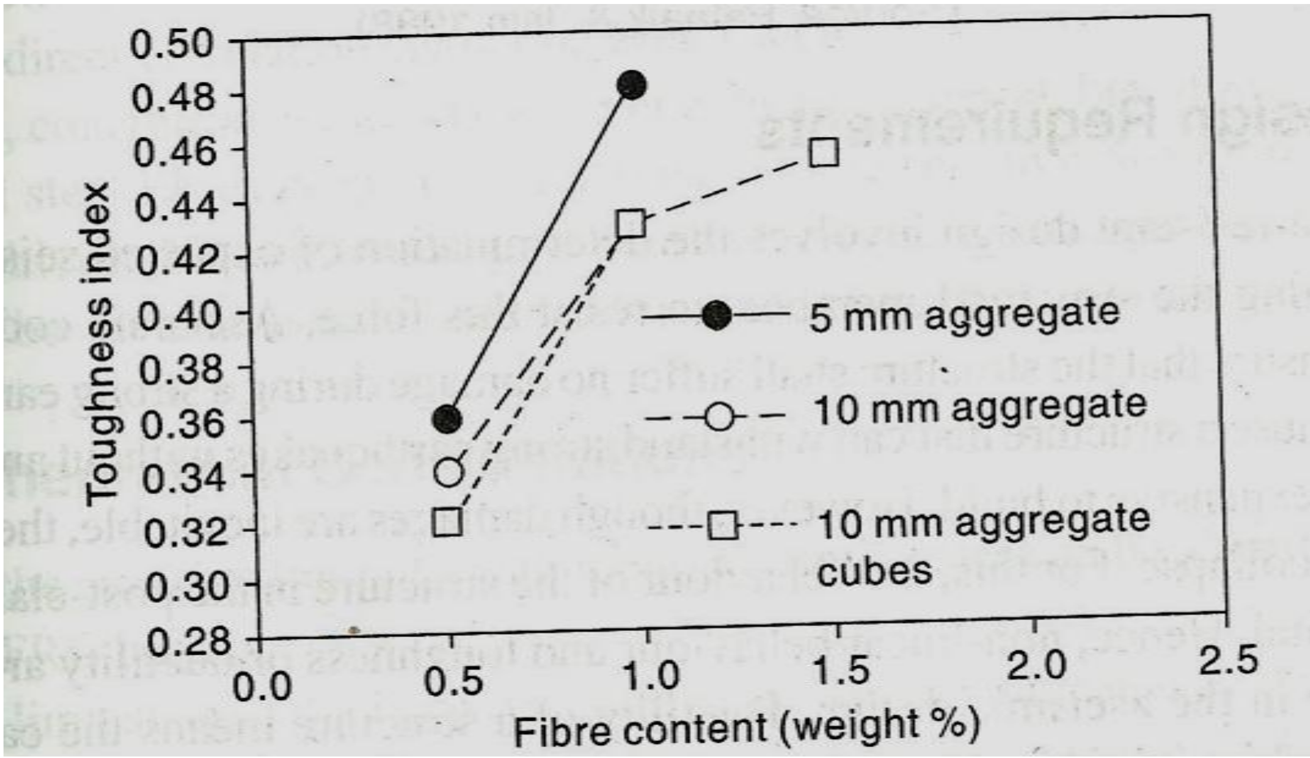


Fig. 2.26: Toughness index of SFRC (Source: B. Barr [121])

A.K. Patnaik and S.K. Jain [119] showed that fiber reinforced concrete functions better under cyclic loading due to improved toughness. The load – deflection behavior of SIFCON beam is shown in Fig. 2.27. It can be seen that under cyclic and reversed cyclic loads fiber reinforced beams showed better results.

C.H. Hanger [128] has reported an experimental comparison between two exterior beam column joints of a typical multistorey frame. One joint was conventionally reinforced while in the other fibrous concrete was used in addition to stirrups at farther spacing. Superior performance of concrete joint was evident from results of his investigation.

M. Lakshmipathy [125] has studied the replacement of stirrups with fiber concrete in beam column junctions with various amounts of replacement. From her experimental investigations it was concluded that ductility was approximately increased to three times for fibrous joints (Fig. 2.28). She also reported an elaborate experimental investigation of two quarter full sized seven storey frame, one made of RC and the other of FRC joints. The frames were subjected to earthquake type lateral load. Fig. 2.29 shows a comparison of cumulative energy absorption capacities for FRC and RC frame. It is evident that the FRC frame exhibits more than twice the cumulative energy absorption capacity as the RC frame.

2.8 High Performance Concrete

High-performance concrete is defined as concrete that meets special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices [136]. Ever since the term high-performance concrete was introduced into the industry, it had widely used in large-scale concrete construction that demands high strength, high flow ability, and high durability. A high-strength concrete is always a high performance concrete, but a high-performance concrete is not always a high-strength concrete [6,13,136,]. Durable concrete specifying a high-strength concrete does not ensure that a durable concrete will be achieved. It is very difficult to get a product which simultaneously fulfills all of the properties. In general better durability performance has been achieved by using high strength low w/c ratio concrete [136,137]. Though in this approach the design is based on strength and the result is better durability, it is desirable that the high performance is addressed directly by optimizing critical parameters such as the particle size of the required materials.

High strength concrete exhibits sensitivity to early drying and faster autogenous shrinkage. The high autogenous shrinkage of silica fume in high strength concrete was noticed [136]. This effect is due to the high paste volume used in high strength concrete. A high autogenous shrinkage leads to early age cracking. This disadvantage can be overcome by proper mix proportioning and early efficient curing. R.K. Dhir [110] has shown that the shrinkage strain is not really a problem and its value is less than that of conventional strength concrete as shown in Table. 2.19 and Fig. 2.27

Table. 2.19: Comparative values of indicative shrinkage strains (Source: R.K. Dhir [110])

	Conventional concrete	High-strength concrete
Total shrinkage strain	470	320
Extrapolation to the ultimate	650	340
Autogenous shrinkage strain	120	200
Extrapolation to the ultimate	120	220
Desiccation shrinkage strain	350	120
Extrapolation to the ultimate	530	120

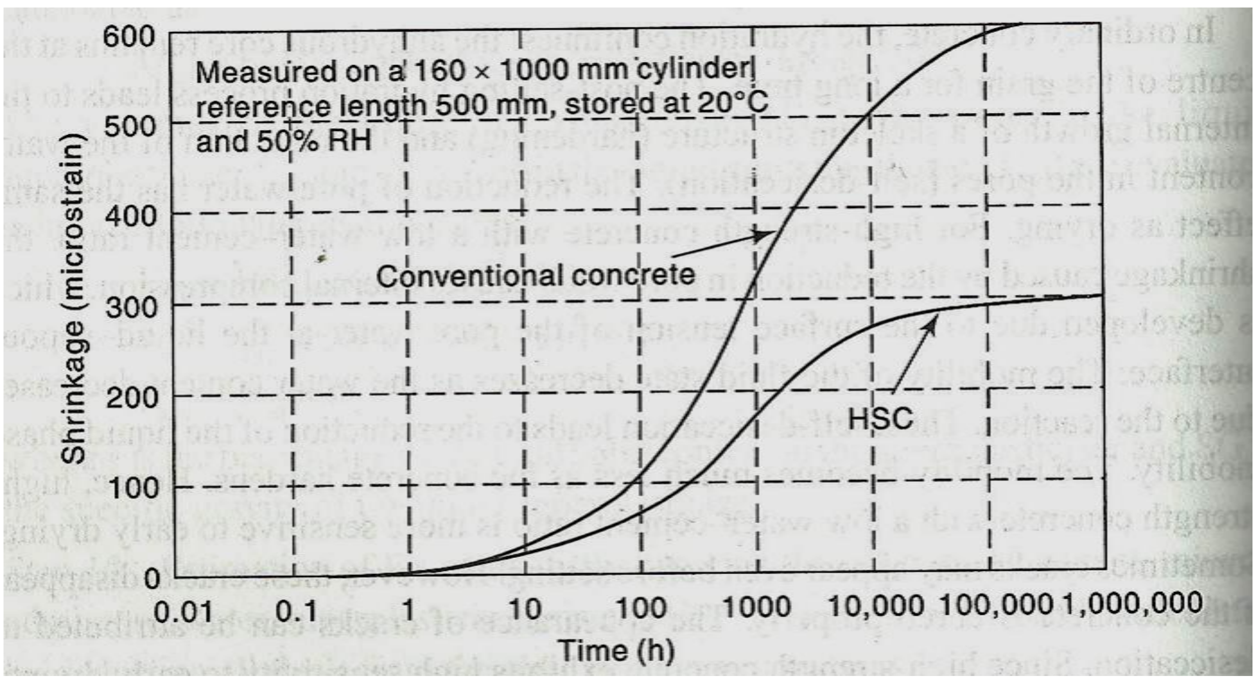


Fig. 2.27: Shrinkage of high strength concrete (Source: R.K. Dhir [110])

High strength concrete is considerably more brittle than normal concrete. S.P. Shah and S.H. Ahamed [155] explained the uniaxial compressive stress- strain curve for ultra high strength concrete (Fig. 2.28) with normal concrete. To obtain the falling branch of the stress strain curve of high strength concrete it is necessary to test the specimens in a closed loop digitally strain controlled machine. The post peak response of high strength concrete is characterized by a steep descent compared to the gradual decrease witnessed in normal concrete.

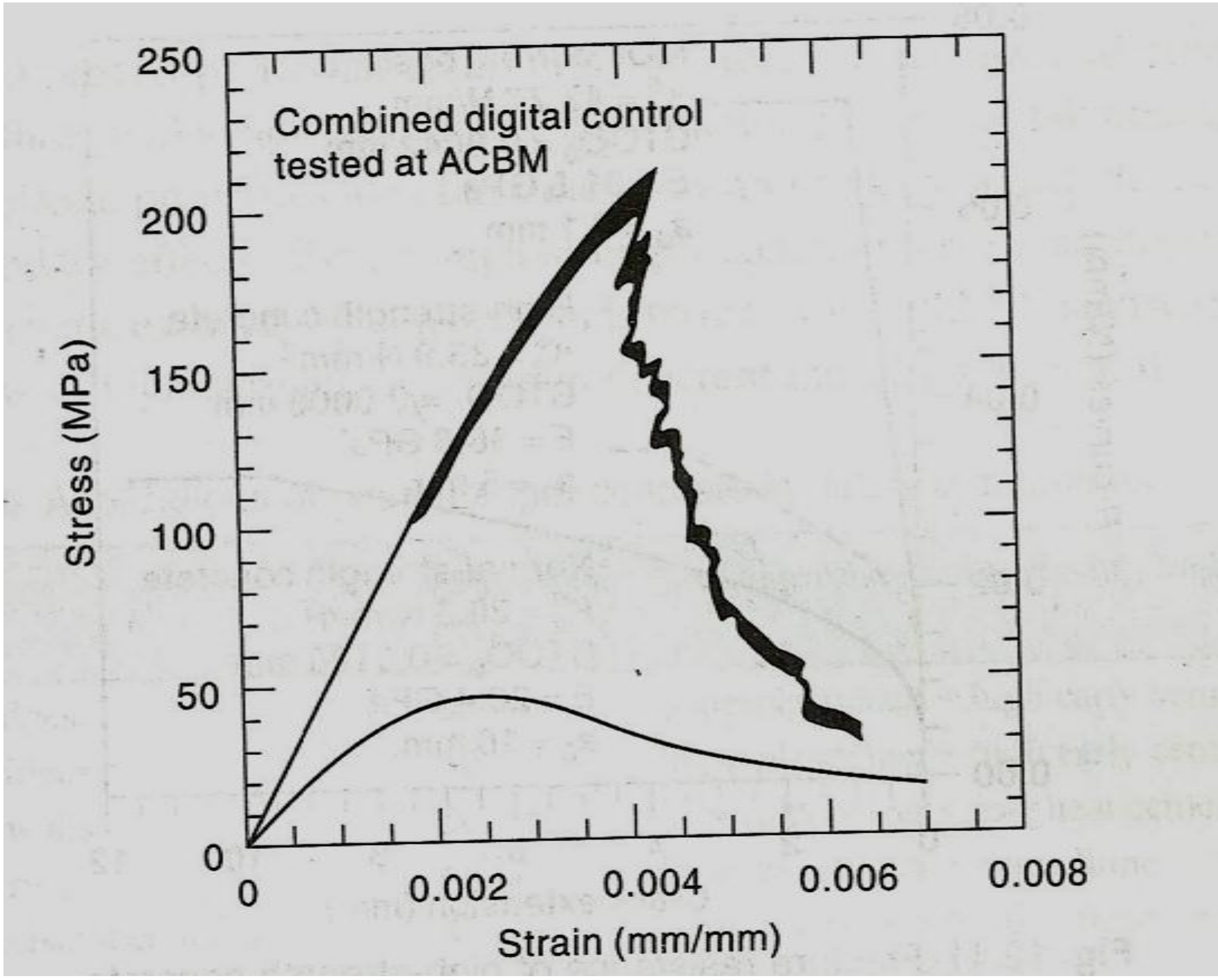


Fig. 2.28: Stress strain curve for ultra high strength concrete. (Source: S.P. Shah and S.H. Ahmed [155])

Partial replacement of cement by mineral admixtures reduces water requirement to obtain a particular consistency [136]. The water reduction and increase in mobility is caused by both spherical particle shape and adsorption i.e. dispersion mechanism that is similar to water reducing admixtures. Fine particles of mineral admixture get adsorbed on oppositely charged surface of cement particles and prevent them from flocculation [136]. Fig. 2.29 shows the absorption levels of concrete made with different percentages of PFA content as explained by R. K. Dhir [110]. The result shows that the excellent permeation properties can be achieved with different strengths depending upon the percentages of PFA used. Clearly a particular permeation level can be achieved with a lower strength provided the percentage of PFA is more.

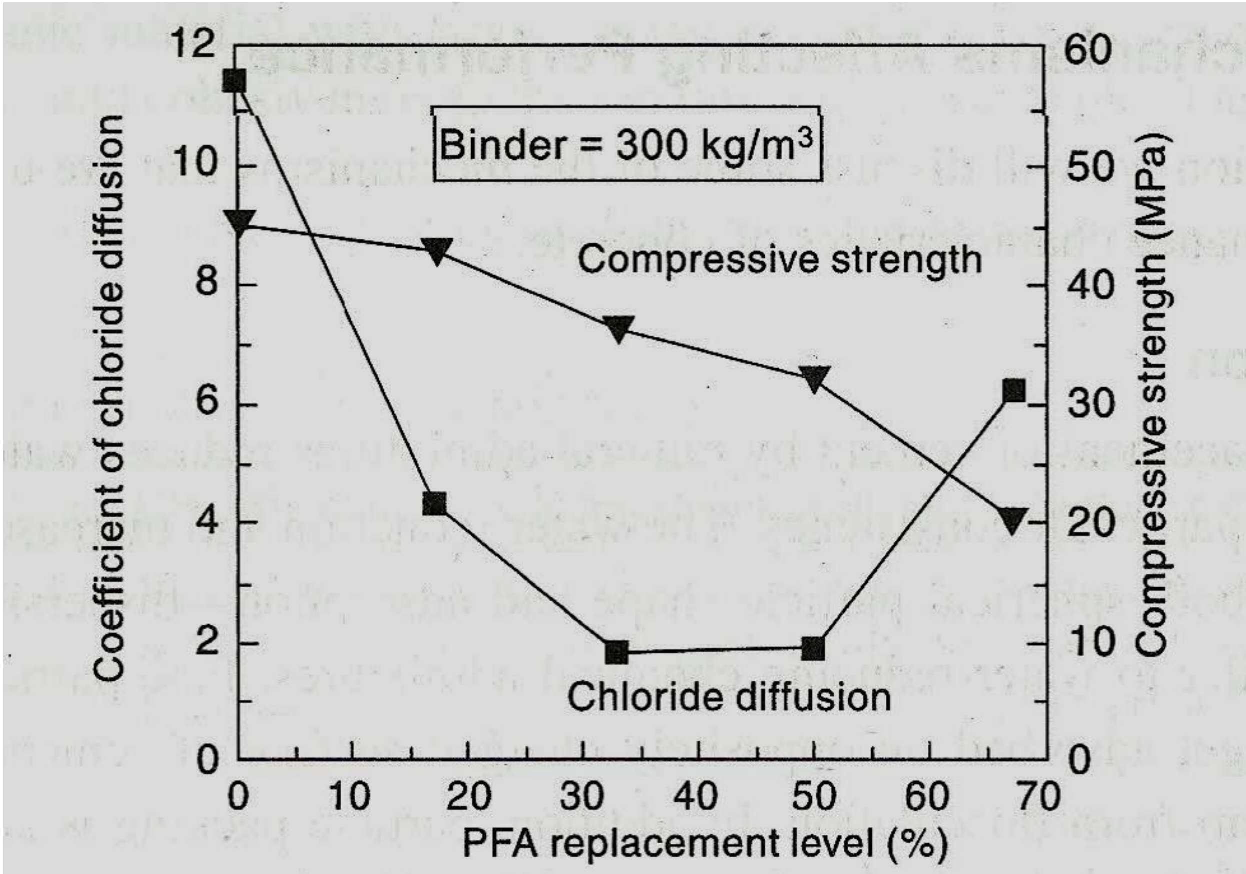


Fig. 2.29: Absorption levels of concrete made with different percentages of PFA (Source: R. K. Dhir [109])

Study done by R. Jones et al [134] showed that mineral admixtures cannot control carbonation as shown in Fig. 2.30. Concrete made with Portland cement has the lowest carbonation depth. It is evident that higher strength can control carbonation depth.

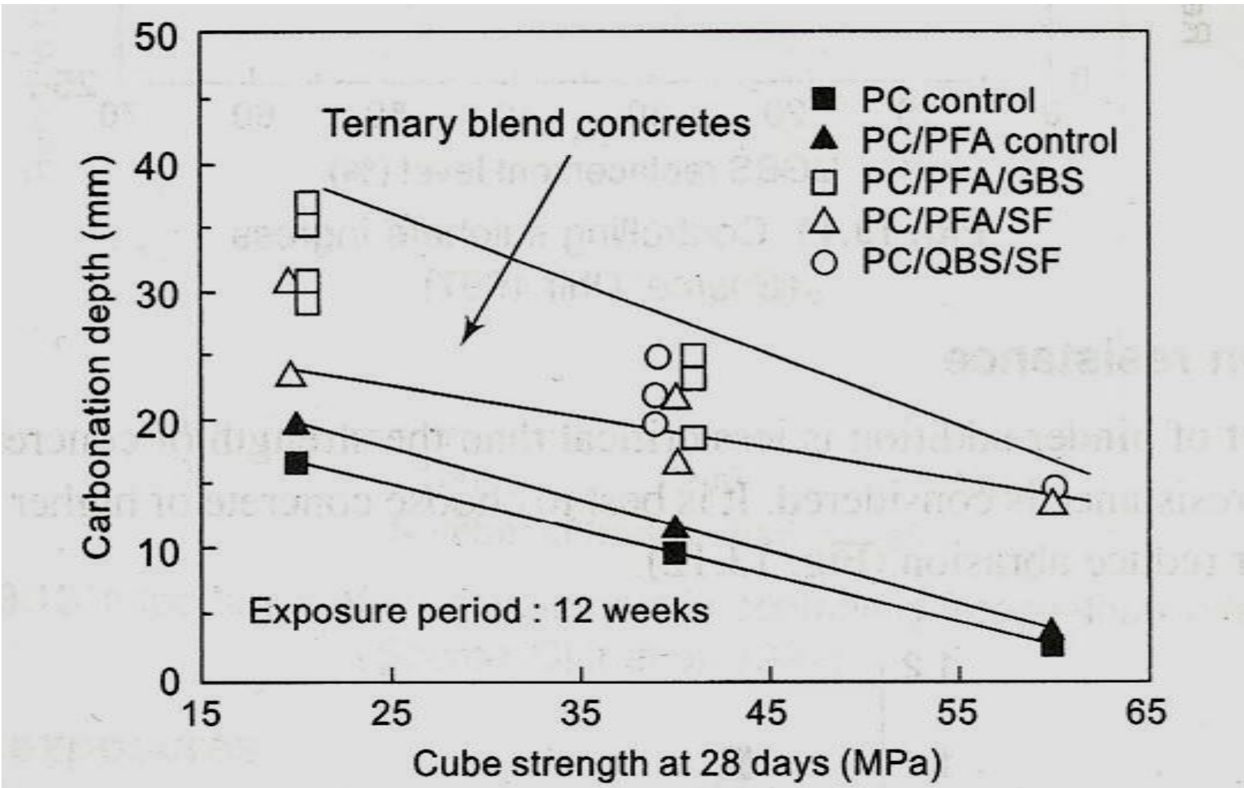


Fig. 2.30: Importance of concrete strength in controlling carbonation depth (Source: R. Jones et al [134])

Francois de Larrard and Thierry Sedran [101] proposed a mix proportioning for HPC considering packing density and segregation ability of dry packing particles. They focused on the properties of fresh concrete and the mechanical properties of hardened concrete using a model of aggregate particles surrounded by cement based matrix. The practical example is also presented, dealing with the design of special HPC for pavement application

G. Siva Nageswara Rao [112] proposed a mix proportioning method to obtain strength to effective w/b ratio relationship for a given set of materials and for the same workability for the HPC with fly ash and ground granulated blast furnace slag. When mineral admixtures are used, their effect on the strength of concrete varies significantly depending on the properties of mineral admixtures and with the characteristics of concrete mixture. They also discussed that the effectiveness of superplasticizers depends on the dosage used, ambient temperature, cement chemistry, fineness and other characteristics of the binder. They proposed two efficiency factors, first, a general efficiency factor and the second factor, corresponding to the percentage replacement. If the efficiency factor is known, the strength of mineral admixture mixes can be determined by the equation

$S = A_1 [c /w] + A_2$ for without mineral admixtures ---------------------------------(2.1)

$S = A [c+kf /w] + A_2$ for with mineral admixtures ----------------------------------(2.2)

where, S is the compressive strength in MPa, c is the cement content in kg/m^3, f is the mineral admixtures content in kg/m^3, k is the efficiency factor and A_1, A_2 are arbitrary constants. These arbitrary constants are reported to be influenced by type, size and grading of aggregate, type of cement, period of curing, etc. Hence, it is necessary to obtain strength to effective w/b ratio relationship for a given set of materials and for the same workability.

