EXPERIMENTAL STUDY ON IMPROVING MECHANICAL AND DURABILITY PROPERTIES OF SUSTAINABLE CONCRETE BY USING NEW AGE ADDITIVES.

Thesis submitted to Faculty of Engineering and Technology, Jadavpur University in the partial fulfillment of the requirements for the degree of

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With specialization in

STRUCTURAL REPAIR AND RETROFITTING ENGINEERING

By

ARNAB MONDAL

Exam Roll No.: M6CNE19014.

Registration No-100780 of 2007-08

Under the guidance of

Dr. Partha Ghosh
Associate Professor,
Jadavpur University.
&
Dr. Kushal Ghosh
Assistant Professor
NIT SIKIM.

DEPARTMENT OF CONSTRUCTION ENGINEERING
FACULTY OF ENGINEERING AND TECHNOLOGY
JADAVPUR UNIVERSITY
KOLKATA-7000106.

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JADAVPUR UNIVERSITY
DEPARTMENT OF CONSTRUCTION ENGINEERING
FACULTY OF ENGINEERING AND TECHNOLOGY
KOLKATA-7000106.

Certificate of Recommendation

*This is to certified that the thesis entitled **“Experimental study on improving mechanical and durability properties of sustainable concrete by using new age additives .”** has been prepared by **Arnab Mondal** (Exam Roll No.: M6CNE19014 ,Registration No-100780 of 2007-08) for partial fulfillment of requirements for the award of masters degree in Construction Engineering ,is a record of research work carried out under my supervision and guidance .I hereby approve this thesis for submission and presentation.*

Dr. Partha Ghosh
Associate Professor
Department of Construction Engineering
Jadavpur University
Kolkata.

Dr. Kushal Ghosh
Assistant Professor
NIT SIKIM

Countersigned by

Head
Department of Construction Engineering
Jadavpur University
Kolkata.

Dean
Faculty of Engineering and Technology
Jadavpur University
Kolkata.

JADAVPUR UNIVERSITY
DEPARTMENT OF CONSTRUCTION ENGINEERING
FACULTY OF ENGINEERING AND TECHNOLOGY
KOLKATA-7000106.

Certificate of approval

The foregoing thesis is hereby approved as a creditable study of an engineering subject carried out and presented in a manner satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by the approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein but approve the thesis only for the purpose of which it has been submitted.

Final Examination for
Evaluation of the Thesis.

(Signature of Examiner)

(Signature of Examiner)

(Signature of Examiner)

*Only in case the thesis is approved.

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DEPARTMENT OF CONSTRUCTION ENGINEERING
FACULTY OF ENGINEERING AND TECHNOLOGY
KOLKATA-7000106.

Declaration of Originality and Compliance of Academic Ethics

I hereby declare that the thesis entitled ***""Experimental study on improving mechanical and durability properties of sustainable concrete by using new age additives ."*** *contains literature survey and original research work done by the undersigned candidate and have been submitted for the partial fulfillment of the continuous assessment of the course in* ***"Structural Repair and Retrofit Engineering "*** *of Jadavpur University.*

All information in this document has been obtained and presented in accordance with academic rules and ethical conduct.

I also declare that as required by these rules and conduct ,I have fully cited and referenced all materials and results that are not original to the work.

Name: **ARNAB MONDAL**

Examination Roll No: **M6CNE19014.**

Registration No: 100780 of 2007-08
Thesis Title: **Experimental study on improving mechanical and durability properties of sustainable concrete using new age additives .**

Supervisor name:	**Dr. PARTHA GHOSH**	**& Dr. Kushal Ghosh**
Designation:	**Associate Professor.**	**Assistant Professor**
Department:	**Construction Engineering.**	**Civil Engineering.**
Instituition:	**Jadavpur University.**	**NIT Sikim**

Signature with date: ______________________________
(Arnab Mondal)

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(ARNAB MONDAL)

SYNOPSIS

In the modern era we are exposed to several environmental issues in terms of depletion of natural resources and production of pollutants affecting our human society .In order to save our human civilization we need to give greater importance to optimum utilization of natural resources to meet up the needs of the future generation and to reduce the risk of environmental impact. So the concept of sustainability has become relevant in the construction industries as well. Portland cement is the one of the most essential ingredients of concrete and is a versatile and relatively high cost material. Large scale production of cement is causing environmental problems on one hand and depletion of natural resources on other hand. This threat to ecology has led to researchers to use industrial by products such as fly ash as supplementary cementations material in manufacturing concrete.

This experimental study has been carried out to investigate the mechanical properties as well as durability exposures of ordinary cement mortars and mortars containing ternary mixtures of supplementary cementitious materials like Ground Granulated Blast Furnace Slag(GGBS), Alccofine 1203 and silica fume (SF) along with cement. For this purpose ternary mixes were prepared by replacing OPC with 30% and 50% by GGBS along with 5%,10% and 15% by Alccofine and Silica fume separately as additive . After preparation of 50x50 cube samples they were cured in water for 7 and 28 days . Assigned samples for durability tests after 28 days of water curing were immersed in 4% H_2SO_4 and 4% $MgSO_4$ solution for 56 days and remaining for thermal exposure up to 800°C . Compressive strength test were performed on different samples to observe SCMs behavior in hardened conditions as well as different exposure conditions (acid, sulphate and thermal)after 7,28 and 56 days respectively. Durability properties were evaluated by capillary absorption (sorptivity and porosity tests).Compressive strength, bulk density, water absorption tests were performed on exposed(thermal and acid) and unexposed samples for the purpose of comparison. Microstructure studies using scanning electron microscopy(SEM) and electron dispersive X-ray(EDX) analysis were performed on samples before and after different exposure conditions. This paper discusses on the effect of different SCM's on fresh, hardened properties as well as durability behavior under different exposure conditions. Based on test results obtained from different tests a comparative study as well as the suitability of different SCM's could be made under normal and different environmental exposure conditions.

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List of Abbrebiations

CH : Calcium Hydroxite.
CSH : Calcium Silicate Hydroxite.
MSH : Magnesium Silicate Hydroxite.
MH : Magnesium Hydroxite.
OPC : Ordinary Portland Cement.
SEM : Scanning Electron Microscope.
EDX : Electron Dispersive X-Ray Spectroscopy.
SE : Secondary Electron .
ITZ : Interfacial Transition Zone.
SP : Super Plasticizer.
SDF : Strength Deterioration Factor.

CHAPTER 1

1.Introduction

1.1General:

The concept of sustainability has made its way to almost all sectors in many countries worldwide. It is inevitable for construction industry to follow suit as well. In a developing country like India, infrastructural development plays a key role. So importance has to be given on producing sustainable concrete. We know concrete is one of the most widely used construction material. However the production of ordinary Portland cement causes huge quantity of CO_2 emission(almost 1ton OPC=1ton CO_2 emission every year) and it is a matter of concern. Not only CO_2 is released from cement industry, but also SO_2 and NOx, which can cause the greenhouse effect and acid rain. This is particularly serious in the current context of climate change caused by carbon dioxide emissions worldwide, causing a rise in sea level [1].Thus to reduce the CO_2 emission and at the same time producing high quality concrete with optimum quantity of cement we are focusing on the use of different industrial by products as partial replacement of OPC. Recent research works have been conducted about how to improve the mechanical as well as durability properties of concrete by incorporating different types of new age Supplementary Cementitious Materials(SCMs) such as Ground Granulated Blast Furnace Slag(GGBS), Alccofine and Silica fume, graphene oxide, Carbon Nanotubes(CNTs), TiO_2. These by products are finer(micro and nano) in nature and due to their fineness they are capable of filling the pore space causing refinement of the concrete and making it more impermeable. The use of different (SCM's) also leads to reduction in rate of hydration process in concrete and reduce the formation of heat during hydration process at the same time which at times lead to the development of a lower compressive strength especially if it is used in higher proportion. Concrete structures are often exposed to sulfuric acid in certain industrial activities during the production process. İt can lead to a fast degradation of the concrete structures. Biogenic sulfuric acid corrosion is often a problem in sewer environments. Therefore there is a substantial need for construction of durable concrete structures in such environments. The refinement property of different admixtures is to make it more resistant against acidic and sulphate environment . Concrete structures are also exposed to high temperatures in industries using furnaces and reactors. Exposure to elevated temperature reduces the mechanical properties such as strength, modulus of elasticity and volume stability of concrete which may change the chemical composition and physical structure of the concrete considerably. Though the addition of SCM's like fly ash and slag increases the durability, it leads to lesser value of initial compressive strength. Thus other SCM's are also needed to be added in order to compensate for the decrease in compressive strength. In this context SCM's such as alccofine, silica fume can be used. This paper investigates the effects on mechanical as well as durability properties of concrete by replacement of cement with GGBS, Alccofine and Silica Fume in different proportions and a comparative study between these additives based on their experimentally obtained results. The samples were subjected to acid, sulphate as well as thermal exposure and they were compared on the basis of different properties such as compressive strength, bulk density, water absorption, sorptivity etc. Following different SCMs have been engaged in this research work.

1.2 Ground Granulated Blast Furnace Slag(GGBS):

GGBS is a by-product formed in the iron industries when molten iron blast furnace slag of about 1500°C temperature is rapidly chilled by quenching it in water and it turns into a fine, granular, almost fully noncrystalline, glassy form . It is also called slag cement and when ground in to particle size less than 10 μm contribute to high early strength up to 28 days and ground to less than 45 microns, contribute to later strength having a surface area fineness of about 400 to 600 m^2/kg Blaine. The relative density (specific gravity) for ground granulated blast furnace slag is in the range of 2.85 to 2.95. The bulk density varies from 1050 to 1375 kg/m^3 (66 to 86 lb/ft^3) [2]. For its use in blended cements, GGBS is ground to improve its reactivity during cement hydration. The main constituents of GGBS include CaO, SiO_2, and Al_2O_3. Slag shows primarily cementitious behavior (latent hydraulic activity) but may show some pozzolanic character (reaction with lime) as well. The activity of GGBFS is determined by the quantities and the properties of amorphous glass, as well as the chemical compositions [3] . Finely ground GGBS when mixed with OPC, it will produce binding properties. The production of slag is more environment friendly and cost effective compared to the production of OPC, thus producing more sustainable concrete than the OPC concrete .It is well documented that addition of GGBS, enhances early strength of the concrete.

1.2.1 Field of application of GGBS:

- High-rise buildings.
- Marine applications such as dams, shore protection construction.
- Effluent and sewage treatment plants.
- Cement products such as tiles, pipes, blocks, etc

1.2.2 Benefits of GGBS:

- Ensures higher durability of structure.
- Reduces the temperature rise and helps to avoid early-age thermal cracking.
- Improved workability.

- It is off-white in colour and substantially lighter than Portland cement. Resultantly it helps soften the visual impact of large structures such as bridges and retaining walls.

1.3 Alccofine:

ALCCOFINE 1203 is a new generation micro fine materials specially produced by product from slag having high glass content and high reactivity obtained through the process of controlled granulation **[17]**. Owing to its unique ultra fine particle size, having fineness greater than 12000 cm^2 /gm and specific gravity 2.9 and bulk density is in the range of 700-900kg/m^3. ALCCOFINE1203 provides reduced water demand for a given workability. The main constituents of Alccofine are CaO (61- 64%)and SiO_2 (21-23%).The presence of activated calcium contributes to high early age strength. Alccofine1203 is known to produce a high-strength concrete and is used in two different ways as a cement replacement, in order to reduce the cement content (usually for economic reasons) and as an additive to improve concrete properties (in both fresh and hardened states).

1.3.1 Field of application of Alccofine:

Alccofine 1203 gas widely been used in different civil engineering works like **[8]**

- Bridges
- Roads and air ports
- High rise buildings

1.3.2 Benefits of Alccofine 1203

In fresh state**[8]**

- The workability of the mix retention is improved.
- Flow ability of the mix is increased.
- Reduction in segregation can be observed in the mix.
- Reduction in heat of hydration of the mix.

In hardened state**[8]**

- Improvement in durability of the mix.
- Strength at all ages is increased.
- Resistance to chemical attack / corrosion is improved as ingression becomes difficult.
- Lowers permeability of the mix.

1.4 Silica fume

Silica fume, also referred to as microsilica or condensed silica fume is a byproduct of silicon metal or ferrosilicon alloys when high purity quartz with coal is reduced in electrical arc furnace at 2000°C (3630°F) .The smoke emits from the furnace operation cools ,condenses and is collected in huge cloth bags. **[2]** Silica fume or micro silica or condensed silica is a relatively new member in the family of pozzolans which are introduced to react with the free lime in the cement matrix and consequently improve its performance. Yet it's fineness and slow nature of pozzolanic effect also imposes some problems in the development of concrete durability and strength. **[18]** . Silica fume is extremely beneficial whenever concrete of impermeable as well as high strength is required. Because of its chemical and physical properties, it is a very reactive pozzolan. Therefore the most important use of this material is as a mineral admixture in concrete. Silica fume consists primarily of amorphous (non-crystalline) silicon dioxide (SiO_2) about 85%. The individual particles are extremely small, approximately 1/100th the size of an average cement particle. The quality of silica fume is specified by ASTM C 1240 and AASHTO M 307. Condensed silica fume is extremely fine spherical particles of less than 1 µm in diameter and average diameter of 0.1µm having surface area of about 20,000 m^2/kg. The relative density of silica fume is generally varies from 2.20 to 2.5. The bulk density of silica fume varies from 130 to 430 kg/m^3 (8 to 27 lb/ft^3). **[2]**

1.4.1 Field of application of Silica fume :

There are several applications of silica fume include **[13]**

- High performance concrete (HPC) containing silica fume for highway bridges, parking decks, marine structures and bridge deck overlays.
- High-strength concrete enhanced with silica fume for greater design flexibility.
- Silica-fume Shotcrete for use in rock stabilization, mine tunnel linings, and rehabilitation of deteriorating bridge and marine columns and piles.
- Oil well grouting.
- Repair products—silica fume is used in a variety of cementitious repair products.

1.4.2 Benefits of Silica fume:

Several benefits of using silica fume includes **[27]**

- Maintain reasonable workability and enhance the strength of concrete.
- Slower development of strength at early age due to slow pozzolanic action but ultimate strength is significant.

- Concrete containing silica fume significantly reduces the bleeding with increase in silica fume content due to its high surface area to be wetted.
- Slow pozzolanic action reduces the early age temperature thus simultaneously reduces the risk of thermal cracking at early as well as later age .
- Silica fume can produce very large reductions in water permeability depending on the mix design and dosage of silica fume.
- Protection against corrosion of embedded reinforcing steel.
- Resistance against ingression of chemical attack (acid, sufate and chlorides) of concrete by reducing permeability significantly.
- Increase abrasion resistance.

1.5 Objective

The main objective of the research is to develop an eco friendly sustainable mortar mix by using varying percentages of GGBS as well as ALCCOFINE and SILICA FUME as partial replacement of OPC and to make a comparative study between the conventional concrete and concrete prepared with GGBS , ALCCOFINE and SILICA FUME micro materials in terms of mechanical as well as durability exposures. This study is also helpful in reducing the cost of concrete replacing a significant quantity of cement with new age admixtures having good mechanical as well as durability properties.

1.6 Scope and Outline

The scope and outline of the research work are as follows:

a)Study of different physical and mechanical properties of concrete like workability ,setting time, compressive strength, water absorption, apparent permeability and sorptivty test of concrete etc.

b) Study of different durability properties of concrete when subjected to various exposure condition like thermal, Sulfuric acid and sulfate exposures etc.

c) Study of behavior of various concrete at microstructural level before and after exposure condition due to addition of different additives.

d) Comparative study on the optimum percentage of respective additives for different mechanical properties and durability exposures for obtaining an ecofriendly sustainable concrete.

CHAPTER 2

2.Literature Review

2.1 General:

This chapter deals with mechanical and durability properties of different Supplementary Cementitious Materials (SCMs) used in this research work such as GGBS, Alccofine 1203 and Silica Fume in terms of their physical and chemical characterization and combined effect when blended with cement as partial replacement and different fresh and hardened properties have been studied For this different journals and research papers have been reviewed and brief of these are discussed in the upcoming literature review.

2.2 Materials properties

2.2.1 Different fresh and hardened properties

Megat et.al (2011) [4] have investigated the influence of GGBS replacement with OPC up to 60% on the workability of concrete. The results showed that concrete blended with GGBS exhibit enhanced workability compared to the concrete without GGBFS **.(Sonowane P.B et.al)[5]** Alccofine contributes to the formation of dense pore structure due to it fine particle size and in built CaO present in the alccofine increases the formation of secondary hydrated product (C-S-H) gel which results in strength gain at early as well as later ages. Due to presence of ultra fine particles having good dispersing property Alccofine produces better workable mix. The packing effect of Alccofine particles improves flow ability and reduces bleeding of concrete in fresh state..

A.Narender Reddy et.al[6] studied on compressive strength behavior of ternary blended concrete incorporating Alccofine 1203 along with GGBS. The combination of Alccofine and GGBS at different ages did not show superior results compared to control concrete . At early ages the decrement of strength was less but with the increase in age of concrete, it has been found that combine effect of Alccofine with GGBS reduces the compressive strength to a greater extent. Though the individual replacements of Alccofine and GGBS proved to increase in compressive strength, the combination proves the incompatibility between Alccofine and GGBS. In the investigation, the highest compression strength was achieved by the combination of Cement - GGBS - Alccofine at 72% - 20% - 8% respectively.

Sourabh Gupta et.al[8] (2015) have carried out investigation on the comparative study on Alccofine and Silica Fume in a ternary blended cement along with fly ash and results indicate that the compressive strength at all age in Alccofine incorporated concrete was higher than that of Silica fume as well as the workability of the concrete in fresh state. **Eva**

Kuzielova et.al[9](2017) have investigated on a quaternary blended cement with partial replacement by SF,GGBS and Metakaolin. Experimentally obtained results showed that the lowest substitution level of cement together with the highest amount of SF in mix led to the best values of compressive strength.

Rafat Siddique et.al [13] reported high pozzolanic activity of SF particularly in earlier ages occurred in mix with high SF content within 7 days of curing as compare to other mixes. It was well documented that initial 2 days compressive strengths of other mixes containing low SF attained lower values than that of referential mix. It was reported that there was an optimal replacement of SCMs above which the refinement and the reduction of the pore volume are not occurring, which leads to the slower improvement of mechanical properties. The development of flexural strength showed the same trend on different curing time and composition of samples as the course of compressive strength.

Mohammad Iqbal Khan et.al[12] have reported the mechanism of Silica fume contributing to the strength development in concrete in terms of significance of bond at interfacial transtition zone between cement paste and aggregates and orientation of CH crystals in it. The addition of Silica fume decreases the thickness of the interfacial transition zone. Thus this mechanism not only the increase the bond strength but also connected with the formation of C-S-H gel at transition zone and proper modification of orientation of CH crystals.

Caijun Shi et.al(2015)[10] showed that with the increase in silica content up to certain optimum percentage(15%) the flow ability of the mix increased. However higher content of beyond that (22%) decreased flow ability because of the fact that Silica Fume contain ultrafine particles which absorb more water and it became problematic to deal with the mix .On the other hand this condition may be counteracted by addition of extra quantity of super plasticizer instead of adding water content of the mix. Similar condition happened in case of compressive strength. Increase in Silica Fume content up to a certain limit show increase in high early strength due to high pozzolanic action of SF but this trend changed at higher percentage of SF more than 25% and became slack..

S.Vijaya Bhaskar Reddy et.al[11]reported addition of mineral admixtures in concrete initially decrease the strength gain at early ages but increase in strength gain occurred accompanied by curing after 56 days. Workability increased noticeably with the addition of GGBS and after reaching an optimum percentage further increase caused decrease in workability. Split tensile strength showed same trend. **Hooton (1993)[13]** examined the influence of silica fume on the splitting tensile strength of concretes up to the age of 182 days . He concluded that except at 28 days, the splitting tensile strength was not improved for silica fume concrete mixes and further addition seriously affect the split tensile strength. **Bhanja and Sengupta (2005)[13]** observed that silica fume seemed to have a pronounced effect on flexural strength in comparison with splitting tensile strength. For flexural strengths, even very high percentages of silica fume significantly improved the strength.

Vireen Limbachiya et.al [19] observed silica fume having different mechanism on development property of concrete due to their high specific surface which enhances greater hydration reaction to occur and refinement mechanism by producing excess Calcium-

Silicate-Hydrate (CSH) gel through the reaction of SiO2 in the SF and the calcium hydroxide (CH) after initial hydration as well as the CaO in the GGBS.

Ahmet Benli et.al [16] reported that compressive strength of control mix as compared to other binary and ternary mixes showed better result after 28 days curing. But with the increase in curing period the SCMs mixed mortars have greater strength. It was also well documented that higher surface area and very small particle sizes of Silica fume increases the water requirement of the mix resulting in decrease in workability. Generally, mixtures containing silica fume perform worse than the control mixture with respect to fresh properties.

2.2.2 Different durability properties

Permeability is one of the major issue whenever we come across the durability properties of concrete. The difference in particle size between cement and admixture enhances packing and extent of hydrated product generated during hydration .The secondary hydrated product formed due to pozzolanic and cementitious hydration reaction fills the pores and reduces the permeability of hydrated product to a great extent and make it more effective against the ingression of aggressive agents in concrete and extend the durability of concrete. Due to its ultrafine particle size distribution having particle size less than cement ,Alccofine improves the performance of concrete in terms of durability.

Sonowane P.B et.al [5] in their experimental study came in a conclusion that there was increase in the strength rapidly upto 20% of alccofine after that the there was reduction in the strength.. **Vireen Limbachiya et.al** [19] reported that the water absorption of control mix is greater than the other SCMs mixes .The reason for lower absorption rate is the presence higher level of fineness and greater quantity of SiO2 within SF results in a greater formation of CSH gel therefore, providing greater matrix densification and decrease in water absorption.

Abhijit singh Parmar et.al(2014)[20] studied the addition of Alccofine on durability and reported that the sorptivity in Silica- Fume is more than that of Alccofine. Hence the rate of capillary rise in Silica-Fume is more than that of Alccofine. **D.Sivakumar et.al(2015)**[21] conducted tests on the durability and mechanical characterization of concrete using Alccofines and concluded that with the inclusion of Alccofine reduction in the permeability significantly.

M.M Magdum et.al [7] **(2017)** have suggested that permeability of concrete blended with Alccofine reduce to great extent and has moderate resistance against thermal exposure. Another durability issue is chloride permeability in concrete.

Perraton et al. (1988)[12] examined the effect of silica fume (5–20%) by weight of cement on the chloride permeability of concretes with water–cementitious ratios of 0.4 and 0.5. The obtained value showed significant reduction in the chloride-ion diffusion with increase in silica fume contents . This is due the addition of silica fume caused to have considerable pore refinement.

P.K Mehta et.al [23] described the sulfate attack which can manifest in the form of expansion and cracking of concrete leading to increase in permeability and ingression of the aggressive water more easily into the interior, thus accelerating the process of deterioration. Calcium hydroxide and C_3A contents of hydrated Portland cement are more vulnerable to attack by sulfate ions. Formation of gypsum during sulfate attack causes expansion and reduces the pH level and ultimately the loss in the stiffness and strength, followed by expansion and cracking, Depending upon the cation type associated with the sulfate solution (i.e., Na+,K+, or Mg2+), both calcium hydroxide and C-S-H present in the hydrated Portland cement paste may be converted to gypsum by sulfate attack:

$$MgSO_4 + Ca(OH)_2 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O + Mg(OH)_2$$

$$\begin{aligned}&3MgSO_4 + 3CaO \cdot 2SiO_2 \cdot 3H_2O + 8H_2O\\&\quad \rightarrow 3(CaSO_4 \cdot 2H_2O) + 3Mg(OH)_2 + 2SiO_2 \cdot H_2O\end{aligned}$$

In the case of magnesium sulfate attack, the conversion of calcium hydroxide to gypsum is accompanied by the simultaneous formation of magnesium hydroxide, which is insoluble and in turn reduces the formation of further C-S-H gel . On the other hand $MgSO_4$ also reacts with the C-S-H and make it unstable by the sulfate solution. The magnesium sulfate attack is, therefore, more severe on concrete.

(Ahmet Benli et.al) [16] explained durability aspect in terms of resistance of concrete against sulphate solution. The erosion materials during the reaction are the formation of sulphate ions which reacts with the cementitious materials essentially consists of calcium hydroxide and Tri calcium aluminate to form gypsum and ettringite or delayed ettringite occurs in the micro voids of the cement mortars and with the nucleation the ettringite touches to the boundary of the voids, producing an expansion force to cement mortar materials. Under the influence of the expansion force happen in concretes which causes the expansion, cracking, deterioration and degradation of concrete structures. The sulphate attack can be resisted by limiting the C_3A, C_3S and by adding different pozzolans like blast furnace slag and silica fume. This beneficial effect is attributed to the reduction in $Ca(OH)_2$ and alumina required for gypsum and ettringite for the improvement of pore structure Some researchers investigated on the effect of addition of fly ash against sulphate resistance and reported that fly ash, especially low-calcium or F class fly ash can effectively increase the resistance of the concrete against sulfate attack. **Hooton (1993)** observed that permeability of concrete decreased with addition of silica fume in the order of less than 1×10^{-17} m/s for concrete mix made with 10% silica fume.

Lee et al. (2005)[12] studied on the effectiveness of silica fume in resisting sulfate exposure. The mortar mixtures made with water/cementitious materials ratios (w/cm) of the 0.35, 0.45 and 0.55 respectively were exposed to sulfate environment, the incorporation of 10% silica fume in OPC matrix showed no evidence of spalling and cracking up to about 1 year of exposure, and effective strength loss occurred with increase in the w/cm ratio; and on an average the total strength loss was greater in mortar specimens without silica fume compared to those with silica fume.

Mohammed Qureshi et.al (2014)[22] investigated the effect of Alccofine on durability against acidic environment and suggested that with increase in fly ash content and decrease in Alccofine reduces the weight loss as well as the compressive strength after 28 days immersion in 5% sulfuric acid solution.

R. Sri Ravindrarajah [24] (2015) described the reaction of biogenic sulfuric acid on sewers in pH less than 2.

$$Ca(OH)_2 + H_2SO_4 = CaSO_4.2H_2O$$

$$3CaO.Al_2O_3.12H_2O + 3(CaSO_4.2H_2O) + 14H_2O = \underset{\text{(Ettringite)}}{3CaO.Al_2O_3.3CaSO_4.32H_2O}$$

$$3CaO.SiO_2.3H_2O + H_2SO_4 = CaSO_4\ 2H_2O + \underset{\text{(Silica gel)}}{Si(OH)_4}$$

In preliminary phase the product formed on the concrete surface is gypsum, an expansive and corrosive product, which results cracking and spalling of concrete. The gypsum in turn reacts with the calcium aluminate phases in the cementitious matrix can form highly expansive ettringite, leading to micro cracking in concrete. The main hydration product ie. C-S-H gel, reacts with the sulphuric acid to form silica gel. Silica fume in concrete improves the pore space refinement and pore-size modification due to its extreme small particles size and decrease the permeability. On the other hand pozzolanic reaction of reactive silica with calcium hydroxide enhances the formation of more C-S-H production which in turn increase the bonding at the interfacial zone between the aggregate and cement paste at later stage. Thus improves the strength of concrete and resist the sulfuric acid attack significantly as well as reduces the weight loss during acidic environment.

E. Hewayde et.al (2007)[14] reported the effect of silica fume on different concentration of sulphuric acid exposures. Ternary blended OPC-slag-silica fume mix specimens were immersed in 7% and 3% H_2SO_4 solution for 61 days .After 61 days exposure the results revealed that specimens exposed to 3% H_2SO_4 solution the silica fume dosages less than 10% offered a marginal reduction in the mass loss of concrete specimens and a higher doses of 15% the reduction in mass loss was observed similar to the control specimens and sometimes the mass loss is slightly greater than that of control specimens in both the solutions. So irrespective of dosage of silica fume contents the mixes had minor effect against resistance to severe sulphuric acid exposure. Silica fume significantly increased the compressive strength and reduced porosity by enhancing the formation of C-S-H gel during hydration process and refining the micro pores within the structure. But during acid exposure C-S-H dissolves to produce salts . In contrast with those reported by Hewayde et .al **Sivakumar Venkatachalam (2008)[15]** who found that partial replacement of OPC by 8% silica fume reduced the mass loss of concrete specimens immersed in H_2SO_4.

P.K Mehta et.al [23] explained the behavior of cement paste at elevated temperature which is greatly depends on the degree of hydration and moisture content. A well hydrated cement paste primarily consists of calcium silicate hydrates (C-S-H), calcium hydroxide, and calcium sulfoaluminate hydrates which at temperature about 300°C lost water chemically combined with their molecular structure. Further dehydration causes decomposition of Calcium Hydroxide (CH) as temperature reaches up to 500°C and finally in the range above 900°C the decomposition of C-S-H gel occurs . From the standpoint view of moisture content the saturated paste contains large quantity of free water and capillary water in addition to adsorbed water which are lost by vaporizing during increase in temperature causes vapor pressure inside the concrete forming microcracks and finally triggers spalling or explosive spalling of concrete if the permeability is very low in concrete. The temperature do not raise further until all the evaporable water is removed from the concrete.

M.S Morsy et.al (2008) [25] studied on behavior of mechanical properties of concrete at elevated temperature and found that the blended mix showed similar behavior in compressive strength at higher temperature as the normal mix up to temperature of about 200°C. The increase in compressive strength in blended mortar due to hydration of unhydrated Silica fume accompanied by steep decrease in $Ca(OH)_2$ content. The improvement in residual strength of blended mortar due to increase in pozzolanic activity of the Silica Fume at the temperature exposure up to 200°C followed by decrease in residual compressive strength as the temperature reached 800°C due to dehydration of hydrated product and finally decomposed at higher temperature.

K.Varun Teja et.al (2018) [26] investigated the effect of Silica Fume blended concrete at elevated temperature which on react with $Ca(OH)_2$ released during hydration of cement to produce extra quantity of C-S-H gel leads to increase in strength. But with the increase in temperature surpassed 600°C the decomposition of C-S-H gel takes place. As a result loss in compressive strength was observed. It was also concluded that the weight loss of blended specimen increased up to 400°C further increase in temperature resulted in decrease in weight loss due to internal expansion of the Silica Fume in the sample specimen.

Rafat Siddique [13] described the effect of concrete blended with different percentage of silica fume subjected to different elevated temperature exposures. Silica fume blended concrete had better strength as compared with that of OPC concrete at room temperature. At a temperature exposure at about 100°C, significant reductions in compressive strength occurred both concrete with and without silica fume; Severe strength losses occurred at a temperature range of 300-600°C in all three mixes containing OPC with partial replacement by 0%, 6% and 10% of silica fume respectively. This was due to the fact that during high temperature exposure the different behavior of concrete constituents occurred simultaneously, the cement paste contracts, whereas aggregates expand disturbing the Interfacial Transition Zone (ITZ). Thus, bonding between aggregates and paste were weakened. Simultaneously chemical decomposition of hydrated products added severe deteriorations and strength loses in concrete. After exposure to 600°C the residual compressive strength of all the samples were approximately same.

CHAPTER 3

3.Experimental Program:

3.1 General :

The experimental program of the study was designed to investigate the mortar mixes with the measurements for mechanical property (compressive strength) and durability properties water absorption and sulfate resistance.

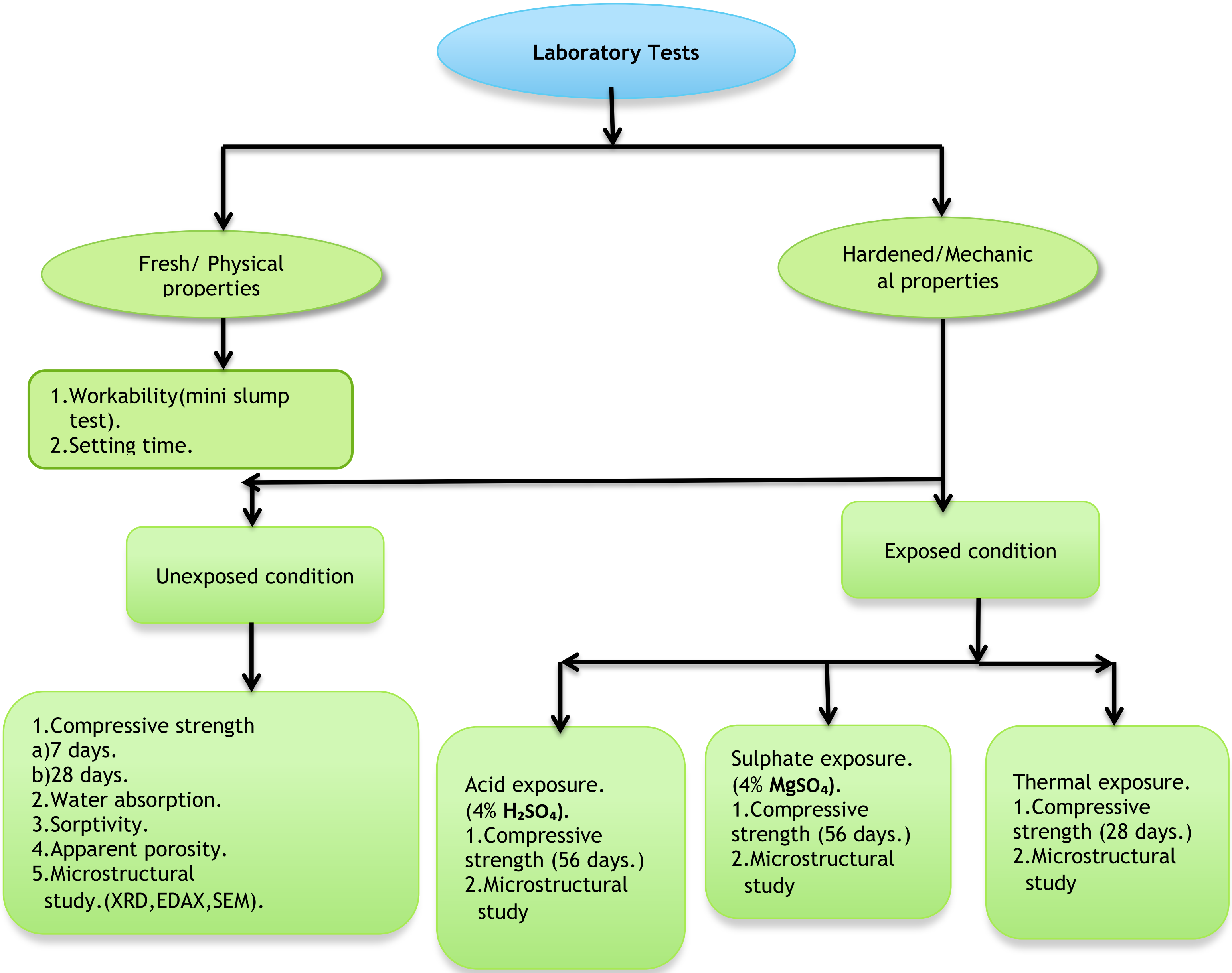


Fig:3.1 Flow diagram of experimental program.