Y. Shi et al [103] investigated the compounding effect of silica fume with phosphorous slag or lime stone powder on the rheological behaviour of HPC and revealed that the partial replacement of cement with silica fume can improve the fluidity and rheological behaviour of HPC. They also concluded that when the silica fume content was up to 12 percent, plastic viscosity and yield stress became maximum, and concrete had lowest fluidity. They found that higher replacement level of fly ash will reduce the temperature rise and with high dosage of super plasticizers it will cause retardation in hydration.

Durability of concrete is a well-known term that expresses the ability of this material to keep its original properties unchanged over time. The term service life has a wider meaning since it defines the time throughout which the whole structure will keep its serviceability, i.e. the service that will be rendered above an acceptable level over an anticipated period. The term service life has become popular in relatively recent time when the research studies carried out on several structures suffering severe damage until failure evidenced that concrete had not deteriorated. This fact, along with the existence of 100-year-old buildings and bridges that are still in service, is the best proof that structure stability does not depend only on concrete durability. In other terms, durability of concrete affects the service life of a structure but must not be confused with it. Nowadays, it is generally acknowledged that the service life of a structure essentially depends on the optimization of four principal factors as follows:

• Materials durability,

• Structural and mix design,

• Construction process,

• Maintenance.

L. Czuban and J. Marchand [57] studied the repair durability of reinforced concrete structures affected by steel corrosion. Special reinforced concrete samples were designed to investigate all aspects of this complex problem. Natural conditions leading to chloride contamination and corrosion initiation were reproduced in the laboratory by subjecting specimens to numerous wetting and drying cycles in a controlled environmental chamber for more than 14 months. The initiation of the corrosion reaction was monitored using three different electrochemical techniques. Samples were then repaired using different techniques and the corrosion behaviour of the repaired specimens was investigated for several months. Test variables included the characteristics of the repair concrete. Results shed a new light on the basic mechanisms affecting the durability of repairs. Data indicate that improper removal of chloride contaminated concrete and inappropriate selection of the repair concrete can have a detrimental influence of the durability of the repaired element.

P. Qiao et al [60] investigated the accelerated degradation and durability of Concrete in Cold Climates and concluded that the damage and degradation in the concrete samples can be effectively accumulated (accelerated) by using the F/T conditioning protocol (ASTM C666). Both the dynamic modulus of elasticity and fracture energy tests were capable of probing the material degradation by the F/T cycles. Fracture energy test method was more sensitive to screen material degradation and better associated with degradation of aggregate, since the degraded aggregate is prone to fracture. After 1500 F/T cycles, the material showed more than 63.8% of fracture energy reduction; while there is only about 25.3% of dynamic modulus reduction after 1500 F/T cycles. The Vickers indentation test can be an effective test method to discern the degradation rate of intra-grannular (like aggregate and cement paste) and inter-grannular (e.g., aggregate-paste interface)

F. Massazza [58] studied about the durability of concrete and through his research he concluded that concrete is a durable material and that serious deterioration of concrete structures is due either to exceptional events or to exquisitely human factors like the lack of knowledge or negligence. This opinion was strengthened by the fact that over the last fifty years science and technology of materials have developed gradually so that cement and concrete performance has appreciably increased. Therefore, a longer service life of concrete structures does not generally depend on concrete durability but upon accurate structural and mix design, careful construction process, and diligent maintenance. These factors are related to human behavior and their improvement requires that engineers and their staff were better educated in relation to the materials properties, with more attention being devoted to surveillance of construction steps and maintenance.

P. Magudeaswaran and P. Eswaramoorthi [22] studied the durability characteristics of high performance concrete. His study was mainly concentrated on the durability characteristics of HPC with partial replacement of cement by fly ash (F) and silica fume (SF). The cement was replaced with 25% F & 12.5% SF, 30% F & 15% SF, 35% F & 17.5% SF. Water cement ratio was kept constant for all mixtures. The main properties that were observed are water absorption capacity, the alkalinity to test and the durability. It was observed that for the increase in the percentage of fly ash and silica fume there was steady increase in the water absorption and alkalinity which significantly indicates the markable change in strength and durability characteristics of concrete.

QCL group of companies [109] investigated the sulphate attack and chloride ion penetration and their role in concrete durability and concluded that Resistance to sulphate attack and chloride ion penetration are two of the latest areas of durability concern to specifiers and users of concrete. Traditionally they were addressed by specifying cements of particular chemical composition, which were not always compatible (e.g. low C3A for sulphate resistance, a higher C3A for marine chloride resistance). The advent of quality assured SCMs capable of being evaluated using a range of performance tests is providing a sound base for revisiting the specification of concrete to achieve these particular durability objectives. While economic constraints may place some limits on the range of SCMs available in different areas of Queensland, data is being obtained which indicate that there is great potential for the use of SCMs to address these and other challenges in achieving durable concrete structures. Based on data reported from the CSIRO research project above, it would appear that in specifying concrete to resist sulphate attack or chloride ion penetration, a suitable approach would be incorporation of at least 20% fly ash or 60% slag; either of which would also be beneficial in reducing any tendency for alkali silica reaction.

B.M. Reddy et al [36] explored the consequences of hydrochloric acid on fly ash and silica fume blended cement concretes. In his study they prepared two different types of blended cement concrete one using fly ash and other using silica fume in which variable dosages of HCl was added in de-ionised water. Dosages of HCl added were 100,150,300,500 and 900 mg/l. For comparing controlled concrete was also prepared in which no HCl was added. Rapid chloride ion permeability (RCP) test was studied along with compressive strength and setting times were determined at 28 and 90 days. From his research it was observed that as the concentration of HCl was increased the initial and final setting time of both fly ash blended cement and silica fume blended cement decreases. The compressive strength of both types of cement concrete has dropped down with the increase in HCl concentration at both 28 days and 90 days of testing. At 28 days and 90 days an increase in HCl concentration decreases the compressive strength of fly ash blended cement concrete and silica fume blended cement concrete in the range of 2 to 19%. With an increase in the concentration of the acid increased chloride ion permeability was observed. X-ray diffraction analysis has also been carried out for both types of concrete at HCl concentration of 500 mg/l in de-ionised water.

A.H.L. Swaroop et al [24] explored the durability studies on concrete incorporating fly ash and GGBS. There study was focused on M30 grade of concrete. Five different mixes of M30 grade of concrete were prepared to evaluate the changes in compressive strength and weight reduction after curing in 1% H_2SO_4 and sea water. Different nomenclature used for identification of concrete were conventional aggregate concrete (CAC), concrete made by replacing 20% of cement by Fly Ash (FAC1), concrete made by replacing 40% of cement by Fly Ash (FAC2), concrete made by replacing 20% replacement of cement by GGBS (GAC1) and concrete made by replacing 40% replacement of cement by GGBS (GAC2). Cubes were immersed in sea water and 1% H_2SO_4 for 7, 28 and 60 days and loss in weight was determined to find the effect of above mentioned solutions. Form their study it can be seen that in severe environmental conditions concrete made by incorporating fly ash and GGBS shows enhanced strength and durability properties when compared to conventional concrete.

R.S. Deotale et al [28] studied the acid resistant and chloride attack test on steel fiber reinforced concrete (SFRC) made by partially replacing cement by rice husk ash (RHA) and fly ash (FA). At 22.5% FA and 7.5% RHA the increase in compressive strength was observed for different mix proportions. At 28days with 22.5% fly ash and 7.5% rice husk ash maximum split tensile strength and flexural strength was observed. Due to use of RHA the amount of w/c ratio becomes important because workability of concrete decreases with increase in RHA content. Burning RHA at 600ºC to 800ºC produces ash with 80% silica content therefore makes it excellent thermal insulation material. Use of RHA is undesirable for human consumption hence it can be a good substitute for silica fume as it is economical and its production cost is nearly equal to zero. Use of RHA decreases the workability of concrete when compared to FA concrete which increases the workability otherwise. So RHA is used with other plasticizer or admixtures to increase the workability and strength of blended cement. Use of RHA improves the mechanical properties of concrete significantly in terms of flexural and split tensile strength. Due to use of fiber unit weight of concrete increases and use of RHA decrease the unit weight of concrete. Also due to addition of steel fiber the workability concrete reduces. Addition of steel fibers marginally improves the compressive strength of concrete at 7,14,28,56 and 90 days of curing. More significantly it affects the flexural strength and tensile strength of concrete at 0.75% volume fraction steel fibers in concrete. Acid attack test and chloride attack test done with 1% H_2SO_4 and 3% NaCl concluded that concrete having 22.5%FA+7.5%RHA is more durable than controlled concrete. Life expectancy of rice husk ash concrete is more than that of normal controlled concrete.

N.K. Amudhavalli and J. Mathew [27] explored the effect of silica fume on strength and durability parameters of concrete. The experiments were focused on M35 grade of concrete in which cement was partially replaced by 0,5,10,15 and 20% of silica fume. Detailed experimental investigations were carried out to find the compressive strength flexural strength and split tensile strength at 7 and 28 days of curing. They also studied the effect of acid attack and percentage loss in mass was compared with controlled concrete. From their study they indicated that use of silica fume in concrete not only improves the strength of concrete but also enhances durability of concrete.

2.9 Research Gap

- Most of literatures concerning with addition of mineral admixture alccofine are subjected to cube and cylinder tests only.
- There is lacuna in literature which provide information about uses of mineral admixture alccofine in HPC.
- Durability of concrete incorporating alccofine reported unsatisfactorily.

2.10 Research Objectives

The primary objectives of this research work are to estimate the strength and durability analysis of concrete incorporating ultrafine slag. Following sub objectives are defined to achieve above main objective of research.

- To determine the optimum dose of ultrafine slag which can provide maximum gain in compressive strength of concrete cubes.
- To find the effect of ultrafine slag on the flexural strength of reinforced concrete beams.
- To find the effect of ultrafine slag on steel fiber reinforced concrete.
- Durability analysis of concrete beams incorporating ultrafine slag.

2.11 Scope of Research Work

To accomplish the defined objectives for this research work the following scope of work is defined

- Collecting and identifying the samples of appropriate micro materials suitable for the concrete mix. In this research work ultra fine slag is used as micro materials
- Detailed laboratory investigations for determination of mechanical properties of high performance concrete like compressive strength, flexural strength, split tensile strength test and slump test were performed with different proportions of ultra fine slag.
- Detailed laboratory investigations to determine the gain in flexural strength of reinforced concrete beams using ultrafine slag

- Detailed laboratory investigations to determine the split tensile strength of steel fiber reinforced concrete using ultrafine slag.

CHAPTER 3

EXPERIMENTAL INVESTIGATIONS

3.1 General

In these chapter different material properties and detailed experimental program and procedure has been discussed. At first most significant properties of structural concrete has been identified and then limits of supplementary cementitious materials is established. Various factors which directly or indirectly effects the properties of concrete is discussed so that the experimental programme can be designed to investigate the comparative influence of SCMs on the properties of concrete

3.2 Materials

Concrete is a hard material that has cementitious medium within which aggregates are embedded. Potential strength and durability of concrete of a given mix proportion is very much dependent on the degree of its compaction. The materials used for preparation of concrete are reviewed in the following sections.

3.2.1 Aggregates

Aggregates are the important constituents in concrete. They give body to the concrete. They also help in reducing shrinkage. Aggregates impart considerable influence on strength, durability and dimensional stability to concrete [137]. At least 75% of the volume of concrete is occupied by aggregates. The aggregates are classified on the basis of their weight and size. The strength of concrete in general cannot exceed the strength of the aggregates that constitute it. However it is not possible to directly test aggregate for its strength. A good average value of the crushing strength of aggregate suitable for concrete is 80-100MPa. The stiffness of aggregate is important for maintaining the dimensional stability of concrete under load. However aggregates of moderate strength and modulus of elasticity can advantageously be used to withstand the volume changes of concrete resulting from thermal or expansive causes. Aggregates are round or angular in shape. The surface texture of aggregate is an index of its smoothness. An aggregate with tough texture will provide a better aggregate- cement bond and hence it is preferred. On the basis of weight

a) Normal weight aggregate
b) Light weight aggregate
c) Heavy weight aggregate

Normal weight aggregate is further classified as natural aggregate and artificial aggregate. Example sand is natural aggregate and broken brick, air cooled slag etc are artificial aggregate.

Aggregates can also be further classified on the basis of their size

a) Coarse aggregate (> 4.75mm)
b) Fine aggregate (< 4.75mm)

Aggregates play an important role to produce high strength concrete. In this study aggregate used is coarse aggregate having maximum size of 20mm. This use is based on the previous research which showed that the use of small coarse aggregate leads to increase in concrete strength in comparison to larger size aggregate.

Almost all the natural aggregates originate from bed rock. There are three kinds of rock namely, igneous, sedimentary and metamorphic. Out of these three igneous rocks make highly satisfactory concrete because they are normally hard, tough and dense. Shape of the aggregate is also an important characteristic since it affects the workability of concrete. From stand point view of economy in cement requirement for a given water-cement ratio rounded aggregates are preferable to angular aggregate [136]. Surface texture measures the relative degree to which particle surfaces are polished or dull, smooth or rough. As the surface smoothness increases contact area decreases as a result a highly polished particle will have less bonding area with the matrix than a rough particle of same volume. Physical properties of aggregates used in this study are presented in Table 3.2 and Table 3.3.

The gradation of coarse aggregates plays an important role in workability and paste requirements. The gradation of fine aggregate affects the workability and finishibility of concrete. Grading is a very important property of aggregate used for making concrete, in view of its effect on the packing of particles, resulting in the reduction of voids. This in turns influences the water demand and cement content of concrete. Arrangements of IS sieves for sieve analysis is shown in Fig. 3.1. Grading is described in terms of cumulative percentage of weights passing a particular IS sieve [139,147]. The grading limits for coarse and fine aggregate are explained in IS 383-1970 [139]. Table 3.3 and Table 3.5 shows the grading of coarse and fine aggregates respectively. Fineness modulus is a gross measure of aggregate gradation and is associated with fine aggregates. For the research work both CA and FA are procured from locally available vendors in Chandigarh. This is incorporated in the mix proportioning process. It is defined as the sum of the cumulative percentage of weight retained on a standard set of sieves divided by 100. Classification of fine aggregates based on fineness modulus is tabulated in Table. 3.1.

Table 3.1: Classification of fine aggregates based on FM (Source: M.S. Shetty [136])

Type	Fineness modulus (FM)
Fine	2.3-2.6
Medium	2.6-2.9
Coarse	2.9-3.2

Fig. 3.1: IS sieves for sieve analysis

Table 3.2: Physical properties of Coarse Aggregates (20mm)

S. No	Type of Test	IS Standard	Results	Specifications as per IS-383
A	Specific Gravity	IS-2386-P-3	2.88	
B	Water absorption	IS-2386-P-3	0.95%	
C	Bulk density	IS-2386-P-3	1478	
1	Aggregate impact Value		8.6	
2	Aggregate Crushing Value		16.5	
3	Aggregate abrasion Value		16.6	
D	Particle shape and size	IS-2386-P-1		
1	Flakiness and Elongation Index		22.9	
E	Soundness	IS-2386-P-5		
1	By Sodium Sulphate		1.5	Max- 12%
2	By Magnesium Sulphate		1.8	Max-18%

Table 3.3: Sieve Analysis of Coarse Aggregate (20mm)

Coarse Aggregate (20mm)					**Specification As per IS-383**					
Total weight in gms= 30000					**Percentage Passing for single size aggregate of Nominal size (mm)**					
IS Sieve	**Weight retained**	**Cumulative weight retained**	**Cumulative % Retained**	**Cumulative% Passing**	**63**	**40**	**20**	**16**	**12.5**	**10**
80mm	0	0	0	100	100		-	-	-	-
63mm	0	0	0	100	85-100	100	-	-	-	-
40mm	0	0	0	100	0-30	85-100	100	-	-	-
20mm	1949.50	1949.50	5.57	94.43	0-5	0-20	85-100	100	-	-
16mm	22970	24920	71.2	28.8	-	-	-	85-100	100	-
12.5mm	5705	30625	87.5	12.5	-	-	-	-	85-100	100
10mm	3731	34356	98.16	1.84	0-5	0-5	0-20	0-30	0-45	85-100
4.75mm	644	35000	100	0	-	-	0-5	0-5	0-10	0-20
Total (35000)										

Table 3.4: Physical properties of Fine Aggregates

S. No	Type of Test	IS Standard	Results	Specifications as per IS-383
A	Specific Gravity	IS-2386-P-3	2.64	
B	Water absorption	IS-2386-P-3	0.7%	
C	Particle shape and size	IS-2386-P-1		
1	Material Finer than 75-micron		1.6	Max-3%

Table 3.5: Sieve Analysis of Fine Aggregates

Fine Aggregate					**Specification As per IS-383**			
Total weight in gms= 1000					**Percentage Passing For**			
IS Sieve	**Weight retained (gm)**	**Cumulative weight retained (gm)**	**Cumulative % Retained**	**Cumulative% Passing**	**Zone- I**	**Zone-II**	**Zone-III**	**Zone-IV**
10mm	0	0	0	100	100	100	100	100
4.75mm	14.2	14.2	1.42	98.58	90-100	90-100	90-100	95-100
2.36mm	57.4	71.6	7.16	92.84	60-95	75-100	85-100	95-100
1.18mm	109.4	181	1.81	98.19	30-70	55-90	75-100	90-100
600µ	90.8	271.8	2.71	97.29	15-34	35-59	60-79	80-100
300µ	175.6	447.4	44.7	55.3	20-5	30-8	12-40	15-50
150µ	452.8	900.2	90.2	9.8	0-10	0-10	0-10	0-15
Pan	99.7	1000	99.7	0				
Total	1000	F.M=2.47						

3.2.2 Binder

3.2.2.1 Ordinary Portland cement

The main raw material for production of cement is clinker. Clinker is an artificial rock made by heating limestone and other raw materials in specific quantities to a very high temperature in a specially made kiln. Portland cement is hydraulic cement made by finely pulverizing the clinker produced by calcining to incipient fusion a mixture of argillaceous and calcareous materials. It is the fine grey powder that is the most important ingredient of concrete as it undergoes a chemical reaction. The bureau of Indian standards (BIS) has classified ordinary Portland cement (OPC) into three grades in order to produce different grades of concrete to meet the demands of the construction industries. This classification has been made on the basis of compressive strength at 28 days as follows.

- Grade 33 Ordinary Portland cement conforming to IS: 269-1989
- Grade 43 Ordinary Portland cement conforming to IS: 8112-1989
- Grade 53 Ordinary Portland cement conforming to IS: 12269-1987

In this research work 43 grade of cement from single source (Jaypee cement) is used. The grade of cement indicates its mortar cube compressive strength at 28 Days in MPa. In the manufacture of cement basic raw material is clinker which is made from lime stone. The properties of cement [149] used in this research work conforming to IS 8112-1989 [145] are tabulated below in Table 3.6. OPC 43 grade was procured from Ambhuja Cement Ltd Darlaghat.

Table: 3.6: Physical and chemical Properties of Cement

Property	Average Value	Standard Value as per IS 8112-1989
Specific gravity	3.15	
Consistency	32%	
Initial setting time	62 min	>30min
Final setting time	260 min	<600min
Soundness	2 mm	<10mm
Fineness	5% retained	
Compressive Strength (N/mm^2)		
3-days	24	>23
7-days	35	>33
28-days	47	>43

3.2.2.2 Fly Ash

It is byproduct obtained during combustion of coal in thermal power plant. The quality and composition of fly ash depends on the type of coal being burnt. During combustion of coal 75-80% of ash flies out with the flue gas and thus called fly ash. Ash that does not fly out is called bottom ash. The collection of fly ash is done using the following two types of precipitators

Bag house precipitators

Electrostatic precipitators

There are many uses of Fly ash. It can be used as filler or can also be used as a mineral admixture. Fly ash can also be used as a synthetic aggregate but it is very expensive.

Fly ash is classified as Class C and Class F.

Class C is obtained from combustion of lignite, sub-bituminous coal. It has high calcium content (15-30% CaO).10-15% of the materials have particle size greater than 45µ and specific surface area is in the range of 300-400 m^2/kg. The particles are primarily solid spheres with a smooth texture having average size less than 20µ.

Class F is obtained from combustion of bituminous and anthracite coal. It has low calcium content (<10% CaO). 15-20% of the materials have particle size greater than 45µ and specific surface area is in the range of 200-300 m^2/kg. The particles are primarily solid spheres with a smooth texture having average size less than 20µ.

In the pozzolanic reaction of Fly ash, the $Ca(OH)_2$ produced during cement hydration reacts with the silicate and aluminates phases of Fly ash to produce calcium silicate and aluminates hydrates. Its pozzolanic activity is attributed to the presence of SiO_2 and Al_2O_3 in amorphous form.

3.2.2.3 Silica fume

It is another material that is used as artificial pozzolanic admixture. It also referred to as micro silica or condensed silica fume. Condensed silica fume is essentially silicon dioxide (more than 90%) in noncrystalline form. Since it is an airborne material like fly ash, it has spherical shape. It is extremely fine with particle size less than1 micron and with an average diameter of about 0.1 micron, about 100 times smaller than average cement particles. Silica fume has specific surface area of about 20,000 m^2/kg, as against 230 to 300 m^2/kg. It is available in powered form or in the form of water slurry. Researchers have shown that it can be used as replacement of 10-12% by mass of total cementitious materials.

This is specially used where high strength is needed and also reduces permeability to water. Concrete containing micro silica showed outstanding characteristics in the development of strength. It is shown that 60 to 80 MPa can be obtained relatively easily. It has been also found out that modulus of elasticity of microsilica concrete is less than that of concrete without microsilica at the same level of compressive strength.