3.2 Materials used :

3.2.1 Cement

Ordinary Portland cement of 43 Grade (Ultratech) conforming to IS 8112-2013 has been used for this investigation. Properties of cement should be given

Table 1. Physical Properties of Cement

Characteristics	Experimental values	As par IS 8112-2013
Grade	46.67	43
Specific gravity	3.03	3.15
Normal Consistency	32%	-
Initial Setting Time	205 min	> 30
Final Setting Time	260 min	< 600
Compressive strength		
7days	38.67	33MPa
28days	46.67	43 MPa

Table 2. Chemical Properties of Cement

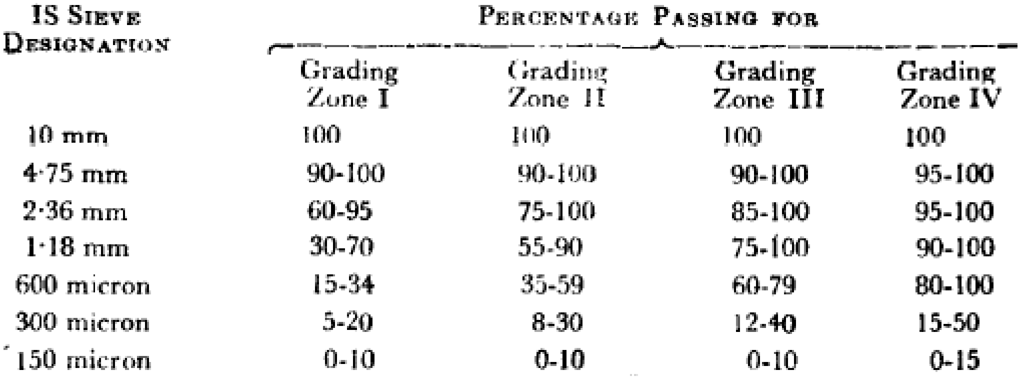
Characteristics	% Values	As par IS 8112-2013
SiO_2	21.3%	-
Al_2O_3	4.5	-
Fe_2O_3	4.0	-
MgO	2.4	6.0
CaO	63.1	-
Na_2O	0.1	0.6
K_2O	1.2	-
SO_3	2.2	3.5

Fig:3.2 Ultratech 43 Grade OPC

3.2.2 Fine aggregate

River sand of grading Zone-II as per codal provision of IS-383-1970(Reaffirmed 2002) has been used in this experimental study.

Table 3. Fine aggregates as par IS-383:1970(Reaffirmed 2002)



IS SIEVE DESIGNATION	PERCENTAGE PASSING FOR			
	Grading Zone I	Grading Zone II	Grading Zone III	Grading Zone IV
10 mm	100	100	100	100
4·75 mm	90-100	90-100	90-100	95-100
2·36 mm	60-95	75-100	85-100	95-100
1·18 mm	30-70	55-90	75-100	90-100
600 micron	15-34	35-59	60-79	80-100
300 micron	5-20	8-30	12-40	15-50
150 micron	0-10	0-10	0-10	0-15

Fig:3.3 Sand conforming to grading zone-II

3.2.3 Mineral Admixtures

3.2.3.1 Ground Granulated Blast Furnace Slag(GGBS)

GGBS so far used in this investigation has been acquired from M/S Owndust India Ltd. Fig :3.4 represents the normal and surface morphology at microstructure level of GGBS powder by SEM. SEM image clearly indicates the GGBS grains characterized by their angular and flakey shapes The physical and chemical properties of GGBS can be found in Table 4 and Table 5 respectively.

Table 4. Physical Properties of GGBS

Characteristics	Values
Specific gravity	2.7-2.89
Fineness (m^2/Kg)	400-600
Bulk density(Kg/m^3)	1050-1375

Table 5. Chemical Composition of GGBS after EDX

Element	Weight %	Atomic%
O K	40.87	58.14
Mg K	4.15	3.89
Al K	8.75	7.38
Si K	17.67	14.32
S K	0.99	0.70
K K	0.45	0.26
Ca K	26.40	14.99
Ti K	0.34	0.16
Mn K	0.38	0.16
Totals	100.00	

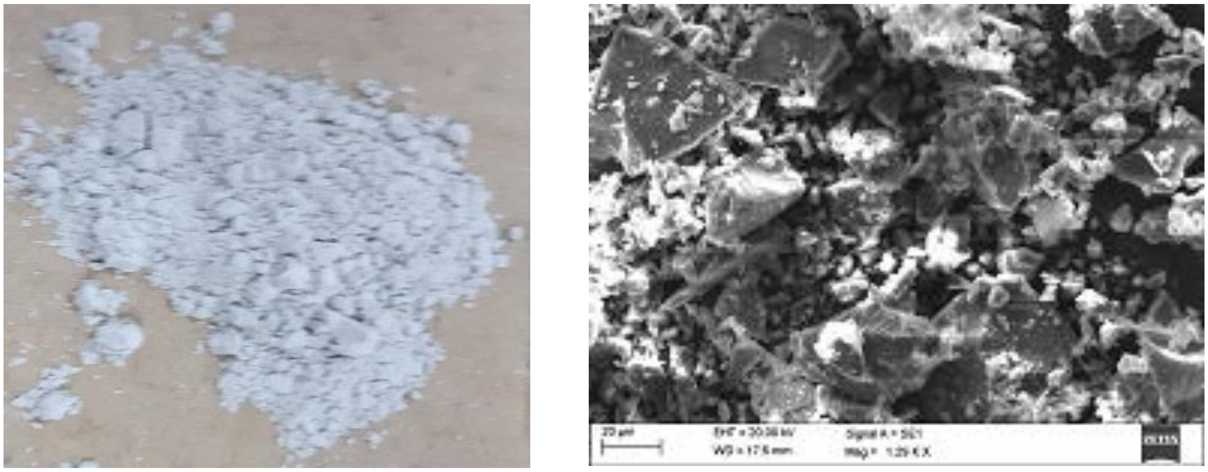


Fig:3.4 GGBS powder and SEM image of GGBS particles.

3.2.3.2 Alccofine 1203

Alccofine 1203 used in this investigation has been acquired from M/S Counto Microfine Products Pvt. Ltd., (CMPP). Fig :3.5 represents the normal and surface morphology at microstructure level of alccofine powder by SEM. SEM image clearly indicates the alccofine grains characterized by their angular and flakey shapes similar to GGBS grains but having finer grain size than former. The physical and chemical properties of Alccofine 1203 can be found in Table 6 and Table 7 respectively.

Table 6. Physical Properties of Alccofine 1203

Characteristics	Values
Specific gravity	2.7-2.84
Fineness (m^2/Kg)	12000
Bulk density(Kg/m^3)	700-900

Table 7. Chemical Composition of Alccofine 1203 after EDX

Element	Weight%	Atomic%
C K	14.11	23.71
O K	36.17	45.62
Mg K	2.87	2.38
Al K	8.12	6.07
Si K	13.03	9.36
S K	0.45	0.28
K K	0.34	0.17
Ca K	23.69	11.93
Ti K	0.42	0.18
Mn K	0.80	0.29
Totals	100.00	

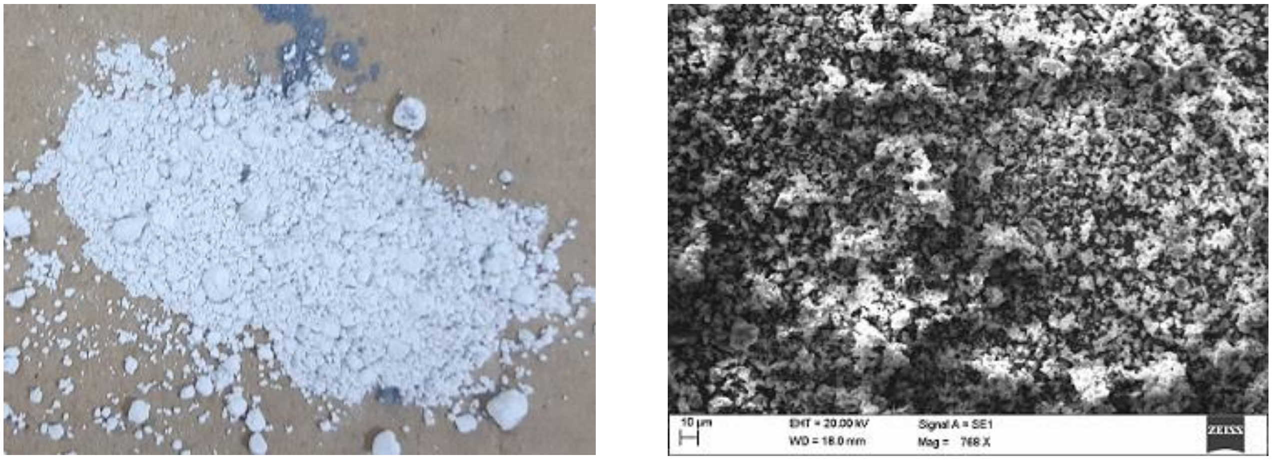


Fig:3.5 Alccofine 1203 powder and SEM image of alccofine particles.

3.2.3.3 Silica Fume

Silica fume or microsilica materials from M/S Silicon Udyog Ltd has been used in this experimental investigation .Chemical and physical properties of which are shown in the following tables

Table 8. Physical Properties of Silica fume

Characteristics	Values
Specific gravity	2.16-2.20
Fineness (m^2/Kg)	15000-35000
Bulk density(Kg/m^3)	130-430

Table 9. Chemical Composition of Silica fume after EDX

Element	Weight%	Atomic%
O K	60.43	72.90
Si K	39.13	26.89
K K	0.44	0.22
Totals	100.00	

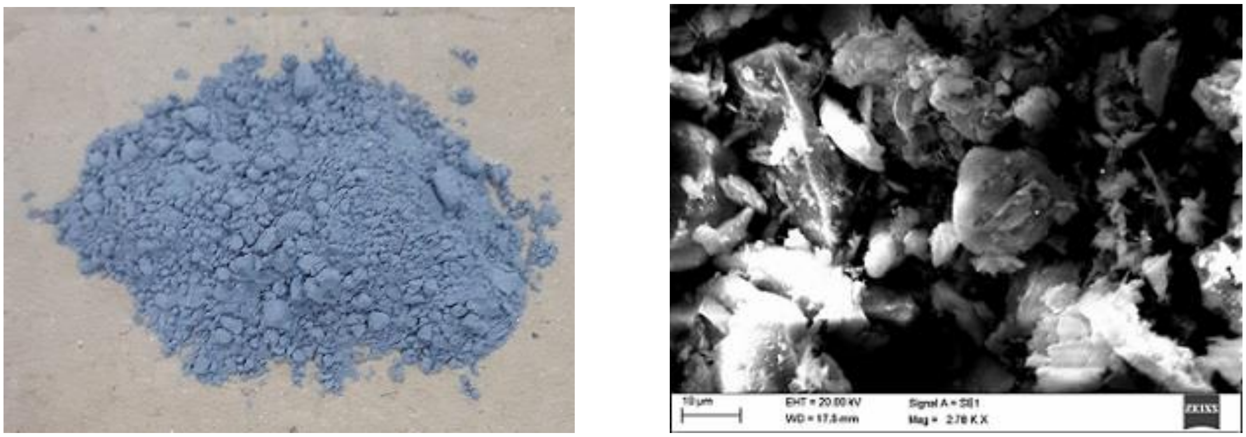


Fig:3.6 Silica fume powder and SEM image of silica fume particles.

3.2.4 Water

Tap water available in university concrete laboratory was used for preparing the sample mixes .

3.2.5 Superplasticizer:

MasterGlenium ACE30 a brown coloured modified polycarboxylic Ether based high range liquid super plasticizer was used to prepare workable mix in the laboratory. After addition of sufficient quantity of water say 70-90% to the mix a suitable quantity of superplasticizer of about 1% of total cementitious materials has been used for preparation of different mixes in each batches. Depending on the particles size and specific surface area of the mineral admixtures the quantity of super plasticizers may increase .

Fig:3.7 Master Glenium ACE 30 super plasticizer.

3.3 Mix preparation :

The samples have been made by preparing total 13 separate mixes (including control mix) in which 6 mixes were prepared using a ternary blended cementitious materials consisting of 30% & 50% replacement levels of cement by GGBS incorporating 5%,10% and 15% Alccofine 1203 by weight of total cementitious materials respectively and remaining 6 mixes by adopting the same process but this time with same percentage levels by GGBS and silica fume and 1 no control mix.The different mixes employed in this investigation are tabulated as shown in the table.

Table 10: Details of mortar mixes using different cement replacement percentages with GGBS and Alccofine 1203 respectively.

Sl No	Mix	Cementitious materials			Superplasticizers (%)	W/Cm
		Cement(%)	Alccofine(%)	Silica Fume(%)		
1	MOPC	100	0	0	1	0.36
2	GG30AF5	70	30	5	1	0.36
3	GG30AF10	70	30	10	1	0.36
4	GG30AF15	70	30	15	1	0.36
5	GG50AF5	50	50	5	1	0.36
6	GG50AF10	50	50	10	1	0.36
7	GG50AF15	50	50	15	1	0.36

Table 11: Details of mortar mixes using different cement replacement percentages with GGBS and Silica fume respectively.

Sl No	Mix	Cementitious materials			Superplasticizers (%)	W/Cm
		Cement(%)	Alccofine(%)	Silica Fume(%)		
1	GG30SF5	70	30	5	1	0.36
2	GG30SF10	70	30	10	1	0.36
3	GG30SF15	70	30	15	1	0.36
4	GG50SF5	50	50	5	1	0.36
5	GG50SF10	50	50	10	1	0.36
6	GG50SF15	50	50	15	1	0.36

3.4 Casting of samples :

Mixing of cementitious materials and sand were carried out using cement and sand ratio of 1:2.75 conforming to ASTM C 109[28] and stirred with the help of mechanical stirrer after adding water maintaining a w/b ratio of 0.36. It was critical to maintain such w/b ratio as the mineral admixtures used were ultrafine in nature and absorbed water due to high surface area. So adding modified polycarboxylate ether based superplasticizer(MasterGlenium ACE 30) at the rate of 1% by weight of total cementitious materials. Special care should be taken while adding superplasticiser and it was recommended to mix superplasticizer after adding some water say about 70-90% of total water required for each batch to the mix and stirred for 3 min. Experimental batches were produced for each mix to obtain the desired slump flow diameter. After preparing the mixes samples were casted in 50mm x 50mm x 50mm cube molds in layers with trowel on a vibrating table. After demolding the cubes were kept immerse in water for curing for 7 and 28 days respectively. Some samples after curing for 28 days were kept for another 56 days curing in 4% H_2SO_4 and 4% $MgSO_4$ solution.

3.5 Samples combination :

After casting the scheduled number of samples and curing them the samples combination were done for different selected tests.

(a)Mechanical properties assessment- compressive, split tensile strength and different microstructural studies for different replacement levels of mineral admixtures as shown in Table 1 & 2 respectively.

(b)Durability properties assessment- Thermal resistance ,Sulfate resistance using (4%) $MgSO_4$ solution and acid resistance using (4%) H_2SO_4 solution different microstructural studies for different replacement levels of mineral admixtures as shown in Table 1 & 2 respectively.

3.6 Test Methods :

Different laboratory tests were conducted for this experimental study to determine the different fresh as well as hardened properties of the sample mixes. These are

1. Consistency of cement.
2. Initial and final setting time of cement.
3. Mini flow table test for determining slumps of different mixes.
4. Bulk density, apparent porosity, water absorption.
5. Sorptivity test.
6. Compressive strength test at 7 and 28 days.
7. Durability against H_2SO_4 and $MgSO_4$ exposure.
8. Durability against thermal exposure.
9. Microstructural studies at different unexposed and exposed condition.

3.6.1. Consistency of cement as par IS: 4031 (Part-4) 1988.

The purpose of this experiment is to determine the normal consistency of standard cement paste using Vicat apparatus conforming to IS : 5513-1976. That means this test is intended to be used to determine the amount of water required to prepare hydraulic cement pastes for resistance against penetration standardised by the code of practice. This test is useful for determine the initial and final setting time of cement as well as soundness of the cement. For this purpose a paste consist of 300 gm of cement(OPC) sample and weighed quantity of potable water available in the laboratory(generally start with 30% of cement weighed) was prepared and filled the vicat mould. Proper precaution was taken during mixing as per codal provision such that the time of adding water to the cement until commencing to fill the mould was within the range of 3-5 minutes. Level the top of mould by striking off with trowel. Immediately after filling the vicat mould lowered the plunger gently to touch the surface of the mould and released it and allowed to sink into the paste. Record the depth of penetration for different percentages of water until the depth of penetration of the plunger was 5-7 mm from the bottom of the vicat mould.

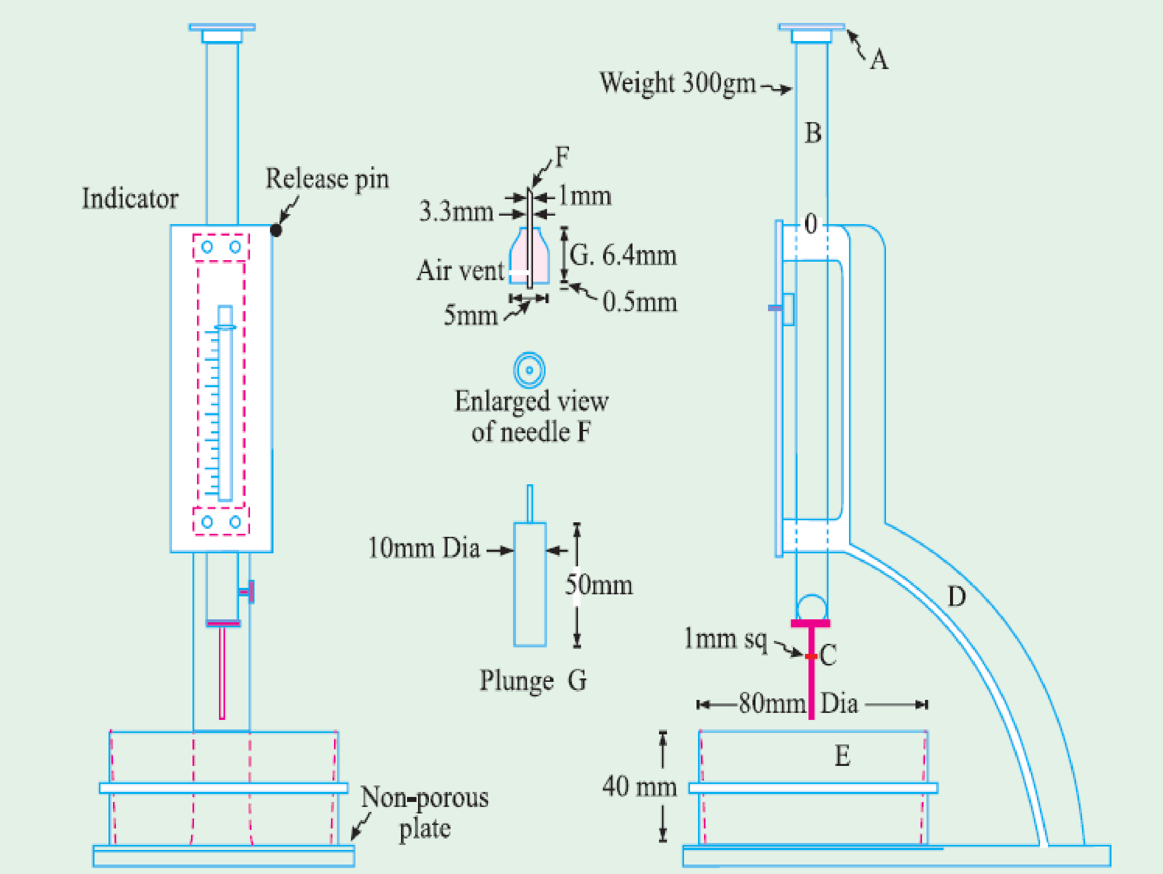


Fig:3.8 Schematic diagram of Vicat apparatus.

The standard consistency was calculated using the formula given below

$$\textbf{Standard consistency (\%)} = \frac{\textbf{Weight of water added}}{\textbf{Weight of cement}} \times 100$$

3.6.2. Initial and final setting time of cement as par IS: 4031 (Part-5) 1988.

The purpose of this experiment is to determine the initial and final setting time of cement of standard cement paste using Vicat apparatus conforming to IS : 5513-1976. This test is useful for determine the initial and final setting time of cement. For this purpose a paste consist of 300 gm of cement(OPC) sample and 0.85 times the water required for standard consistency was prepared and filled the vicat mould. Proper precaution was taken during mixing as per codal provision such that the time of adding water to the cement until commencing to fill the mould was within the range of 3-5 minutes. Level the top of mould by striking off with trowel. Immediately after filling the vicat mould lowered gently the vicat needle of dimension 1mm X 1mm to touch the surface of the mould and released it and allowed to sink into the paste. Record the time elapsed from the time water added to the cement paste to the time the needle failed to penetrate it up to a depth 5 ±0.5 mm from the bottom of the mould ,usually taken as initial setting time. After noting the time for initial setting of cement, the needle shall be replaced by the final setting time needle and released slowly to pierce through the cement paste. Similar trials were performed until the needle only failed to made any impression on the cement paste. The initial and final setting time of cement were within the range as par codal provision.

3.6.3. Mini flow table test for determining slump as par ASTM C-1437-07.

Mini flow table test were conducted for different sample mixes to determine the workability in terms of measurement of flow diameter of different mixes .The purpose of this test was to correlate the extent of workability with their respective flow diameter values .

3.6.3.1 Flow table and frame.

The flow table apparatus consists of an integrally cast rigid iron frame and a circular rigid table top of [255± 2.5 mm] dia attached with a shaft perpendicular to the table top by means of a screw thread .The details of the apparatus as shown in the figure 3.8. The table top mounted on the frame in such way that it can be raised and dropped vertically through a specified height of 12.7± 0.13 mm, by means of a rotated cam. The table top have a fine machined plane surface. The table top shall be of cast brass or bronze having an edge thickness of 0.3 in. [7.5 mm].

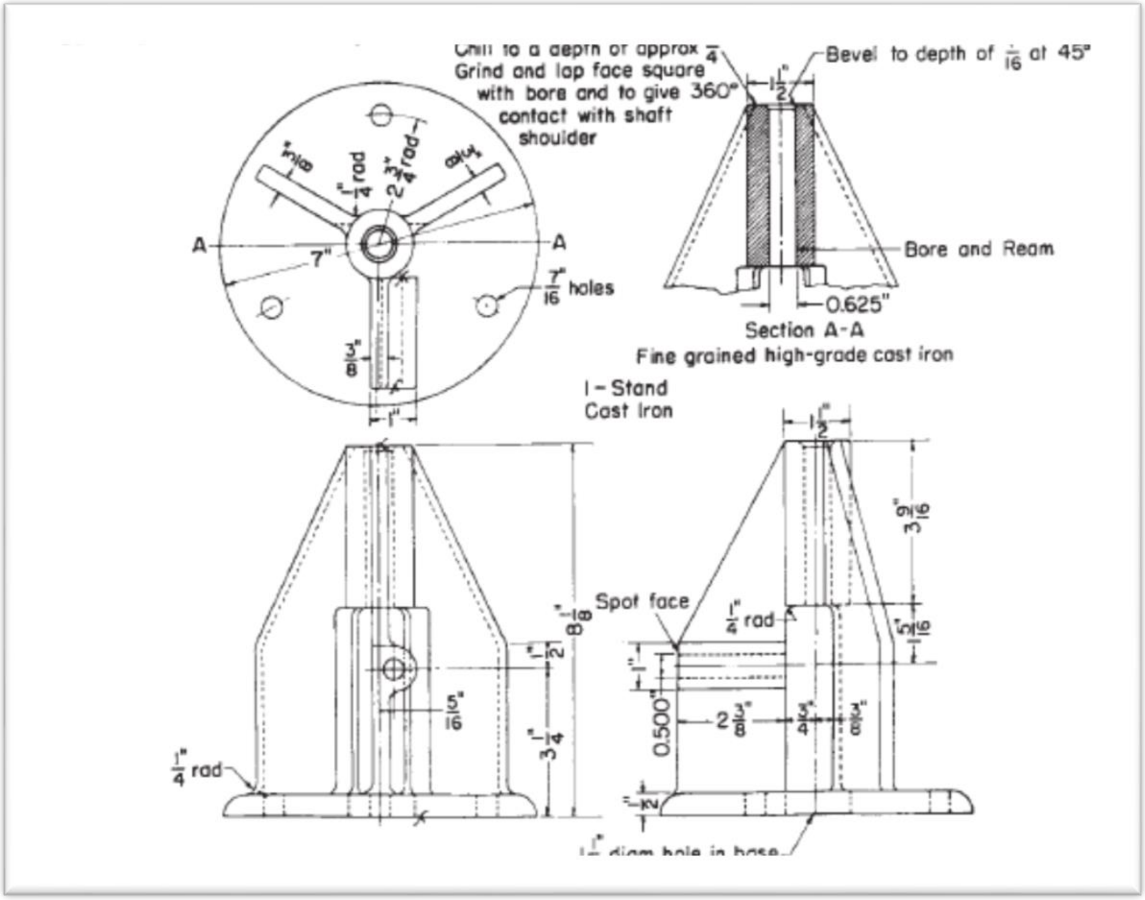


Fig:3.9 Schematic diagram of mini flow table apparatus.

The frame consists of three integral stiffening ribs extending the full height of the frame and located 120° apart. The base of the frame must be fastened with plate or any rigid platform generally on concrete pedestal by means of fasteners.

3.6.3.2 Flow mold and caliper.

The conical mold for casting the flow specimen shall be either of bronze or brass. The height of the mold shall be 50±0.5mm in height. The top opening diameter of the mold shall be of 70±0.5 mm and that of the bottom opening shall be of 100±0.5mm. The top and bottom surface of the mold shall be parallel and at right angle to the vertical axis The mold shall have a minimum wall thickness of 0.2 in. [5 mm].

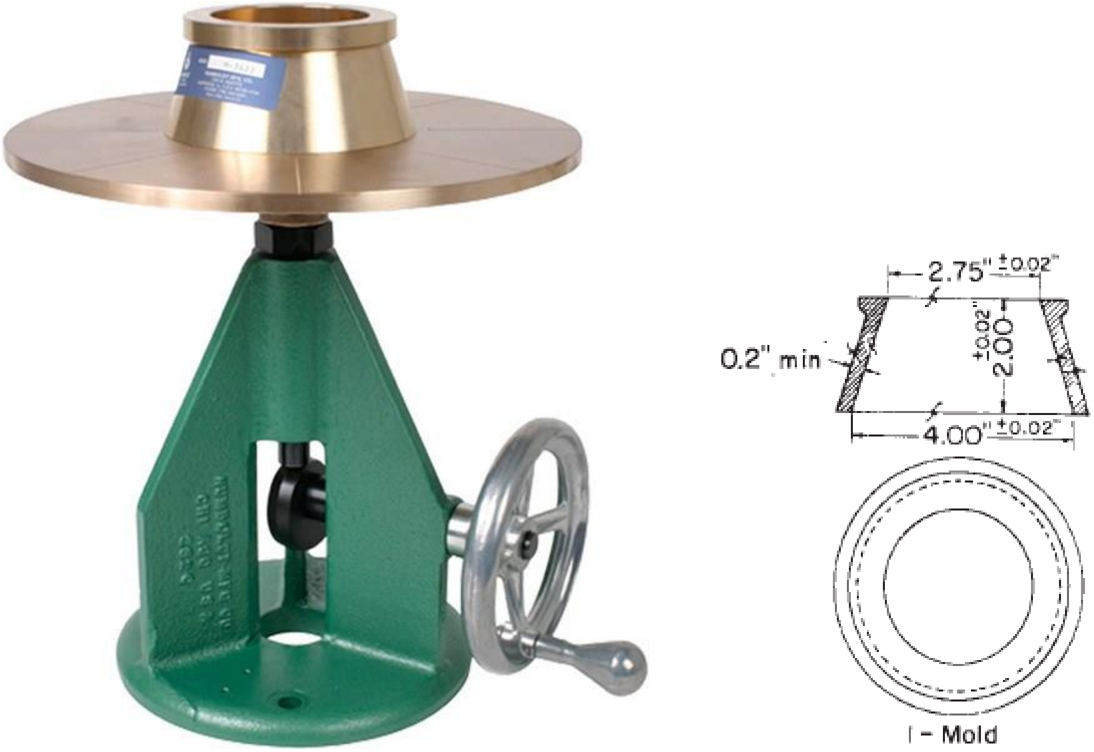


Fig:3.10 Mini flow table apparatus with schematic diagram of mold.

A caliper consists of one fixed jaw and one jaw movable along a permanent scale for measuring the diameter of the mortar specimen spread after 25 drops. The scale shall be divided into 40 increments with 4.0 mm between divisions with major division lines every 5 divisions and the increment number every 10 divisions . The construction and accuracy of the caliper shall be such that the distance between the jaws shall be [100 ± 0.25 mm] when the indicator is set at zero.

3.6.3.3 Procedure.

After lubricating the mold placed at the center of the table top it was filled layer by layer with the specimen mixes not more than 25 mm and tamped 20 times with the tamper. After filling the mold leveled the top surface by striking off with the trowel. Immediately after lifted the mold away from the mortar specimen dropped vertically the table 25 times in 15 s by rotating the cam as specified in the code. Measured the diameter of the sample mixes with the help of caliper or normal measuring scale to the nearest mm along the 4 lines scribed in the table and averaged it to determine the increase in flow diameter which should be correlated with the slump values of the specimen mixes.

Fig:3.11 Mini flow table test procedure and measurement of flow diameter.

3.6.3.4 Calculation.

Average of the four increased flow diameter with respect to the original inside base diameter of the mold was expressed as percentage and computed as follows

$$\%FD = \frac{\text{avge of four readings in mm-the original inside base diameter in mm}}{\text{Original inside base diameter in mm}} \times 100$$

Reported the flow to the nearest 1 %.

3.6.4 Bulk density, Apparent porosity and Water absorption:

One of the major issue regarding durability of concrete is porosity because of the fact that ingression of different harmful chemicals occur through pores present in the concrete causing degradation of concrete as described in the literature review section. So determination of porosity plays a major role in evaluating the effect of concrete deterioration. Porosity was determined conforming to ASTM 642 in the laboratory. For this three set containing 3 nos of sample for each set were prepared and cured for 28 days .

3.6.4.1 Procedure:

After curing for 28 days the three identical samples for each specimen mix were taken out from water and wiped the surface off with the help of a piece of dampened cloth and kept in air until saturated surface dry condition. Then the samples were kept in hot oven at a temperature of 110±5°C and dried for not less than 24 hours .Samples were dried until reached a constant weight and dry weight (D) of the samples were taken until they attained normal temperature and then immersed in water for not less than 48 hours. After taken out from water wiped it with damp cloth and saturated or soaked weight (W) were recorded. Immediate after taking soaked weight the samples were weighed on a pan immersed in water as shown in the figure and recorded as submerged weight(S) of the samples. After taking all necessary weights as described above the following can be determined.

$$\boxed{\textbf{Bulk Density}(\gamma_b) = \left(\frac{D}{W - S}\right) \times \rho} \quad \text{Kg/m}^3. \qquad (1)$$

Where ρ ,unit wt of water.

$$\boxed{\textbf{Apparent Porosity}(\%) = \left(\frac{W - D}{W - S}\right) \times 100} \qquad (2)$$

$$\boxed{\textbf{Water Absorption }(\%) = \left(\frac{W - D}{D}\right) \times 100} \qquad (3)$$

Fig-3.12: Submerged weight of samples taken at laboratory.

3.6.5 Sorptivity Test in accordance to ASTM C-1585-04:

This test was introduced by Hall in 1970 studying the importance of unidirectional flow of water in concrete specimen. The cumulative quantity of absorbed water per unit area of inflow surface are determined and relate to the square root of the elapsed time .The relationship is given by

$$\boxed{I = S_i \cdot \mathbf{t}^{0.5}} \qquad (4)$$

Where, I=The cumulative absorbed volume of water per unit area of inflow surface , in mm.

S_i=Sorptivity or coefficient of sorptivity, in mm/$t^{0.5}$.

t = Time elapsed expressed in square root .

Basically sorptivity is defined as the capillary absorption of water and is proportional to area of concrete exposed to the moisture with time. Some of the basic conditions hold good for conducting this test and these are

1) Material homogeneity: the material must be homogeneous over the scale of the penetration distance

2) Sample geometry: the capillary absorption flow must be normal to the inflow face and should not converge or diverge

3) Water exposure: water must be freely available at the inflow surface

4) Test procedure: gravitational effects must not be apparent in the absorption process

Further investigation on sorptovity ascertained the presence of small initial value at t=0. This was due to the initial rapid filling of open surface pores present on the side faces of the test specimens. To account for this Hall, introduced an initial value constant A into the relationship to give the following:

$$\boxed{I= S_i \, . \, t^{0.5} + A} \qquad (5)$$

More often permeability was used as the primary criteria for concrete durability consideration but this was not entirely accurate. Permeability was related to the ingression of moisture through saturated porous medium under pressure gradient. However the existence of concrete structures in such condition are considered to be unlikely except in different hydraulic structures. In such case sorptivity is quite relevant and considered to be an effective way to relate the capillary absorption with the movement of moisture in concrete structures .In super structure portion , the sun and wind dry the exposed region of concrete while the substructure remains at a higher degree of saturation. This differential in saturation creates capillary forces that become the dominant transport mechanism.[29]

3.6.5.1 Test procedure:

For evaluating sorptivity test each mixture containing three identical samples for each specimen mix for different proportion of SCMs were prepared and cured for 28 days. After curing for 28 days the immersed samples were taken out from water and wiped the surface off with the help of a piece of dampened cloth and kept in air until saturated surface dry condition. Then put them in to oven at 110±5°C and dried for not less than 24 hours .Samples were dried until reached a constant weight . To avoid evaporation and achieve unidirectional water flow, four sides of the samples were sealed by coated with water proof painting and the other opposite sides remain kept open. Immediate after drying the paint the initial weight of the samples were taken .Placed the support device at the bottom of the pan and filled the pan in such a way that the top of the water level was 1 to 3mm above the support devices and maintained the water level for the total duration of the test . Put the samples on the support devices as shown in the figure . and weighed the samples at regular intervals of 60s, 5min, 10 min,20 min, 30 min, 60 min, 2h,3h.4h,5h,6h .After the initial 6 hours measured the weight of the samples once in a day up to 3 days and remaining measurements were taken at an interval of 24 hours up to day 7 and a final weights were taken after 24 hours from the measurements taken on day 7. During each measurements samples were taken out and wiped the wetted surface with a damp cloth .Immediate after taking measurements the samples were placed on the support devices. Any tolerances during weighing and recording time was maintained conforming to ASTM C 1585-04[28].

Fig-3.13: Test set up for sorptivity.

3.6.5.2 Calculation:

The sorptivity coefficients can be calculated as the following formulation described in code

Initial Absorption:

$I = S_i \cdot t^{0.5} + A$ (Points measured up to 6 hours were used)

Secondary Absorption :

$I = S_i \cdot t^{0.5} + A$ (Points measured after the first day were used)

The results were plotted in a graph sheet and determined the sorptivity indicated by the slope of the line. The slope of the line obtained became linear up to the initial 6 hours readings and is defined as the initial absorption . Remaining readings up to day 8 were represented by a line which had different slope as compared with the previous one was defined as the secondary absorption. Now for each sets of samples the average of the sorptivity values for initial and secondary absorption were calculated and compared the values with different samples for which the different sorptivity values were taken.

3.6.6 Compressive strength test in accordance to ASTM C-109/C109M-02:

Test method for compressive strength was carried as per ASTM C-109/C109M-02 and prepared samples were cured for 7 and 28 days respectively. Three identical samples for each specimen mix were selected and compressive strength on selected samples were performed after 7 days and 28 days. After curing for specified time the samples were placed under a compressive strength testing machine and loads were applied until cracks appeared on the sample surface as shown in fig:3.14.

Fig-3.14: Compressive strength test set up and failure pattern of sample after compression.

3.6.6.1 Calculation:

Recorded the test load indicated by the testing machine and calculations were carried out as follows:

$$\boxed{f_m = P/A}$$

Where,

f_m = Compressive strength in MPa.

P= Applied load in KN.

A=Cross sectional area of the sample in mm^2.

Test records were taken on at least three samples and averaged the same gave the results.