3.2.2.4 Rice Husk Ash

It is obtained by burning rice husk in a well controlled manner. Rice husk ash exhibits high pozzolanic characteristics and contributes to high strength and high impermeability of concrete. Rice husk ash (RHA) essentially consists of amorphous silica (90% SiO_2), 5% carbon, and 2% K_2O. The specific surface of RHA is between 40- 100 m^2/gm. India produces about 122 million ton of paddy every year. Each ton of paddy produces about 40 kg of RHA. There is a good potential to make use of RHA as a valuable pozzolanic material to give almost the same properties as that of micro silica [136]. According to the report by P.K. Mehta [87,88], the current yearly production of Paddy rice is approximately 500 million tones that give about 100 million tons of rice husks as a waste product from milling. Controlled burning of rice husk between 500ºC and 600ºC for short duration of about 2 hrs yields ash with low unburnt carbon and anamorphous silica. If it is burnt in uncontrolled manner the ash which is essentially silica is converted into crystalline forms and is less reactive.

3.2.2.5 Metakaoline

Highly reactive pozzolanic material with average diameter around 1-2 µ. Its pozzolanic reaction is considered to be similar to that of silica fume. Researchers have shown that metakaoline increases the performance of concrete at long term ages [61,96,121]. Highly reactive metakaoline is made by water processing to remove unreactive impurities to make 100% reactive pozzolan. Such a product, white or cream in colour, purified, thermally activated is called High Reactive Metakaoline (HRM). High reactive metakaoline shows high pozzolanic reactivity and reduction in $Ca(OH)_2$ even as early as one day [123,126]. It is also observed that the cement paste undergoes distinct densification. The improvement offered by this densification includes an increase in strength and decrease in permeability

3.2.2.6 Ground granulated blast furnace slag (GGBS)

Ground Granulated Blast furnace Slag popularly called GGBS is a nonmetallic product consisting essentially of silicates and aluminates of calcium and other bases. The molten slag is rapidly chilled by quenching in water to form a glassy sand like granulated material. The granulated material when further ground to less than 45 micron will have specific surface of about 400 to 600 m^2/kg (Blaine).

3.2.2.7 Alccofine

Ultra fine slag or Alccofine is more advanced form of GGBS in which slag is further ground to less than 20 micron. As a result its specific surface area is increased dramatically to 3000-5000 m^2/kg (Bet Analysis). Particle shape of ultrafine slag is spherical (Scanning electron microscope) which due to ball bearing effect gives increased workability at much reduced water content. Pozzolanic reaction increases due to increase in specific surface area. Silica content is found to be more that 80% as a result it acts as a good pozzolanic material. Segregation and bleeding is not observed hence giving a good impermeable material which in turns increases its durability. A joint venture with Ambuja cement ltd and Alcon developers produces ultrafine slag with a brand name Alccofine. It is manufactured in the controlled conditions with special equipments to produce optimized particle size distribution which is its unique property (Table. 3.7). Alccofine 1203 and Alccofine 1101 are two types of Alccofine with low calcium silicate and high calcium silicate respectively. Alccofine 1200 series is of 1201, 1202, 1203 which represents fine, micro fine, ultrafine particle size respectively. Alccofine 1203 is slag based SCM having ultra fineness with optimized particle size distribution whereas Alccofine 1101 is a micro finer cementitious grouting material for soil stabilization and rock anchoring [156]. The performance of Alccofine is superior to all the other admixtures used in India. For this research work Alccofine was procured from Ambhuja cement Ltd Goa.

Table 3.7: Physical and chemical properties of alccofine

Fineness	Specific gravity	Bulk density	Particle size		
			D10	D50	D90
>12000cm^2/kg	2.9	700-900kg/m^3	1.5μ	5μ	9μ
Chemical Properties					
CaO	SO_3	SiO_2	Al_2O_3	Fe_2O_3	MgO
61-64%	2-2.4%	21-23%	5-5.6%	3.8-4.4%	0.8-1.4%

3.2.3 Water

One cannot think concrete without water. Water is the next most important ingredient after cement for making concrete. It is also least expansive. Careless use of water can lead to poor quality concrete. Therefore a detailed study of the quantity and quality of water required for making good quality concrete is essential. Water used can be either for mixing different ingredients or for curing. When water is added then hydration reaction starts which forms strength giving C-S-H gel. It is well assumed that if water is suitable for drinking than it is suitable for making concrete. Water suitable for making concrete is also determined from its pH value. If pH value lies between 6 to 8 and free from organic compounds than it is suitable for making concrete. Strength of concrete also depends on water-cement ratio. Fig. 3.2 shows schematic representation of cement gel hydration with w/c ratio 0.2, 0.3 and 0.5. It can be noted that a small amount of water is needed to hydrate cement. Additional water is required to lubricate the mix. Too much water can lead to creation of capillary pores. More water no doubt contributing to workability of concrete but reduces its strength to some extent [137]. Amount for water needed to achieve desired workability is usually more than that needed for complete hydration of the cement. Water used in this study was portable having properties are tabulated in Table 3.8.

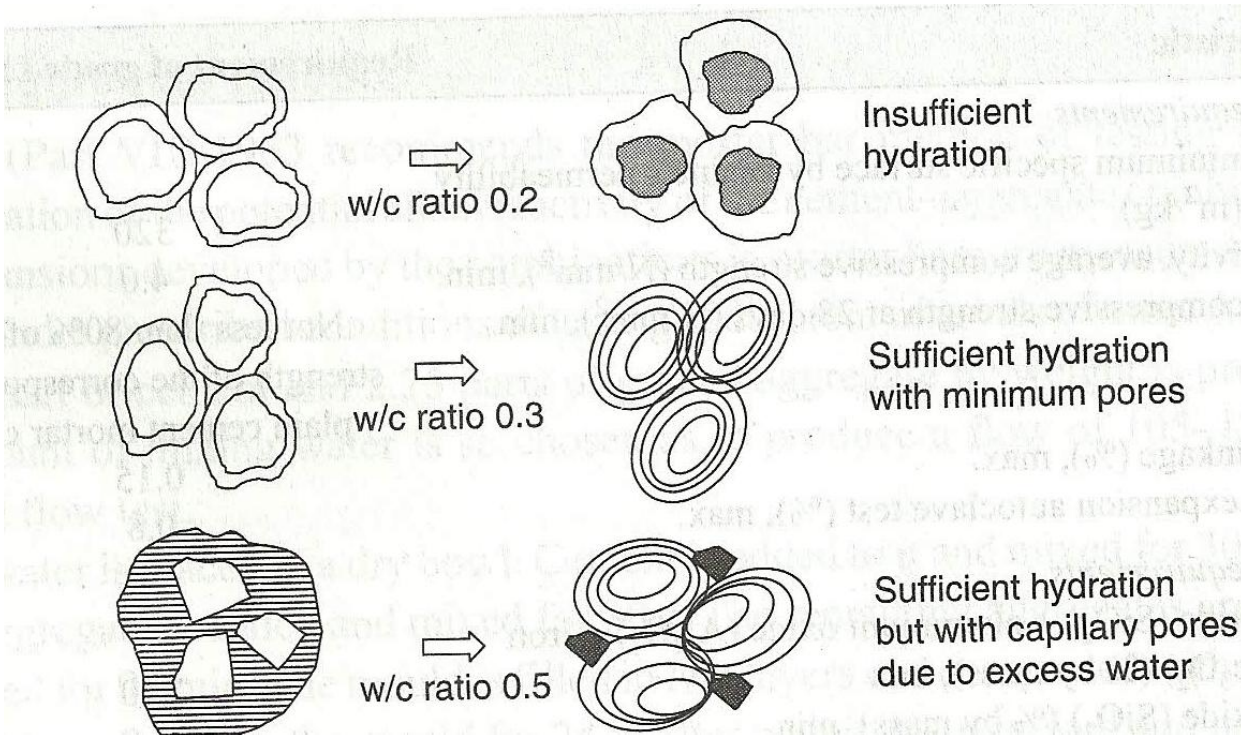


Fig. 3.2: Schematic representation of insuffient, sufficient and excess water for hydration

(Source: A.R. Santhakumar [137])

Table 3.8: Physical and Chemical properties of water

Parameters	IS Standards	Results obtained	Maximum permissible limits as per IS 456: 2000
Sulphates	IS 3025 Part 24	75mg/l	400mg/l
Chlorides	IS 3025 Part 32	55mg/l	2000mg/l for PCC and 500mg/l for RCC
pH		6.8	Shall not be less than 6

3.3 Research Methodology

In order to achieve the objectives as described in chapter 1, a sequential research methodology has been proposed. The experimental program consisted of four main stages, the layout of which shown in Fig 3.3.

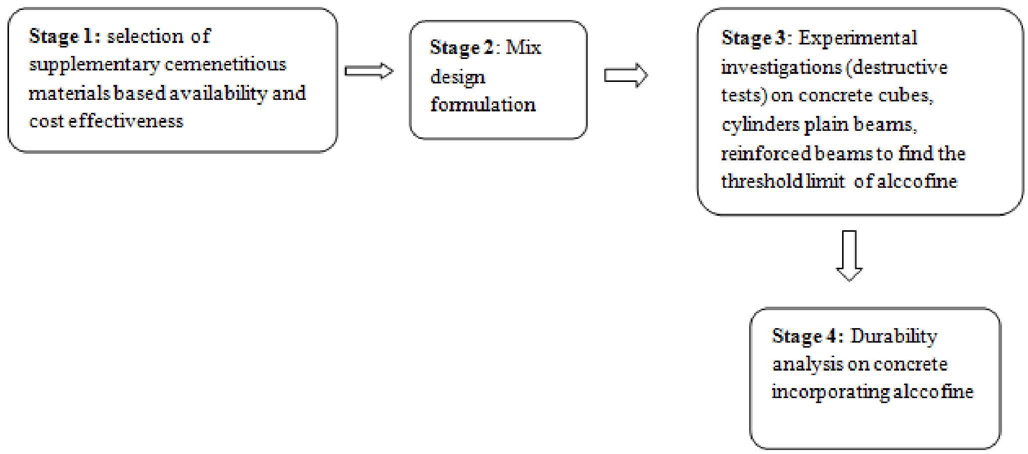


Fig. 3.3: Layout of experimental program

Stage 1: Selection of Supplementary cementitious materials

After thorough literature review the best suitable supplementary cementitious material was selected as per availability and cost effectiveness. Out of different materials as discussed in preceding chapters ultrafine slag (Alccofine 1203) was selected for experimental investigation due to following reasons

a) Since its particle size is very less it acts as a good filler effect.

b) Due to the decrease in size and increase in specific surface area pozzolanic reaction increases.

c) Silica content in ultra fine slag is more than 80% which makes it good pozzolanic material.

d) Segregation and bleeding is not observed hence giving a good impermeable material which in turns increases its durability

Stage 2: Mix design

After selection of supplementary cementitious material i.e. ultra fine slag (Alccofine) mix design was developed for higher grade of concrete.

Stage 3: Experimental Investigation

Different destructive experimental investigations were done for designed mix by partial replacement of cement with alccofine and threshold limit was determined. Different tests were performed on concrete cubes, cylinders, plain beams and reinforced beams of standard sizes as described in Indian standards codes. The results of stage 3 are discussed in chapter 4

Stage 4: Durability analysis

After finding the threshold limit durability analysis was carried out on concrete incorporating alccofine.

3.4 Mix proportioning

Concrete mix proportioning is governed by the properties required in the fresh and hardened state. The properties of plastic concrete are important for proper compaction. The strength and durability for final structure is provided by hardened concrete. The two are related primarily to the water- cement ratio. Proportioning a concrete mix for a given purpose is thus the art of obtaining a suitable ratio of the various ingredients of suitable concrete with the required properties at the lowest cost. A properly proportioned concrete mix with certain requirements of workability, strength, and durability should have the minimum possible cement content to make the mix most economical.

Mix design can be defined as the process of selecting suitable ingredients of concrete and determining their relative proportions with the object of producing concrete of certain minimum strength and durability as economically as possible. The purpose of designing as can be seen from the above definitions is two-fold. The first object is to achieve the stipulated minimum strength and durability. The second object is to make the concrete in the most economical manner. Cost wise all concretes depend primarily on two factors; namely cost of material and cost of labour. Labour cost, by way of formworks, batching, mixing, transporting, and curing is nearly same for good concrete and bad concrete. Therefore attention is mainly directed to the cost of materials. Since the cost of cement is many times more than the cost of other ingredients, attention is mainly directed to the use of as little cement as possible consistent with strength and durability.

The Concrete mix design was done by Departmental of Environment method popularly known as DOE method. The DOE method utilizes British test data obtained at the building Establishment, the Transport and Road Research Establishment and the British cement association. This method is frequently used in India with minor modifications [137]. The high strength concrete mix design for M60 grade of concrete was taken from past research and shown in Table. 3.9

Table. 3.9: Mix Proportion of Concrete (Source: V.D. Sabale et al [37]

Water (liter)	Cement (Kg)	Fine aggregate(Kg)	Coarse Aggregate(Kg)
179.88	600	551	1133
0.3	1	0.918	1.88

3.5 Batching, Mixing and Casting of specimens

Cubical moulds of size 150mm x 150mm x 150mm were used to prepare the concrete specimens for the determination of compressive strength of concrete. Care was taken during casting. The moulds were placed on the compaction table for proper compaction. Cylindrical moulds of size 100 mm x 200 mm were used to prepare the concrete specimens for the determination of split tensile strength of steel fiber reinforced concrete. Rectangular moulds of 100mm x 100mm x 500mm were used for flexural testing of beams. All the specimens were prepared in accordance with Indian Standard Specifications IS: 516-1959 [143]. All the moulds were cleaned and oiled properly. These were securely tightened to correct dimensions before casting. Care was taken so that there are no gaps left from where there is any possibility of leakage of plastic concrete. A careful procedure was adopted in the batching, mixing and casting operations. The coarse aggregates and fine aggregates were weighed first with an accuracy of 0.5 grams. The concrete mixture was prepared by the concrete mixer. It was cleaned first by water and then dried to ensure any impurities were not adhering to its surface from prior use. Ordinary Portland cement of 43 grade from single source was used in the entire process. Dry fine aggregates were introduced first in the mixer & are thoroughly mixed. After that coarse aggregates were added to it. Cement replaced by ultrafine slag (Alccofine 1203) as per variable percentage by weight was added. Then water was added carefully so that no water was lost during mixing. A total of 84 cubes, 117 beams and 45 cylinders were prepared which consists of cubes, beams, cylinders incorporated with alccofine 1203 along with steel fibers and steel reinforcements in required cases. Proposed checks were made at 7, 14 and 28 days. The vibration table (Fig. 3.4) was stopped as soon as the cement slurry appeared on the top surface of the mould. All the specimens were left in the steel mould for the first 24 hours at ambient condition. After that they were de-moulded with care upon requirement of aging so that no edges were broken and were placed in the curing tank at the room temperature for curing. The room temperature for curing was 27 ± 20 as per IS: 10262-1982 [142]. Concrete must be properly cured to develop its optimum properties. To prevent evaporation of water from the unhydrated concrete, the specimens were immediately covered with wet gunny sack after molded. The specimens were removed from the moulds after 24 hours, cured in water tank as shown in Fig. 3.5

Fig. 3.4: Sample of cubes kept on vibration table for compaction

Fig. 3.5: Curing of specimens

3.6 Tests conducted

3.6.1 Workability

The ASTM: C125-93 has defined workability as the property determining the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity. It is also defined as the ease of placement with segregation. The definition of workability given by ACI: 116R-90 is the property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated and finished. Workability is necessary to compact concrete to maximum possible density. The strength of partially compacted concrete compared to that of fully compacted concrete in terms of strength ratio R $_{strength}$ is given by

$$R_{strength} = \frac{\text{Fck of partially compacted concrete}}{\text{Fck of fully compacted concrete}}$$

Among the factors affecting workability, water content expressed in L/m^3 is most important. IS:456-2000 [145] specifies the maximum water content permitted for different environments with respect to durability. For normal concrete without air entrainment, for the same workability, the water content decreases with increase in the maximum size of aggregates.

Following tests were perform for find out Workability Properties of concrete

- Slump test
- Compaction factor test

3.6.1.1 Slump cone test

Slump cone test is one of the tests which measure the parameters close to workability and provide useful information about it. It is the most commonly used method of measuring consistency of concrete which can be employed either in laboratory or at the site [137]. The apparatus used for this test is the 300mm high frustum of cone. It is placed upright and filled with three layers of concrete. Each layer is tampered 25 times with a 16mm diameter steel rod with a rounded nose. The top of the level is stuck off, and the mould held firmly against the slab base. After this, the mould is lifted gently, causing the unsupported cone to slump. The decrease in height of the cone is designated the slump value and is measured correct to 5mm. Slump test as per IS: 1199-1959 [148] is followed in this research. The recommended slump values as per IS: 456-2000 [146] is shown the Table 3.10. Interpretation of tests results of slump can be shown in Fig. 3.6. It can be seen that due to low water cement ratio used in this research degree of workability is low for all the mixes as compared to Table.3.10. Water cement ratio was kept constant throughout the research. With the increase in alccofine percentages the overall workability reduced as seen from results of slump test.

Table 3.10: Recommended slump value (Source: IS 456: 2000 [146])

Placing Conditions	Degree of workability	Slump(mm)
Blinding concrete	Very low	Too small to measure
Mass concrete	low	25-75
Heavily reinforced	medium	50-100
Trench fill	High	100-150
Tremie concrete	Very high	Too large to measure

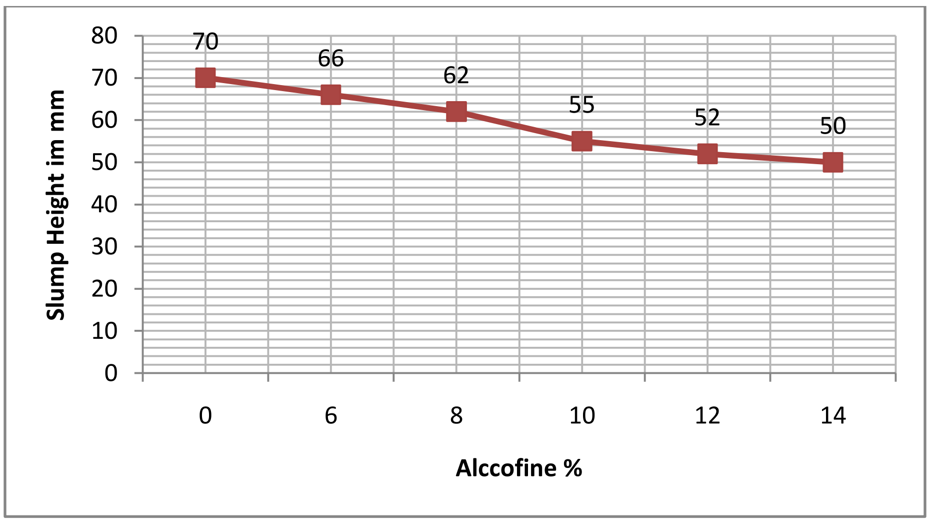


Fig. 3.6: Graphical variation of slump with variable percentages of alccofine

3.6.1.2 Compaction factor test

Since the degree of workability of concrete came to be very low compaction factor test was conducted. It is more precise and sensitive than the slump test and is particularly useful for concrete mixes of very low workability as are normally used when concrete is to be compacted by vibration [136]. Although both compacting factor and slump tests are used for the same purpose of determination of workability of fresh concrete, compaction factor test was conducted to validate slum tests result. Apparatus used for the test is shown in Fig. 3.7.

Fig. 3.7: Compacting Factor apparatus

The value of compacting factor for control mix is the highest, indicating the highest workability, while it decreases with the enhancement of Alccofine amount. Concrete containing 16% of Alccofine indicates the lowest compacting factor value. The reduction in workability is firstly due to lowering the w/c ratio and secondly due to the addition of alccofine percentages in the mix. Variation of compaction factor test is shown in Fig. 3.8

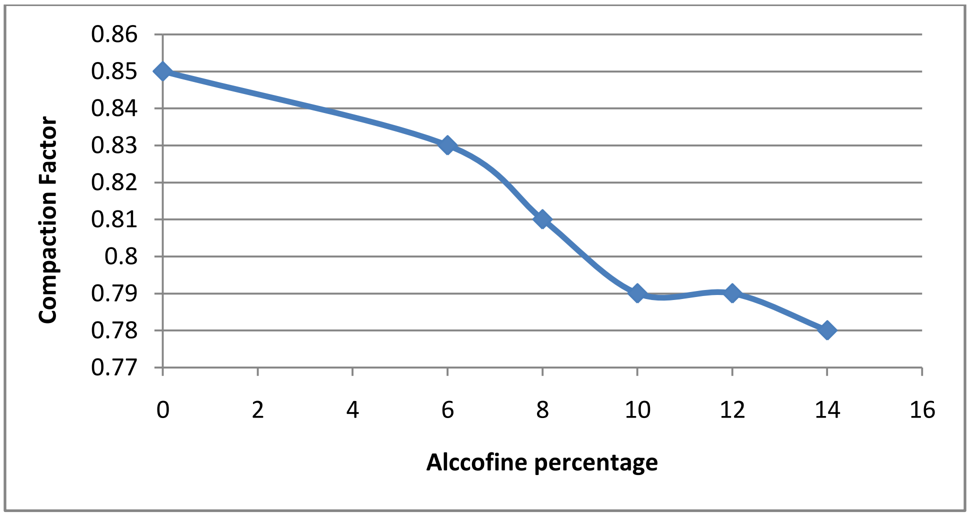


Fig. 3.8: Compaction factor test result

3.6.2 Compressive strength test

Compression test is the most common test conducted on hardened concrete, partly because it is an easy test to perform, and partly because most of the desirable characteristic properties of concrete are qualitatively related to its compressive strength [136,143,144]. The testing machine may be of any reliable type, of sufficient capacity for the tests and capable of applying the load without shock and increased continuously at a rate of approximately 140 $kg/cm^2/min$ until the resistance of the specimen to the increasing load breaks down and no greater load can be sustained. The permissible error shall be not be greater than ± 2 percent of the maximum load. One such arrangement is shown in Fig. 3.9. The measured compressive strength of the specimen is calculated by dividing the maximum load applied to the specimen during the test by the cross-sectional area, calculated from the mean dimensions of the section and shall be expressed to the nearest kg per sq cm. Average of three values is taken as the representative of the batch provided the individual variation is not more than ± 15 percent of the average. Otherwise repeat tests are made.

(a) **(b)**

Fig. 3.9 (a) and (b) Concrete cubes kept in CTM before and after testing

3.6.3 Flexural strength test

The testing machine may be of any reliable type of sufficient capacity for the tests and capable of applying the load at the rate such that the extreme fibre stress increases at approximately 7 $kg/cm^2/min$, that is, at a rate of loading of 400 kg/min for the 15.0 cm specimens and at a rate of 180 kg/min for the 10.0 cm specimens [141]. The load shall be increased until the specimen fails, and the maximum load applied to the specimen during the test shall be recorded. The appearance of the fractured faces of concrete and any unusual features in the type of failure shall be noted. The permissible errors shall be not greater than ± 0.5 percent of the applied load where a high degree of accuracy is required and not greater than ± 1.5 percent of the applied load for commercial type of use. The bed of the testing machine is provided with two steel rollers, 38 mm in diameter, on which the specimen is to be supported and these rollers shall be so mounted that the distance from centre to centre is 60 cm for 15.0 cm specimens or 40 cm for 10.0 cm specimens. The load shall be applied through two similar rollers mounted at the third points of the supporting span that is, spaced at 20 or 13.3 cm centre to centre. The load shall be divided equally between the two loading rollers, and all rollers shall be mounted in such a manner that the load is applied axially and without subjecting the specimen to any torsional stresses or restraints. One suitable arrangement which complies with these requirements is indicated in Fig. 3.10.

Calculation — The flexural strength of the specimen is expressed as the modulus of rupture f_b [143], which, if ‘a’ equals the distance between the line of fracture and the nearer support, measured on the centre line of the tensile side of the specimen, in cm, shall be calculated to the nearest 0.5 kg/sq cm as follows

$$f_b = \frac{pa}{bd^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq 1}$$

when ‘a’ is greater than 20.0 cm for 15.0 cm specimen, or greater than 13.3 cm for a 10.0 cm specimen, or

$$f_b = \frac{3pa}{bd^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq 2}$$

Where If 'a' is less than 17.0 cm for a 15.0 cm specimen, or less than 11.0 cm for a 10.0cm specimen, the results of the test shall be discarded.

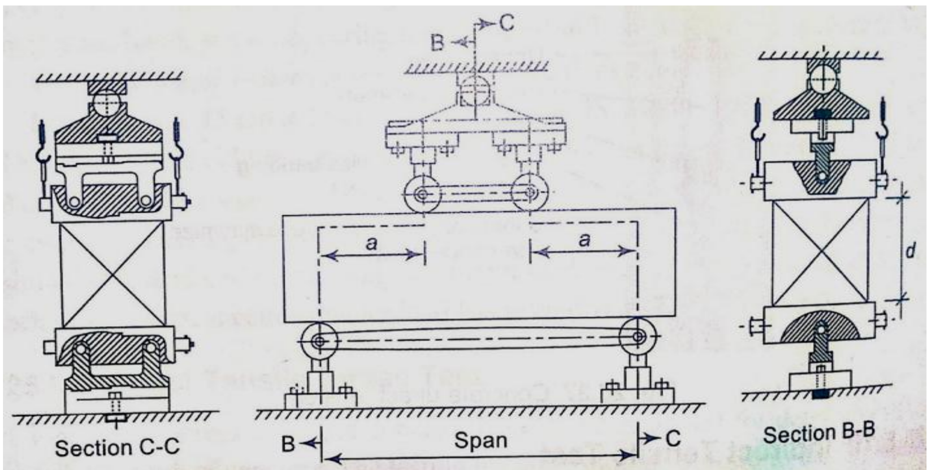


Fig. 3.10: Arrangement for loading of flexural test specimen

3.6.4 Split Tensile Test

A compression machine of sufficient capacity & reliability was used for the tests and was capable of applying the load without shock and accelerated continuously at a nominal rate within the range 1.2 N/(mm^2/min) to 2.4 N/ (mm^2/min) should be used. It shall comply with the requirements given in IS 516:1959 [143] as far as applicable except that the bearing faces of both platens shall provide a minimum loading area of 12 mm multiplied by the length of the cylinder or cube, as the case may be so that the load is applied over the entire length of the specimen. If necessary, a supplementary bearing bar or plate of machined steel may be used. A steel loading plate having minimum hardness value, when tested in accordance with IS 1500 was used between the platen of the machine and the hardboard packing strips. The piece shall not be shorter than the specimen. One such arrangement is shown in Fig. 3.11. Tests were made at the required ages of the test specimens that is at 7, 14 and 28 days of curing. The ages were calculated from the time of the casting of the moulds. The age at test was reported along with the results. At least three specimens were tested for each age of tests. Unless other conditions are required for specific laboratory investigation specimen was tested immediately on removal from the water whilst they are still wet. Surface water and grit was wiped off the specimens and any projecting fins removed from the surfaces if any. Central lines were drawn on the two opposite faces of the cube using any suitable procedure and a device that will ensure that they were in the same axial plane. The mass and dimensions of the specimen were noted before testing. The sides of the specimen, lying in the plane of the pre-marked lines, were measured near the ends and the middle of the specimen and the average taken to the nearest 0.2 mm. The length of the specimen was taken to the nearest 0.2 mm by averaging the two lengths measured in the plane containing the pre-marked lines. Before commencement of testing the bearing surfaces of the testing machine and of the loading strips had been wiped clean and the test specimen was placed in the centering jig with packing strip and loading pieces carefully positioned along the top and bottom of the plane of loading of the specimen. The jig is then placed in the machine so as to locate the specimen centrally. For cylindrical specimen it was ensured that the upper platen is parallel with the lower platen. On manually controlled machines as failure is approached the loading rate decreased at this stage the controls shall be operated to follow possible the specified loading rate as far as. The maximum load applied was then recorded. The appearance of concrete and any unusual features in the pattern of failure were also noted. The measured splitting tensile strength f_{ct}, of the specimen was then calculated to the nearest 0.05 N/mm^2 using the following formula:

$$f_{ct} = \frac{2P}{\pi LD}$$

P = maximum load in N applied to the noted before testing.

L = length of the specimen in mm and

D = cross sectional dimension of the specimen in mm.

Fig. 3.11: Splitting tensile test

3.6.5 Fire resistant test

The 100mm x 100mm x 100mm size cubes were casted and mould was kept in wet place for 24 hours, then prepared cubes were removed from the mould and placed in water for 28 days at room temperature. Later those cubes were heated in the electric muffle furnace (Fig. 3.12) which is provided with a thermostat to maintain constant temperatures at different ranges. At a time 24 cubes i.e. 8 sets of 3 cubes each were prepared out of which half were submerged for 14 days & other half for 28 days. These sets were heated for 1, 2, 3 hours at 4 different temperatures (27ºC, 500ºC, 650ºC, 800ºC). After that these sets were left at room temperature for 24 hours for cooling. Compressive strength has been calculated as per IS: 516-1959 [143]. Each of the samples selected for testing was exposed to the desired duration once it has reached the desired temperature. After fire resistance test, compressive strength of the samples were determined to detect effect of fire on strength properties of concrete cubes. The testing machine for compressive test is reliable of sufficient capacity and capable of applying the load at the rate of approximately 140 kg/cm^2/min until the resistance of the specimen to the increasing load gives in and no greater load can be continued. The permissible error is not greater than ± 2 percent of the maximum load. The testing machine must be equipped with two steel bearing platens with hardened faces. One of the platens (preferably the one that normally will bear on the upper surface of the specimen) is fitted with a ball seating in the form of a portion of a sphere, the centre of which coincides with the central point of the face of the platen. The other compression platen shall be plain rigid bearing block. The bearing faces of both platens shall be at least as large as, and preferably larger than the nominal size of the specimen to which the load is applied. The bearing surface of the platens, when new, shall not depart from a plane by more than 0.01 mm at any point, and they shall be maintained with a permissible variation limit of 0.02 mm. The movable portion of the spherically seated compression platen shall be held on the spherical seat, but the design shall be such that the bearing face can be rotated freely and tilted through small angles in any direction. Three specimens, from different batches, were made for testing at each of the required age. Specimens that were stored in water were tested immediately on removal from the water while they were in the wet condition. Surface water and grit if any should be wiped off along with any projecting fins .The dimensions of the specimens should be checked to the nearest 0.2 mm and their weight before testing. The specimen shall be placed in the machine in such a manner that the load shall be applied to opposite sides of the cubes as cast and not to the top and bottom. The axis of the specimen needs to be carefully aligned with the centre of thrust of the spherically seated platen. No packing should be used between the faces of the test specimen and the steel platen of the testing machine. As the spherically seated block is brought to bear on the specimen, the movable portion shall be rotated manually so that uniform seating may be obtained. The load shall be applied without shock and accelerated continuously at specified rate. The load at which the specimen fails is to be recorded along with the appearance of the concrete. If any unusual patterns are there in the type of failure, they shall be noted. The measurement of the compressive strength of the specimens are to be calculated by dividing the maximum load applied upon the specimen during testing divided by the cross-sectional area, calculated from the mean dimensions of the section and shall be expressed to the nearest kg /cm^2. Only the average of three values should be taken as the representative of the batch provided the individual variation is not more than ± 15 percent of the average value. If so, tests are to be revised. A correction factor according to the height/diameter ratio of specimen after capping shall be obtained from the curve for correction factor for height-diameter ratio of a core presented in IS 516-1959 [143]. The execution of this correction factor and the measured compressive strength is the corrected compressive strength, this being the equivalent strength of a cylinder having a height/diameter ratio of two. The equivalent cube strength of the concrete shall be determined by multiplying the corrected cylinder strength by $\frac{5}{4}$

(a) (b)

Fig. 3.12: Cubes incorporating ultrafine slag at varying temperatures placed in muffle furnace

3.6.6. Durability tests

A long service life is considered synonymous with durability. Since durability under one set of conditions does not necessarily mean durability under another, it is customary to include a general reference to the environment when defining durability. According to ACI Committee 201, durability of Portland cement concrete is defined as its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration; that is, durable concrete will retain its original form, quality, and serviceability when exposed to its environment. No material is inherently durable; as a result of environmental interactions the microstructure and, consequently, the properties of materials change with time. A material is assumed to reach the end of service life when its properties under given conditions of use have deteriorated to an extent that the continuing use of the material is ruled either unsafe or uneconomical.

3.6.6.1 Sulphate attack

Sulphate attack is caused by the chemical reaction between sulphate ions hydration products, leading to ettringite and gym formation. Most soils contain some sulphate in the form of calcium, sodium, potassium and magnesium. They occur in soil or ground water. Because of solubility of calcium sulphate is low; ground waters contain more of other sulphates and less of calcium sulphate. Ammonium sulphate is frequently present in agricultural soil and water from the use of fertilizers or from sewage and industrial effluents. Decay of organic matters in marshy land, shallow lakes often leads to the formation of H_2S, in which can be transformed in to sulphuric acid by bacterial action. Water used in concrete cooling towers can also be a potential source of sulphate attack on concrete. Therefore sulphate attack is a common occurrence in natural or industrial situations. Solid sulphates do not attack the concrete severely but when the chemicals are in solution, they find entry into porous concrete and react with the hydrated cement products. Of all the sulphates magnesium sulphate causes maximum damage to concrete. A Characteristic whitish appearance is the indication of sulphate attack. The term sulphate attack denote an increase in the volume of cement paste in concrete or mortar due to the chemical action between the products of hydration of cement and solution containing sulphates. In the hardened concrete, calcium sulpho aluminate, forming within the framework of hydrated cement paste.

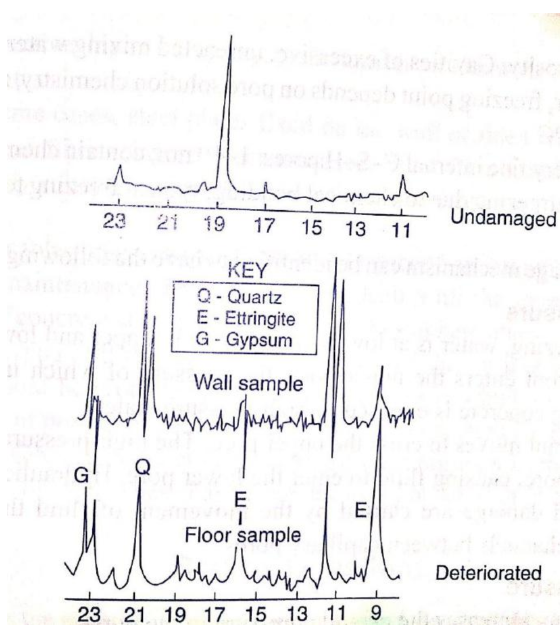


Fig. 3.13: X ray diffraction analysis of undamaged and deteriorated concrete

Because of the increase in volume of the solid phase which can go up to 227 percent, a gradual disintegration of concrete takes place. Another factor influencing the rate of attack is the speed in which the sulphate gone into the reaction is replenished. For this it can be seen that when the concrete is subjected to the pressure of sulphate bearing water on one side the rate of attack is highest. Monosulphate, CH and water combine to form ettringite. The source of sulphate ions are such as sea water, sewage, industrial waste salts in ground water. The expansive forces generate tensile stresses in concrete which leads to severe damage and cracking. The x-ray diffraction analysis of damaged and undamaged concrete is shown in Fig. 3.13

3.6.6.2 Chloride attack

The free chloride content in concrete has been found to be one of the major causes for corrosion of steel and it is one of the critical issues being dealt today by civil engineers globally. In fact, in the marine environment, a large number of concrete bridges, dams, and other mega structures have suffered from safety and serviceability problems due to the deterioration of concrete, can be directly attributed to the chloride penetration into the concrete. It is also understandable from the reported literature that, most of the concrete structures failed in the past are not necessarily due to inadequate design but due to failure of concrete to protect reinforcing steel from aggressive elements like chlorides. The chlorides that are penetrated through concrete pores depend upon the pore structure of concrete and the improvement in pore structure is mainly achieved by the use of mineral admixtures like fly ash, silica fume, metakaolin. In addition, these admixtures reduce the mobility of chloride ions by changing the mineralogy of the cement hydrates. The chloride permeability depends on several factors like chemical composition of cement, water-to cement ratio, types and amounts of mineral admixtures etc. Therefore, in order to improve the resistance of concrete to chloride penetration, the mix proportions of concrete should be carefully selected considering the above parameters. Many studies have been carried out on the use of admixtures, however search for efficient alternative admixture is still continuing. Thus in the present work, studies were carried out on the compressive strength and chloride resistance of concrete, thereby reducing the corrosion susceptibility by adding alccofine as a partial replacement of cement.

3.6.6.3 Curing in acid solution

Curing is adopted to promote the hardening of concrete under conditions of humidity and temperature which are conducive to the progressive and proper setting of the constituent cement. Curing has a major influence on the properties of hardened concrete such as durability, strength, water-tightness, wear resistance, volume stability, and resistance to freezing and thawing. Concrete that has been specified, batched, mixed, placed, and finished can still be a failure if improperly or inadequately cured. Curing is usually the last step in a concrete project and, unfortunately, is often neglected even by professionals. 3 sets of five different mixes of M60 Grade namely referral concrete (AC_0), concrete made by replacing 12% of cement by Alccofine (AC_{12}), concrete made by replacing 14% of cement by Alccofine (AC_{14}) were prepared & so on. The cubes were demoulded after 1 day of casting and then kept in respective solutions of 5% H_2SO_4, 5% HCL & in referral solution of 100% H_2O for curing, at room temperature with a normal humidity. The cubes were taken out from curing after 30 days and compressive strength was determined. The surface of specimen was cleaned and weights were measured. The mass loss and strength of specimen due to acid attack was determined at 30 days.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General

In this chapter, Compressive strength, Flexural Strength, Split tensile strength, Fire resistance test and Chloride resistance of various concrete mixes incorporating ultrafine slag (Alccofine-1203) in varying percentages is discussed. All the tests conducted were in accordance with the methods described in chapter three. Results were compared and checked for compressive strength, split tensile strength, fire resistance, and chloride resistance of concrete.

4.2 Tests Conducted

4.2.1 Compressive strength Test

Concrete was prepared under moderate exposure condition and quality control was good. It was poured into cubical moulds and placed on vibrating table to minimize air entrapped which would otherwise affect the compressive strength. After 24 hrs the moulds were removed and the specimens were kept for curing at room temperature until taken out for testing. Specimens were tested at different ages i.e. 3 days, 7 days and 28 days of curing for determination of compressive strength. The load was applied at a constant rate thus ensuring progressive increase in stress as failure approached. Table 4.1 shows different nomenclature used for different specimens. Cubical specimens with varying percentages of alccofine are designated by C0, C08, C10, C12, C14, C16 and C18. C0 denotes concrete cubes with 0% alccofine and C18 denotes concrete cubes with 18% replacement of cement with alccofine.

Table 4.1: Nomenclature used for determination compressive strength of concrete cubes

Concrete cubes	% of alccofine replaced
C0	0
C8	8
C10	10
C12	12
C14	14
C16	16
C18	18

Table 4.2: Compressive strength of concrete mixes, incorporating varying percentages of alccofine 1203 at 7, 14 and 28 days

Mix	Compressive strength in MPa			Average compressive strength in MPa			%change of 28 day's strength
	7 Days	14 Days	28 Days	7 Days	14 Days	28 Days	
C0	42.30	47.56	63.1	42.1	48	63.5	0
	41.70	48.23	62.5				
	42.30	48.23	62.5				
C8	42.89	61.45	69.10	43.32	62.6	71.2	12.12
	42.56	62.70	70.56				
	44.51	63.35	73.94				
C10	44.23	79.00	81.63	45.32	79.44	82.40	29.76
	46.50	78.25	82.10				
	45.16	81.07	83.40				
C12	44.57	82.21	89.20	47.32	83.13	88.60	39.52
	46.56	83.92	88.43				
	50.83	83.26	88.17				
C14	45.61	70.56	88.96	45.12	71.33	87.83	38.31
	45.36	71.89	88.08				
	44.39	71.54	86.45				
C16	42.91	68.96	80.16	43.27	69.32	81.07	27.66
	43.67	69.23	81.32				
	43.23	69.76	81.75				
C18	41.96	62.50	76.84	41.81	62.58	77.93	22.72
	41.76	62.78	78.54				
	41.72	62.45	78.41				

The test results in Table. 4.2 indicated that, when 8% to 12% by weight replacement of alccofine 1203 for cement was done increase in compressive strength was observed. When 14% replacement of cement was done strength started decreasing. Compressive strength of ultrafine slag concrete at 28 days when compared to control mix was found to increase by 11% to 39 % on increasing the alccofine content from 8% to 12%. Decrease in compressive strength was observed when replacement of cement was increased from 12% to 18%. Graphical variation of compressive strength of concrete cubes with different percentages of alccofine is shown in Fig. 4.1.

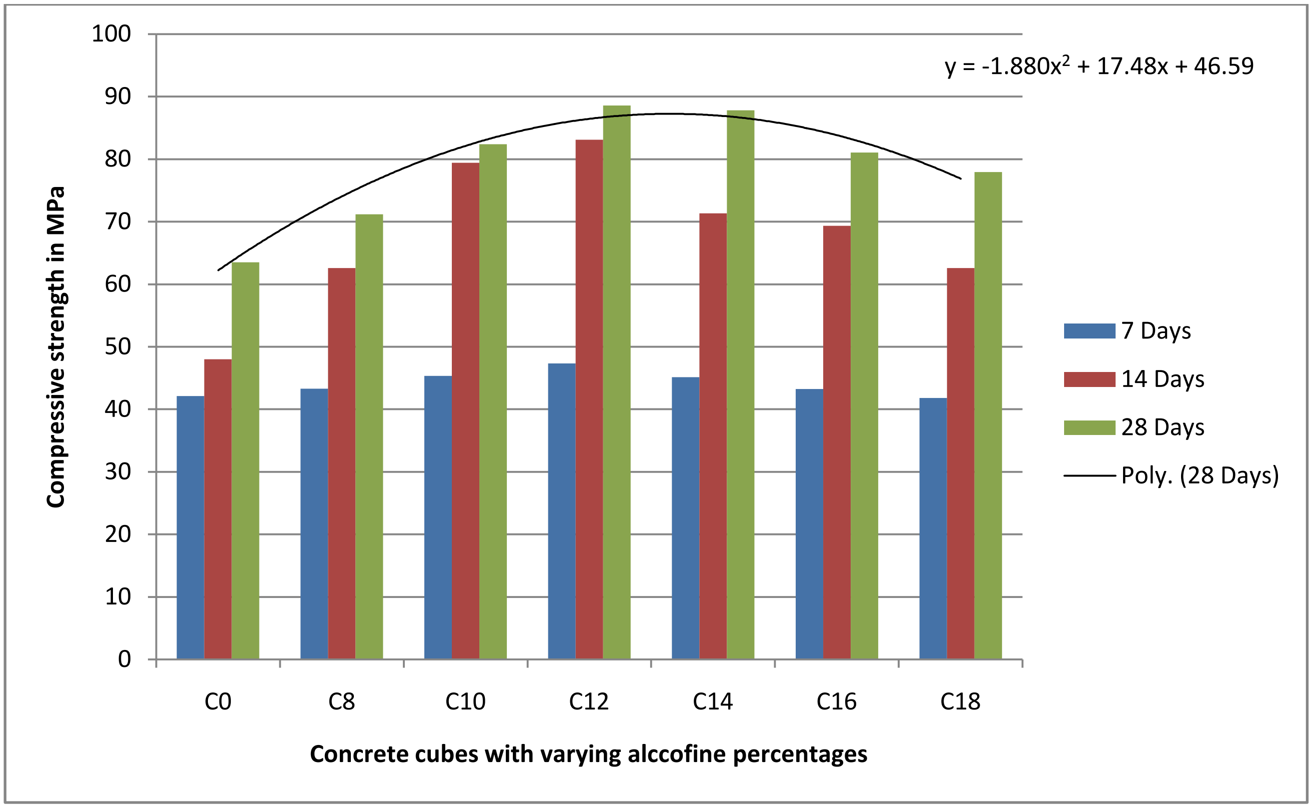


Fig. 4.1: Comparison of compressive strength of concrete cubes at 7, 14and 28 days

4.2.2 Flexural strength test

Flexural strength is one of the important parameter of testing the strength of concrete. For the determination of flexural strength beams of standard size 500mm×100mm×100mm as per IS 516:1959 [143] was adopted. Whole experiments were dived into two parts i.e. plain cement concrete beams and reinforced cement concrete beams. Total 45 nos of beams were casted for each grade and each type i.e plain cement concrete beams and reinforced cement concrete beam to be tested at different ages of curing. Reinforcement used was 2 bars of 8 mm dia as main reinforcement and vertical stirrups using 6mm dia @150mm c/c was used as shown in the fig 4.3 (a). Different nomenclatures used for plane concrete beams and reinforced concrete beams are tabulated in Table 4.3. Beams were cured for 7, 14 & 28 days time age. The beams were placed normal to the casting and symmetrical two point system was adopted for the flexural tensile strength test as per IS 516:1959 [143]. The deflection of the beams were measured by the dial gauge of least count of 0.01mm, which was placed in the middle third portion of the beam.