3.6.7 Durability against H_2SO_4 and $MgSO_4$ exposure:

After curing in water for 28 days three identical samples containing specific proportions of SCMs for each test were chosen and subjected to 4% H_2SO_4 and 4% $MgSO_4$ exposure condition for another 56 days in separate plastic containers .For this acid and sulfate solutions were prepared in the laboratory by adding H_2SO_4 (concentration level of 98%) and $MgSO_4$ to water and diluted to obtain 4% H_2SO_4 and $MgSO_4$ solution . Then the samples were immersed in the solution in separate container. The pH level of the sample was maintained at an interval of one week.

Fig-3.15: Samples stored in 4% H_2SO_4 and $MgSO_4$ solution in laboratory.

The assessment of ternary blended concrete was made based on three performance levels.

1.Visual assessment.

2.Mass loss .

3.Residual compressive strength.

4.Strength reduction factor after exposure to acid or sulfate environment.

3.6.7 .1 Visual assessment:

The visual assessment was made based on scale at different deterioration levels as given below

Table 12. Scale of visual deterioration level of concrete specimens immersed in acidic solutions [15]

Scale	Detorioration Level
0	No attack
1	Very slight attack
2	Slight attack
3	Moderate attack
4	Severe attack
5	Very severe attack
6	Partial disintegration

3.6.7 .2 Mass loss:

It is an important factor for assessing the durability of concrete samples on acid exposure. Due to highly corrosive in nature acid noticeably affected the concrete after 56 days exposure condition. For this purpose the samples subjected to acid as well as sulfate exposure were weighted before immersed in to acid and sulfate solution and a final weight were taken after curing and measurement was made for finding the mass gained or loss of any sample . The average value of the three measurements was considered for assessment.

3.6.7.3 Residual compressive strength:

Residual compressive strength or compressive strength of samples after acid and sulfate exposure was found to be extremely important when dealing with the mechanical properties as well as durability criteria of concrete. After curing for 56 days samples were removed from the solution and kept for drying in room temperature . After drying the samples they were tested under compressive strength testing machine .Three identical samples for each specimen mix were tested and reported the average value .

3.6.7.4 Strength reduction factor after exposure to acid or sulfate environment:

The deterioration of the cube samples after acid and sulfate exposures were investigated using the term Strength Reduction Factor, a relationship between the compressive strength of the sample specimens prior to and after the acid and sulfate exposures were established and expressed as percentage. Strength Reduction Factor of the samples was determined using the equation as follows,

$$\boxed{\textbf{Strength Reduction Factor (\%)} = \left(\frac{f_{c\,28} - f_{expose}}{f_{c\,28}}\right) \times 100}$$

Where,

$f_{c\,28}$ =Average compressive strength of cube specimens curing in water for 28 days in (MPa).

f_{expose} = Average compressive strength of cube specimens immersed in acid or sulfate solution for 56 days in (MPa).

3.6.8 Durability against thermal exposure:

Concrete has been used in structures like chimneys, silos ,reactor walls and furnace are often exposed to enormous thermal exposure and pointed out to be a major issue in durability consideration. So durability of concrete against thermal exposures should be investigated. As reported in the literature review section that with the addition of different SCMs in different percentage and increase in temperature the samples undergo various phases at different temperature and finally loss in compressive strength as well as in weight occurred. Samples subjected to thermal exposures were removed from water immersion after 28 days and air dried for 24 hours and weighed prior to thermal exposures . For each specimen mix three identical samples were taken and kept in furnace at a temperature up to 800°C for 4 hours . The specimens were allowed to cool naturally at normal temperature. After attaining normal temperature weighed the samples again and observed a sharp loss in weight of the samples. Compressive strength of the samples were performed not prior to 24 hours after removal from the furnace and average of the obtained values were taken as the compressive strength after thermal exposure.

Fig-3.16: Samples exposed to high temperature at furnace .

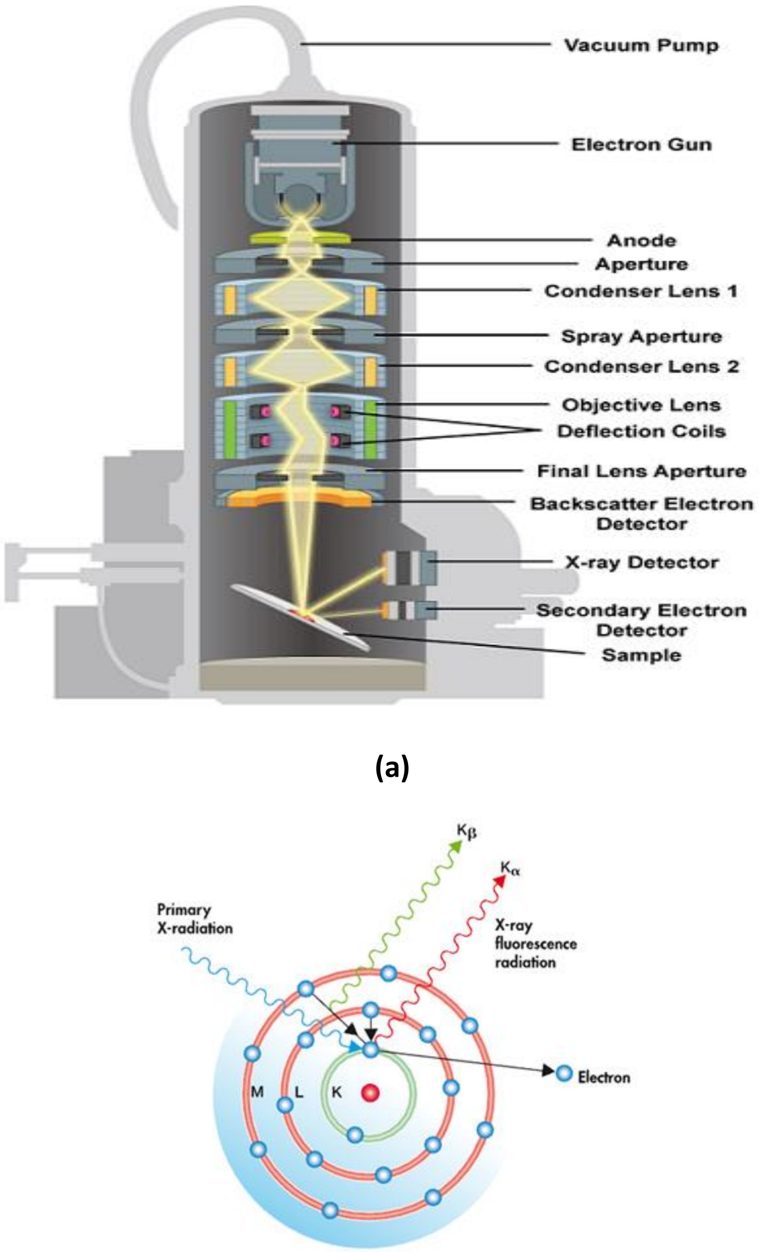
3.6.9 Microstructural studies at different unexposed and exposed condition:

The microstructure of the hydrated products change phases depending upon different factors such as chemical composition , fineness of the cementitious materials ,water binder ratio ,use of chemical admixtures, variation in hydration condition and nature of curing.[30] So the samples need to be investigated at microstructure level before and after exposed condition. The microstructural study of concrete is very much complex and for the sake of simplicity concrete is assumed to be two phase system consisting of coarse and fine aggregates dispersed in cement matrix. Microstructural study also helpful in determining the chemical components as well as phase determination at different ages of the samples[23] .So far two type of studies conducted namely scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) for microstructural studies. First one was used to determine the phase composition at different ages and the later one for determining the chemical composition of the samples.

Secondary Electron (SE) Dispersion mode of SEM is one of the method of different SEM imaging techniques and the working principle is based on focusing a high velocity electron beam on the exposed fractured surface of the targeted samples using electron gun. The high velocity electron beam(Primary electrons) strikes on the sample causing ejection of the electrons from different outer shells of the atoms on the surface of the sample. The knocked out electrons (Secondary electrons) dispersed from the surface and received by secondary electron detector while imaging is done by a secondary electron detector. For obtaining better effects generally samples were coated with carbon or platinum coating as coated samples provide a thin surface for receiving better images. Quality of the image also depends on the quantity of the secondary electrons ejected out from the surface of the samples .Better resolution obtained at medium secondary electrons dispersion.

Nowadays nearly all SEM instruments are also equipped with energy dispersive X-ray spectroscopy (EDX) systems, which instantly provide the specific chemical composition of the desire spot or area being imaged .For this reason SEM is an extremely powerful and informative technique in concrete investigations. [30]

Fig-3.17: Scanning Electron Microscope instrument (courtsey GSI SEM-EDX lab kolkata).



(a)

(b)

Fig-3.18: Schematic diagram showing principle of (a)Scanning Electron Microscope ,(b) Electron Dispersive X-Ray Spectroscopy.

In microstructural studies sample were categorised into different distinct exposure classes viz. normal or unexposed, thermal and chemically(acid and sulphate) exposed condition for better understanding of the effect of different environment the samples were underwent. For normal and thermal durability aspects samples from the specimens after compressive strength test were carefully collected in a polythene packet. Special care must be taken for samples collected for chemical durability ,as it requires the inner and outer core of the affected samples separately for microstructural studies and collected in separate polythene packet. SEM and EDX analysis of different samples were done as per the thesis requirement.

CHAPTER 4

4.Results and discussion:

4.1 General:

Different laboratory experiments were carried out to investigate the various fresh ,hardened and durability properties of mortar mix containing various percentage of SCM's replacing OPC. This chapter will give insight in to some of the noteworthy outcomes on different properties based on the data obtained from these tests.

4.2 Fresh and hardened properties:

4.2.1 Fresh properties:

4.2.1.1 Workability:

Mini flow table tests as discussed in the previous chapter were performed on control mix as well as mix containing different SCM's and flow diameter values are tabulated in **Table 13 & 14**. As seen from the table for the same w/b ratio the control mix has lower flow diameter value than the mix containing different replacement level of OPC with GGBS and alccofine. With 30% replacement level of GGBS and increase in alccofine percentage enhanced the workability is in the range of 18.19% -29.10% compare to control mix and higher values obtained at 5% and 15% alccofine replacement. The trend slightly differs in case of 50% GGBS replacement where better workability observed at 10% and 15 % alccofine replacement and increases the workability ranges from 22.73% - 31.82%. Overall higher value obtained at 50 % and 10% of GGBS and alccofine replacement. As reported in the literature review GGBS and alccofine are microfine particles causing dispersion of cement particles and act as lubricant which reduces the friction between the cement particles .On the other hand addition of GGBS and alccofines

Table 13:Flow diameter values of mixes containing different percentages of GGBS and alccofine:

Mix designation	Materials composition			W/B ratio	Flow dia values(mm)	% increase in slump
	Cement(%)	GGBS(%)	Alccofine(%)			
MOPC	100	0	0	0.36	110	0
GG30AF5	70	30	5	0.36	138	25.45
GG30AF10	70	30	10	0.36	130	18.19
GG30AF15	70	30	15	0.36	142	29.10
GG50AF5	50	50	5	0.36	135	22.73
GG50AF10	50	50	10	0.36	145	31.82
GG50AF15	50	50	15	0.36	138	25.45

reduce the hydration of cement from the instance the water was added and consumed less available water results in increase in workability as compare to control mix.

Table 14: Flow diameter values of mixes containing different percentages of GGBS and Silica fume:

Mix designation	Materials composition			W/B ratio	Flow dia values(mm)	% decrease in slump
	Cement(%)	GGBS(%)	Silica fume(%)			
GG30SF5	70	30	5	0.36	102	7.27
GG30SF10	70	30	10	0.36	105	4.54
GG30SF15	70	30	15	0.36	103	6.36
GG50SF5	50	50	5	0.36	108	1.82
GG50SF10	50	50	10	0.36	105	4.54
GG50SF15	50	50	15	0.36	104	5.45

In case of GGBS(30%) with varying silica fume combination the workability decreased significantly compare to control mix and attained a maximum value at 5% SF replacement. The decrease in workability is in the range of 4.54% -7.27% as the SF contains ultrafine particles (15000-35000 m^2 /kg) having more surface area which tends to absorb more water and consequently increase the superplasticizers demand to attain sufficient workability. Increase in GGBS (50%) content with different percentage of SF causes more workable mix than the previous mixes (GGBS-30% and other SF content) and decrease in workability ranging from 1.82% -5.45%. The reason may be that increase in GGBS content having lesser specific surface area(400-600m^2 /k) and better lubricating effect as well as slower hydration rate compensate the effect of SF by reducing the water demand ,thus providing more available water for ultrafine SF particles. Fig 4.1 shows the graphical representation of flow diameter values of different mixes compare to control mix.

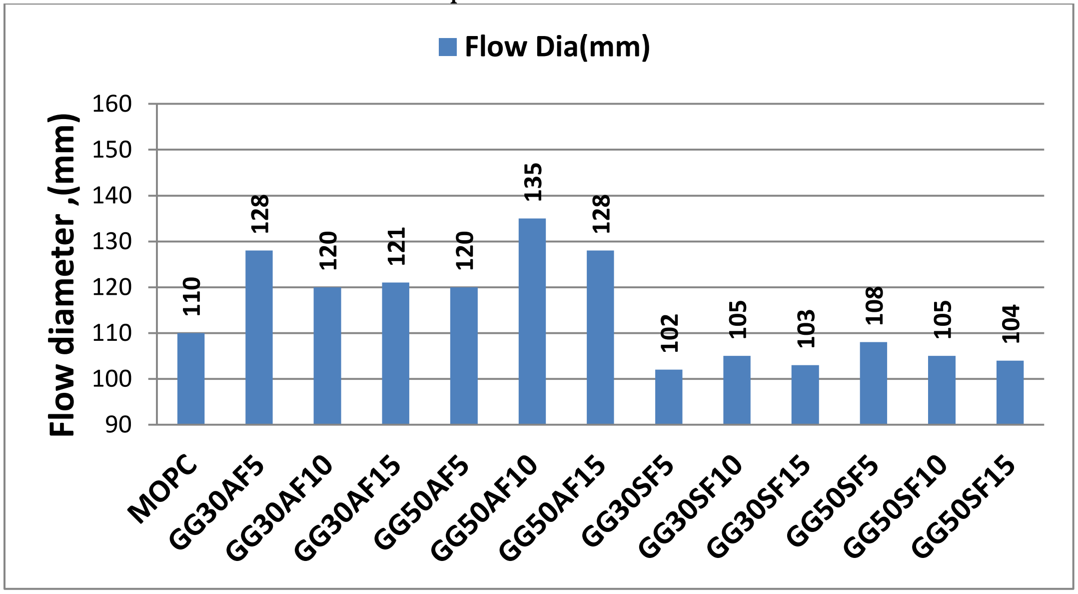


Fig 4.1: Graphical representation of flow diameter values of different mixes .

4.2.2 Hardened properties:

4.2.2.1 Compressive strength:

Variation of compressive strength of different mixes after 7 and 28 days of water curing is tabulated in **Table 15**. The control mix (38.67 MPa) has better performance compare to other mixes after 7 days followed by the compressive strength values belongs to mixes GG30AF10(37.33MPa) and GG30AF15(38.67MPa) .Further inclusion of GGBS percentages (50%) causes decrease in strength. For mixes GG30SF10 and GG30SF5 having a pronounced strength values of 34.67 MPa and 33.33 MPa respectively followed by a decreasing trend in strength as GGBS percentage increased. Furthermore increase in GGBS content yielded significant change in strength values. It is obvious from the strength results that for both alccofine and silica fume mix series increase in GGBS content resulted in decrease in strength after 7days of water curing(Refer fig:4.2). After 28 days of water curing control mix(46.67MPa) still performed better than other mixes except for mix GG30SF10 where maximum compressive strength value of 48.8MPa was observed .For mixes incorporating GGBS and alccofine mix GG30AF10 exhibited better result in alccofine mix series after 28 days .For GGBS alccofine mix series decrease in strength characteristics observed with in increase in GGBS content whereas for GGBS, silica fume mix combination did not yield any substantial changes in strength values with increase in GGBS content after 28 days(Refer fig:4.3). Mixes containing alccofines gained high early strength compare to the SF as alccofine contributes to the formation of dense pore structure due to it fine particle size and in built CaO (61- 64%) present in the alccofine increases the formation of secondary hydrated product (C-S-H) gel which results in strength improvement at early as well as later ages. Both GGBS and alccofine participate in hydration process as well as pozzolanic activity with ages. On the other hand SF showed lesser strength improvement compare to alccofine after 7 days curing having maximum 34.67MPa for GG30SF10 as the presence of silica fume does not participate in the hydration causing lesser improvement in strength .Further increase in GGBS causes drastic changes in strength after 7 days ranging from 20.00MPa to 26.53MPa. But with increase in age pozzolanic activity comes into effect causing significant gain in strength as shown in table:14.The strength value reaches 48.8MPa for mix GG30SF10 followed by 44.93 MPa for mix GG50SF15 after 28 days . This enhancement in strength interprets the development property of silica fume on concrete due to their high specific surface , matrix densification ,refinement mechanism as well as greater hydration reaction to occur by producing excess secondary Calcium-Silicate-Hydrate (CSH) gel through the reaction of SiO_2 in the SF and the calcium hydroxide (CH) after initial hydration as well as the CaO in the GGBS as pointed out in literature review section.

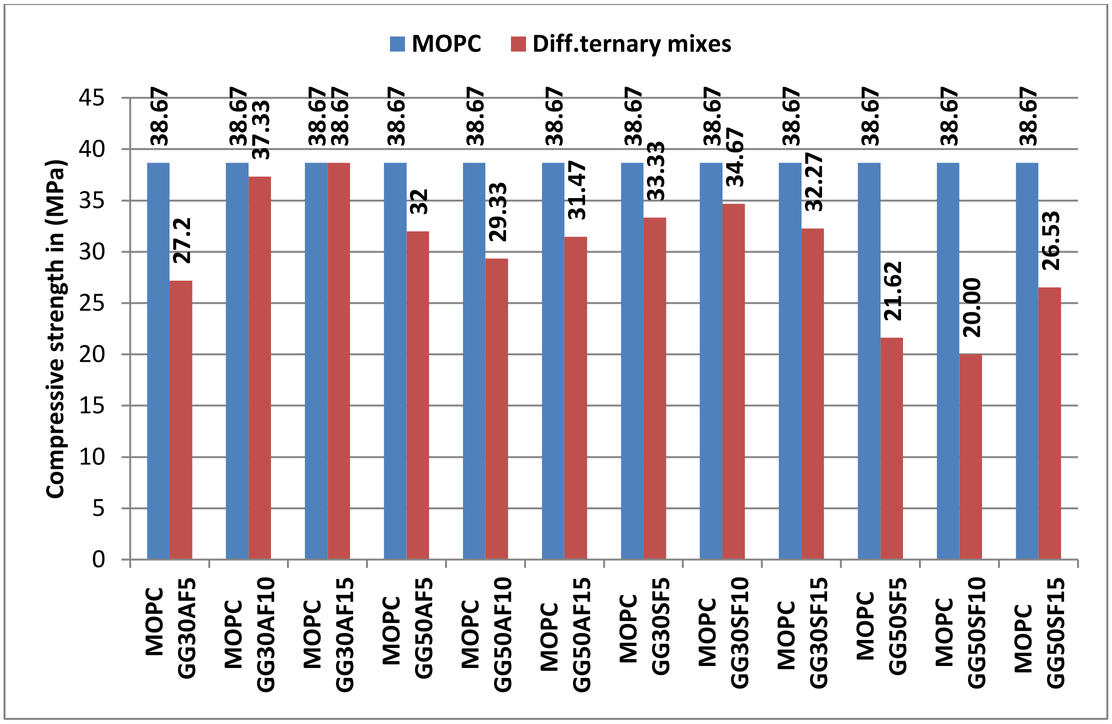


Fig 4.2: Comparison of control mix and different ternary mixes after 7days.

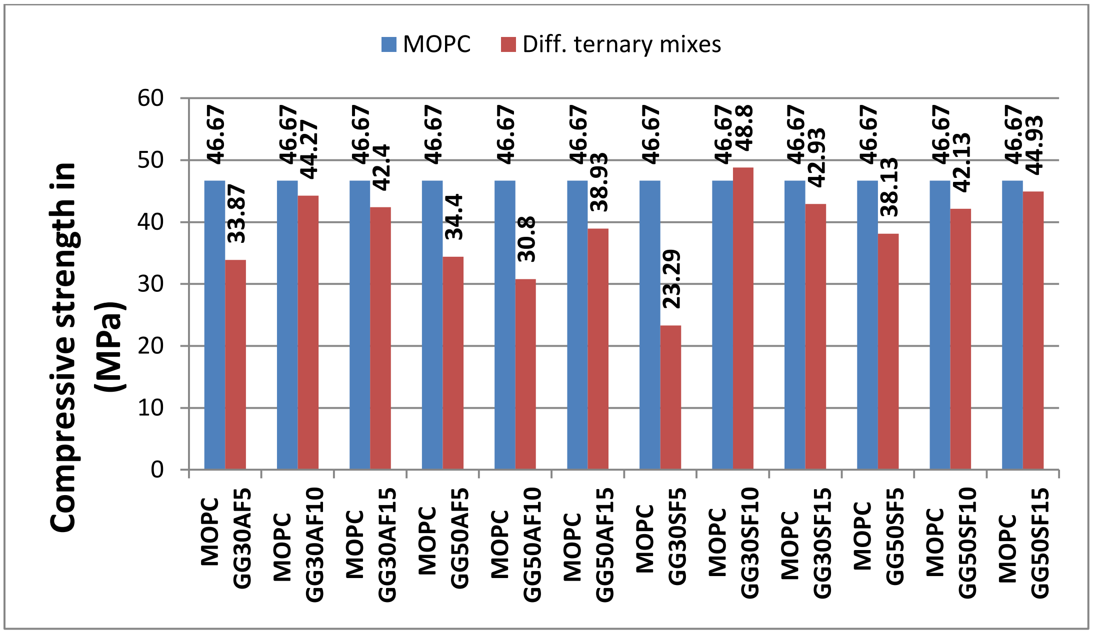


Fig 4.3: Comparison of control mix and different ternary mixes after 28days..

Table 15:Variation in compressive strength of different mixes compare to control mix after 7 & 28 days of water curing.

Sl.no	Mix type	Compressive strength after 7days(MPa)	Variation decrease (%)	Compressive strength after 28days(MPa)	Variation decrease (%)	Variation increase (%)
1	MOPC	38.67	Control mix	46.67	Control mix	Control mix
2	GG30AF5	27.2	29.66	33.87	27.43	
3	GG30AF10	37.33	3.47	44.27	5.14	
4	GG30AF15	38.67	0.00	42.4	9.15	
5	GG50AF5	32.00	17.25	34.40	26.29	
6	GG50AF10	29.33	24.15	30.8	34.00	
7	GG50AF15	31.47	18.62	38.93	16.58	
8	GG30SF5	33.33	13.81	23.29	50.10	
9	GG30SF10	34.67	10.34	48.8		4.56
10	GG30SF15	32.27	16.55	42.93	8.01	
11	GG50SF5	21.61	44.12	38.13	18.30	
12	GG50SF10	20.00	48.28	42.13	9.73	
13	GG50SF15	26.53	31.39	44.93	3.73	

Furthermore it can be seen from table 14 that percentage variation decrease in strength compare to control mix was marginal for mix GG30AF10 and GG30AF15 respectively after 7 days with values 3.47% and 0% ,whereas the maximum value of 29.66% occurred for mix GG30AF5 .This may be attributed to the fact that presence of CaO in alccofines enhances the formation of primary hydration product at early age in these mixes . For mixes GG50AF5 to GG30SF15 this value ranges from 16.55% to 24.15% after 7days . These values was significantly high ranging from 31.39% to 48.28% for mix GG50SF5 to GG50SF15 indicating ineffective participation of silica fume and GGBS in primary hydration thus lesser formation of primary hydration products. This variation in percentag marginally improved for mix GG30AF5 and reached the value from 29.66% to 27.43% after 28 days whereas mixes GG30AF10(5.14%) and GG30AF15(9.15%) show slight increase in variation after 28 days .For mixes GG50AF5 to GG50AF15 the significant variation in strength compare to control mix was observed which depicts the lesser formation of secondary hydration product, C-S-H gel even after 28 days of water curing. Another important finding comes out from the present study that mixes containing silica fume performed exceptionally well than alccofine after 28 days and percentage variation ranging from 3.73% -18.30% compare to control mix .Even for mix GG30SF10 the variation surpasseed the value of control mix by 4.56%. The results depicted in table 14 indicate that silica fume has the tendency to accelerate the formation of more secondary hydration product ,C-S-H gel compare to alccofine at later ages resulting in high strength after 28 days . Fig 4.9 represents the comparison of strength achieved of different mixes after 7 and 28 days respectively.

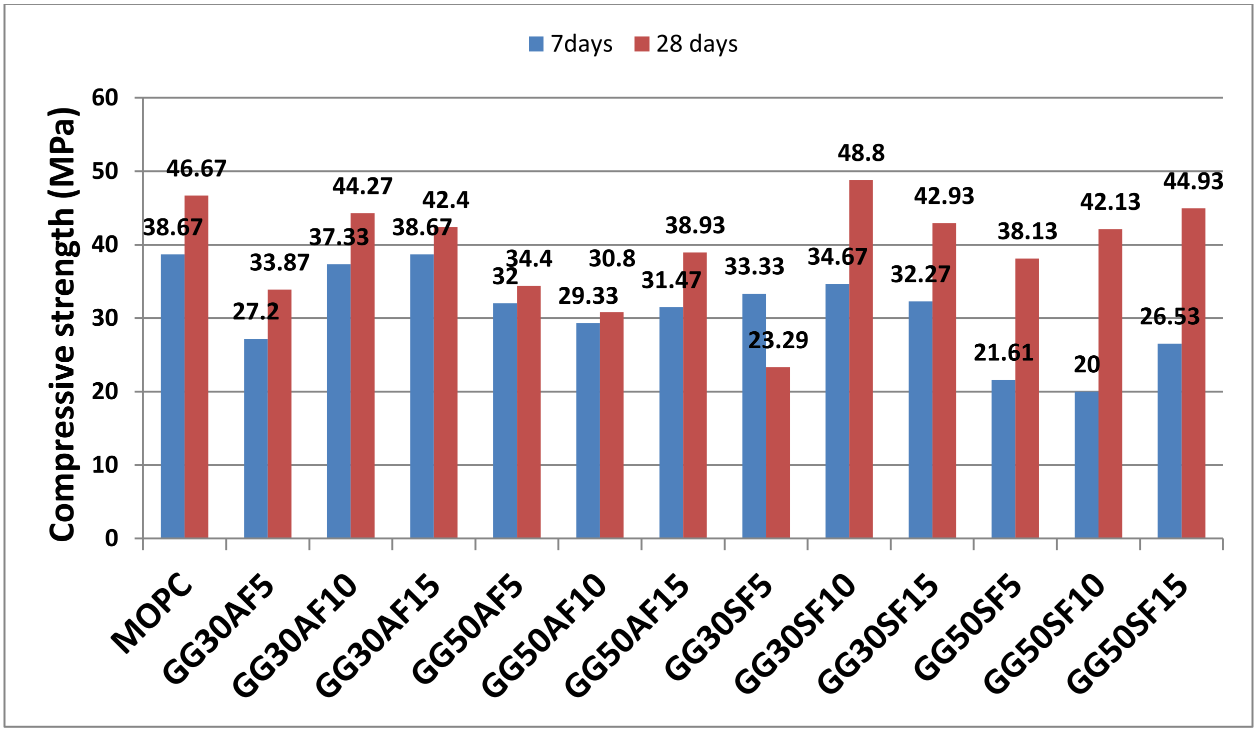


Fig 4.4: comparison of strength of different mixes after 7 and 28 days respectively.

4.3 Durability properties:

Durability study of concrete is nowadays a major issue in research perspective as concrete structures often subjected to harsh and aggressive environment. So as to ensure the durability of concrete present study deals with different durability aspects such as water absorption , apparent porosity ,bulk density, sorptivity, acidic and sulphate environment ,thermal exposure etc.

4.3.1 Water absorption:

As indicated in **table 16** the water absorption of control mix was comparatively higher (8.28%) than the other mixes containing different percentages of SCM's. This may be due to the water requirement during hydration of the cement is quite high and filling ability of cement due to large particles size is low enough to fill the of pore spaces . On the other hand owing to their matrix densification properties accompanied by formation of C-S-H gel there is merely any pores available for water to absorb in SCM's mixes. Mixes containing various percentage of GGBS and alccofines respond better and have lowest value 2.24% for mix GG50AF15.This may be due to high reactivity of alccofine on the formation of primary hydration products which effectively reduces the pore spaces. On the other hand mixes GG30SF5 ,GG30SF10 and GG50SF5 have higher percentages of water absorption with values 5.37%,4.16% and 4.26% respectively . This results oppose the pore refinement mechanism as expected from silica fume even after 28

Table 16: Water absorption values (%) of different mixes after 28 days water curing.

Mix type	Water absorption(%)	Mix type	Water absorption(%)
MOPC	8.28	GG30SF5	5.37
GG30AF5	3.13	GG30SF10	4.16
GG30AF10	2.85	GG30SF15	3.82
GG30AF15	3.04	GG50SF5	4.26
GG50AF5	3.12	GG50SF10	3.05
GG50AF10	3.95	GG50SF15	3.61
GG50AF15	2.24		

days as shown in fig 4.5 .The reason may be the agglomeration of fine silica fume particles in the mix samples or there may unreacted silica fume particles present in the mixes which enhanced the water requirements. But further incorporation of GGBS (50%) content the water absorption gets decreased and optimum value obtained at 3.05% for mix GG50SF10 as GGBS promotes the pore size refinement in addition to silica fume which eventually decreased the water absorption.

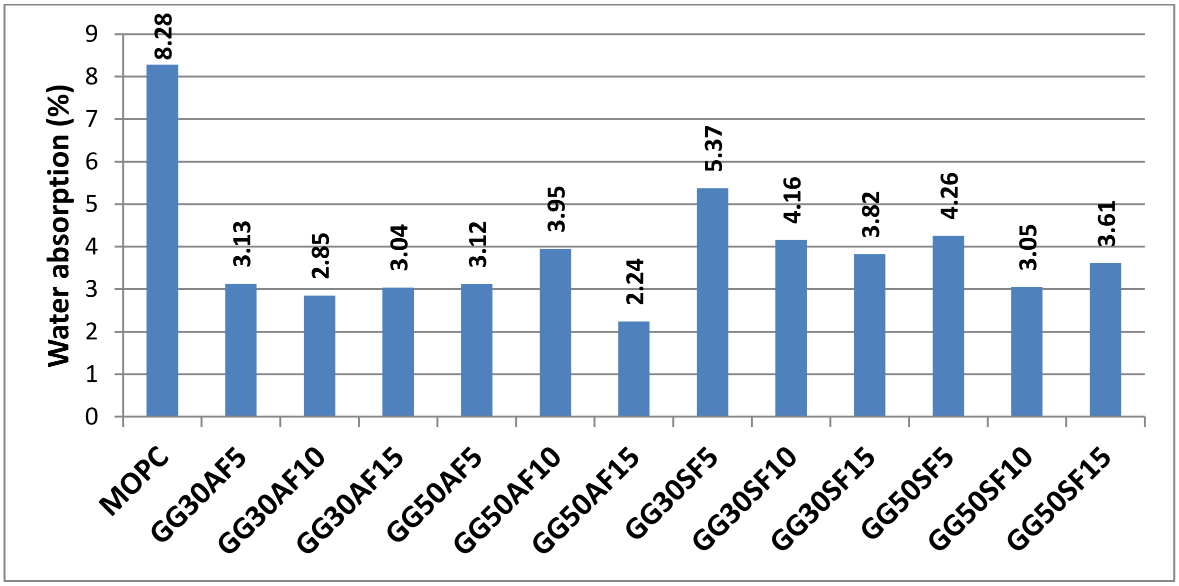


Fig 4.5: Water absorption of different mixes.

4.3.2 Apparent porosity:

The term apparent porosity measures the volume of voids accessible for water in terms of percentage. Porosity has major influence on properties such as strength and durability of concrete .

Table 17: Apparent porosity (%) of different mixes after 28 days water curing.

Mix type	Apparent porosity(%)	Mix type	Apparent porosity(%)
MOPC	16.96	GG30SF5	10.98
GG30AF5	6.33	GG30SF10	8.52
GG30AF10	5.79	GG30SF15	7.88
GG30AF15	6.11	GG50SF5	8.77
GG50AF5	6.48	GG50SF10	6.33
GG50AF10	7.81	GG50SF15	7.52
GG50AF15	4.55		

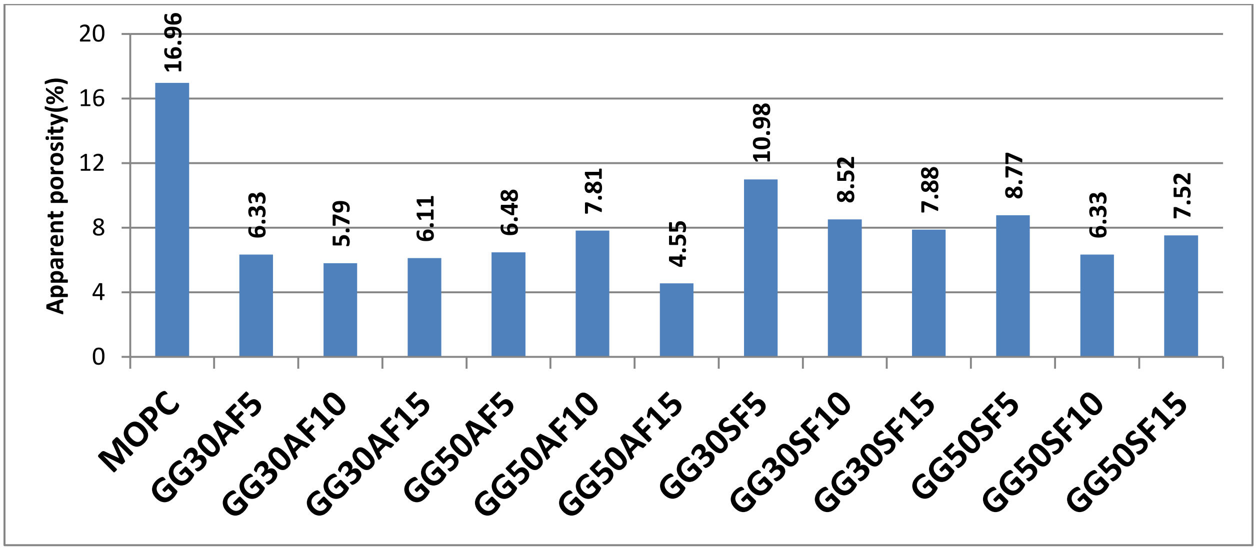


Fig 4.6 :Apparent porosity values of different mixes.