Average flexural strength in plain and reinforced concrete showed an improved flexural strength up to 12% replacement.

Table. 4.3: Nomenclature for specimens of beams used

Plain concrete beams	Reinforced concrete beams
C0	R0
C8	R8
C10	R10
C12	R12
C14	R14
C16	R16
C18	R18

Table. 4.4: Flexural strength of plain concrete beams with varying percentages of alccofine at different ages of curing

Mix	Flexural strength in MPa			Average Flexural strength in MPa			% Change in 28 Day's strength
	7 Days	14 Days	28 Days	7 Days	14 Days	28 Days	
C0	1.32	3.01	5.79	1.27	2.69	5.59	0
	1.22	2.09	5.32				
	1.28	2.98	5.66				
C8	1.51	3.10	6.23	1.34	2.93	6.26	11.98
	1.45	2.75	6.43				
	1.06	2.94	6.12				
C10	1.59	3.48	6.50	1.45	3.25	7.14	27.72
	1.23	2.97	7.40				
	1.53	3.30	7.52				
C12	1.70	3.80	8.56	1.58	3.58	8.14	45.62
	1.13	3.23	8.14				
	1.91	3.71	7.72				
C14	1.53	3.65	8.23	1.55	3.51	7.92	41.68
	1.48	3.35	8.01				
	1.64	3.53	7.52				
C16	1.29	3.08	6.77	1.25	3.11	7.01	25.40
	1.11	3.04	7.11				
	1.35	3.21	7.15				
C18	1.21	2.81	6.23	1.11	2.85	6.15	10.11
	1.01	3.05	6.19				
	1.11	2.69	6.03				

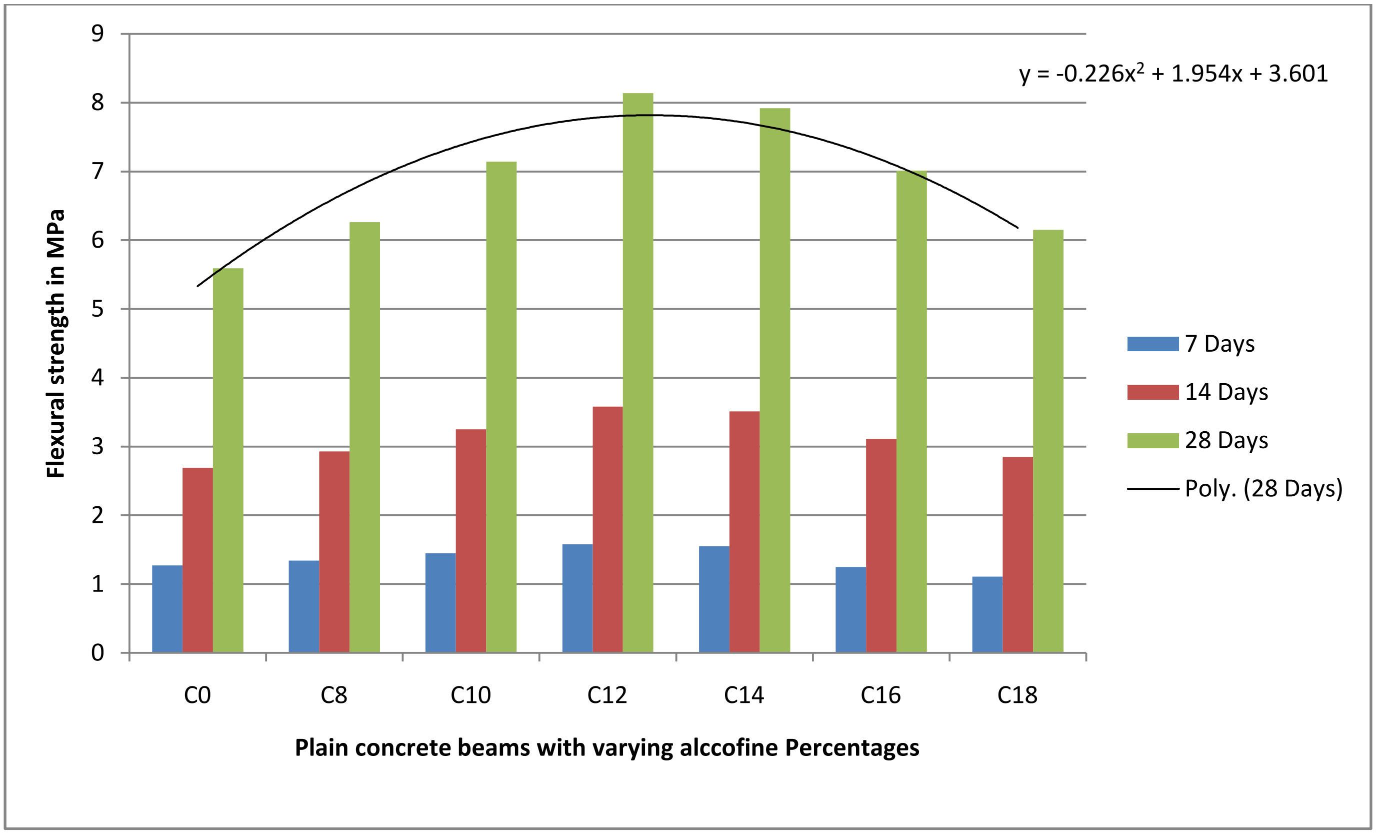


Fig. 4.2: Variation of Flexural strength of plain concrete beams with different % of alccofine

Table 4.5: Flexural strength of reinforced concrete beams with varying percentages of alccofine at different ages of curing

Mix	Flexural strength in MPa			Average flexural strength in MPa			% Change in 28 Day's strength
	7 Days	14 Days	28 Days	7 Days	14 Days	28 Days	
R0	3.15	8.57	18.14	3.02	8.34	18.05	0
	2.89	8.42	17.92				
	3.02	8.03	18.09				
R 8	3.44	8.65	18.01	3.21	8.99	20.49	13.51
	3.45	9.05	21.35				
	2.74	9.27	22.11				
R10	3.78	11.12	25.65	3.55	10.10	23.95	32.68
	3.15	8.89	21.12				
	3.72	10.29	25.08				
R12	4.89	12.75	28.36	4.06	11.84	29.34	62.54
	3.15	11.06	30.15				
	4.14	11.71	29.51				

R14	4.44	11.75	28.30	3.99	11.68	28.98	60.55
	4.06	10.73	30.15				
	3.47	12.56	28.49				
R16	3.29	10.14	22.75	3.43	9.67	22.67	25.59
	3.43	9.32	22.94				
	3.57	9.55	22.32				
R18	3.11	8.92	21.85	3.17	8.96	20.87	15.62
	3.17	9.13	20.63				
	3.23	8.83	20.13				

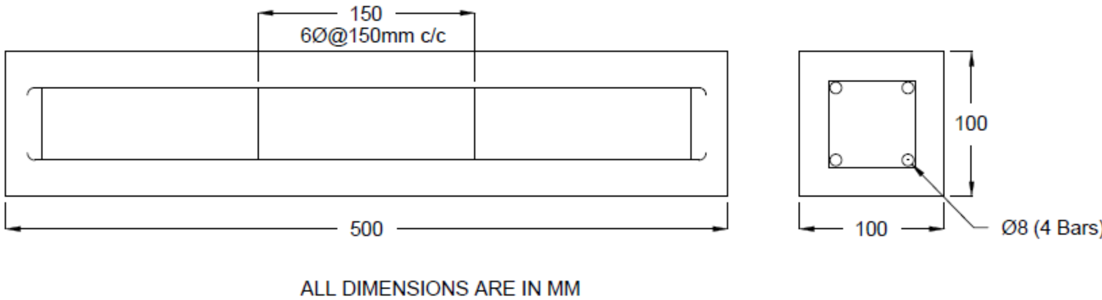


Fig. 4.3 (a): Reinforcement detailing of RCC beam

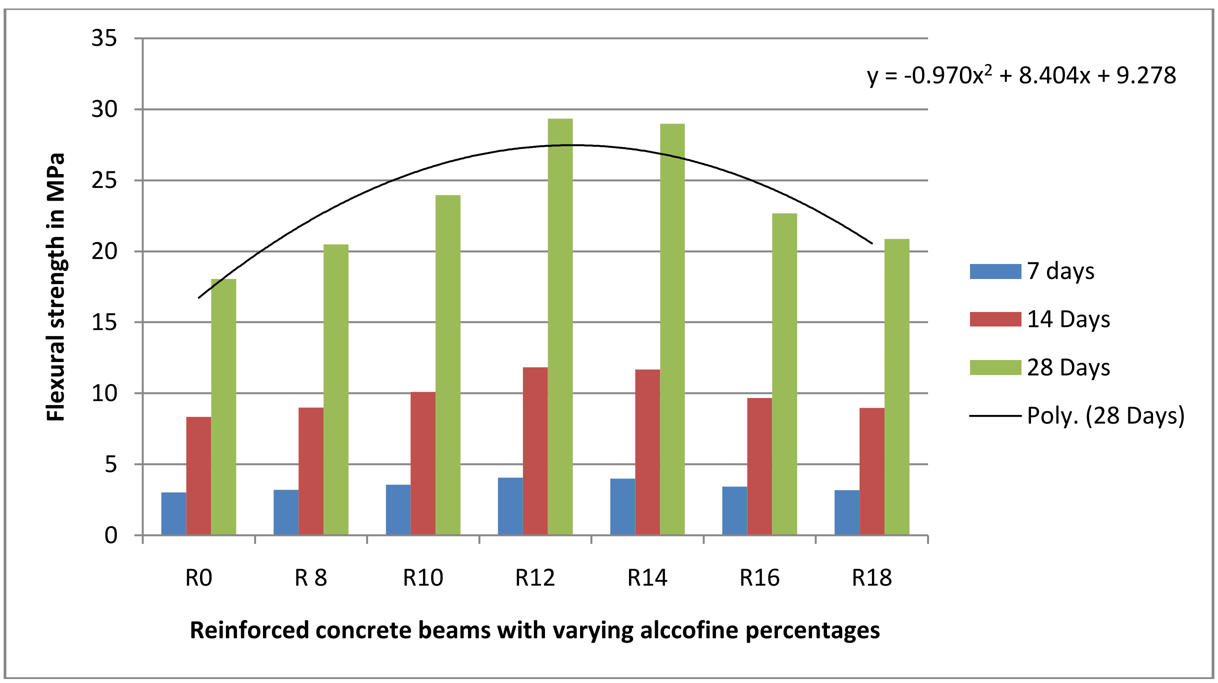


Fig. 4.3(b): Variation of Flexural strength of Reinforced concrete beams with different % of alccofine

Table 4.4 shows the flexural strength values of plain concrete beams with varying percentages of alccofine. Maximum value of flexural strength was obtained at 12% replacement of cement with alccofine. When compared with controlled concrete flexural strength has increased by 45.62% at 28 days. The flexural strength decreased thereafter and at 18% replacement flexural strength has drop down to 10.11%. Fig. 4.2 shows the graphical representation of flexural strength of plain concrete beams with varying alccofine percentages.

Flexural strength of reinforced concrete beams with varying percentages of alccofine at different ages of curing are tabulated in Table 4.5. Flexural strength of reinforced concrete beams in which no alccofine was added (R0) is 18.05MPa. With addition of alccofine the flexural strength of RCC beams also increased and at 12% replacement ratio it has reached the maximum value of 29.34 MPa as shown in Fig. 4.3. Addition of alccofine thereafter reduces the flexural strength. When compared with controlled concrete at 12% replacement of cement with alccofine the change in flexural strength at 28 days is 60.55%. This change reduces as the percentage of alccofine is increased and at 18 % replacement ratio (R18) the change in flexural strength was reported to be 15.62%.

4.2.3 Steel fiber reinforced concrete

Many experiments have been conducted successfully using steel fibers mixed with fresh concrete. When set and hard it improves the mechanical properties of hardened concrete. Fibers used as a reinforcing material may be steel or any natural product such as pine leaves, jutes, etc. These fibers can be of any shapes like circular, triangular or flat in cross section. In this study steel fibers are used and hence the concrete is termed as steel fiber reinforced concrete (SFRC). In many research papers it has been observed that alccofine can be used as a good cementitious material [4,8]. Partial replacement of cement with alccofine results in higher compressive and flexural strength of concrete and optimum dose of alccofine achieved is nearly close to 12% [4,8]. In this paper efforts have been done to improve the crack resistance of steel fiber reinforced concrete incorporating ultrafine slag. Along with crack resistance its toughness and tensile strength also improves. All mechanical properties such as toughness, crack resistance etc mostly depends on the bonding of the steel fibers and concrete and its distribution within the matrix of the fibers [6,99,128]. Most important parameter that plays an important role is the aspect ratio which is defined as the ratio of length to its diameter [6,26,64,70,95]. Shrinkage (both plastic and drying shrinkage) is inherent properties of a hardened concrete. Steel fibers are used to control cracking due to shrinkage [54]. Once control on cracking is achieved it reduces permeability and bleeding of water. Generally steel fires have marginal impact on flexural strength of concrete so they cannot replace entirely the traditional structural steel. Amount of fibers used in concrete is expressed in terms of volume fraction (V_f) which is defined as the amount of fibers added to the total volume of concrete mix. V_f generally ranges from 0.1% to 2% [55,98,92]. If the modulus of elasticity of fibers is kept higher than that of cement matrix then its load carrying capacity increases. But increase in aspect ratio of the fibers reduces the flexural strength and tensile strength of hardened concrete and also creates workability problems.

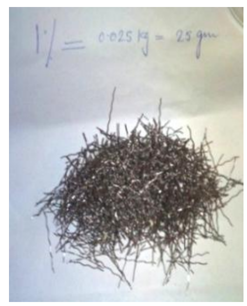
Foremost objective of the present investigation was to find the change in split tensile strength of SFRC incorporating alccofine. Flexural testing of beams with varying percentages of steel fibers and alccofine were also performed. Amount of alccofine used as a partial replacement of cement to get the maximum strength was determined as per compressive strength and flexural strength results. In this work 12% by weight of cement was replaced by alccofine. All tests were performed on M60 grade of concrete with water-cement ratio 0.30. Table. 4.6 shows the properties of steel fibers used in this study.

Table. 4.6: Properties of steel fibers used

<table>
<tr><td>Length</td><td>50mm</td><td rowspan="6">
Steel fibers used</td></tr>
<tr><td>Appearance</td><td>Clear and Bright</td></tr>
<tr><td>Tensile strength</td><td>800-2500 MPa</td></tr>
<tr><td>Shape</td><td>Rectangular</td></tr>
<tr><td>Size</td><td>0.8mmx35mm</td></tr>
<tr><td>Aspect ratio</td><td>43.75</td></tr>
</table>

Then 12% by weight of cement was replaced by alccofine. The concrete was cast in cylindrical moulds of size 100mm ×200mm as conforming to IS: 5816:1999 [140] and also concrete beams were cast in mould size 500mm×100mm×100mm as per IS: 10086:1982 [144]. Fig. 4.5 shows concrete with varying percentage of steel fibers are casted in cylindrical moulds. Water cement ratio was kept as low as 0.3 to maximize the strength. All tests were performed in moderate exposure conditions. Fig. 4.6 shows concrete beams with varying percentage of steel fibers. Using electronic weight balance, different percentage of steel fibers in terms of weight was measured as shown in Fig. 4.4. To ensure homogenous mixing each of the small fibers were dispersed and distributed randomly in the concrete during mixing. At first dry ingredients i.e. cement, aggregates and alccofine were mixed in tilting drum type mixture for 60 seconds and then steel fibers were added. The water is added in the end and mixing is continued for 5 minutes to get a homogenous mix

(a) 0.5% steel fibers of total volumefraction of concrete



(b) 1% steel fibers of total volume fraction of concrete

(c) 1.5% steel fibers of total volume fraction of concrete

(d) 2.0% steel fibers of total volume fraction of concrete

Fig. 4.4: Different proportion of steel fibers**.**

Concrete mixed with steel fibers was prepared under moderate exposure condition and quality control was good. It was poured into cylindrical & rectangular moulds as shown in Fig. 4.5 and Fig. 4.6 and was hand compacted by tamping rod to ensure homogenous distribution of steel fibers to minimize air entrapped which would otherwise affect the compressive strength. After 24 hours the concrete specimens were demoulded and were kept for curing at room temperature until taken out for testing. Specimens were tested at different ages i.e. 7 days, 14 days and 28 days for split tensile test and for flexural strength. The load was applied at a constant rate thus ensuring progressive increase in stress as failure approached. For the cylinders the top surface of the cylinder was kept in contact with the platen of the existing machine. For evolution of performance of concrete using ultra fine slag (alccofine) with varying steel fiber content different specimens were created. Table 4.7 shows nomenclature used for different specimens. Cylindrical specimens with varying percentage of steel fibers are designated by SC0, SC5, SC1, SC15 and SC20 and beam specimens are designated as CB0, CB5, CB1, CB15 and CB20

Fig. 4.5: Concrete cylinders with varying % of steel fibers**.**

Table 4.7: Different nomenclature of specimen used.

Cylinder designation	Beam designation	% of alccofine (by weight)	% of steel fibers (by volume)
SC0	CB0	12%	0%
SC5	CB5	12%	0.5%
SC1	CB1	12%	1.0%
SC15	CB15	12%	1.5%
SC20	CB20	12%	2.0%

Fig. 4.6: Concrete beams with varying % of steel fibers.

4.2.3.1 Split tensile test of SFRC

When compared with controlled concrete, split tensile strength is maximum at 1.5% steel fibers with 12% alccofine common to all mixes. Different values of tensile tests performed on different cylindrical concrete with varying percentages of steel fibers are tabulated in Table. 4.8 For each combination of steel fibers, three cylinders were casted and tested at 7, 14 and 28 days of curing and average strength was determined. One such arrangement of split tensile test is shown in Fig. 4.8. It is seen that the split tensile strength with 12% alccofine and varying % of steel fibers initially there is very less gain of strength but after 28 days there is significant gain of tensile strength. From Fig 4.7 it can be observed that tensile strength of concrete cylinders in SC15 has shown 38% of increase in tensile strength when compared with controlled concrete SC0.

Table. 4.8: Split tensile test on concrete cylinders at different ages with different % of steel fibers

Mix	Tensile strength MPa			Average Tensile strength MPa			% change of 28 days strength
	7 days	14 days	28 days	7 days	14 days	28 days	
SC0	1.2	3.4	5.9	1.2	3.5	5.9	0
	1.1	3.6	6.1				
	1.4	3.6	5.7				
SC5	1.2	3.5	6.1	1.2	3.6	6.1	3.4
	1.2	3.6	6.1				
	1.3	3.6	6.0				
SC10	1.3	3.9	6.7	1.3	3.9	6.7	13.6
	1.3	4.0	6.6				
	1.3	3.9	6.9				
SC15	2.6	4.5	7.9	2.4	4.4	8.2	38.9
	2.3	4.3	8.2				
	2.2	4.4	8.4				
SC20	2.3	3.9	7.5	2.2	3.8	7.6	28.8
	2.3	3.5	7.5				
	2.0	4.0	7.8				

Fig: 4.8: Splitting tensile tests of cylindrical specimen

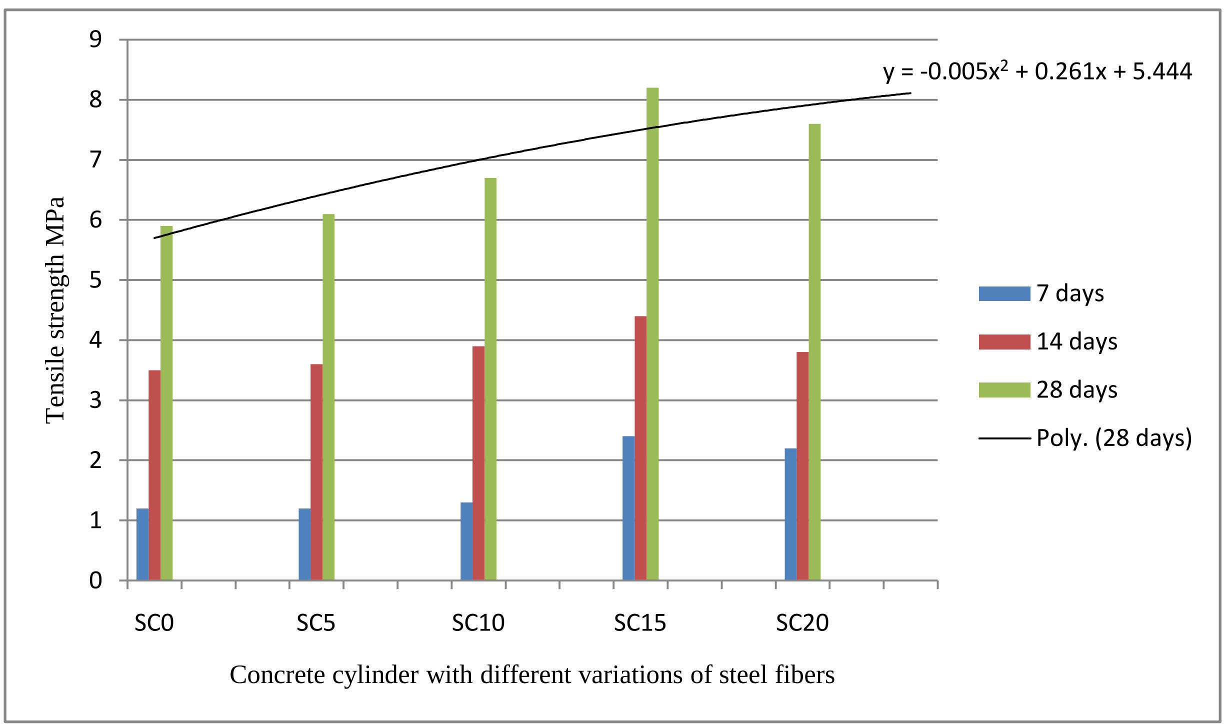


Fig. 4.7: Concrete comparison of tensile strength of concrete cylinders with different variations of steel fibers.

4.2.3.2 Flexural strength of SFRC

For flexural testing, beams of size 500mm×100mm×100mm as shown in Fig 4.6 were casted with 12% alccofine as partial replacement of cement and with varying % of steel fibers . These beams were cured for 7, 14 and 28 days until taken out for testing. Beams were tested under two point of loading as per BIS 516: 1959 [143].One such arrangement of flexural testing of SFRC beam is shown in Fig.4.9. Different values obtained after testing are tabulated in the Table 4.9. Comparison of flexural strength is also shown in the Fig. 4.10 which shows maximum gain of flexural strength of 29% is achieved in SB15 when compared with controlled concrete SB0.

Fig. 4.9: SFRC beam after flexural testing

Table 4.9: Flexure strength of concrete beams at different ages with different % of steel fibers.

Mix	Flexural strength MPa			Average flexural strength MPa			% change in 28 days strength
	7 days	14 days	28 days	7 days	14 days	28 days	
SB0	1.38	3.23	8.10	1.39	3.29	8.06	0
	1.45	3.36	7.88				
	1.34	3.30	8.20				
SB5	1.42	3.48	8.48	1.40	3.40	8.43	4.6
	1.39	3.33	8.39				
	1.40	3.39	8.42				
SB10	1.47	3.44	8.77	1.44	3.44	8.73	8.3
	1.44	3.43	8.72				
	1.41	3.44	8.71				
SB15	1.66	3.88	10.43	1.63	3.81	10.45	29.6
	1.64	3.78	10.48				
	1.60	3.77	10.44				
SB20	1.62	3.57	8.57	1.55	3.52	8.50	5.6
	1.49	3.52	8.43				
	1.55	3.48	8.49				

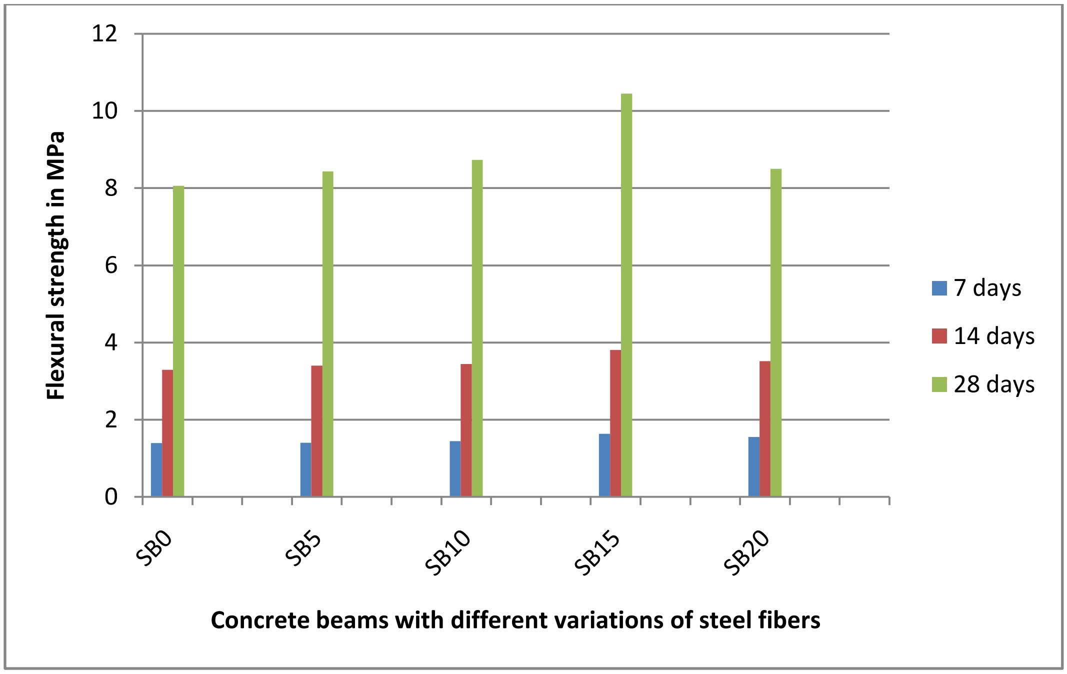


Fig. 4.10: Comparison of flexural strength of concrete beams with different variations of steel fibers.

4.2.4 Resistance to fire

The 100mm x 100mm x 100mm all with optimum dose of 12 % Alccofine - 1203 were casted, moulded and then prepared cubes were removed from the mould after 24 hrs. At a time 36 cubes i.e. 3 sets of 12 cubes each were prepared out of which the first set was submerged for 7 days & other two sets for 14 and 28 days respectively. Later those cubes were heated in the electric muffle furnace which is provided with a thermostat to maintain constant temperatures at different ranges. These sets were heated for 1, 2, 3 hours duration at 4 different temperatures (27ºC, 500ºC, 650ºC, 800ºC). After that these sets were left at room temperature for 24 hours for cooling. Compressive strength has been calculated as per IS 516-1959 [143]. Each of the samples selected for testing has been be exposed to the desired duration once it as reached the desired temperature. After fire resistance test, compressive strength of the samples was determined to detect effect of fire on strength properties of concrete cubes.

Concrete on heating it expands & contracts on cooling [9,44,35,75]. Restraint to contraction causes the development of tensile stresses. The temperature related contraction stress can cause cracking. Cracks may also be caused by differential temperatures in thick members. When the surface layer cools and contracts, movement is restrained by the core of the member which is still at a higher temperature, and hence cracks may form in the surface.

Inferences based upon appearance:

i) At 500ºC: Cubes experience minor cracks and dehydration of the cementitious paste with complete loss of free moisture and a reduction in paste volume.

ii) At 650ºC: Prominent cracking of both the cementitious paste & aggregates due to expansion. Color of concrete turns somewhat pinkish.

iii) At 800ºC: Complete dehydration of the cementitious paste with considerable shrinkage cracking, was observed. Concrete becomes crispy and easily broken down upon contact. Colour of concrete changes to grey.

The variation of Compressive strength with the increase in temperature is studied in terms of the percentage residual compressive strength for different durations of 1, 2 & 3 hours. Initially, the strength increased with temperature 27ºC to 500ºC for different durations and beyond that it was reduced. The maximum Compressive strength was noticed when the cubes were heated at 500ºC for 1 hour duration. The compressive strengths are increased up to 27ºC -500ºC & beyond that it was rapidly reduced with increasing temperature. The compressive strength was lost very much when they are heated to temperatures greater than 800ºC.

The temperature range and exposure duration controls the strength of concrete at an elevated temperature. The test results of concrete cubes kept at different ranges of elevated temperatures are presented in Table 4.10 to 4.12. It can be observed that initially there is gain in compressive strength due to rise in temperature. But there after strength decreases significantly when exposure duration is 3hrs. From Table 4.18 it can be seen that when concrete cubes were kept at 500ºC for 3 hrs then percentage residual compressive strength was 70.97% for normal concrete (C0) but for concrete incorporating 12% alccofine (C12) percentage residual compressive strength came out to be 85.30%. As the temperature and exposure duration increases the percentage residual compressive strength decreases but rate of decrease of this strength is less for alccofine concrete when compared with normal concrete. For normal concrete exposed to elevated temperature of 800ºC for 3hrs the percentage residual compressive strength is 49.74% whereas for alccofine concrete it is 61.35%. Fig 4.11 shows the effect of elevated temperature on concrete cubes. Superficial cracks are generated to cube surface due to thermal gradient. From Table 4.12 it can be observed that initially there is increase in percentage residual compressive strength when cubes are heated at 500ºC but there after its strength decreases.

Table 4.10: Compressive and % Residual compressive strengths of cubes after exposing to elevated temperature cured for 7 days

Temperature		Compressive strength in MPa			% Residual compressive strength in MPa		
		1 hour	2 hour	3 hour	1 hour	2 hour	3 hour
27^0 C	C0	42.10	42.10	42.10	100	100	100
	C12	47.32	47.32	47.32	100	100	100
500^0 C	C0	48.45	39.72	27.53	115.10	94.36	65.39
	C12	56.21	46.47	38.44	118.78	98.21	81.23
650^0 C	C0	45.21	37.32	24.72	107.38	88.65	58.71
	C12	53.62	44.79	33.75	113.31	94.65	71.32
800^0 C	C0	20.23	24.69	20.32	48.05	58.64	48.26
	C12	42.59	33.23	29.52	90.00	70.23	62.38

(a)

(b)

(c)

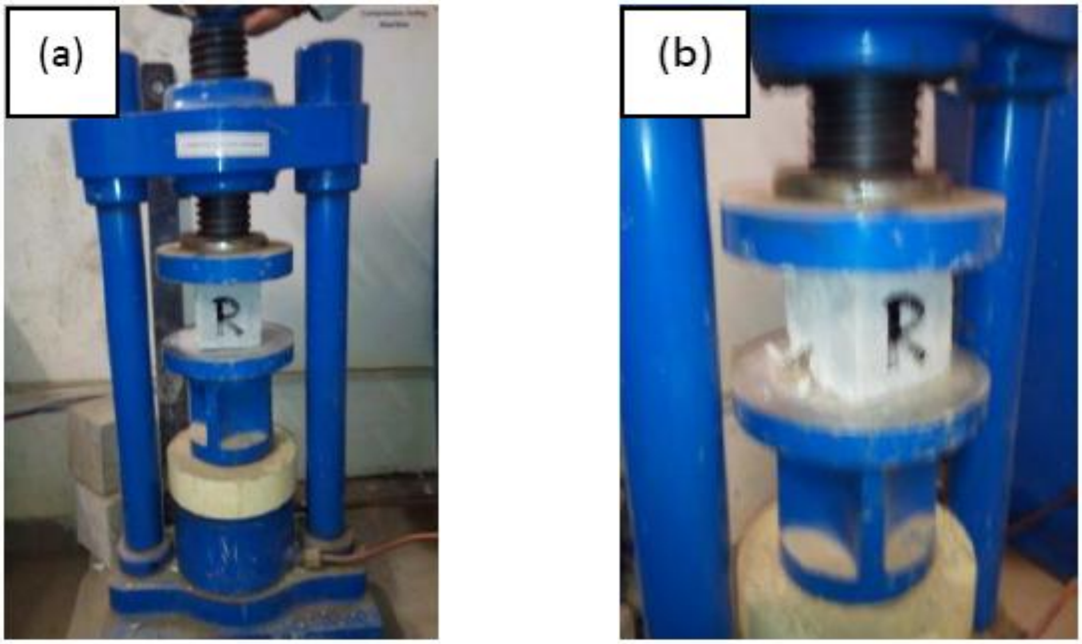
Fig. 4.11: Superficial cracks on cubes due to varying thermal gradient

Table 4.11: Compressive and % Residual compressive strengths of cubes after exposing to elevated temperature cured for 14 days

Temperature		Compressive strength in MPa			% Residual compressive strength in MPa		
		1 hour	2 hour	3 hour	1 hour	2 hour	3 hour
27^0 C	C0	48	48	48	100	100	100
	C12	83.13	83.13	83.13	100	100	100
500^0 C	C0	55.84	45.99	40.10	116.34	95.83	83.54
	C12	98.51	82.00	78.35	118.52	98.65	94.25
650^0 C	C0	45.38	39.99	28.92	94.56	83.33	60.24
	C12	81.97	74.93	66.62	98.61	90.14	80.14
800^0 C	C0	25.52	28.06	23.16	53.17	58.47	48.25
	C12	78.69	65.02	51.10	94.67	78.21	61.47

Table 4.12: Compressive and % Residual compressive strengths of cubes after exposing to elevated temperature cured for 28 days.

Temperature		Compressive strength in MPa			% Residual compressive strength in MPa		
		1 hour	2 hour	3 hour	1 hour	2 hour	3 hour
27^0 C	C0	63.5	63.5	63.5	100	100	100
	C12	88.6	88.6	88.6	100	100	100
500^0 C	C0	73.66	62.61	45.06	116.10	98.61	70.97
	C12	105.25	89.3	75.6	118.80	99.20	85.30
650^0 C	C0	68.91	60.71	33.40	108.53	95.61	52.59
	C12	95.31	80.54	68.21	92.43	90.90	76.90
800^0 C	C0	34.81	33.77	31.21	45.17	46.82	49.14
	C12	77.58	69.54	54.36	87.56	78.48	61.35



(a) Before Testing (b) After Testing

Fig. 4.12 (a) and (b) Specimen kept in CTM before and after testing

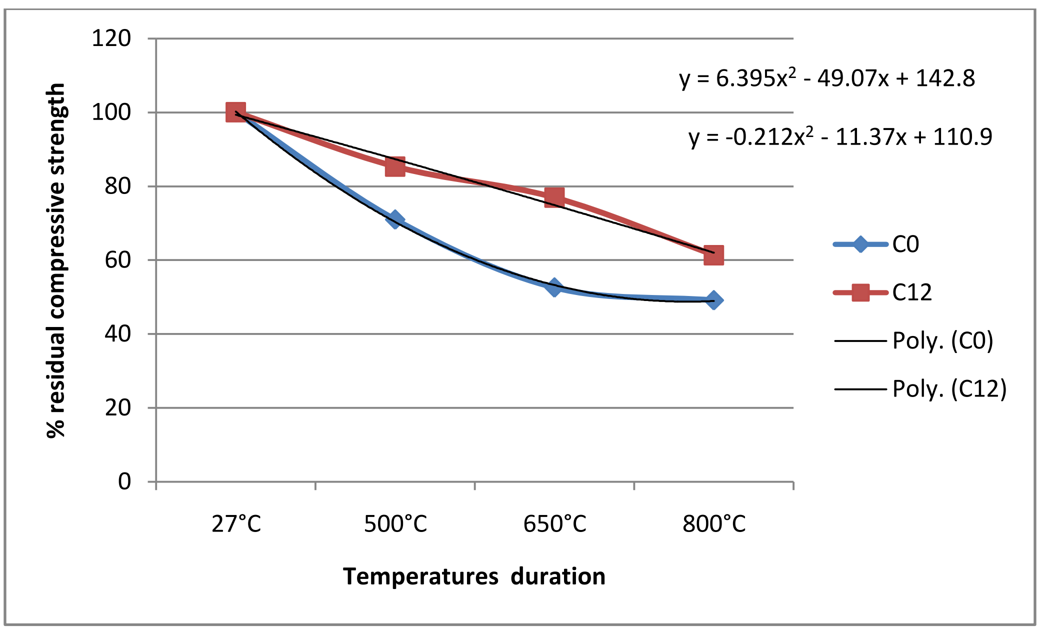
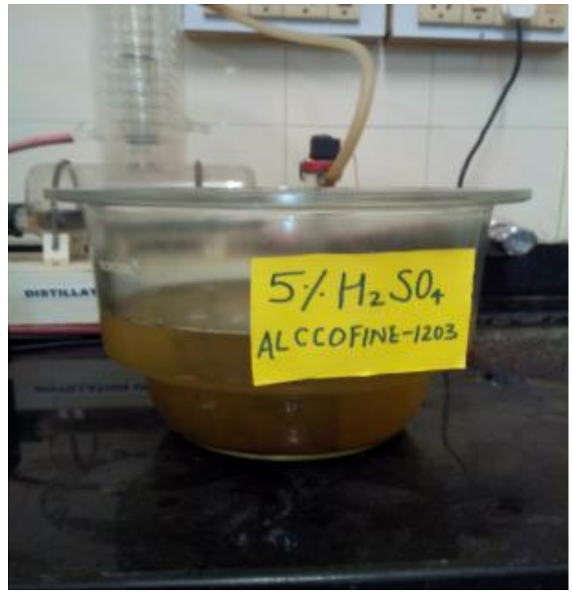


Fig. 4.13: Variation of % Residual compressive strength with varying temperature at 7days of curing

4.2.5 Durability Analysis

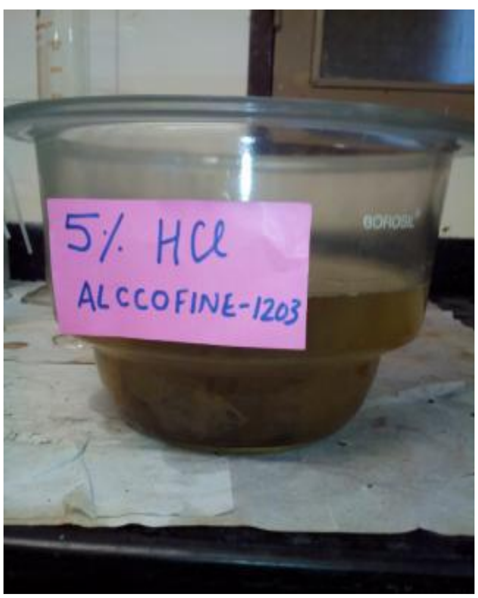
4.2.5.1 Acid attack Test

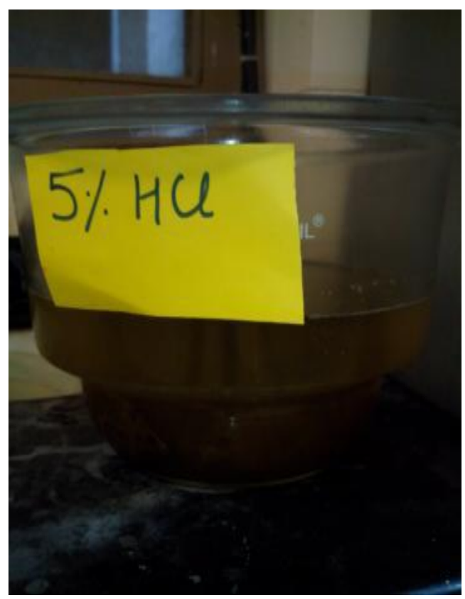
Initially the constituent materials were weighed and dry mixing was carried out for cement, sand and coarse aggregate and ultra fine slag. This was thoroughly mixed manually to get uniform colour of mix. The mixing duration was 2-5 minutes and then the water was added as per the mix proportion. The mixing was carried out for 3-5 minutes duration. Then the mix poured in to the cubical moulds of size 100 x 100x 100 mm and then compacted by placing on compaction table. In this study we prepared 3 sets of six different mixes of M60 grade namely referral concrete (AC0), concrete made by replacing 12% of cement by Alccofine (AC12) & concrete made by replacing 14% of cement by Alccofine (AC14) & so on. Replacement ratios of alccofine taken was 0,6,8,10,12,14%. The cubes were demoulded after 1 day of casting and then kept in respective solutions of 5% H_2SO_4, 5 % HCL & in referral solution of 100 % H_2O for curing, at room temperature with a normal humidity. The cubes were taken out after 30 days of curing and tested in compressive testing machine and loss in strength is calculated. The concentration of acids was maintained throughout this period (in interval of 15 days). After 30 days the specimens were taken out from respective solutions. The surfaces of specimens were cleaned and weights were measured. The mass loss and strength of specimen due to acid attack was determined. Fig. 4.14 (a) shows the demonstration of normal cube kept in 5% H_2SO_4 solution and Fig. 4.14 (b) shows the curing of concrete cubes with varying percentages of alccofine in 5% H_2SO_4 solution. Fig. 4.15 (a) and (b) shows the curing process of cubes kept in 5% HCl solution. Fig. 4.16 shows the pictorial view of concrete cubes kept for curing in 100% water. After 30 days of curing for referral concrete kept for curing in water there is no loss in compressive strength as seen from Table 4.13.