Apparent porosity was maximum for control mix (16.96%) followed by mix GG30SF5(10.98%). Again mixes having GGBS and alccofine combination performed better and least value obtained (4.55%) for mix GG50AF15.(Refer Fig 4.6) . Poor overall performance observed in case of SCM’s incorporating silica fume and GGBS mixes as compare to alccofine blended ternary mixes. But in both the cases optimum percentage obtained at 15% and 10% replacement by alccofine and silica fume respectively along with higher percentage inclusion of GGBS (50%) as the presence of GGBS decreases the pore size and subsequently better results obtained. Furthermore in both the mix series incorporation of higher percentage (50%) of GGBS decreased the apparent porosity values marginally

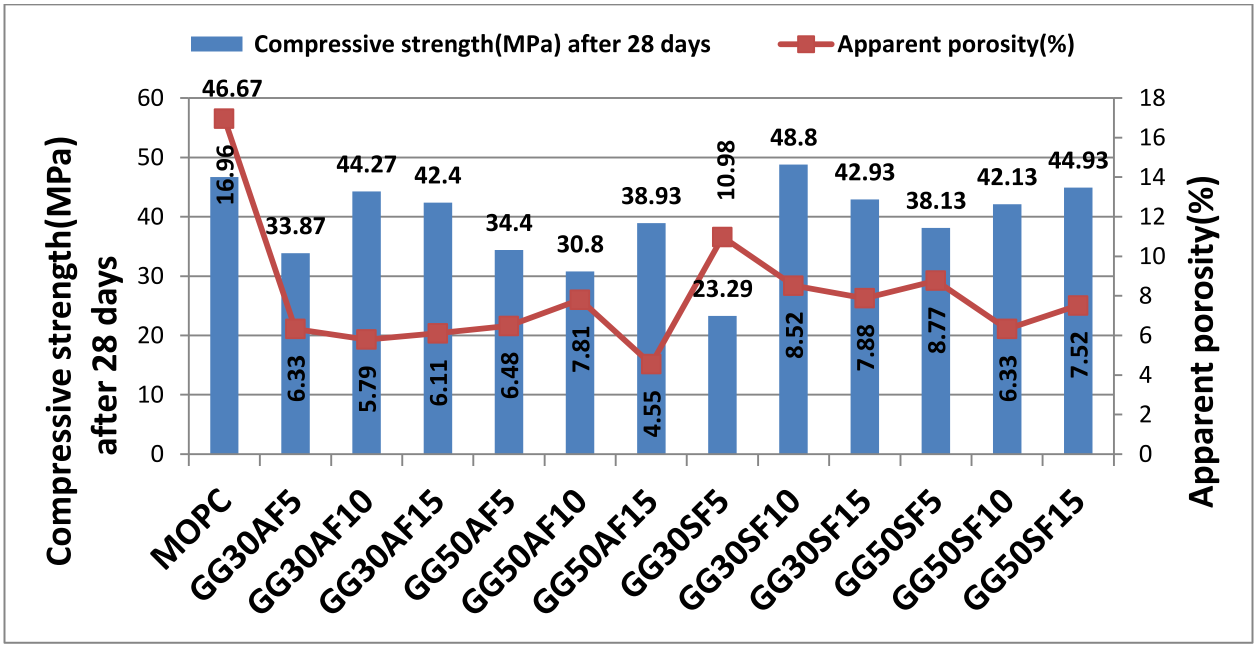


Fig 4.7:Relationship between apparent porosity and Compressive strength(MPa) after 28 days of water curing of different mixes.

Although alccofine GGBS combination have lower apparent porosity value but they could not achieve higher compressive strength as compare to silica fume GGBS combination where they attained higher compressive strength even having worst performance in case of apparent porosity(Refer fig 4.7) Similar trend in results for silica fume as reported by Ahmet Benli,et al(2017) [20] in their research work. which exhibits the onset of substantial pozzolanic reaction of silica fume accompanied by higher absorption of water and lower packing density beyond 28 days.

4.3.3 Bulk density:

Refer to fig 4.8 the mixes comprising of GGBS and silica fume have increasing trend in bulk density as compared to GGBS and alccofine combination. This signifies the packing density and pore refinement efficiency of silica fume compare to alccofine triggering greater density. GGBS has significant influence on pore size reduction and combining effect with silica fume gives better results. Fluctuation in bulk density values observed for alccofine GGBS mix series having higher GGBS content .Further Incorporation of GGBS content produced an increasing trend in bulk density values in GGBS alccofine mix series as shown in fig :4.8.Mixes GG50SF5 to GG50SF15 shows improvement in bulk density compare to control mix and highest value of 2082.69 Kg/m^3 obtained for GG50SF15 followed by mix GG50AF5 (2077 Kg/m^3) and lowest value of 1976.66Kg/m^3 observed for GG50AF10.

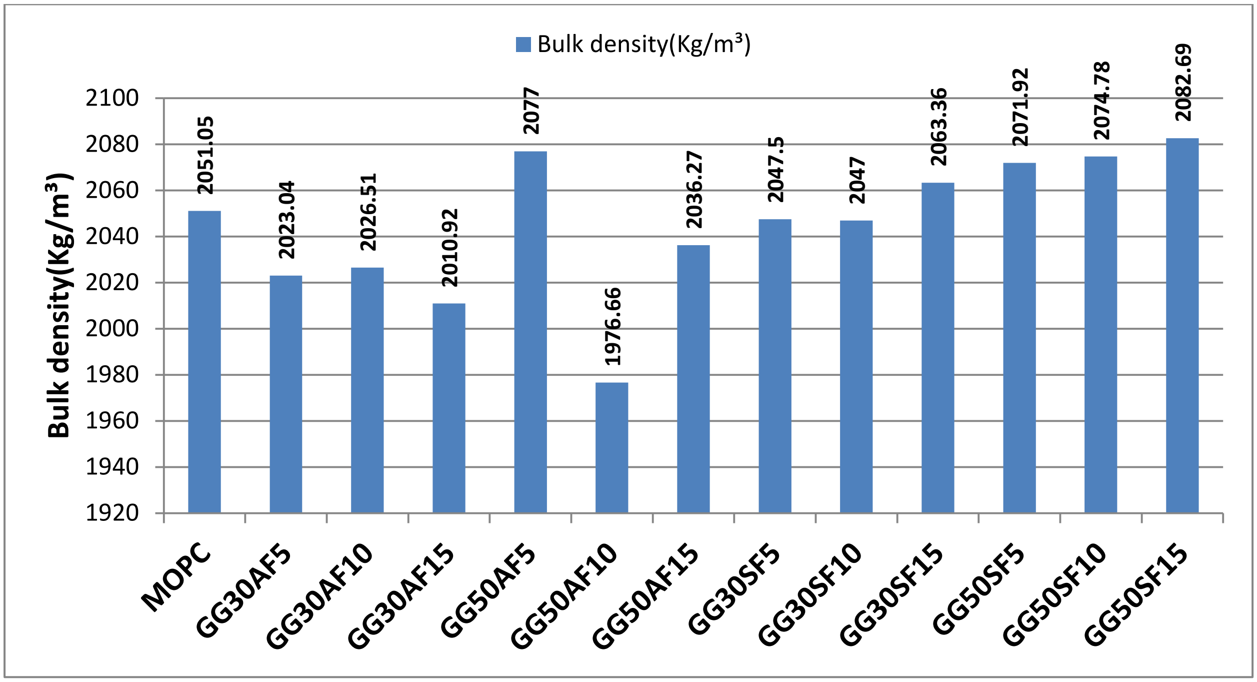


Fig 4.8:Bulk density(Kg/m^3) values of different mixes.

4.3.4 Sorptivity:

Like other durability related tests sorptiviy test is one of the major test to determine ingress of moisture and nature of transport properties of concrete in terms of capillary action. Sorptivity co-efficient represents the slope of the absorption curves (Refer fig 4.9) and two distinct slopes, a steeper followed by relatively flatter one indicating initial(early ages) and secondary(late ages) absorption respectively. The point of conflict where slope changes distinctively is called the nick point . Nick point indicates the level of saturation of samples at early age. Steeper the slope of the initial curve early the occurrence of nick point which suggests that maximum damage occurred at early age. On the other hand samples having later occurrence of nick point(almost mild slope both in initial and secondary absorption) indicates the delayed saturation even after 8 days and eventually have outstanding performance. Thus sorptivity is considered to be an useful tool for predicting relative service life of the concrete

Sorptivity co-efficient values for different mixes were determined as described in ASTM C 1585-04 using experimentally obtained plot as shown in fig :4.9 for different mixes . As discussed earlier that higher sorptivity coefficient value indicates considerable damage

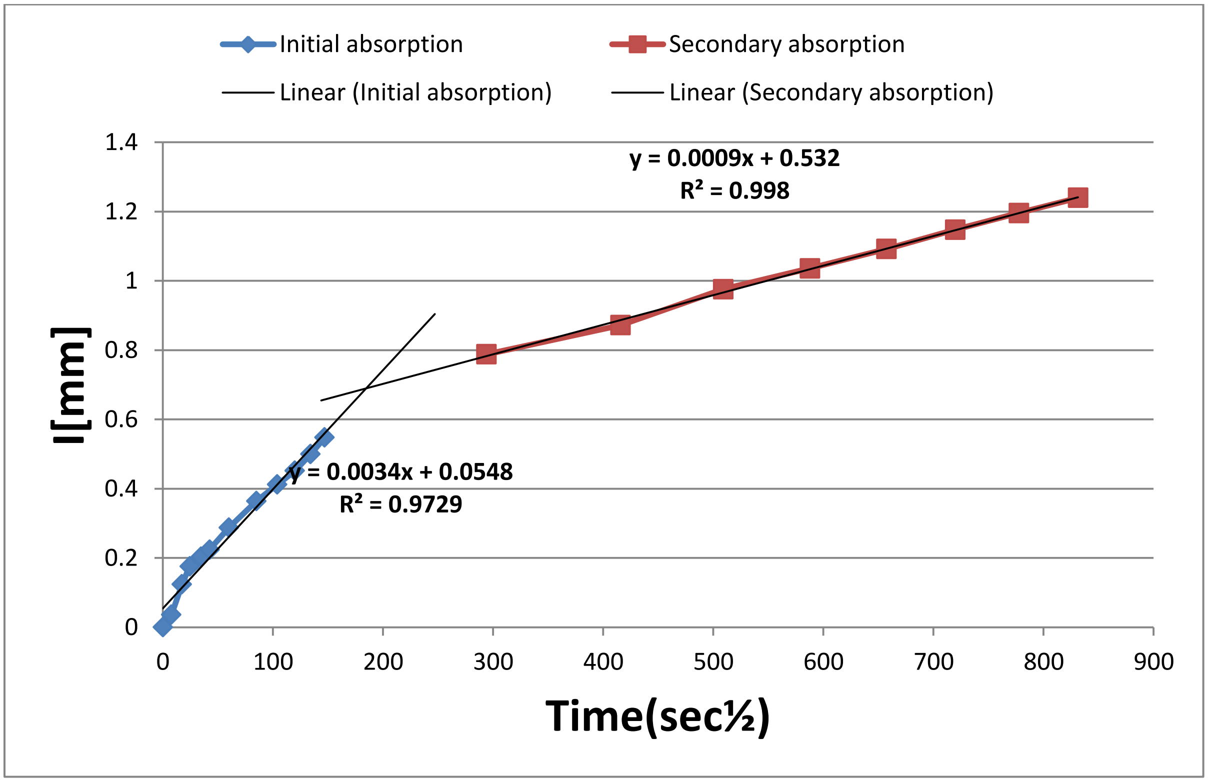
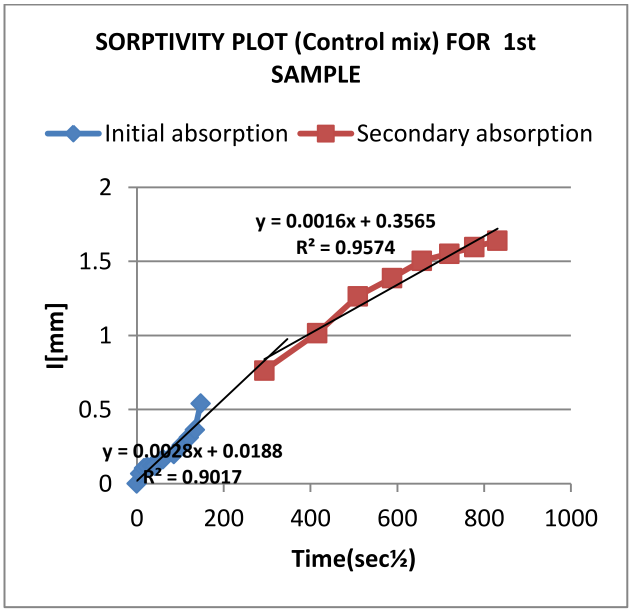
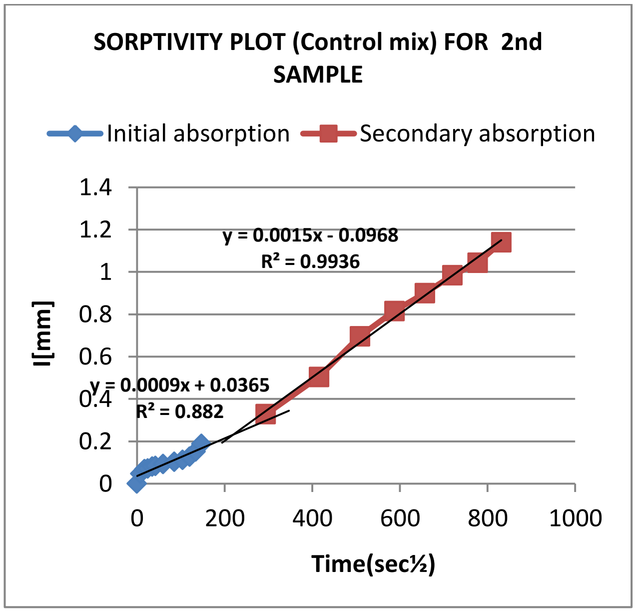


Fig 4.9:Typical sorptivity plot of mix (GGBS-30%,AF-5%) showing initial and secondary absorption.





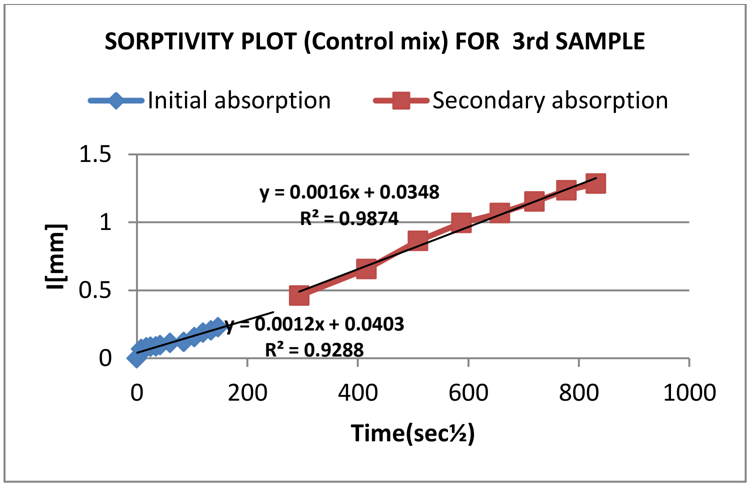


Fig 4.10:Sorptivity plot of control mix samples.

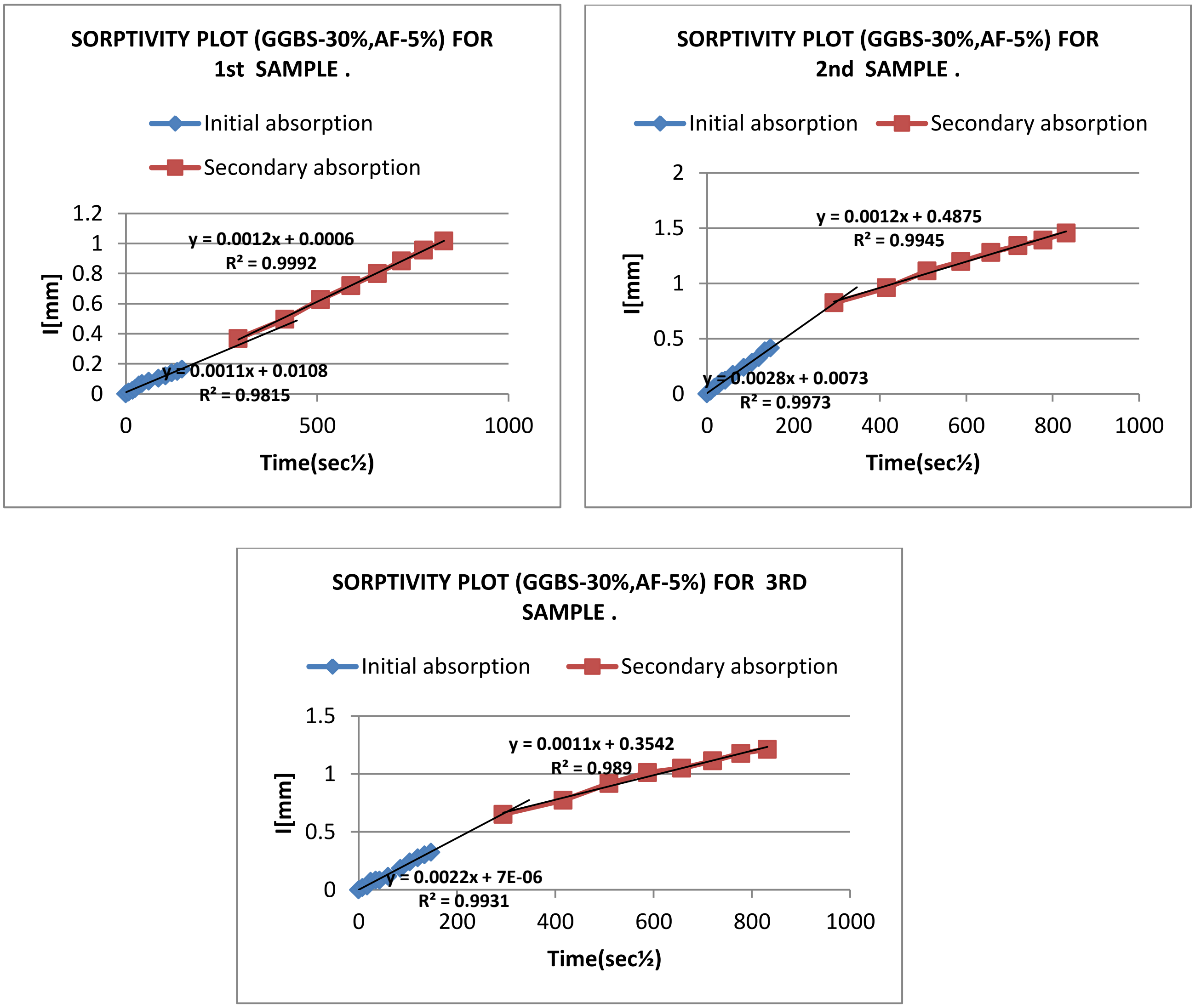
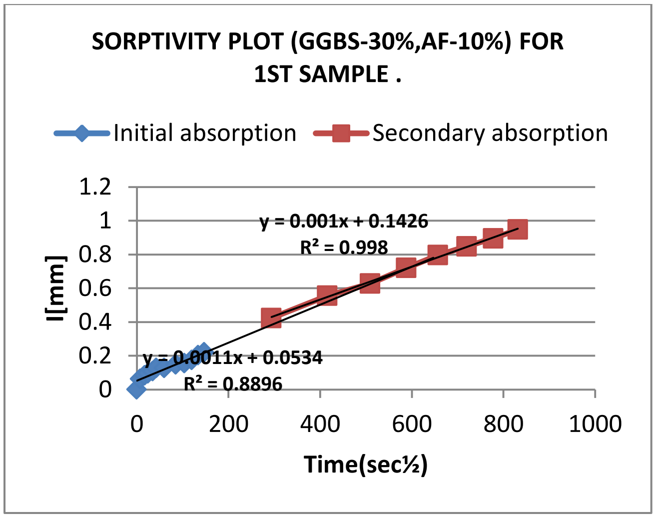
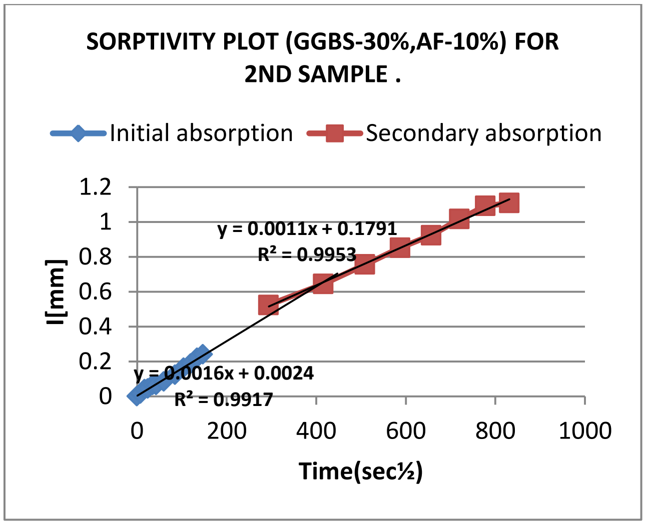


Fig 4.11:Sorptivity plot of GG30AF5 mix samples.





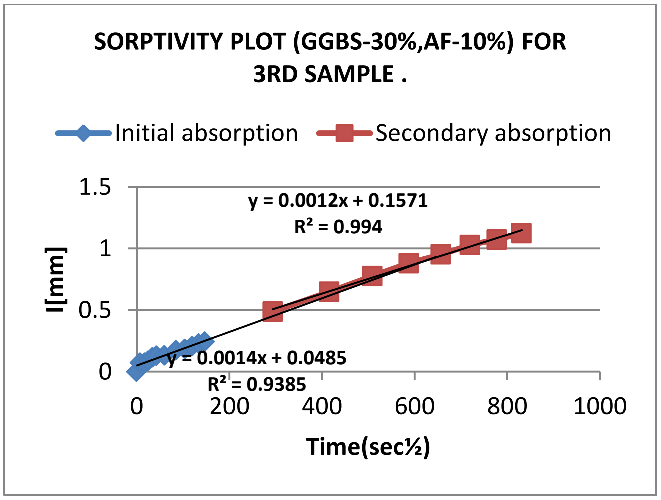


Fig 4.12:Sorptivity plot of GG30AF10 mix samples.

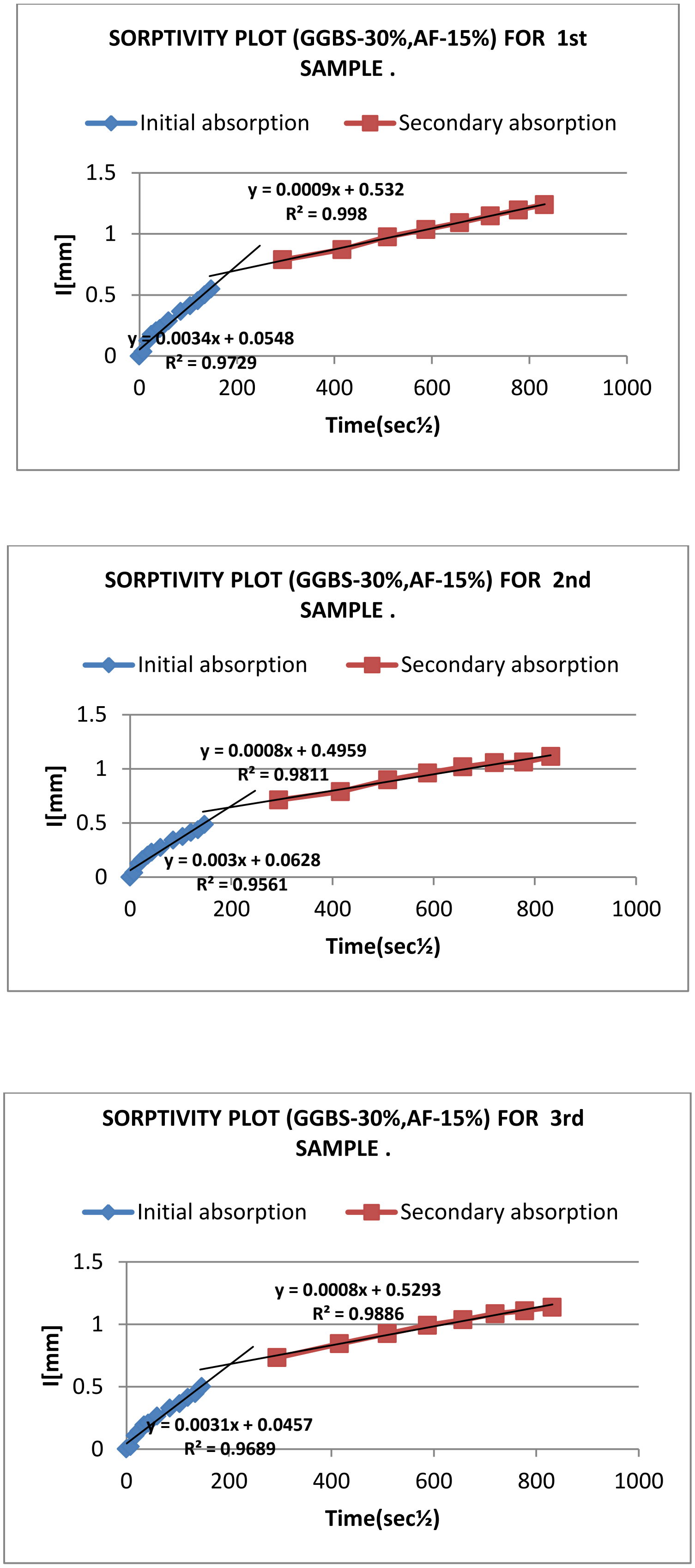


Fig 4.13:Sorptivity plot of GG30AF15 mix samples.

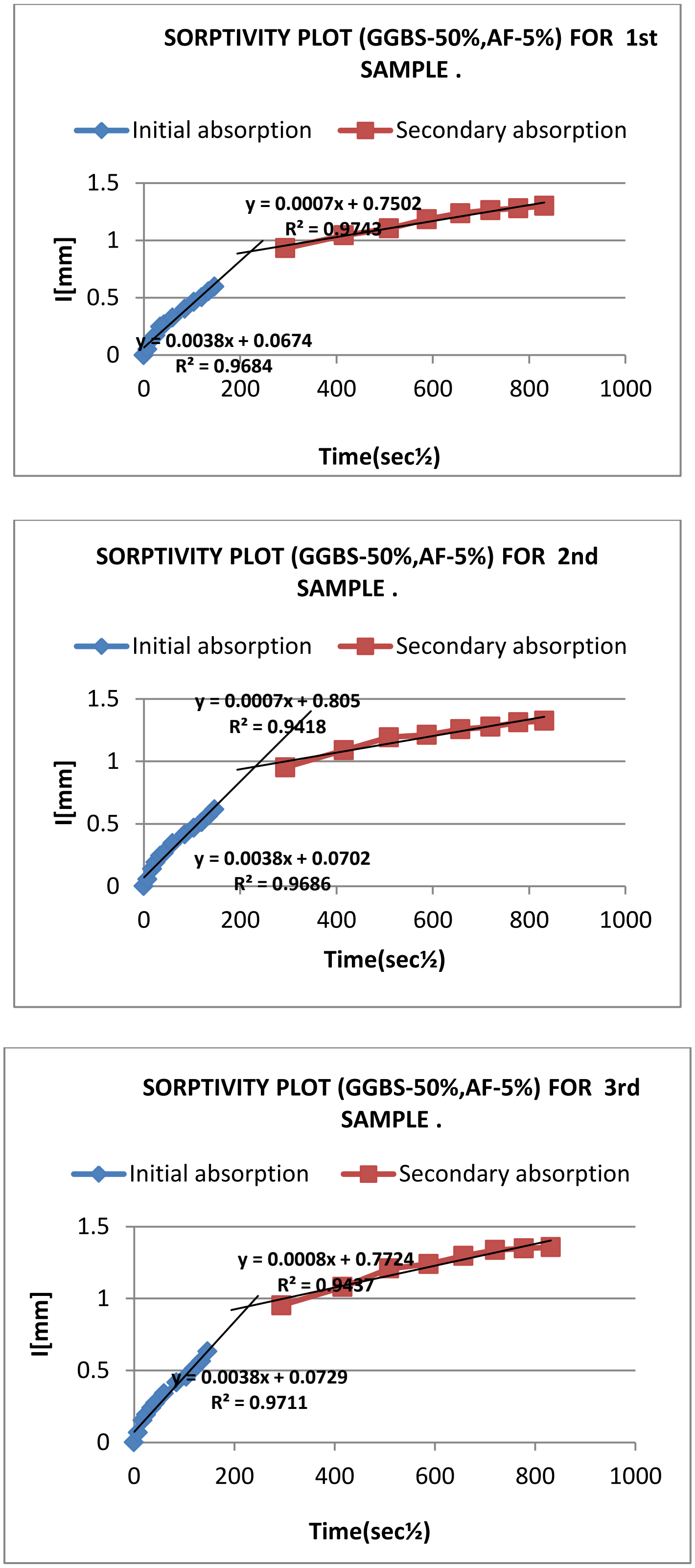


Fig 4.14:Sorptivity plot of GG50AF5 mix samples.

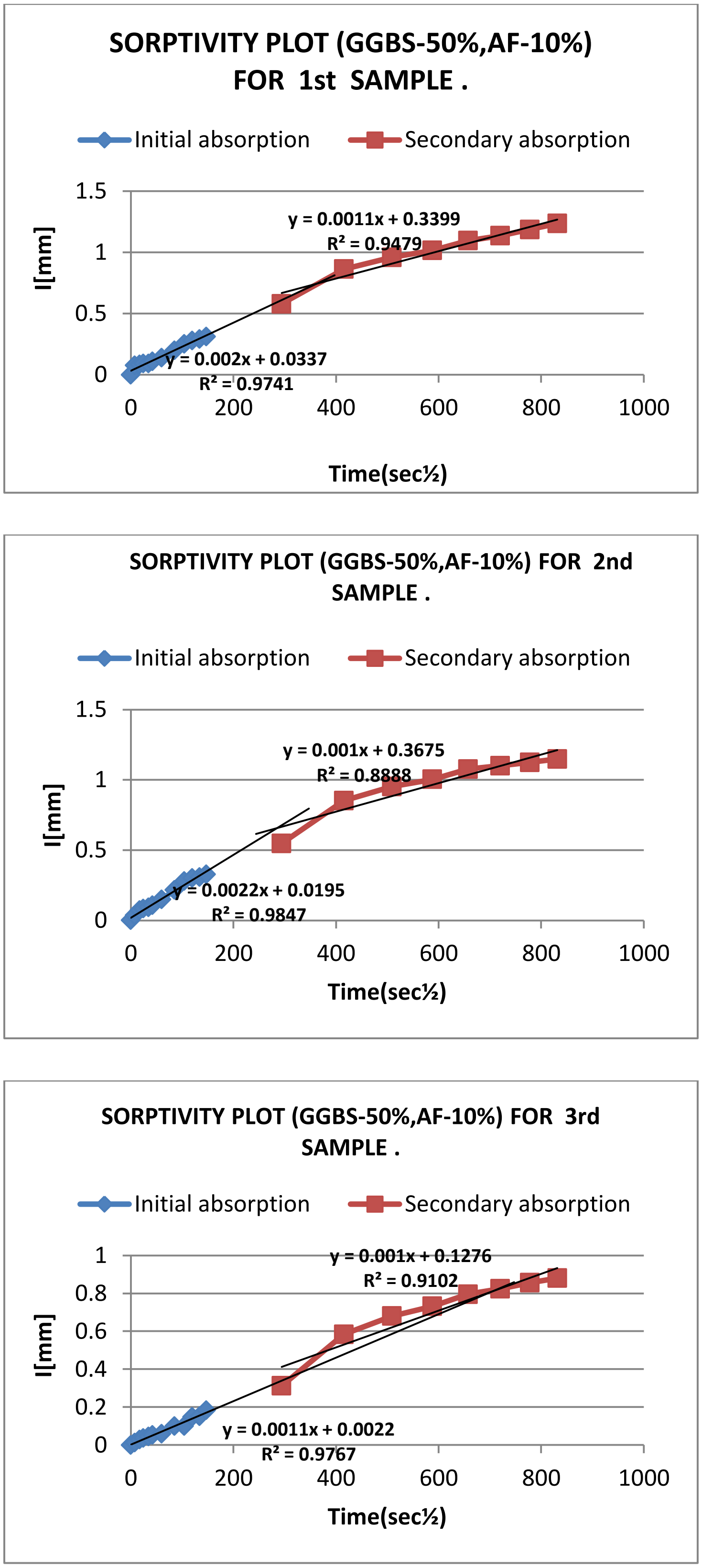
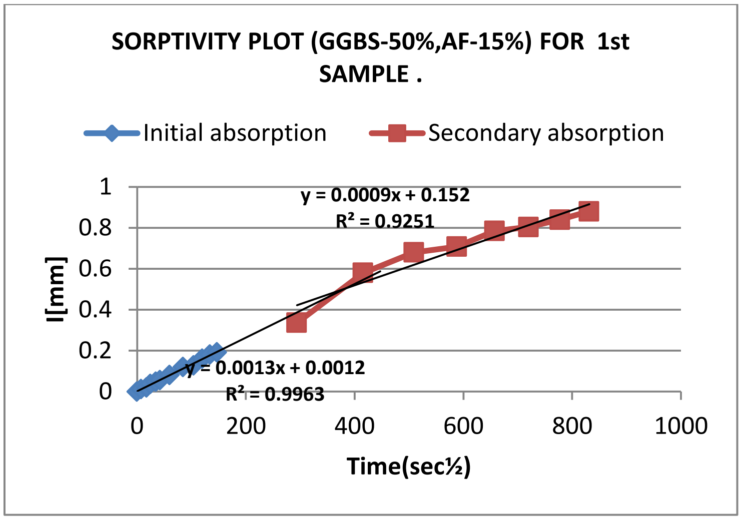
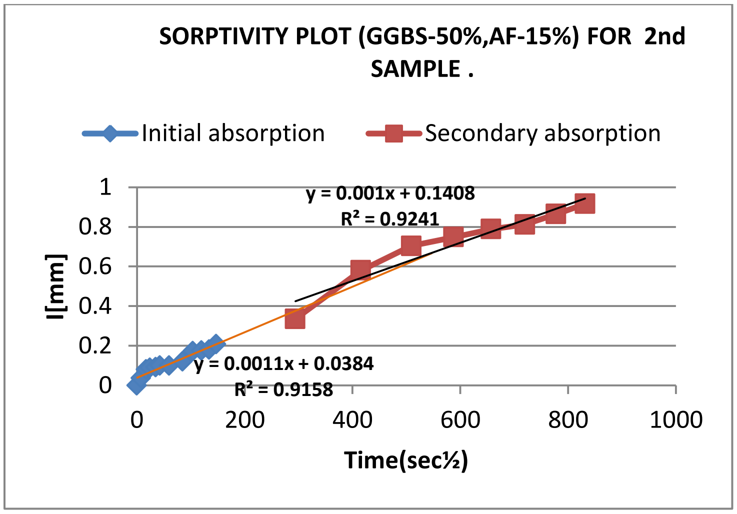


Fig 4.15:Sorptivity plot of GG50AF10 mix samples.





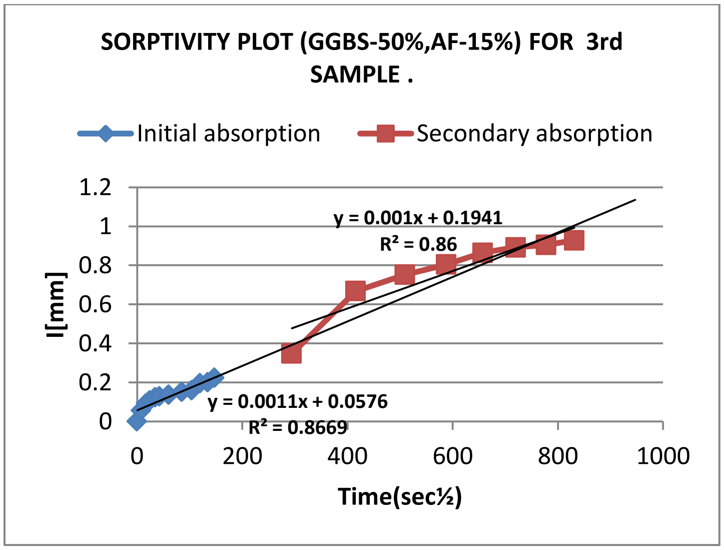


Fig 4.16:Sorptivity plot of GG50AF15 mix samples.

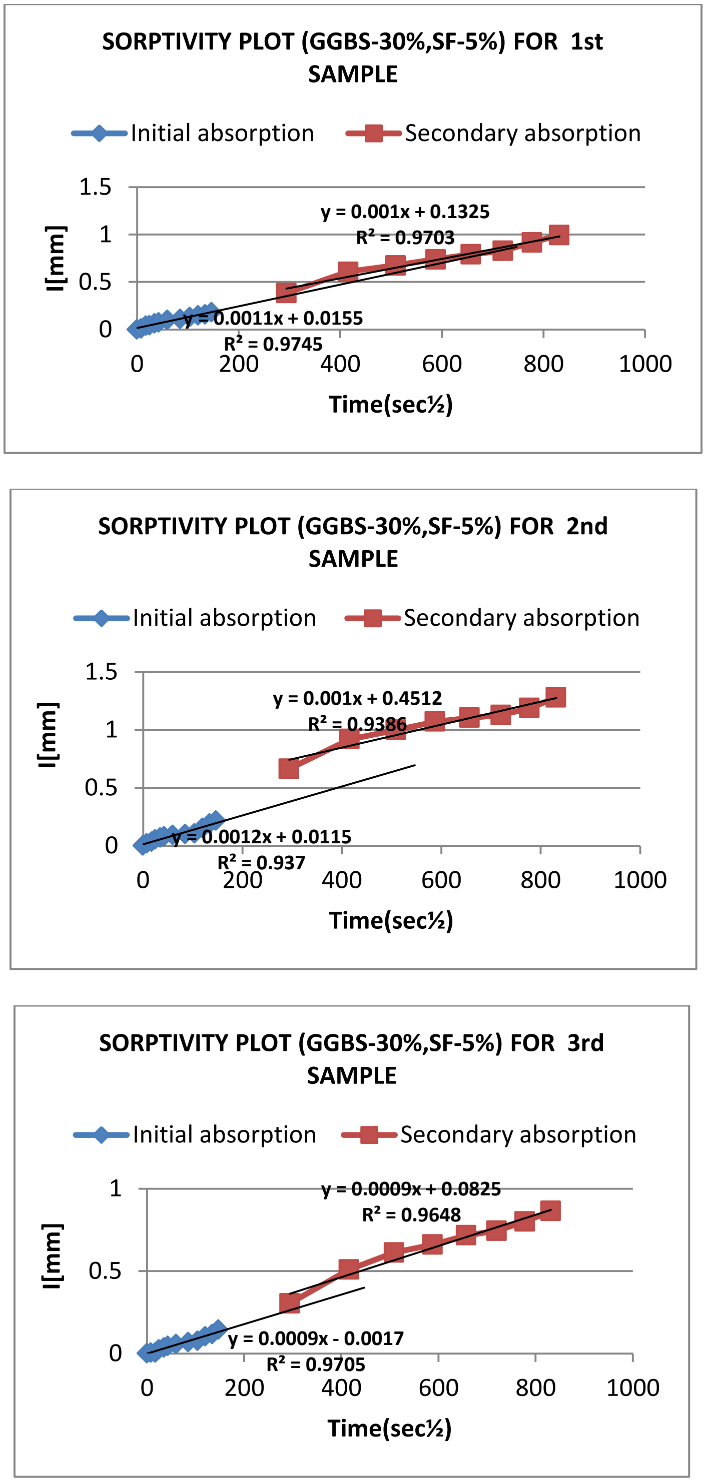


Fig 4.17:Sorptivity plot of GG30SF5 mix samples.

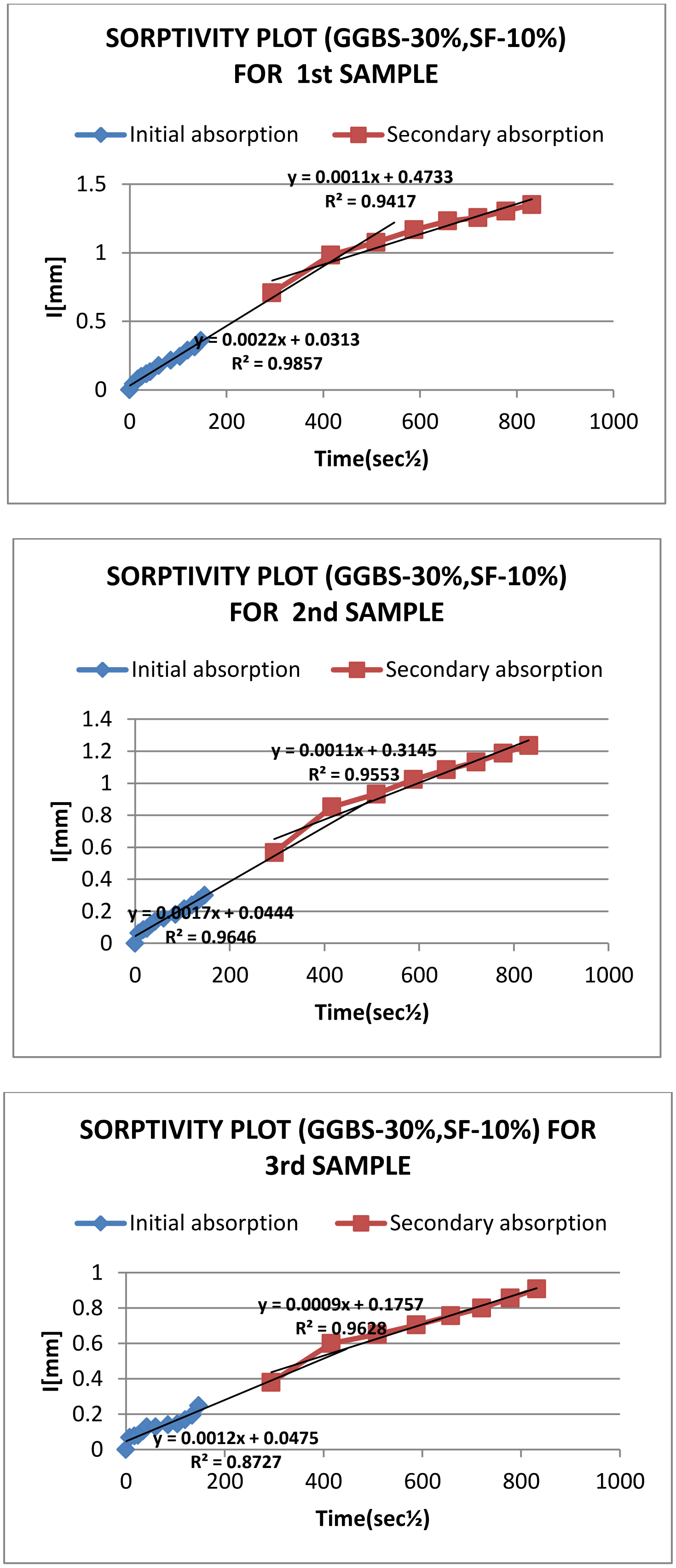


Fig 4.18:Sorptivity plot of GG30SF10 mix samples.

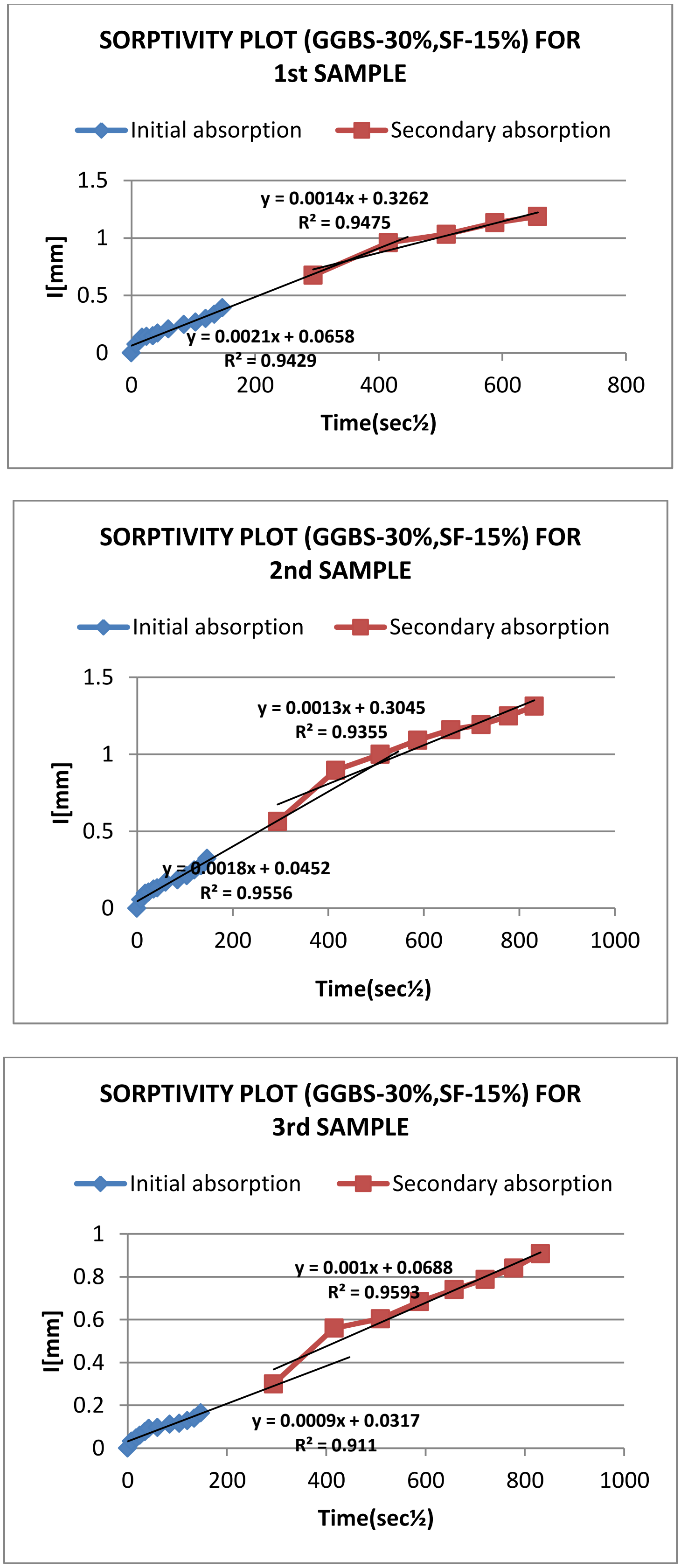
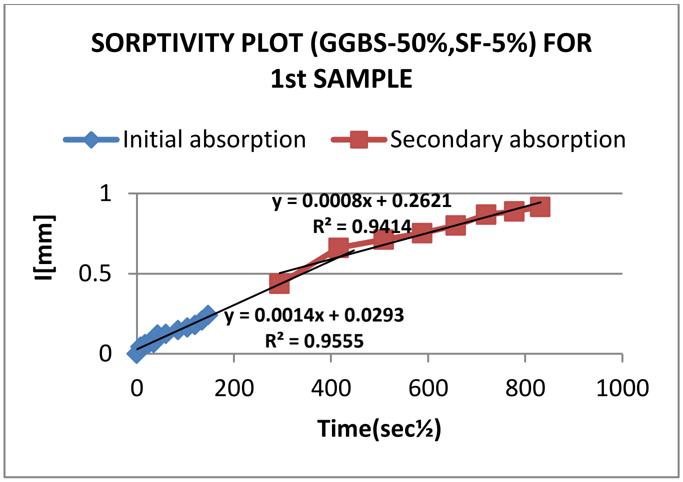
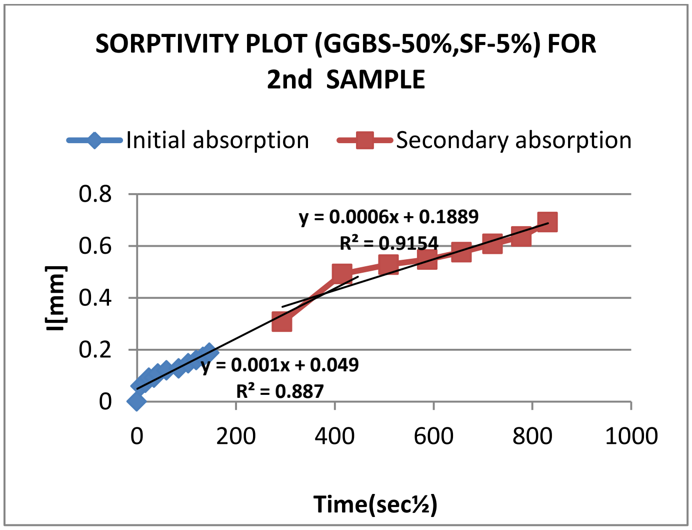


Fig 4.19:Sorptivity plot of GG30SF15 mix samples.





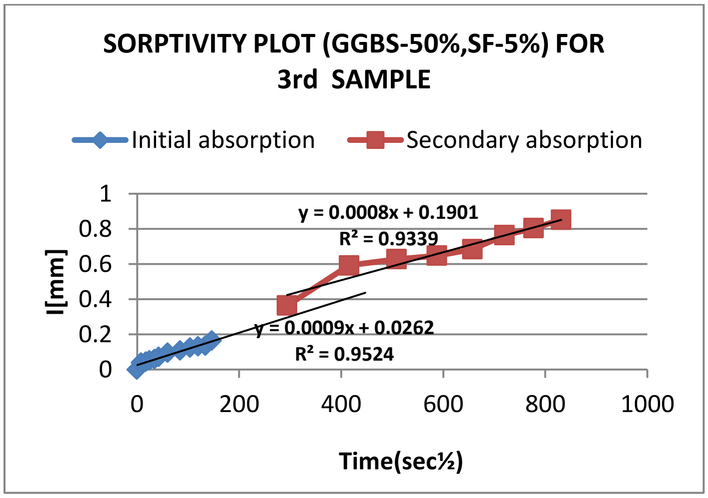


Fig 4.20:Sorptivity plot of GG50SF5 mix samples.

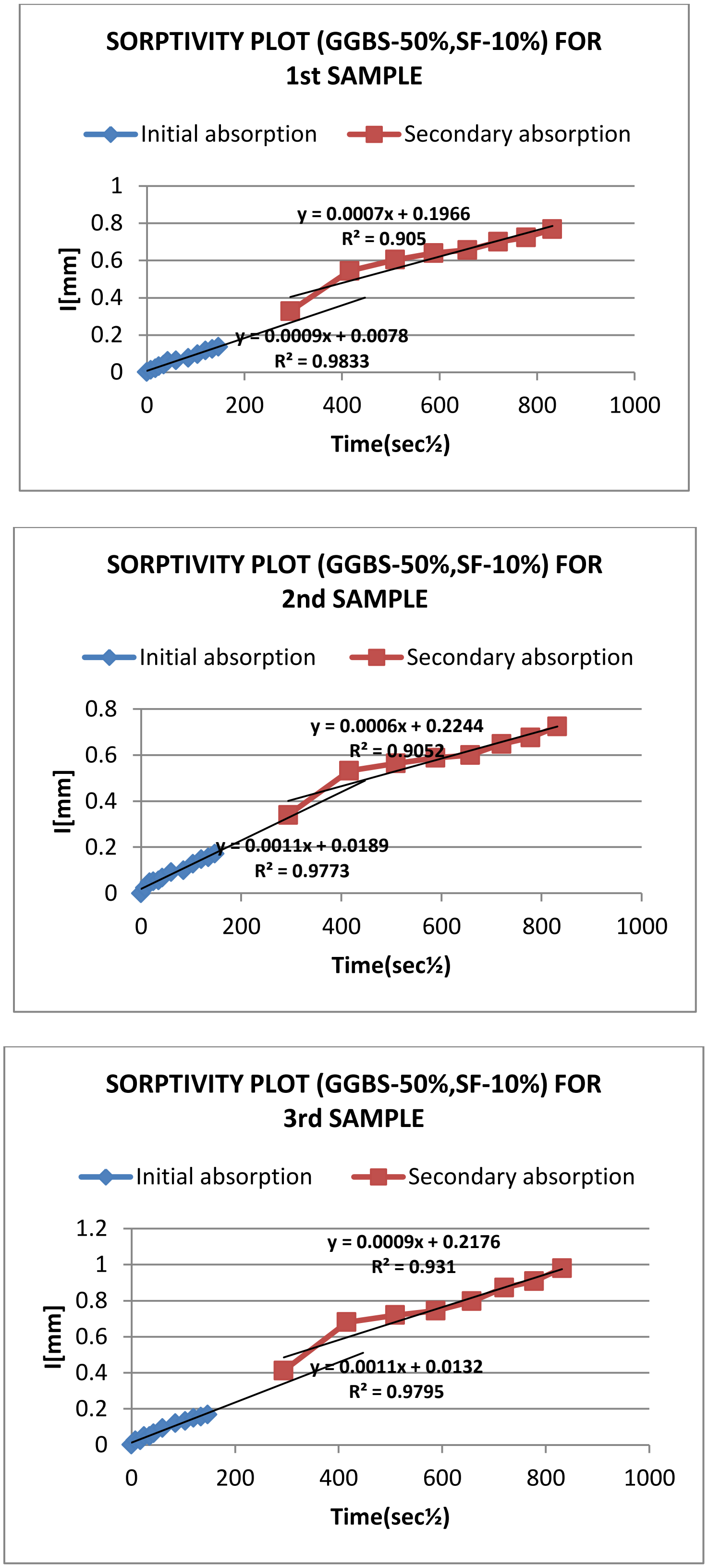


Fig 4.21:Sorptivity plot of GG50SF10 mix samples.

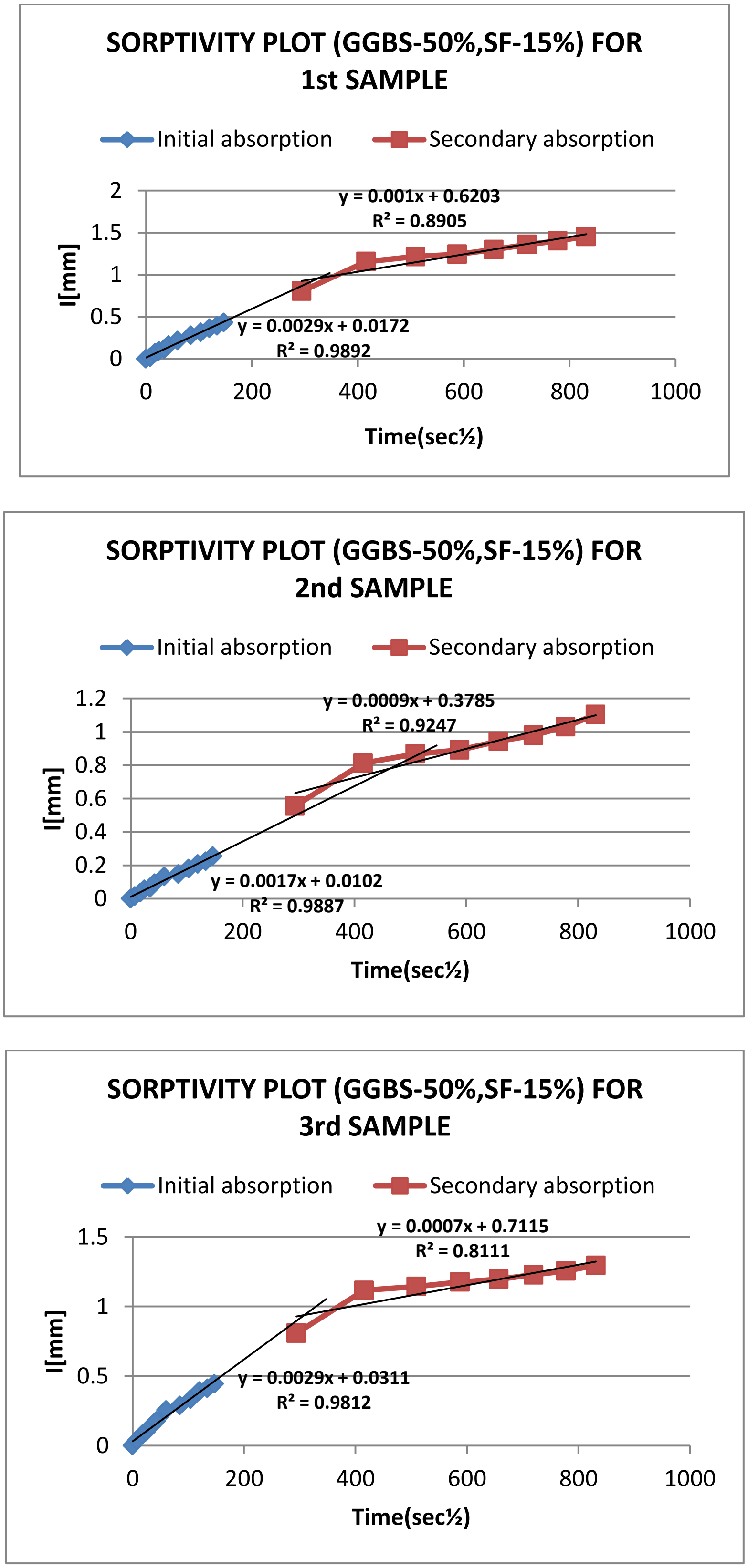


Fig 4.22:Sorptivity plot of GG50SF15 mix samples.

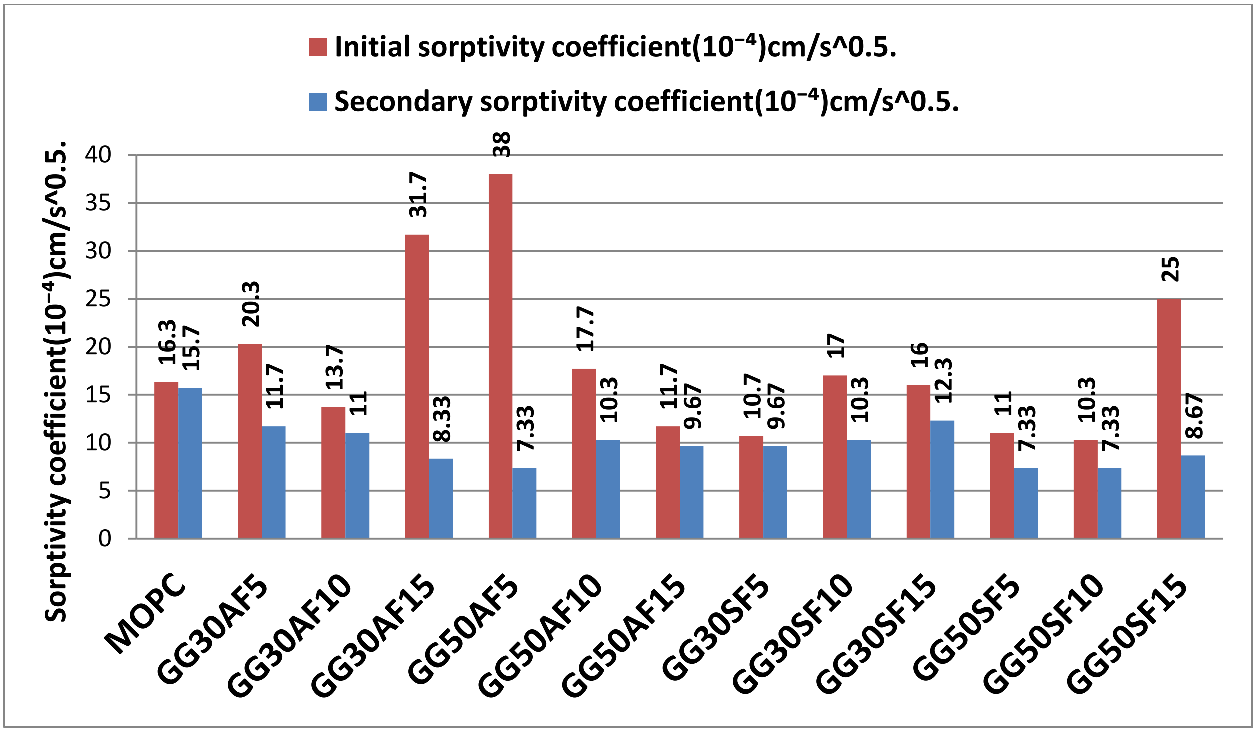


Fig 4.23: Sorptivity coefficients of different mixes after 28 days water curing.

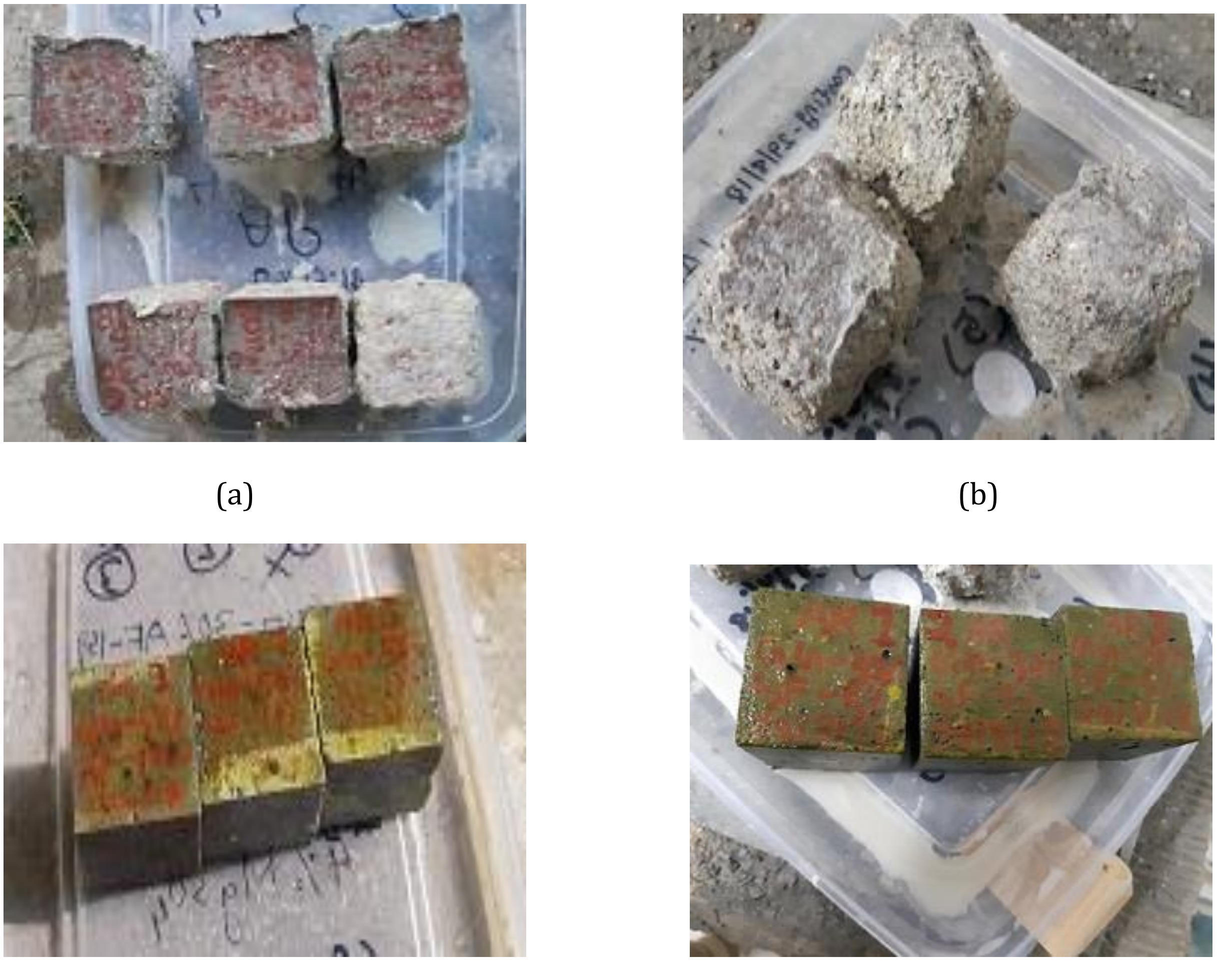
potential at early age .It can be seen from fig 4.23 that GG30AF15 and GG50AF5 got considerable ingression of water having sorptivity coefficient values 31.7x10^{-4} cm/s$^{\wedge 0.5}$ and 38x10^{-4} cm/s$^{\wedge 0.5}$ respectively. The overall performance of silica fume was quite better compare to alccofine. The reason may be that the silica fume promotes pore refinement and matrix densification mechanism and enhancement in formation of C-S-H gel at later age .Thus inhibits both initial as well as secondary water absorption significantly compare to other mixes except for GG50SF15. On the other hand alccofine mix series attained higher values of sorptivity co-efficient which signifies lower resistance to water penetration which is an indicative measure of poor pore refinement mechanism of alccofine. Increase in percentage replacement both by GGBS and alccofine improved pore size refinement to some extent . Silica fume and GGBS combination have better performance and increase in GGBS content further improves the formation of dense matrix causing better inhibition to water penetration.

4.3.5 Durability against acid and sulphate exposure:

Many concrete structures are often exposed to different aggressive chemical (acid and sulphate) environment. Most common example is corrosion of concrete sewer due to formation of biogenic sulphuric acid. Other such examples are effluents from tannery ,dairy firm, refinery industries and offshore concrete structures which often causes chemical degradation of concrete .So durability against H_2SO_4 and $MgSO_4$ of concrete is of major concern in this study.

4.3.5.1 Visual assesment:

A thorough visual assessment was carried out for each sample after removed from the acid and sulphate solution. Fig 4.24(a-d) showed the degree of damage of samples of ternary mixes both for alccofine and silica fume combined with different percentage replacement by GGBS after getting exposed to 4% H_2SO_4 and 4% $MgSO_4$ solution for 56 days. Samples containing ternary mixes (OPC+alccofine+GGBS) suffered less as compared to ternary mixes (OPC+silica fume +GGBS)[Refer fig.4.24(a) & (b)] when exposed to H_2SO_4 .Overall condition of both categories of sample were almost same after $MgSO_4$ exposure as per visual observation. [Fig 4.16(c) & (d)].



(a) (b)

(c) (d)

Fig 4.24: Damage of samples of ternary mixes (OPC+AF+GGBS) & (OPC+SF+GGBS) after H_2SO_4 exposure (a-b) and $MgSO_4$ exposure(c-d).

Disintegration on the surface as well as corners of the samples occurred in both the samples as shown in fig4.24(a) and (b) after H_2SO_4 exposure. Extent of deterioration was attributed to the formation of white pulpy surface layer under laid by fluffy mass as acid penetrates into the concrete and destroys the C-S-H gel and turns in to gypsum(Calcium sulphate hydrate) which eventually reacts with C_3A to form ettringite causing substantial expansion of the effected zone as discussed in literature review section. The level of deterioration as observed was significantly greater in case of silica fume samples where entire surface was peeled off leaving the white fluffy mass . On the other hand low marginal effects in terms of visual observation were noticed for both the samples subjected to $MgSO_4$ exposure.

4.3.5.2 Change in weight:

As discussed in the previous section acid or sulphate diffusion in to concrete causes depletion of C-S-H gel accompanied by formation of gypsum which eventually results in change in weight.

Table 18: Change in weight(%) and corresponding compressive strength of different mixes after 4% H_2SO_4 exposure.

Sl.no	Mix type	Change in Weight (%)	Residual compressive strength(%)
1	MOPC	4.81	45.15
2	GG30AF5	3.07	44.08
3	GG30AF10	5.06	40.37
4	GG30AF15	9.07	33.33
5	GG50AF5	3.1	27.12
6	GG50AF10	3.09	47.63
7	GG50AF15	-4.07	64.04
8	GG30SF5	22.18	47.53
9	GG30SF10	4.95	34.43
10	GG30SF15	-1.82	39.76
11	GG50SF5	-0.64	43.72
12	GG50SF10	3.0	47.47
13	GG50SF15	-8.87	44.51

In addition to gypsum, formation of ettringite takes place .Both of them are expansive products and responsible for significant change in weight in terms of weight loss or gain. Fig: 4.25 depicted the percentage change in weight of different mixes in comparison with control mix after 4% H_2SO_4 exposure for 56 days. Overall performance of different mixes in terms of percentage change in weight after H_2SO_4 exposure for 56 days as shown in fig 4.26 .

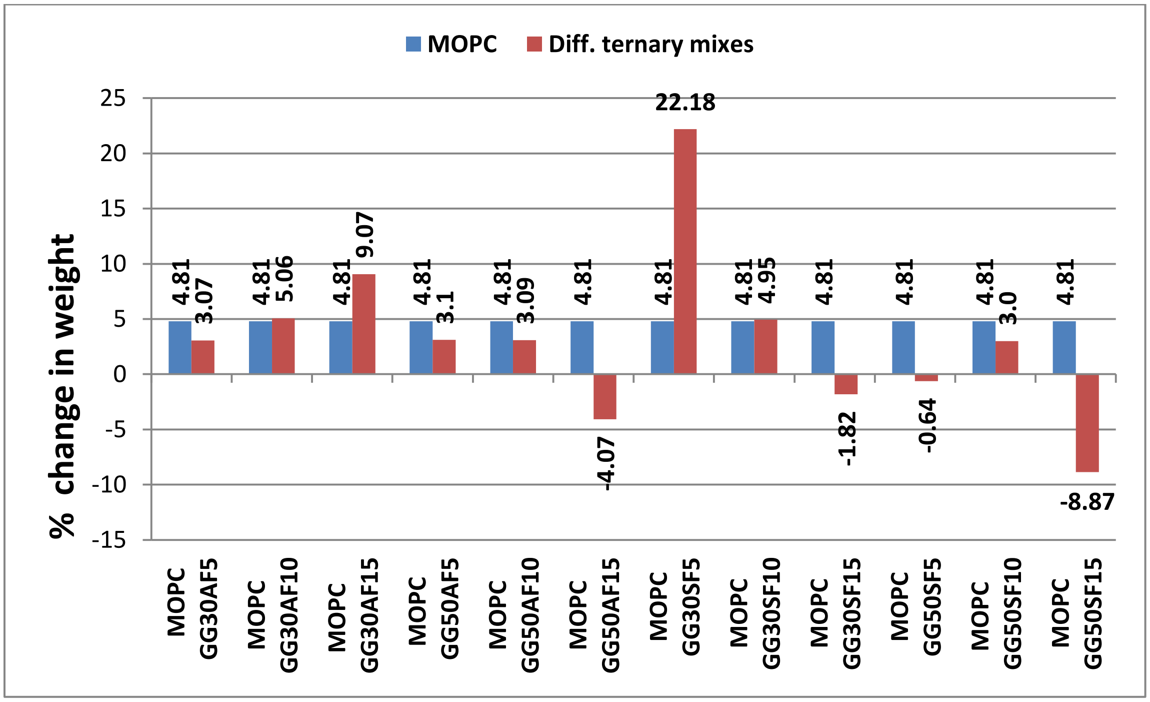


Fig 4.25 Comparison of Change in weight of control mix and different ternary mixes after 4% H_2SO_4 exposure for 56 days

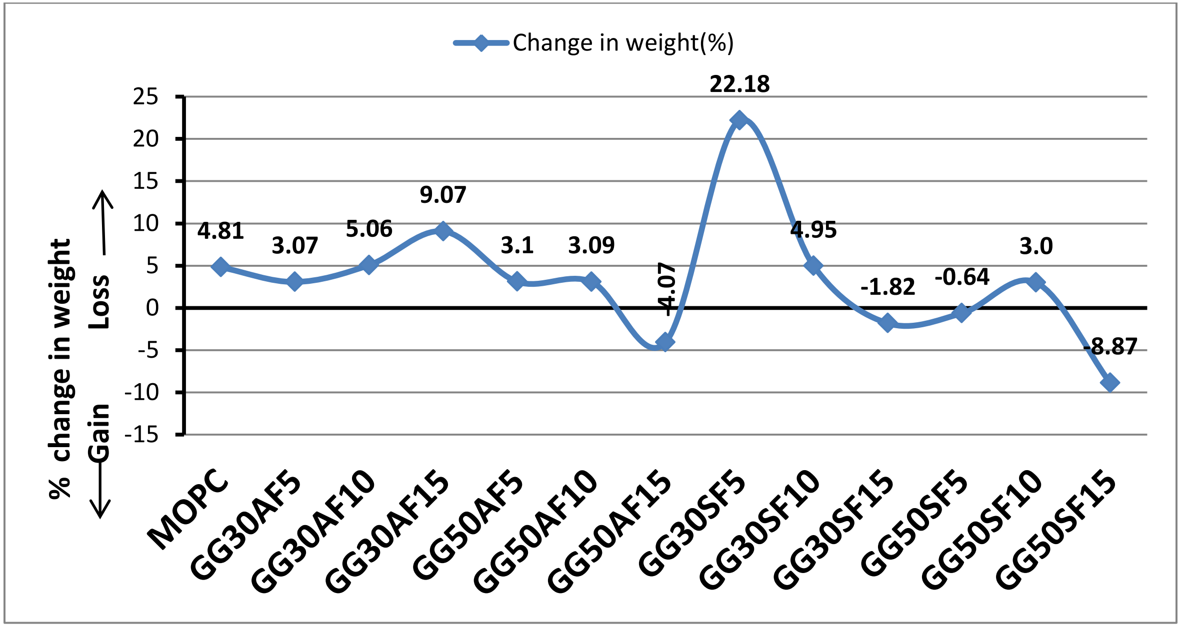


Fig :4.26: Comparison of % change in weight of different mixes after 4% H_2SO_4 exposure.