(a) **(b)**

Fig. 4.14: (a) and (b): Concrete cubes kept in 5% H_2SO_4 solution





(a) (b)

Fig. 4.15 (a) and (b): Concrete cubes kept in 5% HCl solution

Fig. 4.16: Concrete cubes kept for curing in 100% H_2O

Table. 4.13: % reduction in compressive strength of concretes after curing in water

Nomenclature	% of alccofine	Solution for curing	Compressive strength MPa	% reduction in compressive strength
AC_0	0	100% Water	63.50	00
AC_6	6	100% Water	69.25	00
AC_8	8	100% Water	71.20	00
AC_{10}	10	100% Water	82.40	00
AC_{12}	12	100% Water	88.60	00
AC_{14}	14	100% Water	87.83	00

Table. 4.14: % reduction in compressive strength of concretes after curing in 5% HCl Solution

Nomenclature	% of alccofine	Solution for curing	Compressive strength MPa	% reduction in compressive strength
AC_0	0	5% HCl	61.50	3.15
AC_6	6	5% HCl	68.84	0.59
AC_8	8	5% HCl	70.79	0.57
AC_{10}	10	5% HCl	81.94	0.56
AC_{12}	12	5% HCl	88.14	0.52

AC_{14}	14	5% HCl	87.56	0.31

Percentage reduction in compressive strength of cubes with and without alccofine cured in 5% HCl solution are represented in Table. 4.14. For referral concrete in which no alccofine was added (AC_0) when cured in 5% HCl solution compressive strength has dropped down to 61.50 MPa with a percentage reduction of 3.15%. But there is significant improvement in compressive strength of cubes incorporated with alccofine. At 6% replacement of cement with alccofine (AC_6) percentage reduction is only 0.59%. With increase in alccofine content this % reduction is also decreasing and at 12% replacement level (AC_{12}) percentage reduction has dropped down to 0.59%. This shows that concrete cubes incorporating alccofine not only improves the hardened properties of concrete but also helps in chloride attack.

Table. 4.15: % reduction in compressive strength of concretes after curing in 5% H_2SO_4Solution

Nomenclature	% of alccofine	Solution for curing	Compressive strength MPa	% reduction in compressive strength
AC_0	0	5% H_2SO_4	59.02	7.05
AC_6	6	5% H_2SO_4	64.23	7.25
AC_8	8	5% H_2SO_4	60.18	15.48
AC_{10}	10	5% H_2SO_4	58.65	28.82
AC_{12}	12	5% H_2SO_4	57.27	35.36
AC_{14}	14	5% H_2SO_4	55.89	36.36

Table.4.15 shows the percentage reduction in compressive strength of cubes with and without alccofine cured in 5% H_2SO_4 solution. For referral concrete in which no alccofine was added (AC_0) when cured in 5% H_2SO_4 solution compressive strength has dropped down to 59.02 MPa with a percentage reduction of 7.05 %. With increase in percentage of alccofine the concrete suffers a rapid loss of compressive strength as soon as it is exposed to sulphuric acid. This may be due to Sulphate attack which denotes an increase in the volume of cement paste in concrete or mortar due to the chemical action between the products of hydration of cement and solution containing sulphates. The graphical variation of percentage reduction in compressive strength with varying percentage of alccofine is shown in Fig. 4.14. It can be seen that % loss due to sulphuric acid is for AC_{12} specimen is nearly 35.36%. But loss in compressive strength due to

hydrochloric acid is very less. Thus replacement of Alccofine is found to have increased the durability against hydrochloric acid attack. This is due to the silica present in alccofine which combines with calcium hydroxide and reduces the amount susceptible to acid attack.

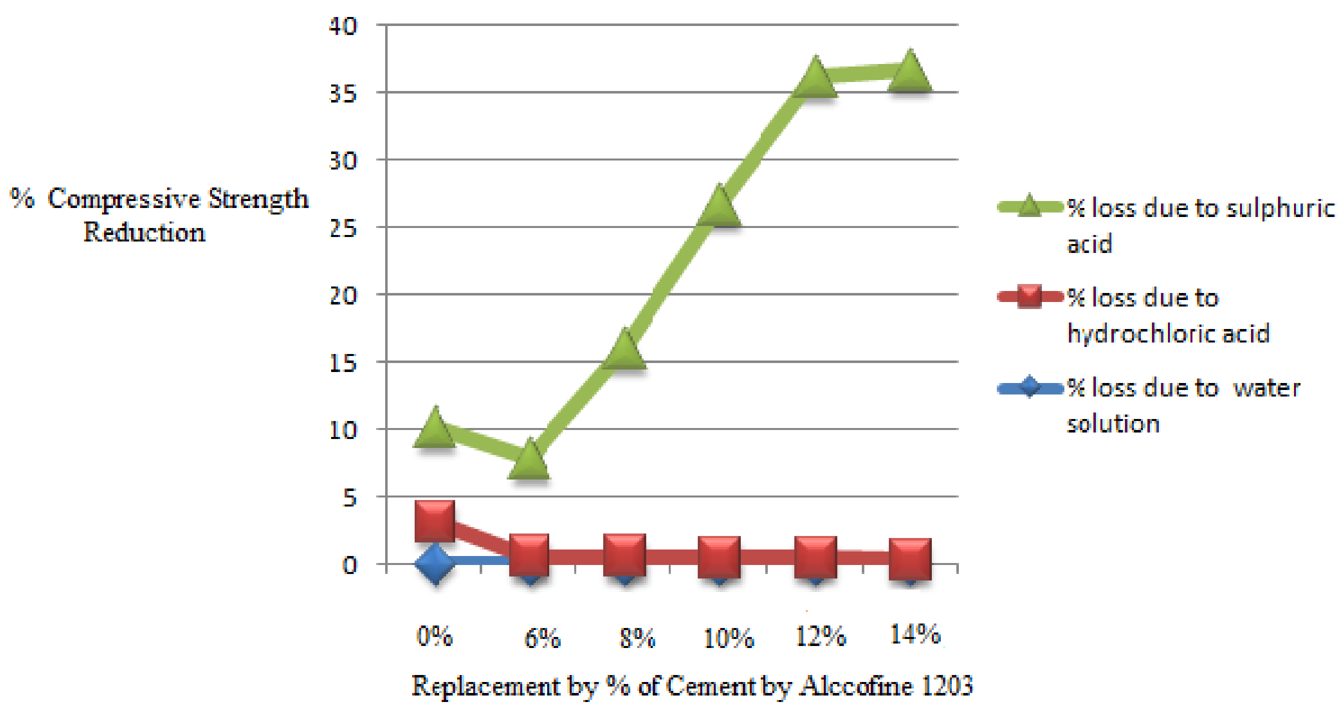


Fig. 4.17: Reduction in compressive strength of concrete cubes cured under different solutions

4.3 Comparison of test results obtained from past literatures

Test results obtained in this study was compared form previous literatures and comparative study is made. For the comparison purpose only those literatures were taken in which M60 grade of concrete. A. Shukla et al [43] studied the properties of fresh and hard concrete by partially replacing cement with rice husk ash. In his study they used M60 grade of concrete having a water/cement ratio of 0.35. In his research workability of the mixes tends to decrease with adding percentages of rice husk ash. Similar results were obtained when alccofine was used in this research. V.D Sabale et al [37] conducted similar studies on silica fume used as partial replacement of cement. They used M60 grade of concrete in which silica fume was added and compressive strength and flexural strength were determined. Though in their research variation of silica fume percentages were different of what has been done in this study for the purpose of comparison intermediate values were interpolated. One such comparison is shown in Fig. 4.18. It can be seen that compressive strength of concrete incorporating alccofine shown better results than silica fume incorporated concrete. Change in compressive strength at 28 days in case of silica fume concrete is only 24% when compared to alccofine concrete which is 39.5%. Flexural strength when compared with past research also indicated that alccofine shows better results both in terms of strength and durability. Fig. 4.19 shows one such comparison of flexural strength of alccofine concrete with silica fume concrete.

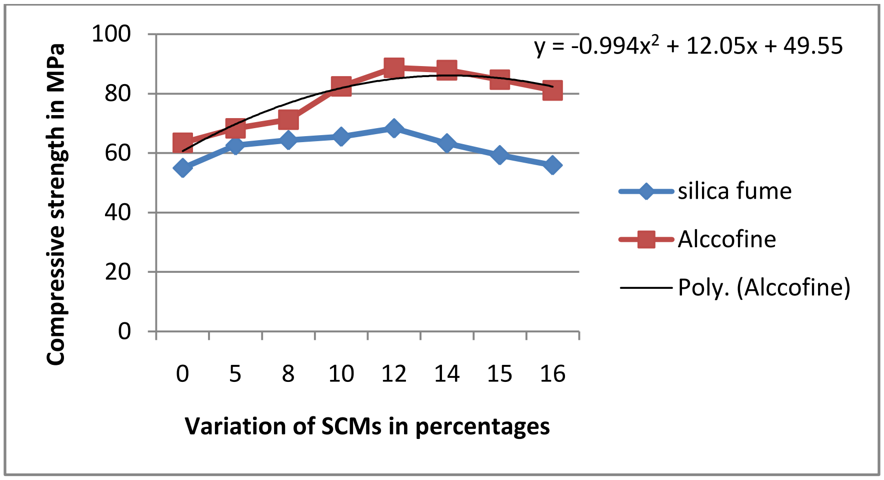


Fig. 4.18: Comparison of compressive strength results

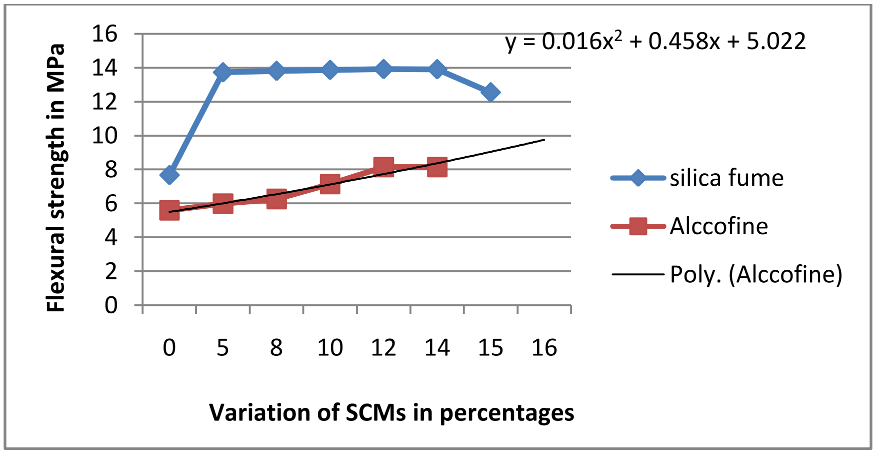


Fig. 4.19: Comparison of Flexural strength results

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

Detailed laboratory experiments performed on M60 grade of concrete with water cement ratio 0.3 is discussed in preceding Chapters. Main aim of this study is find the optimum dose of alccofine that can be preplaced by cement and how this material affects the strength and durability of concrete. The major experimental outcomes are as follows

- Compressive strength of concrete increases after adding alccofine. Optimum dose of alccofine that can be replaced is 12%. As compared with controlled concrete there is 39.5% increase in compressive strength.
- Flexural strength of plain concrete beams at 12% replacement of cement with alccofine shows 45% increase in flexural strength when compared with controlled concrete.Flexural strength of reinforced concrete beams at 12% replacement of cement with alccofine shows 62% increase in flexural strength when compared with controlled concrete. From Table 2.11 it can be concluded that to achieve same amount of deflection higher amount of load is required in case of concrete incorporated with alccofine.
- There is significant increase in split tensile strength of steel fiber reinforced concrete when compared with controlled concrete. There is increase in 38% of split tensile strength of concrete cylinders with 12% alccofine and 1.5% by volume of steel fibers. There is also significant increase in flexural strength of steel fiber reinforced concrete beams with same amount of alccofine and steel fibers.
- Fire resistant test was also conducted to find the residual compressive strength after increasing the temperature of concrete upto 800ºC. It has been observed that along with increased compressive and flexural strength of concrete, it can also withstand the elevated temperature upto a certain value. As seen from Fig. 3.6 at 28 days of curing maximum %

residual compressive strength was noticed when the cubes were heated at 500ºC for 1 hour.

- From durability analysis test it can be concluded that the concrete incorporating ultra fine slag (alccofine) shows much improved resistant to acid attack. From Table 2.16 it can be observed that % reduction in compressive strength of concrete cubes incorporating alccofine cured in 5% HCl is much less than ordinary concrete cured under same conditions.

5.2 Future scope of research work

- Following work is limited to only static loading but this work can be extended to dynamic loading also. Moreover study should be made how this admixture behaves in presence of other mineral admixtures.

- This work can be extended to find out pozzolanic activity index and strength activity index.

- There is also a scope for a comprehensive laboratory testing of ultra fine slag in ultra high performance concrete.

REFERENCES

[1] Karri, S.K., Rao, G.V.R. and Raju, P.M. (2015). "Strength and Durability Studies on GGBS Concrete", *International Journal of Civil Engineering*, 2(10).

[2] Chaithra, H.L, Pramod, K., and Chandrashekar, A. (2015). "An Experimental Study on Partial Replacement of Cement by Ggbs and Natural Sand by quarry sand in concrete", *International Journal of Engineering Research & Technology*, 4(5).

[3] Sharma D., Gupta S., Kapoor A., and Sharma A. (2015), "A Review on Alccofine- A New generation Micro Fine Concrete Material for High Strength Concrete", *National Conference on Sustainable Infrastructure Development*, pp. 68-75.

[4] Saurav and Gupta, A.K. (2014). "Experimental study of strength relationship of concrete cube and concrete cylinder using ultrafine slag Alccofine, *International Journal of Scientific & engineering Research*, 5(5).

[5] Divsholi, B.S., Lim Darren, T.Y. and Teng, S. (2014). "Durability Properties and Microstructure of Ground Granulated Blast Furnace Slag Cement Concrete", *International Journal of Concrete Structures and Materials*, Springer, 8(2).

[6] Shukla, H., Srivastava, V., Agarwal, V.C. and Mehta, P.K. (2014), "*Optimum dose of metakaolin in steel fiber reinforced Portland pozzolona cement concrete"*. Journal of Academia and Industrial Research, Vol. 3, Issue 5

[7] Praveen N.S, Narashimhan H.S.,and Raghunandan V.K. (2014),"*Hardened Properties of Concretes made with Micro Silica and Alccofine- A Performance Optimization based Comparative Study*", International Journal of Engineering Research and Development, 10(8).

[8] Upadhyay, S.P. and Jamnu, M.A. (2014). "Effect on compressive strength of high performance concrete incorporating alccofine and fly Ash", *International Journal of Innovative Research and Development,* 3(2).

[9] Abdullah Keyvani. (2014). "Thermal performance & fire resistance of autoclaved aerated concrete exposed humidity conditions", *International journal of research engineering and technology, IJRET*, 3(3).

[10] Arivalagan, S. (2014). “Sustainable Studies on Concrete with GGBS As a Replacement Material in Cement”, *Jordan Journal of Civil Engineering*, 8(3).

[11] Sangeetha, S.P. and Joanna, P.S (2014). “Flexural behaviour of reinforced concrete beams with partial replacement of GGBS”, *American Journal of Engineering Research* (AJER), 3(1).

[12] Tangchirapat, W., Rattanashotinut, C., Buranasing, R. and Jaturapitakkul, C. (2013). “Influence of Fly Ash on Slump Loss and Strength of Concrete Fully Incorporating Recycled Concrete Aggregates”, *Journal of Materials in Civil engineering, ASCE*, 25(2).

[13] Solanki, J. and Pitroda, J. (2013). “Flexural strength of beams by partial replacement of cement with fly ash and hypo sludge in concrete”, *International Journal of Engineering Science and Innovative Technology (IJESIT)*, 2(1).

[14] Pawar, M.S. and Saoji, A.C. (2013). “Effect of alccofine on self compacting concrete”, *The International Journal of Engineering And Science*, 2(6).

[15] Patel, Y.H., Patel, P.J., Patel, J.M. and Patel, H.S. (2013). “Study on durability of high performance concrete with alccofine and fly ash”, *International Journal of Advanced Engineering Research and Studies*, 2(3).

[16] Suthar, S.B., Shah, B.K. (2013). “Study on Strength Development of High Strength Concrete Containing Alccofine and Fly-Ash”, *Indian journal of research*, 2(3).

[17] Soni, D., Kulkarni, S. and Parekh, V. (2013). “Experimental Study on High-Performance Concrete with Mixing of Alccofine and Flyash”, *Indian Journal of Research*, 3(4).

[18] Pradhan, D. and Dutta, D. (2013). “Influence of Silica Fume on Normal Concrete”, *International Journal of Engineering Research and Applications*, 3(5)

[19] Venkatesan, G., Raman, S.R. and Sekaran, M.C. (2013). “Flexural behaviour of reinforced concrete beams using high volume fly ash concrete confinement in compression zone”, *Journal of Civil Engineering*, 21(2).

[20] Madhavi, T.P., Sampathkumar, V. and Gunasekaran, P. (2013). “Partial replacement of cement and fine aggregate by using fly ash and glass aggregate”, *International Journal of Research in Engineering and* Technology, Conference Issue

[21] Arezoumandi, M., Volz, J.S. and Myers, J.J. (2013). “Shear Behavior of High-Volume Fly Ash Concrete versus Conventional Concrete”, *Journal of materials in civil engineering, ASCE*, 25(10).

[22] Magudeaswaran, P. and Eswaramoorthi, P. (2013). "Experimental Study on Durability Characteristics of High Performance Concrete, *International Journal of Emerging Technology and Advanced Engineering*, 3(1).

[23] Teng, S., Lim, T. Y. D. and Sabet, D.B. (2013). "Durability and mechanical properties of high strength concrete incorporating ultra fine ground granulated blast-furnace slag", *Construction and Building Materials*, 40.

[24] Swaroop, A.H.L., Venkateswararao, K. and Kodandaramarao, P. (2013). "Durability Studies on Concrete with Fly Ash & GGBS, *International Journal of Engineering Research and Applications*, 3(4).

[25] Choi, S.J., Lee, S.S. and Monteiro, P.J.M. (2012). "Effect of Fly Ash Fineness on Temperature Rise, Setting, and Strength Development of Mortar", *Journal of materials in civil engineering, ASCE*, 24(5).

[26] Shende, A.M., Pande, A.M., and Pathan, M.G. (2012). "*Experimental Study on Steel Fiber Reinforced Concrete for M-40 Grade". International Refereed Journal of Engineering and Science,* 1(1).

[27] Amudhavalli, N.K. and Mathew, J. (2012). "Effect of silica fume on strength and durability parameters of concrete", *International Journal of Engineering Sciences and Emerging Technologies,* 3(1).

[28] Deotale, R.S., Sathawane, S.H. and Narde, A.R.,(2012). "Effect of Partial Replacement of Cement by Fly Ash, Rice Husk Ash with Using Steel Fiber in Concrete", *International Journal of Scientific & Engineering Research*, 3(6).

[29] Kannan V.,and Ganesan K. (2012). "Mechanical and transport properties in ternary blended self compacting concrete with metakaolin and fly ash", *IOSRJMCE*, 2(4).

[30] Connell, M., McNally, C. and Richardson, M.G. (2012). "Performance of Concrete Incorporating GGBS in Aggressive Wastewater Environments", *Construction and Building Materials, Elsevier*, 27(1).

[31] Chanakya, A. (2012). "Effects Due to Replacement of Ingredients of Concrete", Ph.D Thesis, pp. 1-338

[32] Hassan, A. and Mohamadien. (2012). "The effect of marble powder and silica fume as partial replacement for Cement on mortar", *International Journal of Civil and Structural Engineering*, 3(2).

[33] Roy, D.K.S. and Sil, A. (2012). "Effect of Partial Replacement of Cement by Silica Fume on Hardened Concrete", *International Journal of Emerging Technology and Advanced* Engineering, 2(8).

[34] Pitroda, J., Zala, L.B. and Umrigar, F.S. (2012). "Experimental Investigations On partial replacement of cement with fly ash in design mix concrete, *International Journal of Advanced Engineering Technology*, 3(4).

[35] Sreenivasulu, A. and Rao, K.S. (2012). "Mechanical Properties Of Heated Concrete Of M100 Grade", *International journal of engineering research and applications*, 2(4)., July-august 2012.

[36] Reddy, B.M., Rao, H.S. and George, M.P. (2012). "Effect of Hydrochloric Acid (HCl) on Blended Cement (Fly Ash based) and Silica Fume Blended Cement and their Concretes" *International Journal of Science and Technology*, 1(9).

[37] Sabale, V.D., Borgave, M.D., Shinde, S.D. and Bhagwat, M.D. (2012). "Experimental Study on High Performance Concrete", *International Journal of Electronics, Communication & Soft Computing Science and Engineering*, 3(1).

[38] Rupnow, T. D. (2012). "Evaluation of ternary cementitious combinations." Rep. No. FHWA/LA.11/486, Louisiana Transportation Research Center, Baton Rouge, LA

[39] Shi, X., Xie, N., Fortune, K., and Gong, J. (2012). "Durability of steel reinforced concrete in chloride environments: An overview", *Construction and Building Materials*, 30.

[40] Sabet, D. B., Lim, T. Y. D., & Teng, S. (2012). "Ultra durable concrete for sustainable construction", *Advanced Materials Research*, 368–373.

[41] Kogbara, R.B. and Al-Tabbaa, A. (2011). "Mechanical and Leaching Behaviour of Slag-Cement and Lime-activated Slag Stabilized/Solidified Contaminated Soil", *Science of the Total Environment, Elsevier*, 409 (11).

[42] Elsayed, A.A. (2011). "Influence of Silica Fume, Fly Ash, Super Pozz and High Slag Cement on Water Permeability and Strength of Concrete", *Jordan Journal of Civil Engineering*, 5(2).

[43] Shukla, A., Singh, C.K. and Sharma, A.K. (2011). "Study of the properties of concrete by partial replacement of ordinary Portland cement by rice husk ash", *International conference on advances in civil engineering.*

[44] Kulkarni, K.S.,Yaragal, S.C.and Narayan, K.S.B., (2011) "Effect of elevated temperatures on mechanical properties of microcement based high performance concrete", *International Journal of Applied Engineering and Technology,* 1(1).

[45] Shi, X., Yang, Z., Liu, Y., and Cross, D. (2011). "Strength and corrosion properties of Portland cement mortar and concrete with mineral admixtures", Construction and Building Materials, 25(1).

[46] Nazari, A., & Riahi, S. (2011). "Splitting tensile strength of concrete using ground granulated blast furnace slag andSiO_2 nanoparticles as binder", *Energy and Buildings*, 43.

[47] Tikalsky, P., Taylor, P., Hanson, S., and Ghosh, P. (2011). "Development of performance properties of ternary mixtures: Laboratory study on concrete." Rep. No. DTFH61-06-H-00011 Work Plan 12 Pooled Fund Study TPF-5(117), *National Concrete Pavement Technology Center, Ames,* IA.