Observation made so far revealed that the trend in weight loss was significant both for control mix as well as mixes blended with different percentage level of alccofine and GGBS .GG30AF15 suffered greater weight loss (9.07%) as compare to control mix(4.81%) except for GG50AF15 where weight gain(shown as negative values) occurred to the extent of 4.07% due to formation of expansive product. This may be due to the fact that depletion of CH or portlandite content in SCM's mixes attributed to the formation of secondary C-S-H gel, thus contribution of CH in the formation of gypsum is secondary rather than decomposition of C-S-H gel leads to dissolved solution (Calcium Sulphate Hydrate) when exposed to severe sulphuric acid attack . Remarkable weight loss observed for mix GG30SF5 (22.18%) but for other mixes from GG30SF10 to GG50SF15 a reverse trend was observed except for mix GG50SF10 where slight weight loss occurred to the tune of 3%.

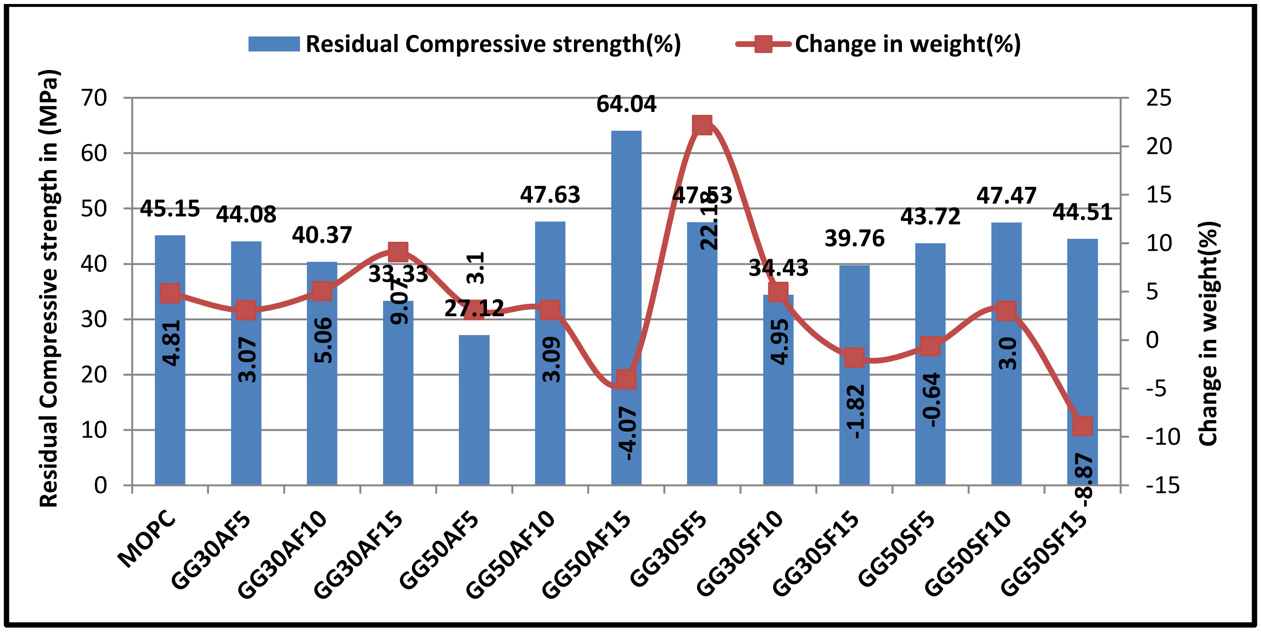


Fig:4.27:Relationship between % change in weight and residual compressive strength values of different mixes after 4% H_2SO_4 exposure for 56 days.

Fig:4.27 illustrated the change in weight of different mixes with their corresponding residual compressive strength values. It is clear from the figure that ternary mixes blended with different percentage of GGBS and alccofine having decreasing trend in residual strength accompanied by increase in weight loss values .Further inclusion of GGBS content exhibited the reverse trend and for mix GG50AF15 where weight gain occurred accompanied by higher residual compressive strength (64.04%). On the other hand mixes incorporating GGBS and silica fume offered better resistance against sulphuric acid attack as indicated in the figure having comparatively higher values of residual compressive strength. Coexistence of greater percentage weight loss as well as higher residual compressive strength value (47.53%) occurred for mix GG30SF5 after which a decreasing trend in change in weight along with increasing percentages of GGBS content .Conversely an increasing trend in residual compressive strength was observed as GGBS content increases. This may be attributed to the fact that the weight gain leading to formation of expansive products which in turn filling up the pore spaces causing densification of the mortar matrices and higher values of residual compressive strength obtained.

Table 19: Change in weight(%) and corresponding compressive strength of different mixes after 4% $MgSO_4$ exposure.

Sl.no	Mix type	Change in Weight (%)	Residual compressive strength(%)
1	MOPC	-0.29	105.14
2	GG30AF5	-0.15	143.70
3	GG30AF10	-0.12	128.91
4	GG30AF15	-0.22	86.16
5	GG50AF5	-0.42	110.09
6	GG50AF10	0.46	185.29
7	GG50AF15	-0.37	118.16
8	GG30SF5	-0.10	206.10
9	GG30SF10	-1.08	96.72
10	GG30SF15	-0.074	116.77
11	GG50SF5	0.084	120.64
12	GG50SF10	-0.08	118.68
13	GG50SF15	-0.83	84.29

Conversely greater formation of expansive products occurred in case of $MgSO_4$ exposure compare to sulphuric acid exposure leading to weight gain (Refer fig 4.28). In comparison to other mixes control mix got marginal weight gain to the tune of 0.29%. Ternary mixes incorporating GGBS and alccofine with different percentage levels also have marginal weight gain varying from 0.15 % to 0.42 % except for mix GG50AF10 where slight loss in weight was observed having value 0.46%. For ternary mixes having different percentage level of GGBS and silica fume weight gain occurred in almost all mixes except for GG50SF5 where nominal weight loss of 0.084% occurred. Overall performance of different mixes in terms of percentage change in weight after $MgSO_4$ exposure for 56 days as shown in fig 4.29 Contribution to the formation of expansive materials was relatively greater for alccofine and GGBS mixes compare to silica fume mixes though mix GG30SF10 and GG50SF15 have better weight gain with individual values of 1.08% and 0.83% respectively which indicates the overall performance of alccofine is still better compare to silica fume mix series.

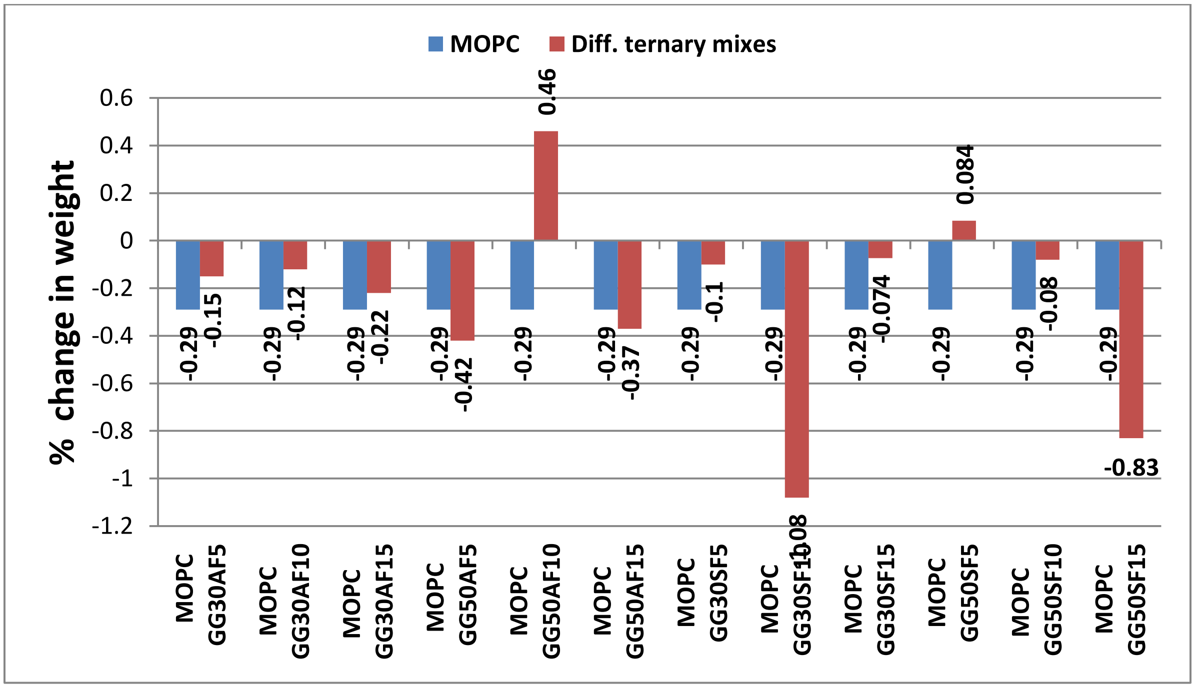


Fig 4.28: Comparison of Change in weight of control mix and different ternary mixes after 4% $MgSO_4$ exposure for 56 days.

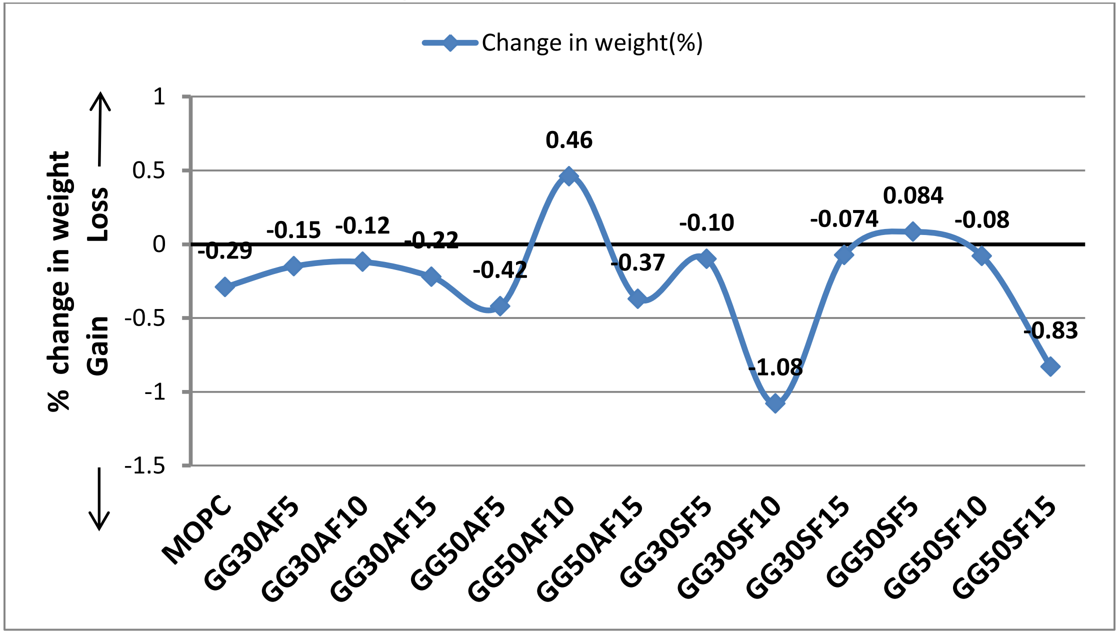


Fig:4.29:Comparision of % change in weight of different mixes after 4% $MgSO_4$ Exposure.

A relationship between change in weight and corresponding residual compressive strength of different mixes after $MgSO_4$ exposure as depicted in fig 4.30 . There was a decreasing trend in residual compressive strength values for alccofine GGBS mix series having considerable increase in weight gain values ranging from 0.12% to 0.22%. Here also further inclusion of GGBS a reverse trend in residual compressive strength values were observed from the fig 4.30 and maximum value of 185.29% attained for mix GG50AF10 even at weight loss of 0.46%. In case of ternary mix series incorporating GGBS and silica fume a drastic fluctuation in residual strength value from 206.1% to 96.72% was observed for mix GG30SF5 with considerable weight gain (1.08%) followed by a slight increase in residual strength value 116.77% for mix GG30SF15 accompanied by nominal weight gain of 0.074%.Results also confirmed that increase in GGGBS percentage reduces residual compressive strength values as weight gain increases and a minimum strength of 84.29% observed for mix GG50SF15

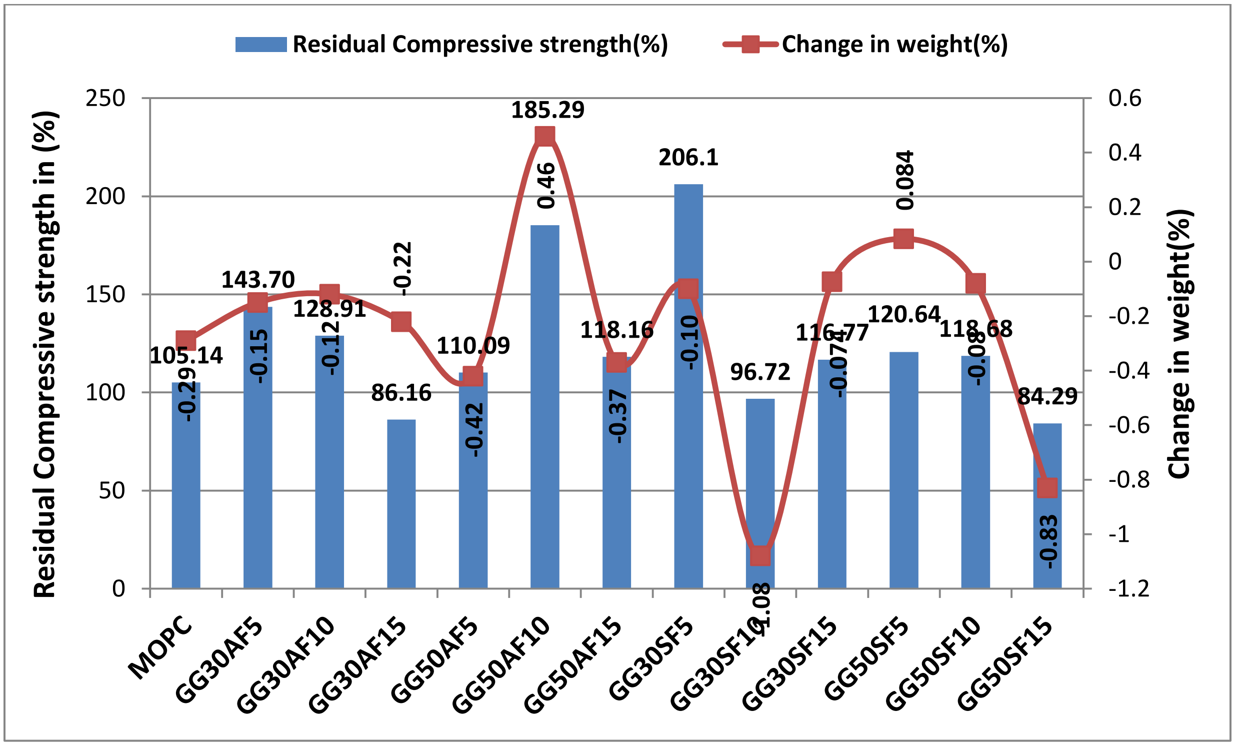


Fig:4.30: Relationship between % weight change and residual compressive strength values of different mixes after 4% $MgSO_4$ exposure.

having weight gain of 0.83% . The reason may be the extent of $Mg(OH)_2$ or Brucite formed as a result of predominant decalcification of C-S-H gel rather than $Ca(OH)_2$ reacting with $MgSO_4$. The overall performance of mixes incorporating silica fume and GGBS getting better which in turn shows greater resistance against sulphate attack.

4.3.5.3 Strength deterioration factor for H_2SO_4 exposure:

This is an indicative measure of damage in terms of compressive strength loss in concrete during acid exposure. **Table:20** shows strength deterioration factor of different mixes after 56 days of acid exposure.

Table 20: Strength deterioration factors of different mixes after H_2SO_4 exposure for 56 days.

Sl.no	Mix type	Compressive strength after 28days(MPa)	Compressive strength after aci exposure (MPa)	Strength Deterioration Factor(%)
1	MOPC	46.67	21.07	54.85
2	GG30AF5	33.87	14.93	55.92
3	GG30AF10	44.27	17.87	59.63
4	GG30AF15	42.4	14.13	66.67
5	GG50AF5	34.40	9.33	72.88
6	GG50AF10	30.8	14.67	52.37
7	GG50AF15	38.93	24.93	35.96
8	GG30SF5	23.29	11.07	52.47
9	GG30SF10	48.8	16.8	65.57
10	GG30SF15	42.93	17.07	60.24
11	GG50SF5	38.13	16.67	56.28
12	GG50SF10	42.13	20.00	52.53
13	GG50SF15	44.93	20.00	55.49

Observation made so far (Refer fig:4.31 indicates that GG50AF5 suffered significantly with an SDF value of 72.88% .In contrast mix GG50AF15 offered greater resistance to sulphuric acid exposure having a minimum SDF value of 35.96% . In ternary mixes incorporating GGBS and alccofine the presence of GGBS influences the resistivity significantly .Results confirmed that with lower percentage replacement level of GGBS(30%) accompanied by incremental percentages levels of alccofine there is an increasing trend in SDF values ranging from 55.92% to 66.67%. but with increase percentage level both in GGBS(50%) and alccofine offered better resistance against acid attack as indicated in the fig (mix GG50AF10 and GG50AF15) except for mix GG50AF5. Similar trend observed for mixes incorporating GGBS and silica fume also as GGBS facilitated the $Ca(OH)_2$ or portlandite availability by lowering the pozzolnic activity . Significant deterioration takes place for mix GG30SF10 having value 65.57% whereas mix GG30SF5 offered better resistance with minimum SDF value of

52.47%. The overall performance of silica fume blended ternary mixes is better rather than alccofine blended mixes.

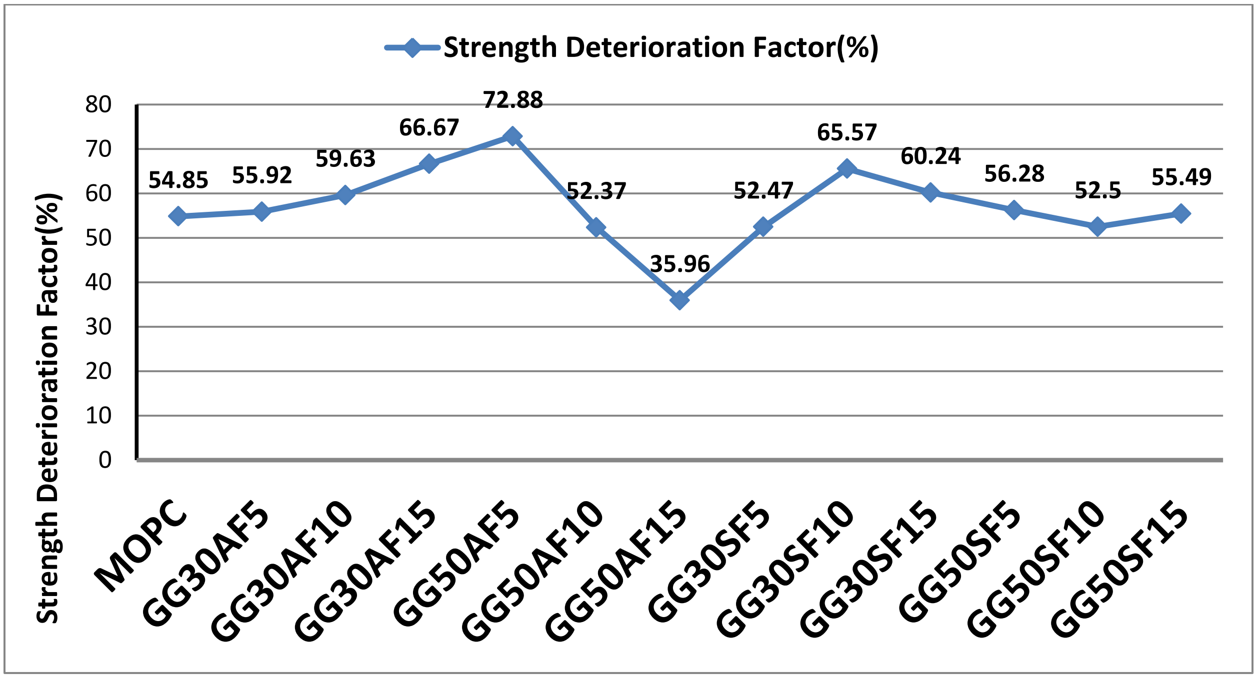


Fig:4.31:Strength Deterioration Factor(%) for different mixes after H_2SO_4 exposure for 56 days.

.There is clear evidence that the increase in SCM,s in mixes triggering steep depletion in $Ca(OH)_2$ or portlandite level which exacerbate the gypsum formation predominantly by decalcification of C-S-H gel .Control mix shows better performance compare to SCM's mixes after 56 days of acid exposure .This may be due to lower depletion level of $Ca(OH)_2$ or porlandite contributing primerily to the formation of gypsum rather than C-S-H gel .

4.3.5.4 Strength deterioration factor for $MgSO_4$ exposure:

Table 21 represents strength deterioration factor of different mixes after 56 days of $MgSO_4$ exposure.

Table 21: Strength deterioration factors of different mixes after $MgSO_4$ exposure for 56 days.

Sl.no	Mix type	Compressive strength after 28days(MPa)	Compressive strength after $MgSO_4$ exposure (MPa)	Strength Deterioration Factor(%)
1	MOPC	46.67	49.07	-5.14
2	GG30AF5	33.87	48.67	-43.70
3	GG30AF10	44.27	57.07	-28.91
4	GG30AF15	42.4	36.53	13.84
5	GG50AF5	34.40	37.87	-10.09
6	GG50AF10	30.8	57.07	-85.29
7	GG50AF15	38.93	46	-18.16
8	GG30SF5	23.29	48	-106.10
9	GG30SF10	48.8	47.2	3.28
10	GG30SF15	42.93	50.13	-16.77
11	GG50SF5	38.13	46	-20.64
12	GG50SF10	42.13	50.00	-18.68
13	GG50SF15	44.93	37.87	15.71

Table 21 indicates the strength gain occurred almost all the mixes except for mix GG30AF15,GG30SF10 and GG50SF15 having SDF values 13.84% , 3.28% and 15.71% respectively. The graphical representation of the SDF values of different mixes as shown in

fig: 4.32. Massive strength gain observed for mix GG30SF5(106.1%) followed by mix GG50AF10(85.29%). For other mixes incorporating GGBS(30%) and alccofine the lower percentage replacement of alccofine inevitably produced better result (43.69%) for mix GG30AF5 but with increase in alccofine content consequent increase in SDF values as observed from fig:4.32 . Finally an SDF value of 13.84% obtained with 15 % replacement of alccofine . A reverse trend observed with increase in GGBS (50%) percentage which implies that GGBS reduced the pozzolanic activity causing ample $Ca(OH)_2$ or portlandite available in the solution and consequently increase in the extent of $Mg(OH)_2$ or Brucite formed as a result of $Ca(OH)_2$ reacting with $MgSO_4$, is relatively insoluble product clogs the pores and prohibits the further intrusion of deleterious materials ,thus protects the C-S-H gel from $MgSO_4$ attack.

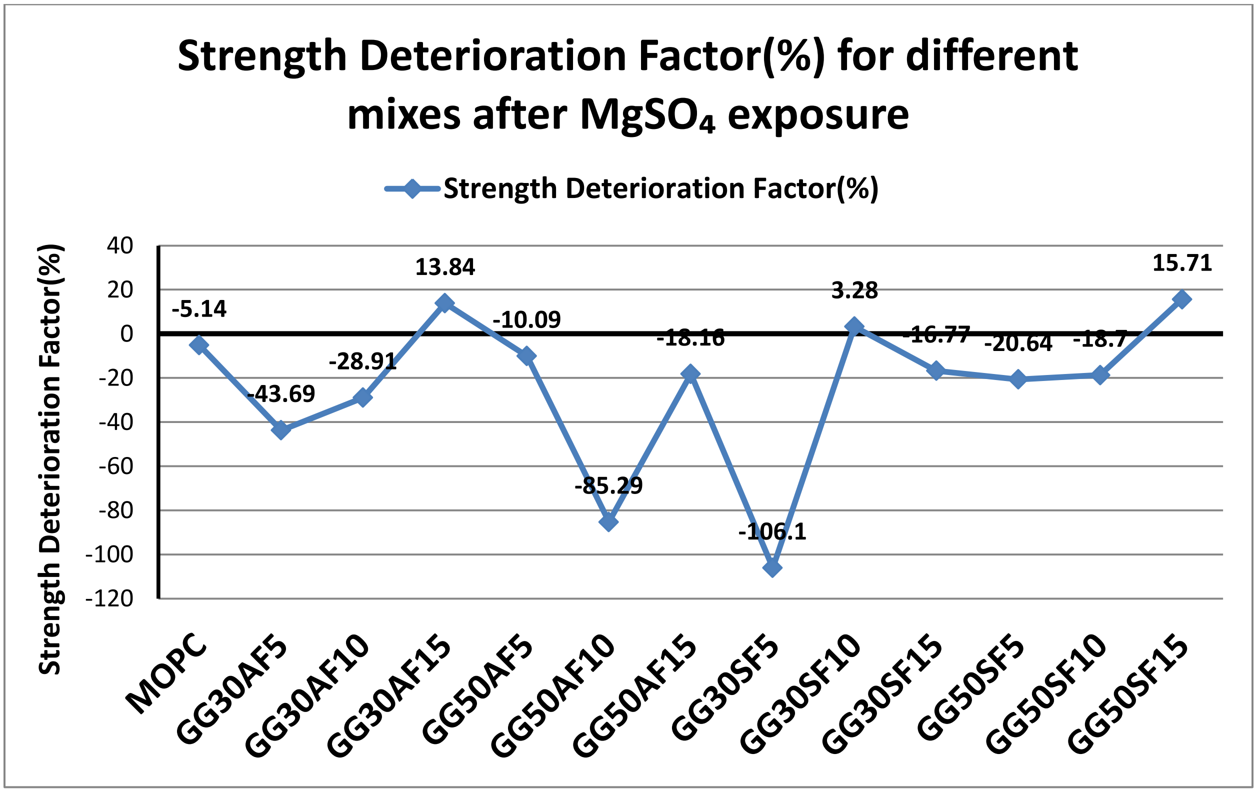


Fig:4.32 Strength Deterioration Factor(%) for different mixes after $MgSO_4$ exposure for 56 days.

leading to increase in strength .Mix GG50AF10 achieved an increase in strength of 85.29% whereas further increase in alccofine causes reduction in strength up to 18.16% for mix GG50AF15 .Results of mixes incorporating GGBS and silica fume indicate predominant formation of ettringite and gypsum except for mix GG30SF5 .As a consequence of high pozzolanic activity of silica fume decrease in $Ca(OH)_2$ takes place in the solution and whenever exposed to $MgSO_4$ it tend to attack the C-S-H gel rather than to react with $Ca(OH)_2$ to form $Mg(OH)_2$ or brucite and consequent disintegration of the C-S-H gel occurred.

4.3.6 Thermal durability properties:

4.3.6.1 Weight loss due to thermal exposure:

Concrete structures more often exposed during fire hazard or in reactors . Considerable change in their physical as well as chemical composition occurs at different exposure levels. This may results in undesirable change in mechanical properties owing to structural failure in concrete structures. Use of different SCM's in concrete provide substantial fire resistance whenever exposed to elevated temperature.

Table 22*: Weight loss and compressive strength of different mixes after thermal exposure.*

Sl.no	**Mix type**	**Weight loss(%)**	**Compressive strength after 28days(MPa)**	**Compressive strength after thermal exposure (Mpa)**	**Strength retained in (%)**
1	MOPC	8.24	46.67	8.27	17.72
2	GG30AF5	9.99	33.87	14.67	43.31
3	GG30AF10	10.28	44.27	14.13	31.92
4	GG30AF15	8.31	42.4	18.67	44.03
5	GG50AF5	9.79	34.40	9.99	29.04
6	GG50AF10	8.8	30.8	14.13	45.88
7	GG50AF15	8.22	38.93	12.85	33.01
8	GG30SF5	8.76	23.29	13.87	59.55
9	GG30SF10	8.45	48.8	12.53	25.68
10	GG30SF15	9.42	42.93	10.93	25.46
11	GG50SF5	9.27	38.13	10.67	27.98
12	GG50SF10	8.81	42.13	11.47	27.23
13	GG50SF15	9.64	44.93	11.2	24.93

Present study evaluates the effect of SCM’s on concrete exposed to elevated temperature and compare with the control mix. Samples undergo weight loss as well as loss in compressive strength simultaneously whenever exposed to elevated temperature upto 800°C .The weight loss and compressive strength retained of different mixes after thermal exposure as shown in table 15. Experimental results revealed that mix GG30AF10 shows greater loss in weight (10.28%) followed by mixes GG30AF5(9.99%) and GG50AF5(9.79%) respectively(Refer fig:4.33). The presence of alccofine in the mixes enhances the weight loss ranges from 8.22% to 10.28% .It was also observed that mixes incorporating silica fume have lesser tendency of weight loss and reaches a maximum value (9.64%) for mix GG50SF15 whereas for mixes GG30SF5 to GG50SF10 the value ranges from 8.45% to 9.42%. This may be attributed to the fact that the weight loss of blended specimen decreases due to internal expansion of the Silica Fume in the sample specimen at high temperature. Furthermore in alccofine GGBS mix series lower content of GGBS causes significant weight loss whereas increase in GGBS doesn’t yield weight loss substantially. Conversely mix series blended with GGBS and silica fume a reverse trend in weight loss values observed. Moreover , control mix performs better than the mixes containing SCM’s in terms of weight loss.

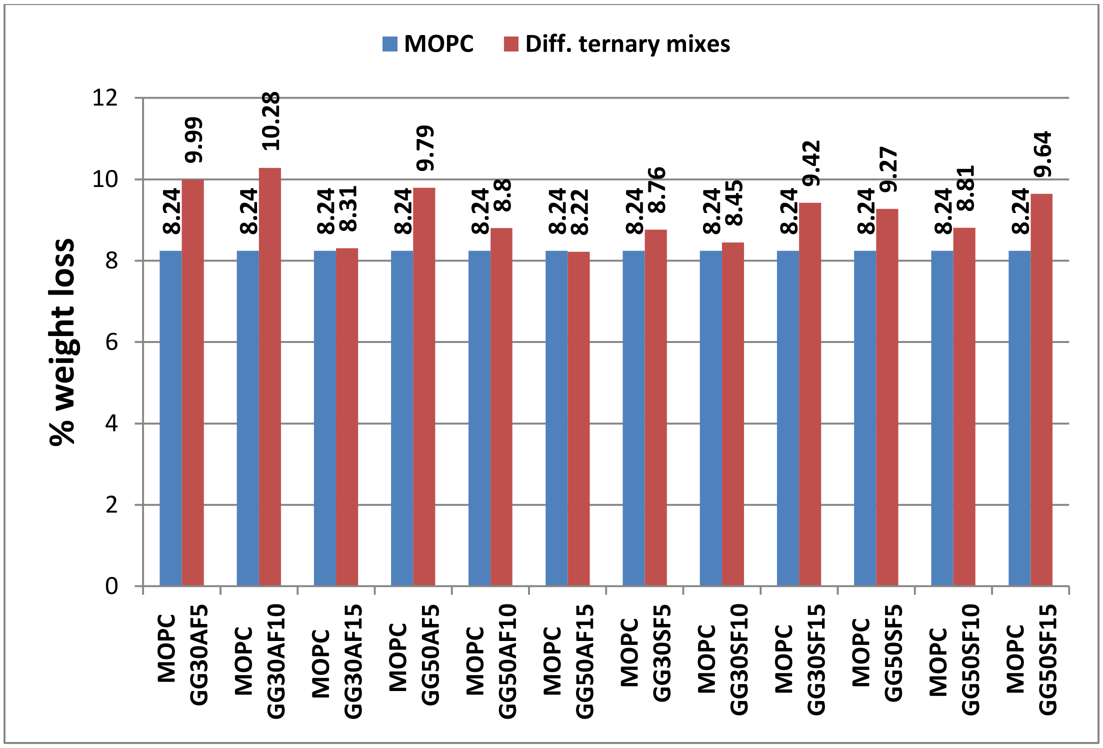


Fig 4.33: Comparison of weight loss of control mix and different ternary mixes after thermal exposure.

4.3.6.2 Compressive strength retained after thermal exposure:

Table 21 revealed that the residual compressive strength of samples consisting of SCM's after thermal exposure have better performance than control mix .Comparing to other mixes mix GG30SF5 retained better strength (59.55%) after thermal exposure although overall percentage retained in compressive strength for mixes comprising of GGBS and Alccofine remains better compare to GGBS ,silica fume combination as depicted in fig:4.34 have almost same peak values ranging from 24.93% to 27.98% except for mix GG30SF5 (59.55%).In GGBS alccofine mix series higher peak values observed for mix GG30AF5(43.31%),GG30AF10(44.03%) and GG50AF10(45.88) respectively. In this context it may be noted that mixes containing GGBS and silica fume have no such significant peak values obtained except for mix GG30SF5(59.65%).Owing to their high reactivity properties/pozzolanic activity accompanied by formation of high quantity of C-S-H gel which in turn compensate the decomposition of C-S-H gel at higher temperature the SCM's have the better resistance against thermal exposure in terms of compressive strength retained as pointed out in literature review section.