[48] Pazhani, K. and Jeyaraj, R. (2010). "Study on Durability of High Performance Concrete with Industrial Wastes", *Applied Technologies and Innovations*, 2(2).

[49] Pathik A., Rao., Vyasa.A.N., Pai B V B., Dordi C., (2010). "Micro Technology for High Performance Concrete", *Roving National Seminar On Concrete Sustainability Through Innovation Materials And Techniques*, pp.64-69

[50] Islam, M. and Islam, S. (2010). "Strength Behaviour of Mortar Using Fly Ash as Partial Replacement of Cement, *Concrete research letters*, 1(3).

[51] Pofale, A.D. and Deo, S.V. (2010) "Replacement of Natural Sand by Fly Ash in Concrete", *Indian concrete Institute,* pp:657-665

[52] Agarwal, V. (2010). "Concrete Durability through High Volume Fly Ash Concrete (HVFC) A literature review", *International Journal of Engineering Science and Technology*, 2(9)

[53] Christy, C.F. and Tensing, D. (2010). "Effect of Class-F Flyash as a partial replacement with cement and fine aggregate in mortar", *Indian journal of engineering and Materials Sciences*, 17(1).

[54] Ali, E. (2010), "Experimental study of steel fiber concrete slab. Part I: behavior under u.d.l", *International Journal of concrete structure and materials*, 4(2).

[55] Mohammed A.Y. (2010), “Normal Strength Steel Fiber Reinforced Concrete Subjected to Explosive Loading”, *International Journal of Sustainable Construction Engineering & Technology*, 1(2).

[56] Hadj-Sadok, A., Kenai, S., Courard, L., and Khatib, J. M. (2010). “Transport properties of mortars and concretes modified with medium hydraulic activity ground granulated blast furnace slags”, *In Second International Conference on Sustainable Construction Materials and Technologies*, Ancona, Italy.

[57] Czuban, L. and Marchand, J. (2010). “Repair durability of reinforced concrete structures affected by steel corrosion”, *PhD Symposium in Kgs. Lyngby, Denmark*.

[58] Massazza, F. (2010). “Durability of concrete and service life of italcementi group structures”, *Two solvable problems, Italcementi Group*

[59] Kadri, E.H. and Duval, R. (2009). “Hydration heat kinetics of concrete with silica fume. Construct”, *Building Material*, 23(11).

[60] Qiao, P., David I., McLean, Wen, H., Chen, F. and Liu, J. (2009). “Accelerated Degradation and Durability of Concrete in Cold Climates”, *AUTC Project* (410029)

[61] Shi, H. S., Xu, B. W., & Zhou, X. C. (2009). “Influence of mineral admixtures of compressive strength, gas permeability and carbonation of high performance concrete”, *Construction and Building Materials*, 23(5).

[62] Sabet, D. B., and Jong, H.C. (2009). “Modeling of carbonation of PC and blended cement concrete”, *The IES Journal Part A: Civil and Structural Engineering*, 2(1).

[63] Yazdami, N., Filsaime, M. and Islam, S. (2008). “Accelerated Curing of Silica-Fume Concrete”, *Journal of materials in civil engineering, ASCE*, 20(8).

[64] Singh, S.P., Ambedkar, B.R., and Mohammadi, Y. (2008), “Flexural fatigue strength prediction of steel fibre reinforced concrete”, *Electronic Journal of Structural Engineering*, 8(1).

[65] Kilic, A., Atis, C.D., Teymen, A., Karahan, O., Ozcan, F., Bilim, C. and Ozdemir, M. (2008). “The influence of aggregate type on the strength and abrasion resistance of high strength concrete”, *Cement and Concrete Composites. Elsiever*, 30(4).

[66] Behnood, A. and Ziari, H.(2008). “Effects of silica fume addition and water to cement ratio on the properties of high-strength concrete after exposure to high temperatures”, *Cement and Concrete Research, Elsevier*, 30(2).

[67] Shariq, M., Prasad, J., and Ahuja, A.K. (2008). “Strength Development of Cement Mortar and Concrete Incorporating GGBFS”, *Asian Journal of Civil Engineering (Building and Housing),* 9(1).

[68] Yijin. L., Shiqiong, Z., Jian, Y. and Yingli, G. (2008). “The Effect of Fly Ash On the Fluidity of Cement Paste, Mortar and Concrete”, *Central South University, PRC Journal*,

[69] Mullick, A.K. (2007). “Performance of Concrete With Binary And Ternary Cement Blends”, *Indian Concrete Journal*, 81(1).

[70] Ganesan, N., Indira. P.V., and Abraham, R. (2007), “Steel Fibre Reinforced High Performance Concrete”, *ISET Journal of Earthquake Technology, Technical Note*, 44(3,4).

[71] Andrew, J.M., Jason, H.I. and Maria, C.G.J. (2007). “Alkali silica reactivity of agglomerated silica fume”, *Cement and Concrete Research, Elsevier,* 37(2).

[72] Ashby, M., Shercliff, H., and Cebon, D. (2007). “Materials: Engineering science, processing and design, 1st Ed., *Elsevier, Oxford, U.K.*

[73] Sakr, K. (2006). “Effects of Silica Fume and Rice Husk Ash on the Properties of Heavy Weight Concrete”, *Journal of materials in civil engineering, ASCE,*18(3).

[74] Mehta, P. K. and Monteiro, P.J. (2006). “Concrete: Microstructure, properties, and materials, McGraw-Hill, New York

[75] Hossain, Md. A., Islam, Md. N. and Karim, Md. K., (2006), “Fire resistance of cement mortar containing high volume fly ash”, *31st conference on our world in concrete & structures*: pp.16-17

[76] Sabet, D. B. and Jong, H.C. (2006). “Effect of preconditioning of concrete under accelerated test”, *In 31st Conference on Our World in Concrete and Structures,* 31

[77] Bhanja, S. and Sengupta, B. (2005). “Influence of silica fume on the tensile strength of concrete”, *Cement and Concrete Research*, 35(4).

[78] Wong, H.S. and Razak, H.A. (2005). “Efficiency of calcined kaolin and silica fume as cement replacement material for strength performance”, *Cement and Concrete Research, Elsevier,* 35(4).

[79] Gopalakrishnan,S., Lakshmanan,N., Rajamane,N.P., Krishnamoorthy,T.S., Neelamegam,M., Chellappan,A., AnniePeter,J. Balasubramanian,K., Prabhakar,J.,

Bharatkumar,B.H., Dattatra,J.K. and Sabitha, D (2005). "Demonstration of utilizing high volume fly ash based concrete for structural applications- A report prepared for confederation of Indian Industry (CII) India", *Structural Engineering Research Centre*, Chennai

[80] (2005). "Demonstration of utilizing high volume fly ash based concrete for structural applications- A report prepared for confederation of Indian Industry (CII) India", *Structural Engineering Research Centre*, Chennai

[81] Gao, J.M., Qian, C.X., Liu, H.F., Wang, B. and Li, L. (2005). "ITZ microstructure of concrete containing GGBS", *Cement and Concrete Research, Elsevier*, 35 (7).

[82] Hani, H.N. and Nakin, S. (2005). "Effect of Silica Fume Particles On the Mechanical Properties of High Performance Concrete", *The International Society of Offshore and Polar Engineers, Conference Paper*.

[83] Wang, P. Z., Trettin, R. and Rudert, V. (2005). "Effect of fineness and particle size distribution of granulated blast furnace slag on the hydraulic reactivity in cement systems", *Advanced in Cement Research*, 17(4).

[84] Mazloom, M., Ramezanianpour, A.A. and Brooks, J.J. (2004). "Effect of silica fume on mechanical properties of high-strength concrete", *Cement and concrete composition, Elsevier*, 26(4).

[85] Dhir, R., McCarthy, M., Zhou, S., and Tittle, P. (2004). "Role of cement content in specifications for concrete durability: Cement type influences." *Structural Building*, 157(2).

[86] Juenger, M.C.G. and Ostertag, C.P. (2004). "Alkali–silica reactivity of large silica fume-derived particles", *Cement and Concrete Research, Elsevier, 34*(8).

[87] Mehta, P.K. (2004). "High-Performance, High-Volume Fly Ash Concrete For Sustainable Development" *Journal of Concrete International*, 3(1).

[88] Malhotra, V.M. and Mehta, P.K. (2004). "Pozzolanic and Cementitious Materials", *Advances in concrete technology, Taylor & Francis*, 1(1).

[89] Perumal, K. and Sundararajan, R. (2004). "Effect of partial replacement of cement with silica fume on the strength and durability characteristics of high performance concrete", *29th Conference on Our world in concrete & structures*,

[90] Hueste, M. B. D., Chompreda, P., Trejo, D., Cline, D. B. H., and Keating, P. B. (2004). “Mechanical properties of high strength concrete for prestressed members”, ACI Structural Journal. 101(4).

[91] Ji, Y. and Jong, H.C. (2003). “Effects of densified silica fume on microstructure and compressive strength of blended cement pastes”, *Cement and Concrete Research*, 33(10).

[92] Khan, M.I. (2003). “Permeation of High Performance Concrete”, *Journal of materials in civil engineering, ASCE*, 15(1).

[93] Song, P.S., and Hwang, S. (2003), “Mechanical properties of high strength steel fibre reinforced concrete”, *Construction and building materials*, pp 669-673

[94] Rao, G.A. (2003). “Investigations on the performance of silica fume-incorporated cement pastes and mortars”, *Cement and concrete research, Elsevier*, 33(11).

[95] Tatem, Andrew J., et al. (2003) "Increasing the spatial resolution of agricultural land cover maps using a Hopfield neural network”, *International Journal of Geographical Information Science*, 17(7)

[96] Potrzebowski, J. (2003), “The splitting test applied to steel fibre reinforced concrete”, *Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, wi tokrzyska, Poland*

[97] Venkatesh D.L,and Natesan S.C.(2003),“Studies on Strength and Durability Characteristics of High Performance Silica Fume Concrete”, *Proceedings of the INCONTEST* , pp.262–267

[98] Thelend, D. (2003). “The make-or-break process: With and eye on the bottom line, the producer increasingly is trying to optimize the curing process”, *The Concrete Producer*, July.

[99] Neves, R.D., and Fernandes de Almeida, J.C.O. (2003), *“Compressive behavior of steel fibre reinforced concrete”. Structural concrete*, 6(5).

[100] Chini, A.R., Muszynski, L.C. and Hicks, J. (2003). “Determination of acceptance permeability characteristics for performance-related specifications for Portland cement concrete”, *Florida Department of Transportation Research No. BC 354-41*. University of Florida, Gainesville, Fla.

[101] Francois de Larrard and Thierry Sedran (2002). "Mixture Proportioning of High Performance Concrete", *Cement and Concrete Research*, 32(1).

[102] Langan, B.W., Weng, K. and Ward, M.A. (2002). "Effect of silica fume and fly ash on heat of hydration of Portland Cement", *Cement and concrete research*, *Elsevier*, 32(7).

[103] Shi, Y., Matsui, I. and Feng, N. (2002). "Effect of compound mineral powders on workability and rheological property of HPC", *Cement and Concrete Research*, *Elsevier*, 32(1).

[104] Balendra, R.V., Zhou, F.P., Nadeem, A., and Leung, A.Y.T. (2002), "Influence of steel fibres on strength and ductility of normal and light weight high strength concrete", *Building and environment*, pp 1361-1367

[105] Gopalakrishna S., Rajamane, N.P., Neelamegam M., Peter J.A., Dattatreya, J.K. (2001). "Effect of partial replacement of cement with fly ash on the strength and durability of HPC*", The Indian Concrete Journal*, pp.335-341.

[106] Polder, R. B. (2001). "Test methods for onsite measurement of resistivity of concrete: A RILEM TC-154 Technical recommendation," *Construction and Building Materials*, 15(2,3).

[107] Papadakis, V. G. (2000). "Effect of supplementary cementing materials on concrete resistance against carbonation and chloride ingress", *Cement and Concrete Research*, 30(2).

[108] Padmarajaiah, S.K. (1999). "Influence of fibers on the behavior of high strength concrete in fully/partially prestressed beams: an experimental and analytical study", *Ph.D. thesis*, Indian Institute of Science, Bangalore, India.

[109] QCL Group of companies (1999). "Sulphate attack and chloride ion penetration: their role in concrete durability", *Technical Note.*

[110] Dhir, R.K. (1997). "High durability performance concrete", in proceedings of TCDC, *International Workshop, Advances in HPC Technology and application, SERC,* 13(34).

[111] Lohtia, R.P. and Joshi, R.C. (1996). "Mineral admixtures. In: Ramachandran, V.S. (ed.)", *Concrete Admixture Handbook, 1153pp. Noyes Publications, USA.*

[112] Siva Nageswara Rao, G. (1996). "Effective utilisation of flyash in concrete for aggressive environment", *Ph.D. Thesis*, IIT, Madras.

[113] Bayasi, Z. and Zhou, J. (1993). “Properties of silica fume concrete and mortar”, *ACI Material Journal*, 90(4).

[114] Khayat, K.H., Aitcin, P.C. (1993). “Silica fume: a unique supplementary cementitious material*”, In Ghosh, S.N. (ed.) Mineral Admixtures in Cement and Concrete*, vol. 4, pp. 227–265., ABI Books Private Limited.

[115] Bentz, D.P., Stutzman, P.E., and Garboczi, E.J., (1992). “Experimental and Simulation Studies of the Interfacial Zone in Concrete”, *Cement and Concrete Research,* 22 (5).

[116] Oh, B.H. (1992). “Flexural analysis of reinforced concrete beams containing steel fibers.” *Journal of structural engineering,* 118(10).

[117] Holland, T.C. (1989). “Working with silica fume in ready-mixed concrete: U.S.A. experience.” *Proceedings, 3rd Int. Conf., Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, SP-114, Vol. 2, Farmington Hills, Mich., 763–781

[118] Ghosh, S., Battacharya, C. and Ray, S.P. (1989). “Tensile strength of steel fiber reinforced concrete.” *Institute of Engineers (India),* 69(1).

[119] Patnaik, A.K. and Jain, S.K. (1988). “Ductility requirements in Indian codes for a seismic design of RC frame structures: A review”, *Bulletin of the ISTE*, 28(2).

[120] Ramakrishnan, V. (1987). “Material and Property of fiber reinforced concrete”, in *Proceedings of the International Symposium on fiber Reinforced Concrete*, Madras, India, Volume 1.

[121] Barr, B. (1987). “Compact shear test specimens for FRC materials”, *Composites, Elsevier*, 18(1).

[122] Scali, M. J., Chin, D. and Berke, N.S. (1987). “Effect of microsilica and fly ash upon the microstructure and permeability of concrete”, Proc., *9th Int. Conf. on Cement Microscopy, International Cement Microscopy Association, Duncanville,* Tex., 375–387.

[123] Feldman, R.F. and Cheng-yi, H. (1985). “Influence of silica fume on the micro structural development in cement mortars”, *Cement and concrete research, Elsevier*, 15(2).

[124] Huang, Cheng-Yi, and Feldman, R.F. (1985). “Influence of Silica Fume on the Micro structural Development in Cement Mortars,” *Cement and Concrete Research*, 15(2).

[125] Lakshmipathy, M. (1983). “Ductility of reinforced fibrous concrete structural members”, *Ph.D Thesis, University of Madras*.

[126] Sellevold, E.J., Badger, D.H., Klitgaard, Jensen, K. and Knudsen, T. (1982). “Silica Fume-Cement Pastes: Hydration and Pore Structure,” *Condensed Silica Fume in Concrete, Proceedings of the Nordic Research Seminar on Condensed Silica Fume in Concrete,* O. *Norwegian Institute of Technology, Trondheim, Norway*, pp. 19-50.

[127] Uchikawa, H. and Uchida, S. (1980). “Influence of pozzolans on the hydration of C_3A”, *Seventh International Congress on the Chemistry of Cement, Paris, pp. IV-23–IV-29.*

[128] Hanger, C.H. (1977). “Steel fibrous Concrete Joint for Seismic Resistance structures, Reinforced concrete structures in Seismic Zone”, *ACI publications, SP53.*

[129] Mangat, P.S. (1976). “Tensile strength of steel fiber reinforced concrete”, *Cement and concrete research,* Volume 6.

[130] Kelly, A. (1970). “Interface effects and the work fracture of a fibrous concrete”, in *Proceedings of Royal Society of London”, A319.*

[131] Cembureau.(2015). “Activity report 2015.” ⟨http://www.cembureau.eu /sites/default/files/AR2015.pdf⟩ (Jul. 6, 2016).

[132] Brunauer, Stephen, and Copeland L. E. (1964) "The chemistry of concrete." Scientific American, Pg No.80-92.

[133] Mangat, P.S. (1975), “Tensile strength of steel fiber reinforced concrete”, *Cement and Concrete research, Elsevier.* 6(2)

[134] Jones, R., Hirsch, J.T.J. and Stephenson, H.K. (1997). ACI monograph, no 6 p. 178.

[135] Naville, A.M. and Brooks, J.J. (2010). “Concrete Technology, 2nd edition”, *Pearson Education Limited, London*

[136] Shetty, M.S. (2005). “Concrete Technology-Theory and Practice”, S. Chand and Co.

[137] Santhakumar, A.R. (2007). “Concrete Technology”, *Oxford University Press*.

[138] Gambhir, M.L. (1995). “Concrete Technology, 2nd edition”, *Tata McGraw- Hill, New Delhi*.

[139] IS 383: 1970, “Indian standard Specifications for coarse and fine aggregates from natural sources for concrete”, *Bureau of Indian Standards,* New Delhi.

[140] IS 5816: 1999, “Splitting tensile strength of concrete method of test,” *Bureau of Indian Standards*, New Delhi.

[141] IS 9399: 1959, “Specification for apparatus for flexural testing of concrete”, *Bureau of Indian Standards*, New Delhi

[142] IS 10262: 1982, “Recommended guidelines for concrete mix design”, *Bureau of Indian Standards,* New Delhi.

[143] IS 516: 1959, “Methods of tests for strength of concrete,” *Bureau of Indian Standards*, New Delhi.

[144] IS10086:1982, “Specification for Moulds for use in tests of cement and concrete”, *Bureau of Indian Standards,* New Delhi

[145] IS 8112: 1989, “43 grade ordinary Portland cement-specification”, *Bureau of Indian Standards,* New Delhi.

[146] IS 456: 2000, “Indian Standard Plain and Reinforced Concrete Code of Practice, 4th revision, *Bureau of Indian Standards,* New Delhi.

[147] IS 2386(Part 1):1963, “Methods of test for aggregates for concrete: Part 1 Particle size and shape, Jan 2007

[148] IS: 1199-1959, “Methods of sampling and analysis of Concrete”, *Bureau of Indian Standards,* New Delhi.

[149] IS: 4031-1988, “Methods for Physical Tests for Hydraulic Cement”, *Bureau of Indian Standards,* New Delhi.

[150] IS 3812: 2003. “Pulverized fuel ash -specification part 1 for use as pozzolana in cement, cement mortar and concrete”, *Bureau of Indian Standards,* New Delhi.

[151] Kulkari.,Vijay, R. and Pathak, S.R. (2013). “Laboratory Investigations for Assessing Chloride Ion Permeability of Medium Strength Concrete Mixes”, *The Indian Concrete Journal*, 87(1).

[152] Krishna, R.N. (2012). “Rice husk ash – an ideal admixture for concrete in aggressive environments”, *37th Conference on Our World in Concrete & Structures*, 29-31 August 2012, Singapore.

[153] Kishore, R., Bhikshna, V. and Prakash, P.J. (2011). “Study on Strength Characteristics of High Strength Rice Husk Ash Concrete”, *Procedia Engineering, Elsevier*, 14(1).

[154] Venu, M. and Rao, P.N. (2010). “High Performance Concrete with GGBS and ROBO Sand”, *International Journal of Engineering Science and Technology*, 2(10).

[155] S.P. Shah, and Ahamed, S.H. (1994). “High Performance Concrete: Properties and applications”, *McGraw Hill, New York.*

[156] Patel, P.J. (2014). “Health analysis of high performance concrete by using waste material”, *Ph.D Thesis, Ganpat University, Kherva.*

LIST OF PUBLICATIONS

6.1 Journal Publications

[1] Saurav, Gupta, A.K. (2018). “Experimental investigation to find the optimum dose of steel fibers in concrete incorporating ultrafine slag”. *Journal of Engineering science and Technology*, 13(1), 187-195. [**Scopus Indexed**]

[2] Saurav, Gupta, A.K. (2016). “Experimental study to find the Flexural strength of reinforced concrete beam incorporating ultra fine slag”. *International journal of engineering and Technology*, 8(6), 2772-2778. **[Scopus Indexed].**

[3] Saurav and Gupta, A.K., (2014). “Experimental study of strength relationship of concrete cube and concrete cylinder using ultrafine slag Alccofine”. *International Journal of Scientific & engineering Research*, 5(5), 102-107. **[*GOOGLE Scholar*] (3 Citation)**

[4] Saurav. (2012). “Application of Nano Technology in building materials”. *International journal of Engineering research and applications,* 2(5), 1077-1082 **[*GOOGLE Scholar*] (3 Citation)**

[5] Saurav, Gupta, A.K. (2017). “Comparative experimental study of different cementitious materials used as partial replacement of ordinary Portland cement”. *International Journal of Applied Engineering Research.* **(communicated)**

Submission Info

SUBMISSION ID	822852385
SUBMISSION DATE	07-Jun-2017 11:01
SUBMISSION COUNT	1
FILE NAME	Thesis_SAURAV.pdf
FILE SIZE	6.45M
CHARACTER COUNT	224046
WORD COUNT	43615
PAGE COUNT	176
ORIGINALITY	
OVERALL	15%
INTERNET	13%
PUBLICATIONS	6%
STUDENT PAPERS	10%
GRADEMARK	
LAST GRADED	N/A
COMMENTS	0
QUICKMARKS	