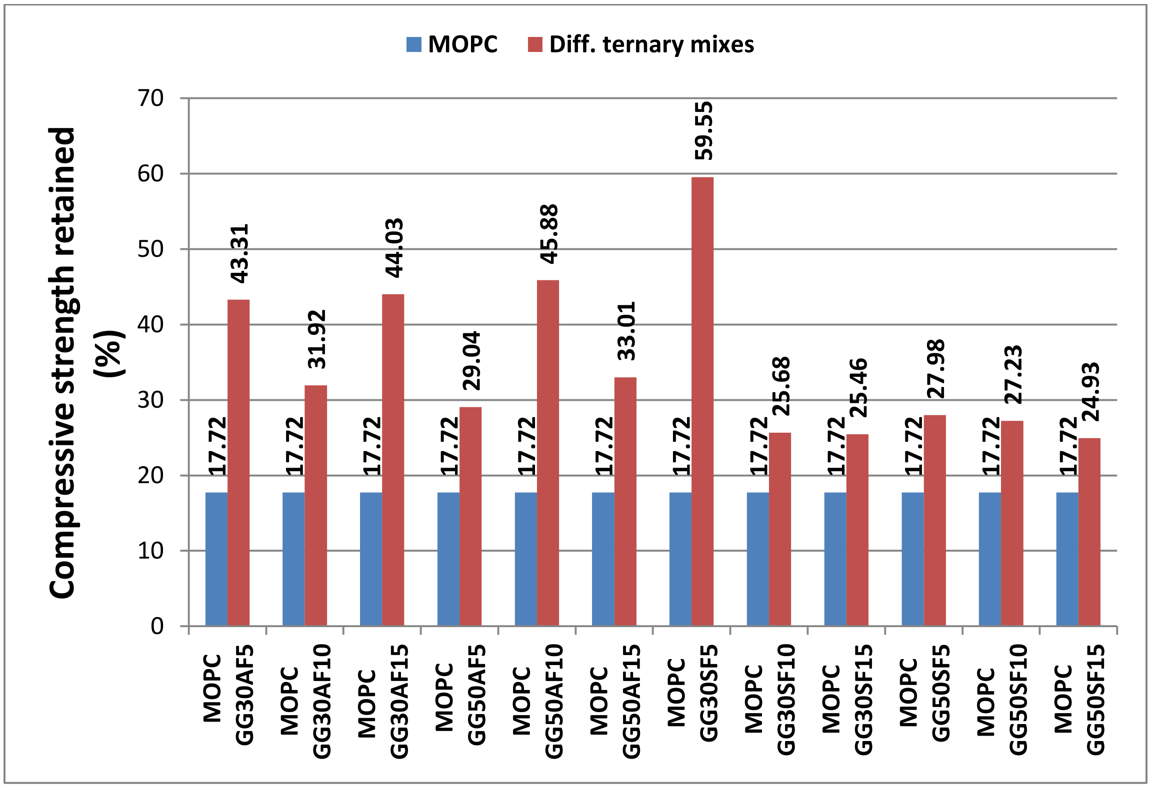


Fig 4.34: Comparison of compressive strength retained values of control mix and different ternary mixes after thermal exposure.

Relationship between %weight loss and compressive strength retained for different mixes as shown in Fig 4.35. For the same range of % weight loss mix GG30SF5 retained better strength followed by GG50AF10 whereas mix GG50SF10 shows lower retention of strength. Mix GG30AF5 surprisingly performed better at 9.99% weight loss . Overall performance of GGBS alccofine mix series is remarkably better compare to GGBS silica fume mix series even at higher percentage weight loss. Whereas for control mix even at relatively lower percentage of weight loss (8.24%) performed worst among all the mixes in terms of compressive strength retained.

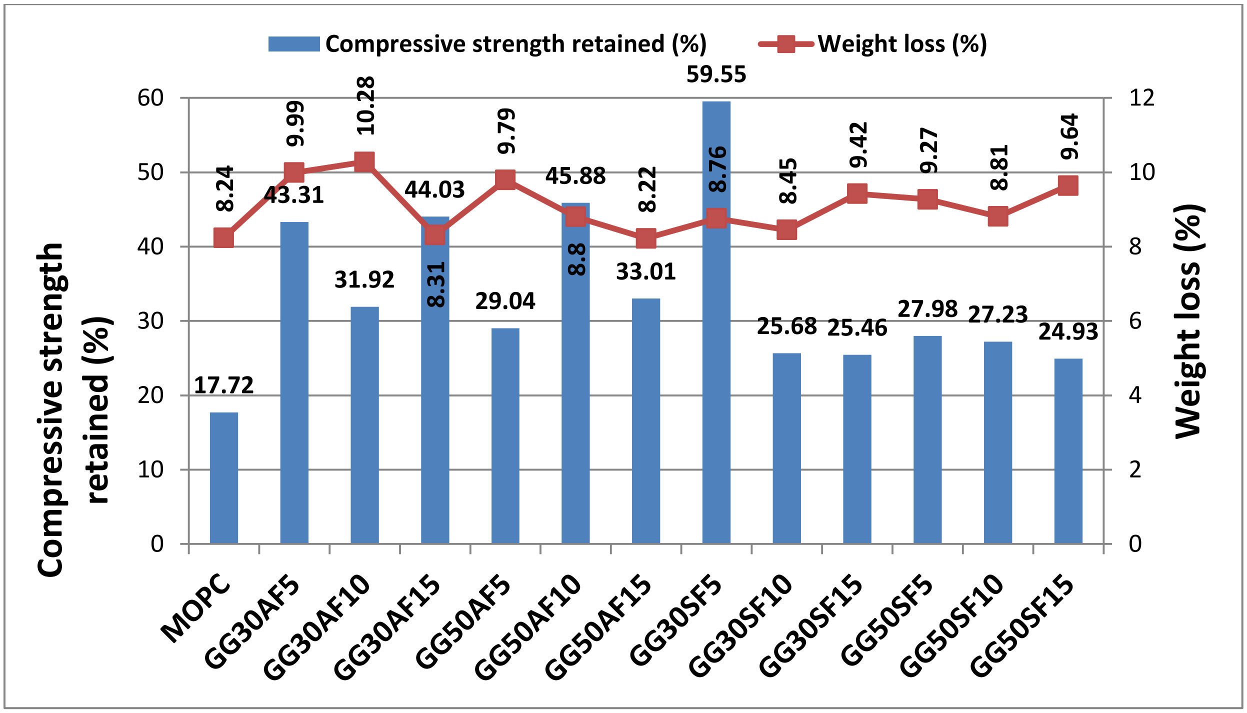
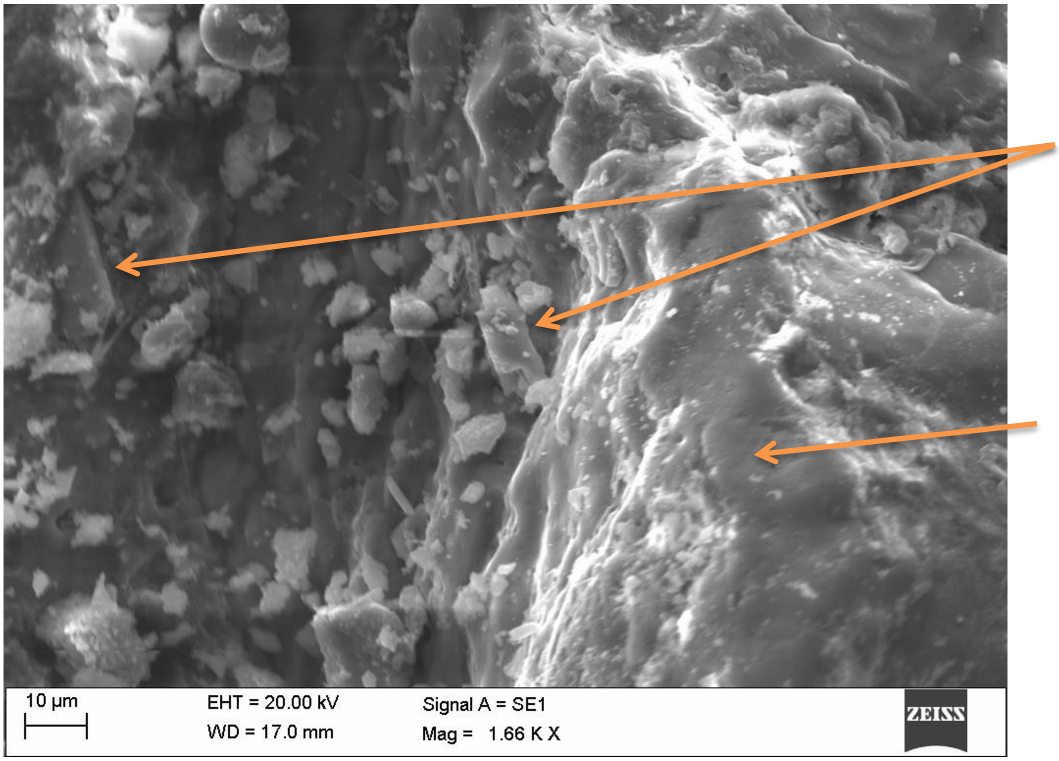


Fig 4.35 :Relationship between % weight loss and % compressive strength retained of different mixes after thermal exposure.

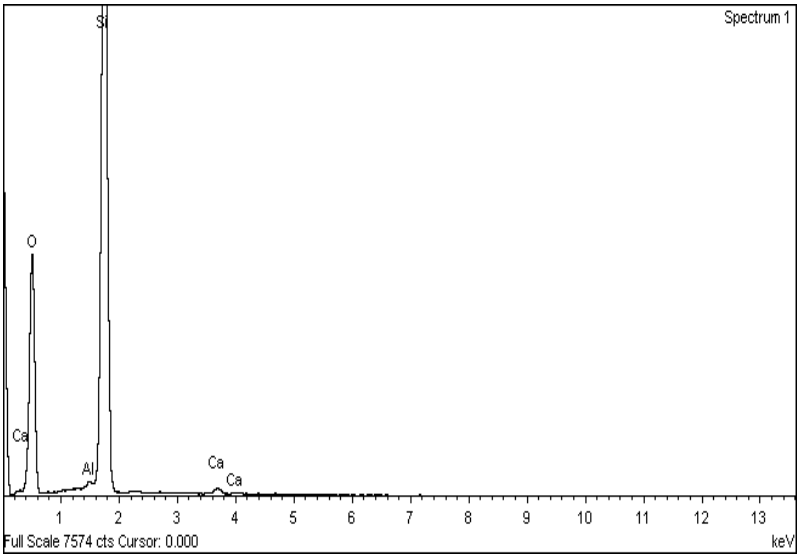
4.4 Microstructural study:

Microstructure studies using SEM and EDX were performed to investigate the change in hydration state at different ages as well as for better understanding of the surface morphology of different samples at normal and different exposure conditions.



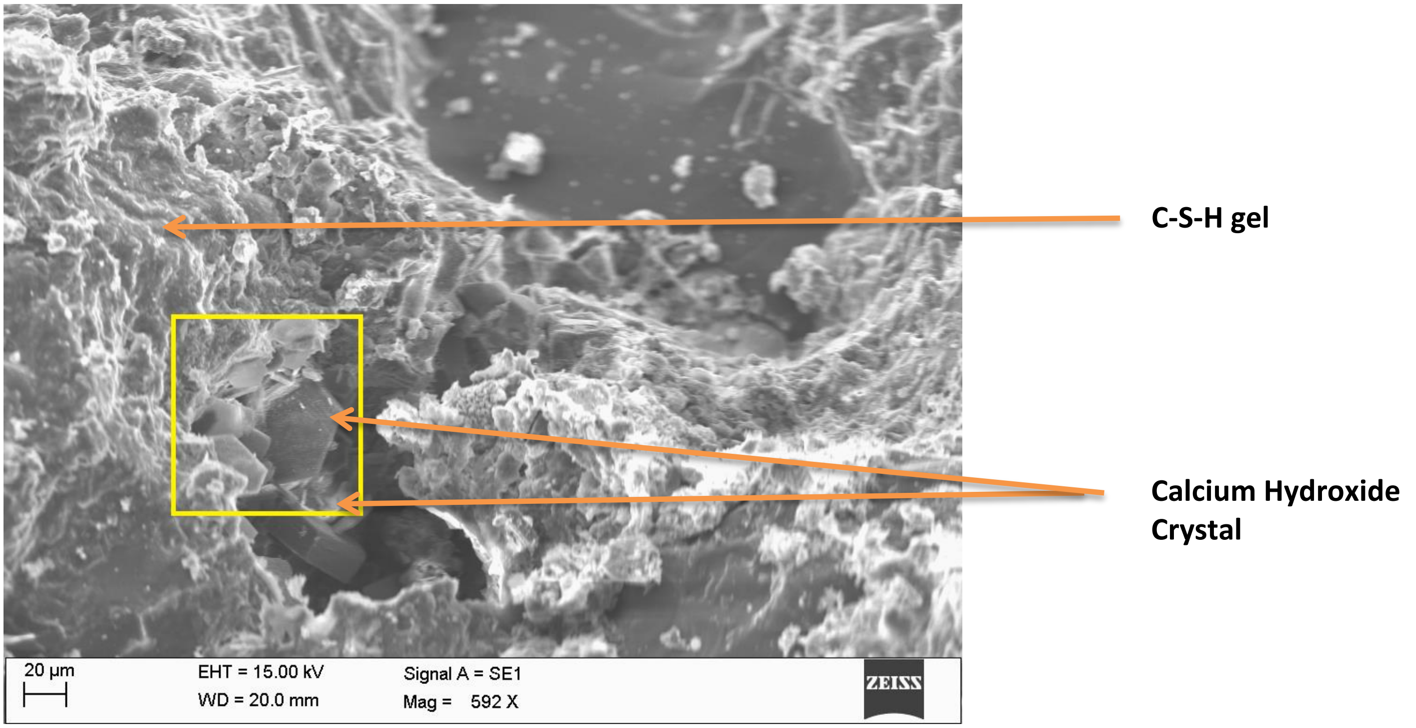
Plates of Calcium Hydroxide

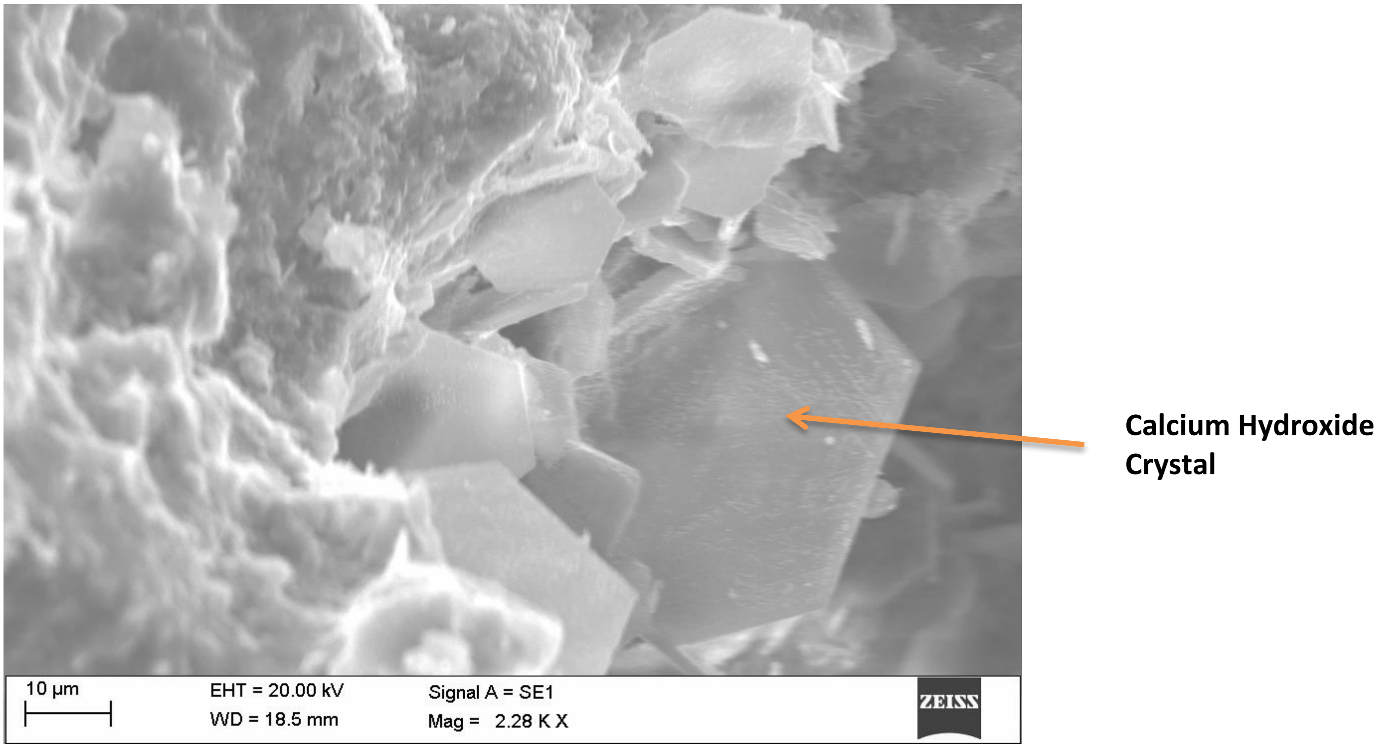
C-S-H gel

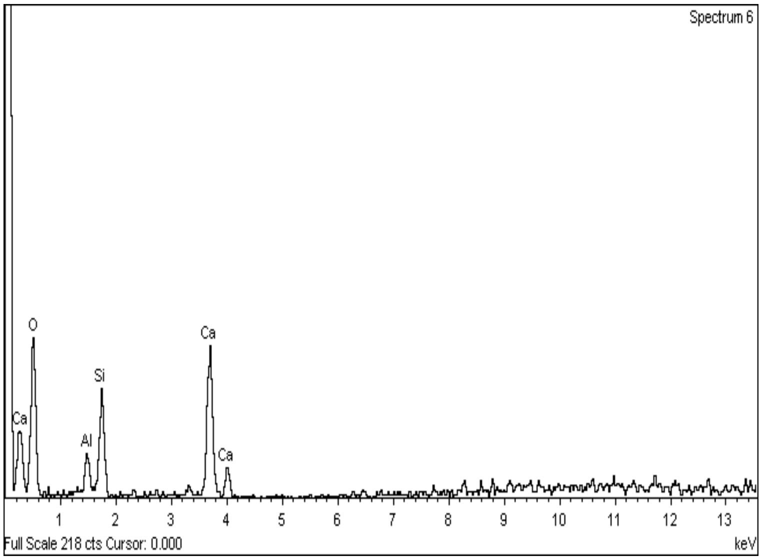


Element	Weight%	Atomic%
O K	56.81	69.86
Al K	0.31	0.23
Si K	42.26	29.61
Ca K	0.62	0.30
Totals	100.00	

Fig 4.36 :SEM image and EDX profile along with elemental composition of control mix after 28 days water curing.


C-S-H gel
Calcium Hydroxide Crystal
20 µm
EHT = 15.00 kV
WD = 20.0 mm
Signal A = SE1
Mag = 592 X
ZEISS

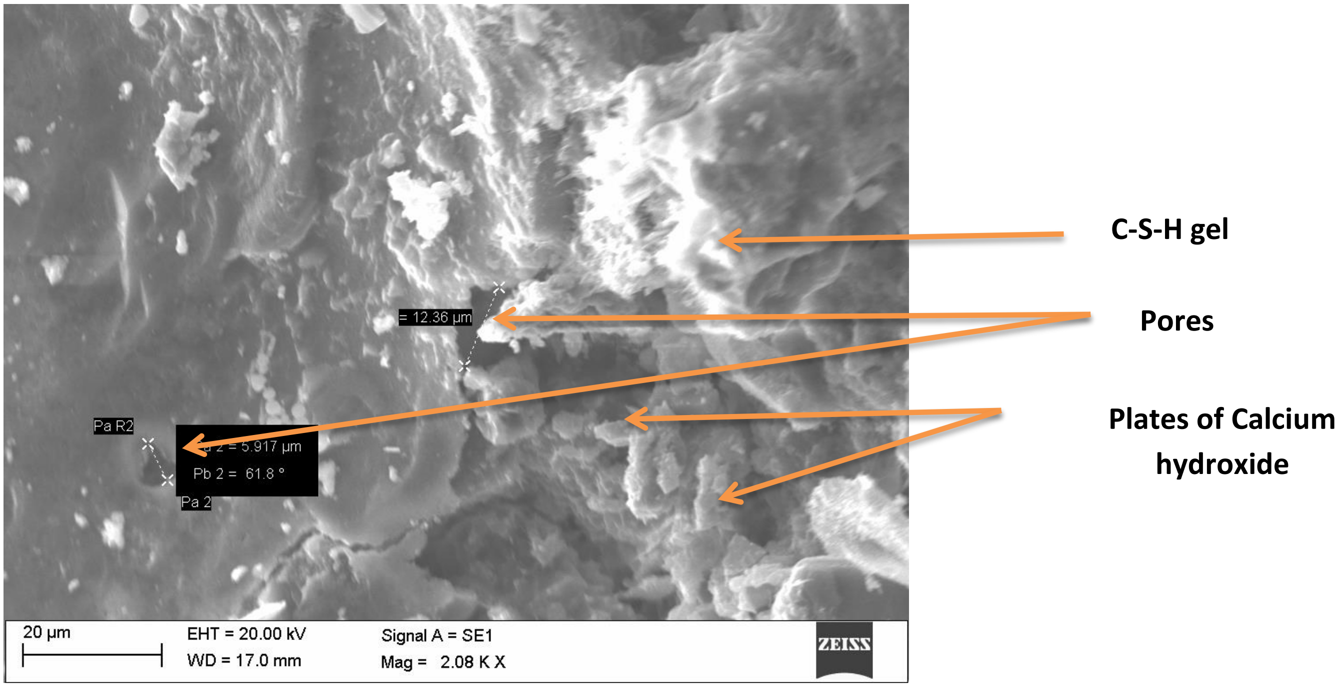

Calcium Hydroxide Crystal
10 µm
EHT = 20.00 kV
WD = 18.5 mm
Signal A = SE1
Mag = 2.28 K X
ZEISS

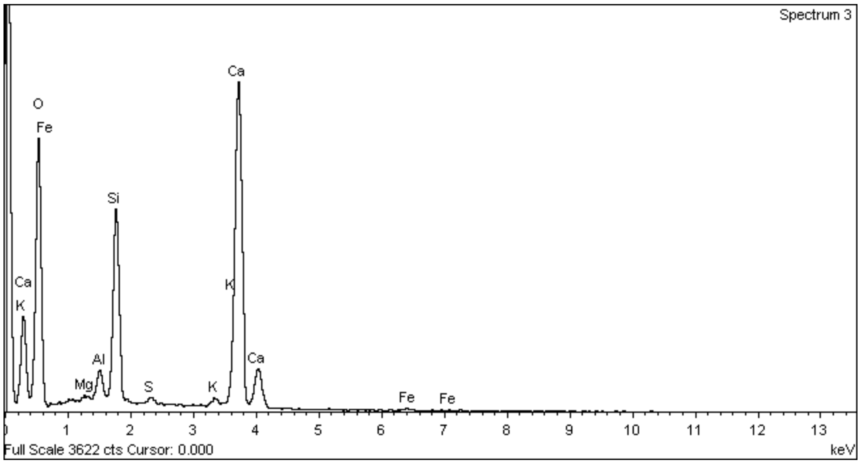


Element	Weight%	Atomic%
O K	64.80	79.92
Al K	3.64	2.66
Si K	8.98	6.31
Ca K	22.57	11.11
Totals	100.00	

Fig 4.37 :SEM image and corresponding EDX profile along with elemental composition of GG30AF10 mix after 28 days water curing.

The surface morphology as well as EDX spectrum of different mixes after 28 days of water curing has been shown in figs:4.36-4.38.SEM image of control mix revealed the traces of ample quantity of CH or portlandite along with formation of C-S-H gel (Refer fig:4.36) which indicates the maximum hydration occurred after 28 days in control mix. For mix GG30AF10 SEM image confirmed the traces of few portlandite or CH .In addition to the formation of C-S-H gel the presence of unreacted GGBS along with alccofine grains surrounded by C-S-H gel also observed as shown in Fig:4.37.This may be due to the fact that the hydration degree of GGBS is very low of even after 28 days. Similar observations have also been reported by Banti A.Gedam et.al(2015)[32]. EDX profile showing high peaks of Ca,Si indicates sufficient formation of C-S-H gel with limited occurrence of portlandite. As seen from the SEM image GG30SF10 mix (Refer fig:4.38) produced more denser microstructure and formation of compacted hydration products. Limited occurrence of portlandite also found which implies the onset of pozzolanic activity of silica fume even after 28 days. With increase in curing period mixes containing different SCM's shows better result. Similar observations have also been reported by Ahmet Benli et.al(2017)[20]. EDX profile indicated the ample formation of C-S-H gel accompanied by higher peaks of Ca and Si. The Ca/Si ratio decreased from 2.51 to 2.49 for mix GG30AF10 and GG30SF10.This calcium deficiency clearly associated with the consumption by reaction with SCM's to form more C-S-H gel.





Element	Weight%	Atomic%
O K	65.78	80.90
Mg K	0.32	0.26
Al K	1.39	1.01
Si K	8.96	6.28
S K	0.33	0.20
K K	0.49	0.25
Ca K	22.34	10.97
Fe K	0.40	0.14
Totals	100.00	

Fig 4.38 :SEM image and corresponding EDX profile along with elemental composition of GG30SF10 mix after 28 days water curing.

In SCM's blended mixes calcium content decreased considerably, while silicon and aluminium contents increased causing significant change in ratios of Ca/Si and Al/Ca respectively. Observations made by J.I. Escalante et.al (2004)[31] revealed similar outcomes.

Samples subjected to 4% H_2SO_4 solution after 56 days underwent microstructural investigation found occurrence of C-S-H gel dissolution. SEM image of GG50AF15 (fig:4.39) confirmed scare dissolution of C-S-H gel accompanied by formation of gypsum. This may be the possible cause of weight gain due to formation of expansive materials as observed earlier in the experimental results section.

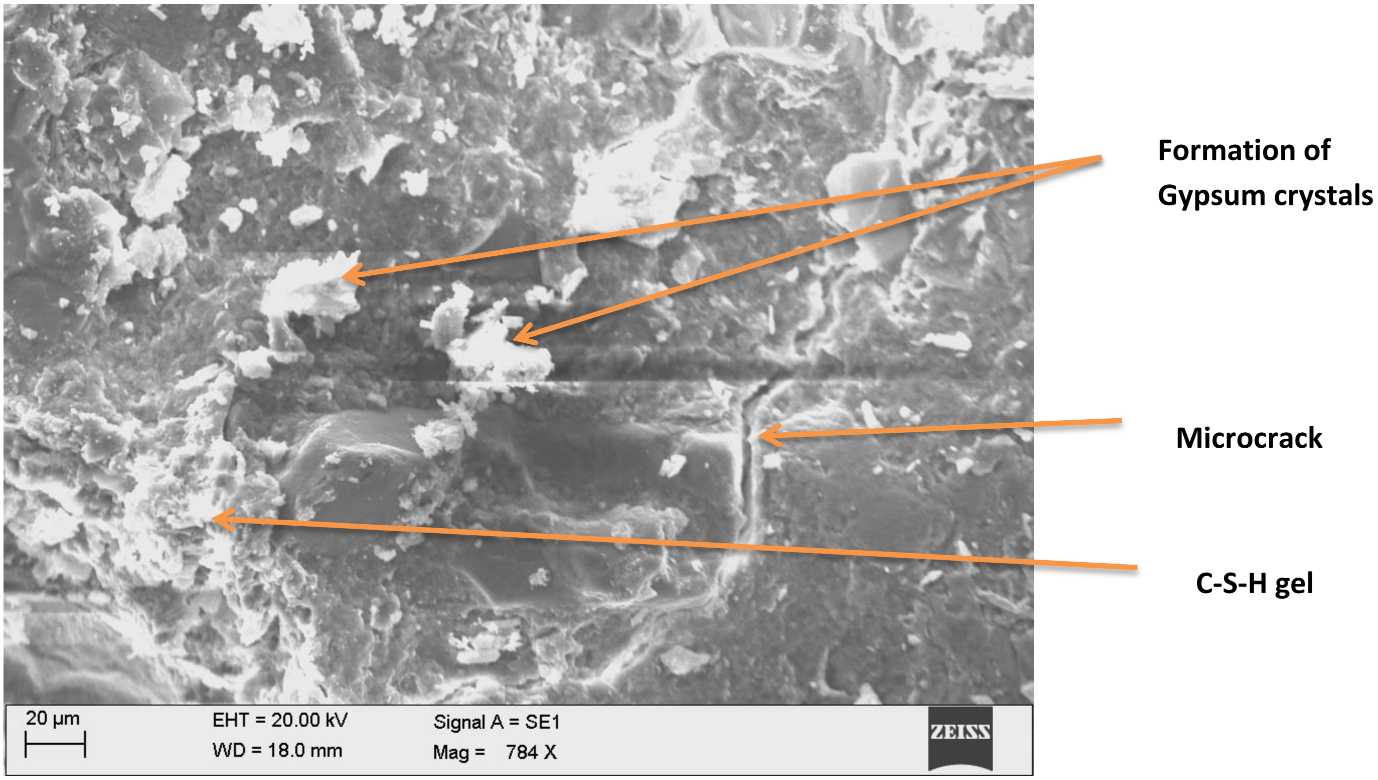
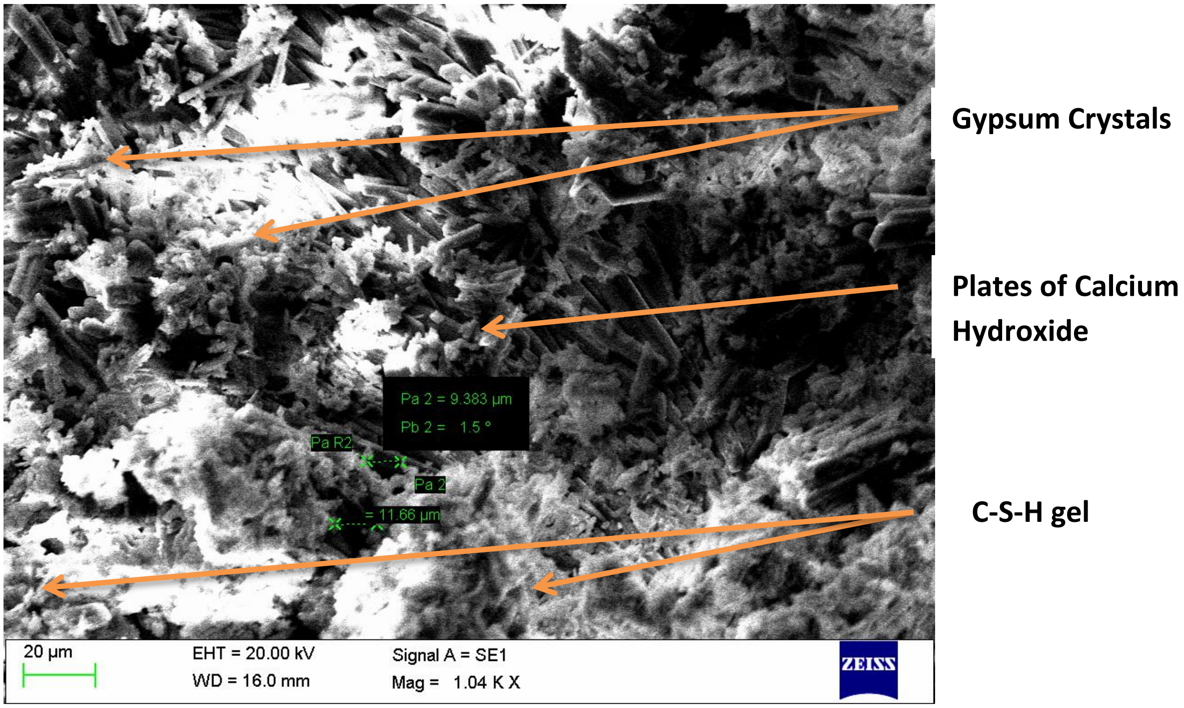
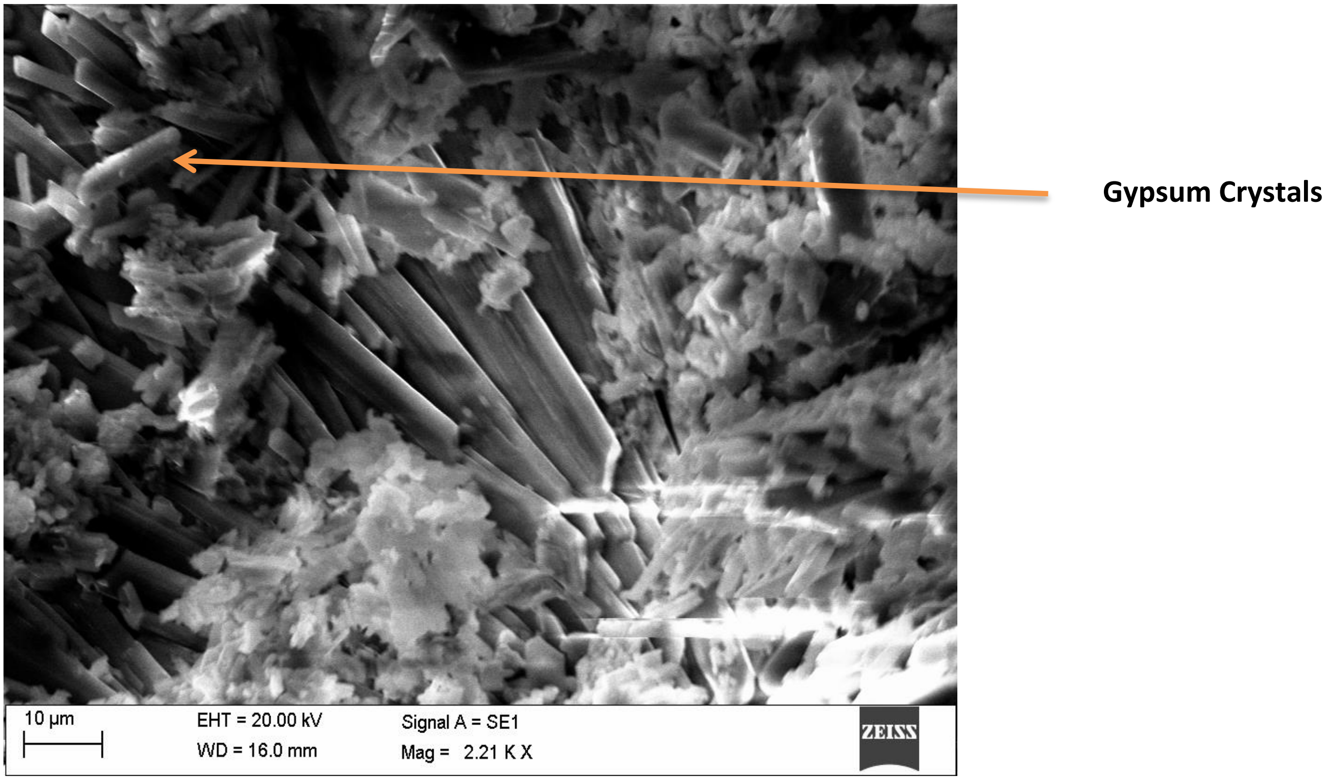
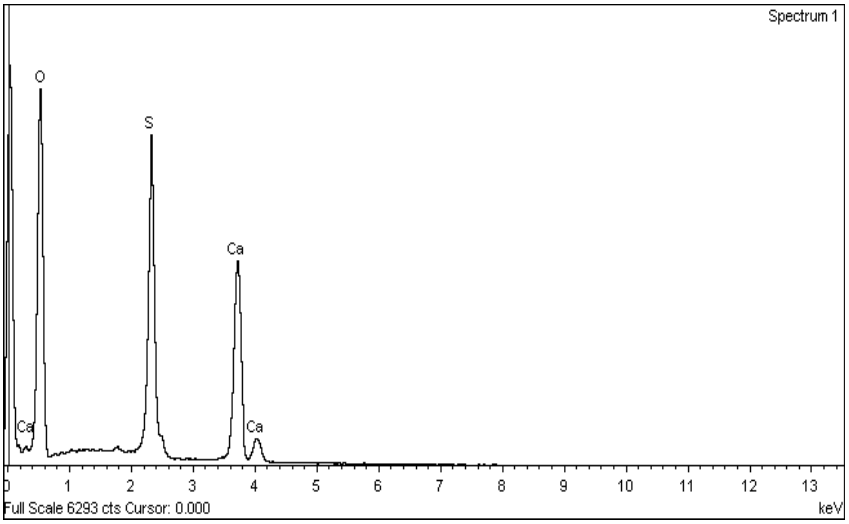


Fig 4.39 :SEM image of GG50AF15 mix after 56 days of H_2SO_4 exposure.

There was rarely observed portlandite or CH content in the SEM image which may be clearly suggested the formation of gypsum primarily by consuming more CH rather than decalcification of C-S-H gel. In contrary SEM image of GG30SF5 mix (fig:4.40) exhibited the clear disintegration of C-S-H matrix and greater formation of gypsum crystals over the surface of the sample exposed to acid .Traces of ample plate shaped $Ca(OH)_2$ crystals


Gypsum Crystals
Plates of Calcium Hydroxide
C-S-H gel
Pa 2 = 9.383 µm
Pb 2 = 1.5 °
Pa R2
Pa 2
= 11.66 µm
20 µm
EHT = 20.00 kV
WD = 16.0 mm
Signal A = SE1
Mag = 1.04 K X
ZEISS

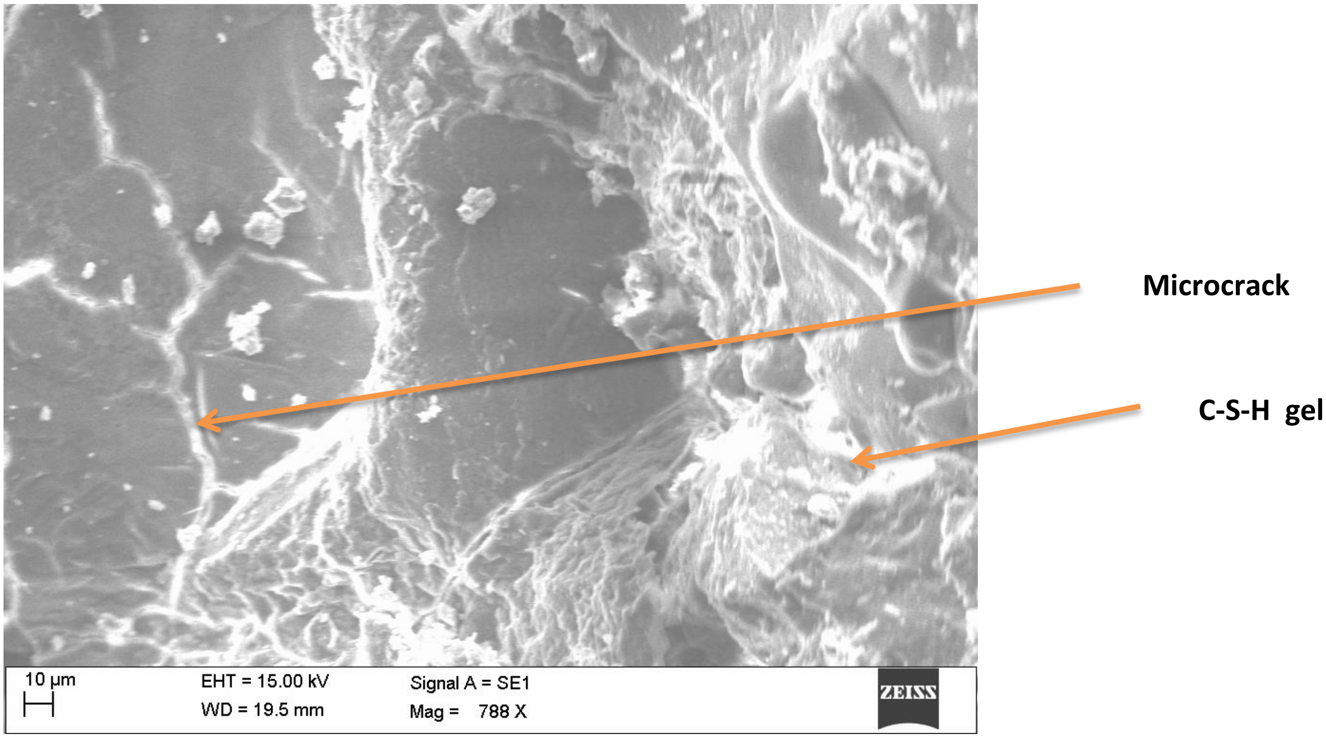

Gypsum Crystals
10 µm
EHT = 20.00 kV
WD = 16.0 mm
Signal A = SE1
Mag = 2.21 K X
ZEISS

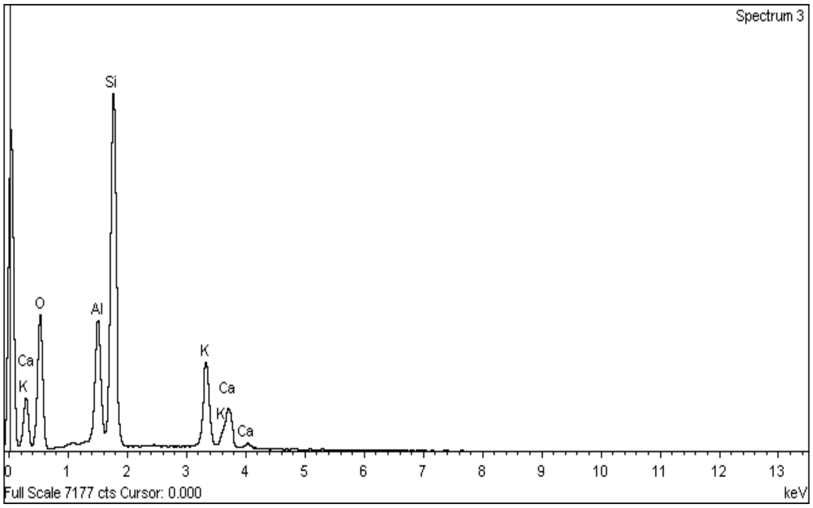


Element	Weight%	Atomic%
O K	63.14	79.30
S K	17.70	11.09
Ca K	19.16	9.60
Totals	100.00	

Fig 4.40 :SEM image and corresponding EDX profile along with elemental composition of GG30SF5 (surface) mix after 56 days of H_2SO_4 exposure.

and needle shaped etrringite were also found. This may be due to the fact that existence of portlandite indicates that decalcification of C-S-H primarily attributed to the formation of gypsum not from consumption of portlandite or CH which has detrimental consequences for concrete . EDX spectrum indicated the notable peaks of calcium and sulphur suggesting possible formation of gypsum due to acid exposure. The atomic ratio of Ca/S

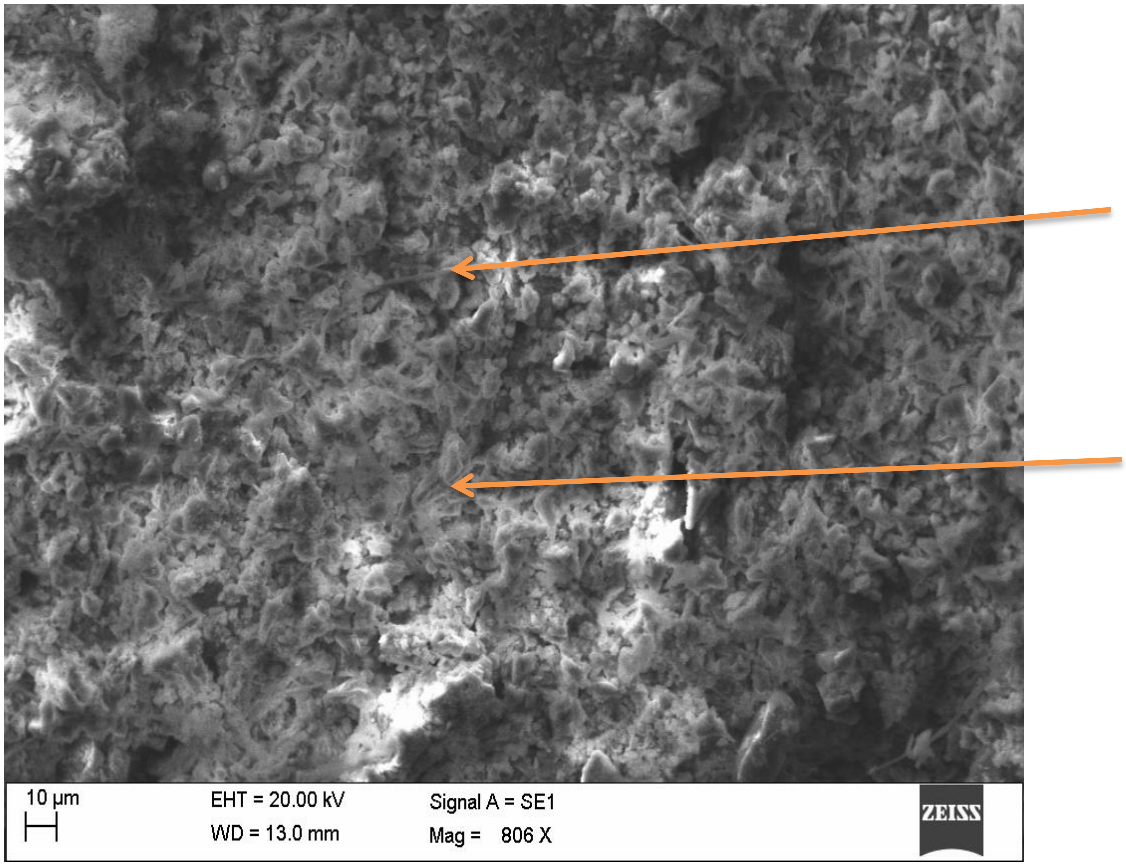




Element	Weight%	Atomic%
O K	42.10	58.42
Al K	8.64	7.11
Si K	29.59	23.39
K K	12.99	7.38
Ca K	6.67	3.70
Totals	100.00	

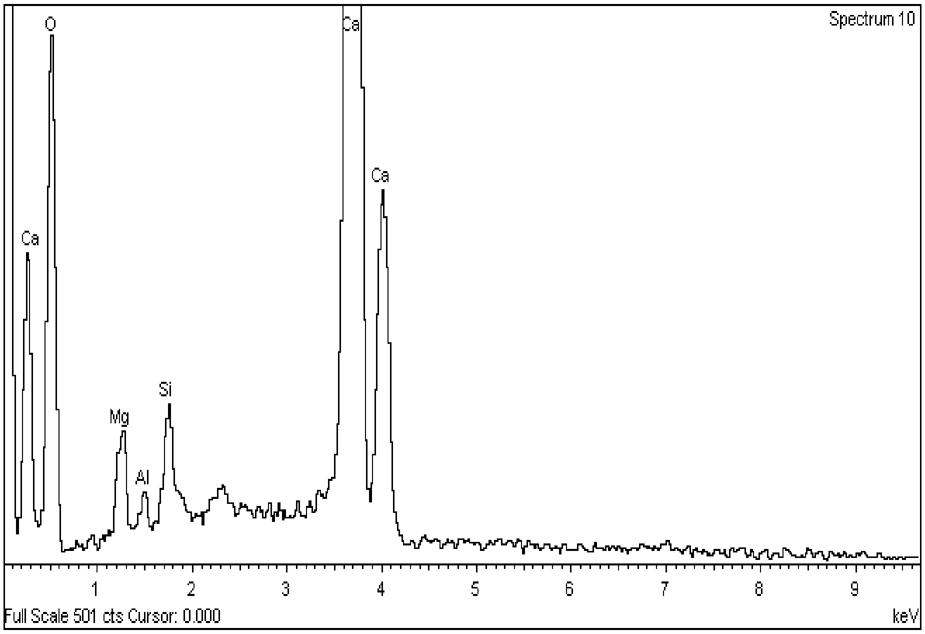
Fig 4.41 :SEM image and EDX profile along with elemental composition of GG30SF5 (core) mix after 56 days of H_2SO_4 exposure.

This may be the reason the sample underwent weight loss as well as low residual compressive strength value as reported in the experimental results section. SEM image taken at inner part of GG30SF5 sample revealed sound matrix .Unless some unreacted silica fume grains and micro crack there was rarely any traces of disintegration of C-S-H gel. EDX spectrum showed high peaks of Si ,Al and to some content of Ca except S peak which clearly justify the absence of acid intrusion at the inner part of the sample.



Needle shaped ettringite

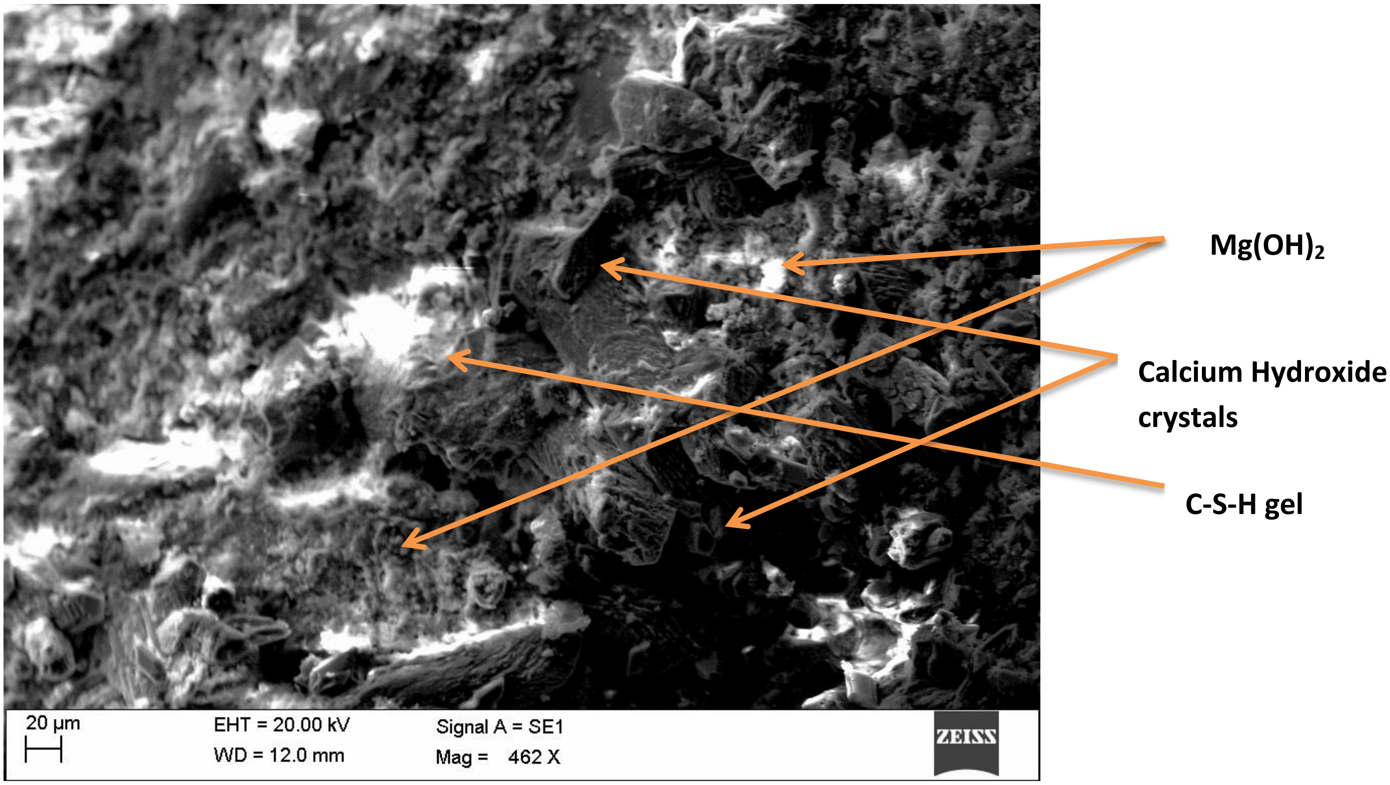
C-S-H gel

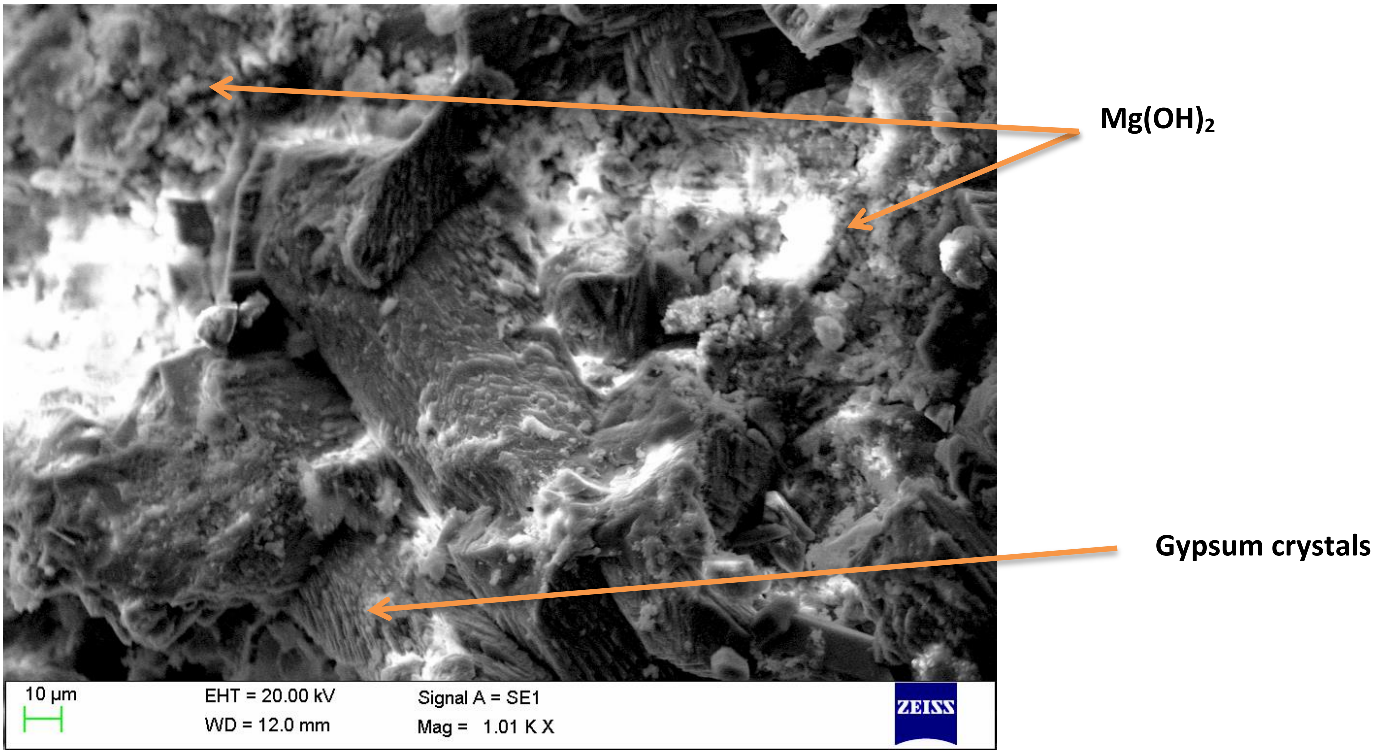


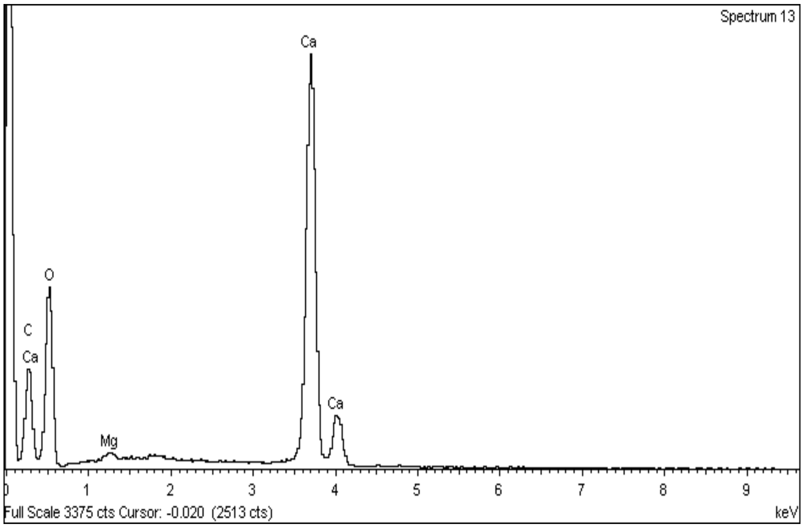
Element	Weight%	Atomic%
O K	52.57	72.83
Mg K	1.59	1.45
Al K	0.47	0.39
Si K	1.05	0.83
Ca K	44.32	24.51
Totals	100.00	

Fig 4.42 :SEM image and EDX profile along with elemental composition of GG50AF10 mix after 56 days of $MgSO_4$ exposure.

SEM image of mix GG50AF10 revealed the dissociation of C-S-H gel over the entire surface when exposed to $MgSO_4$ solution for 56 days .In addition to the disintegration of C-S-H gel rare formation of ettringite (expansive product) was also observed causing weight loss of the sample as reported earlier in experimental result section. Formation of MH or Brucite was quite prominent as shown in the fig:4.42 .EDX spectrum also confirmed the existence of MH and ettringite formation. Production of Brucite or MH as observed from the SEM image is relatively insoluble in nature and clogged the pores ,thus prohibited the further intrusion of deleterious materials .It acted as protective shield for the C-S-H gel against further deterioration from $MgSO_4$ attack. This observation made is in agreement with the residual compressive strength values as observed from the experimental data.



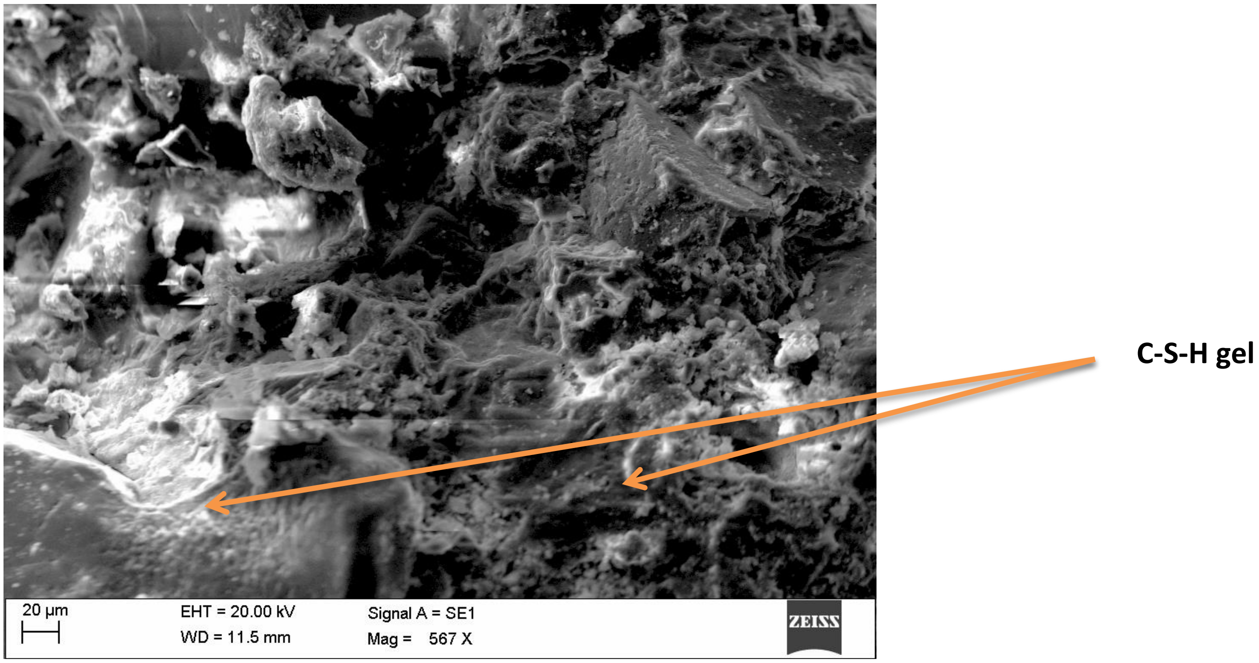


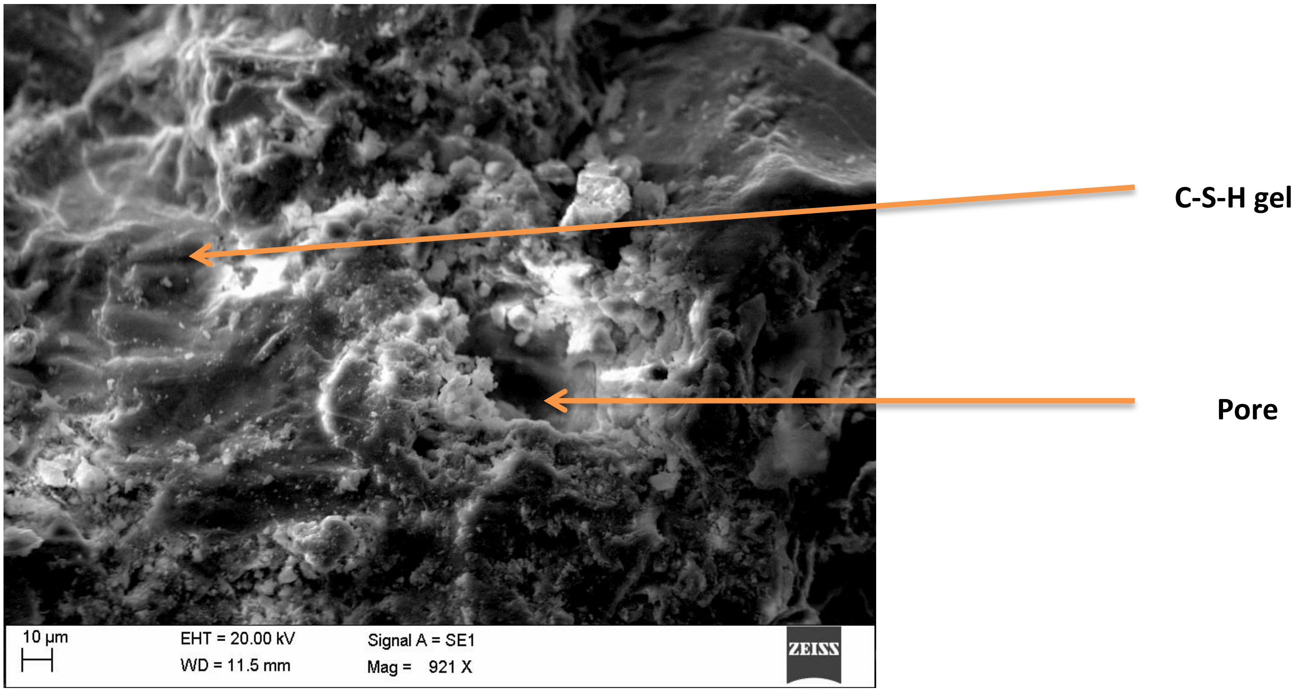


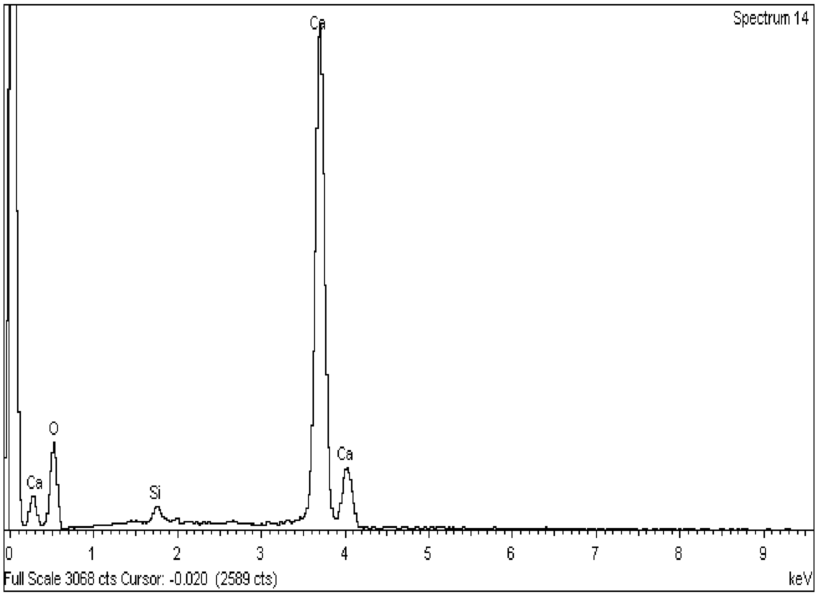
Element	Weight%	Atomic%
C K	17.11	25.31
O K	56.74	63.01
Mg K	0.30	0.22
Ca K	25.85	11.46
Totals	100.00	

Fig 4.43 :SEM image and EDX profile along with elemental composition of GG30SF15 (Surface) mix after 56 days of $MgSO_4$ exposure.

Surface morphology of the sample collected from outer part (surface) of the mix GG30SF15 as shown in fig:4.43. SEM image reported the co-existence of CH (portlandite) and MH (brucite) indicating the formation of brucite predominantly attributed by the decalcification of the C-S-H gel rather than portlandite. EDX profile also interpreted the above incidence having peaks of Ca,Mg and Si respectively. SEM image also revealed the limited occurrence of layered formation of gypsum crystals as shown in fig:4.43. Similar observation has been reported by F.Girardi et.al (2011) [33] . Limited formation of gypsum indicates the sample underwent slight gain in weight. Observations made so far are in conjunction with the data obtained from laboratory experiments.







Element	Weight%	Atomic%
O K	52.63	73.40
Si K	1.00	0.79
Ca K	46.37	25.81
Totals	100.00	

Fig 4.44 :SEM image and EDX profile along with elemental composition of GG30SF15 (core) mix after 56 days of $MgSO_4$ exposure.

Considering the inner part of the same sample SEM image(Refer Fig:4.44) ensured sound C-S-H matrix with limited formation of brucite indicating inner part of the same sample remain unaffected by the $MgSO_4$ solution. . EDX spectrum also reported peaks of Si , Ca except S peak which clearly justify the absence of deleterious materials at the inner part of the sample.

CHAPTER 5

5. Conclusion:

5.1.General:

The effectiveness of different SCM's such as Alccofine ,Silica fume and GGBS as partial replacement of OPC has been studied under different fresh ,hardened and durability considerations and discussed in details in the preceding section. A comparative study on the strength and durability characteristics of Ordinary Portland cement with or without these different SCM's has also been investigated throughout this experimental work.

5.2. Conclusions and major findings of this experimental investigation:

This experimental study has been carried out to investigate the mechanical properties as well as durability exposures of ordinary cement mortars and mortars containing ternary mixtures of supplementary cementitious materials(SCM's) like Ground Granulated Blast Furnace Slag(GGBS), Alccofine and silica fume (SF) along with cement. Based on observations and experimentally obtained results the following conclusions can be drawn:

1. Considering fresh properties of concrete, use of SCM's provided satisfactory results compare to control mix. GGBS and alccofine mix series achieved better workability compare to control mix and increase in workability up to 31.82% obtained for mix GG50AF10 whereas for GGBS silica fume mix series the workability reduced up to 7.27 % for mix GG30SF5 with respect to control mix. The extreme fineness of the silica fume particles considerably effected the workability of the mix.

2. Characteristic of compressive strength gain of different mixes were studied after 7 and 28 days water curing. Control mix performed better compare to other mixes in both the cases. Mix series containing GGBS and alccofine confirmed early age strength gain in contrast with GGBS silica fume mix series. But after 28 days water curing mix series incorporating GGBS and silica fume got better results compare to their GGBS ,alccofine counterpart. Strength value was reported in the result section even surpassed the value of control mix by 4.56% for mix GG30SF10. Furthermore it can be concluded that mixes containing different percentages of SCM's would have better gain in compressive strength values due to effective pozzolanic activity at later ages.

3. Ternary mix series blended with GGBS and alccofine showed better performance over the ternary mix series comprising of GGBS and silica fume in terms of Water absorption and Apparent porosity values whereas a reverse trend was observed in

case of Bulk density values. Sorptivity test was carried out to assess the transport characteristics of deleterious materials in to the concrete. Initial sorptivity coefficient values observed for different mixes confirmed the matrix densification phenomenon of GGBS, silica fume mix series accompanied by lower initial sorptivity coefficient values compare to GGBS alccofine ternary mis series. Percentage increment in both the alccofine and silica fume replacement causes an increase in sorptivity coefficient values.

4. Behaviour of different mixes exposed to H_2SO_4 solution can be expressed in terms of both change in weight and also residual compressive strength values. GGBS and alccofine mix series showed decreasing trend in residual compressive strength values accompanied by greater weight loss but increase in GGBS replacement starting from mix GG50AF5 to GG50AF15 resulted in higher residual compressive strength values as well as a gain in weight. GGBS ,silica fume mix series maintained sufficient residual compressive strength values without compromising the change in weight due to acid exposure. Here also increase in GGBS replacement yielded sufficient residual strength even at weight gain for mix GG50SF15.Considering strength deterioration factor GGBS silica fume mix series performed better over the ternary mix series containing GGBS and alccofine.

5. Mixes exposed to $MgSO_4$ solution underwent gain in weight with decreasing trend in residual compressive strength values for GGBS alccofine mix series except loss in weight accompanied by drastic increase in residual strength was observed for mix GG50AF10. For GGBS silica fume mix series change in weight did not yield significant change in residual compressive strength values except for mix GG30SF10. Maximum samples exposed to $MgSO_4$ solution exhibited negative strength deterioration factor i.e strength gain instead of strength loss to some extent. GGBS ,alccofine mix series showed superior performance compare to GGBS silica fume mix combination.

6. Thermal durability study of different mixes confirmed high degree of weight loss compare to control mix as reported in the preceding section. Though mix series containing GGBS and alccofine suffered greater weight loss, they retained better strength as well compare to GGBS silica fume mix series . GG30SF5 mix performed superior over the other mixes even at higher weight loss.

7. SEM image revealed dense C-S-H matrix formation accompanied by presence of CH or portlandite in GG30SF10 mix compare to GG30AF10 and control mix after 28 days of water curing. Traces of gypsum and etteingite formation were found from SEM image of both alccofine and silica fume mix series after H_2SO_4 exposure for 56 days. EDX spectrum confirmed no acid intrusion in to the inner part of the GG30SF5 mix. In addition to the disintegration of C-S-H gel formation of MH or Brucite and CH or Portlandite were quite prominent from the SEM image for both alccofine and silica fume mix samples.

5.3 Limitation of this experimental investigation:

1. Due to limited time period it was not possible to study the effect of GGBS, alccofine and silica fumes with more percentage variations.

2. Compressive strength behavior of different mixes under normal condition could not be studied with different variations in curing periods .

3. Durability behavior of different mixes needs to be studied under extended curing periods against H_2SO_4 and $MgSO_4$ exposure. This will helpful in better understanding of the effectiveness of different SCM's on long term durability under different exposure conditions.

4. UPV and Rebound hammer test could not be done on 50x50x50 mm cubes as this will lead to erroneous results.

5. Thermal durability assessment of different samples should be carried out at various temperature as this will helpful in better understanding of the behaviour of SCM's under different temperature exposure.

5.4 Future scope of this experimental investigation:

1. Durability behavior of different mixes exposed to acid should not be limited to H_2SO_4. Therefore further studies should be conducted against HCL and HNO_3 exposure also.

2. Similar studies should be carried out for different sulphate solutions in addition to $MgSO_4$ solution.

3. Water absorption, apparent porosity, bulk density and sorptivity coefficient values of different mixes need to be studied after H_2SO_4 and $MgSO_4$ exposure also to compare the durability behavior of SCM's under different exposure conditions.

4. Further studies should be extended to variation in water binder ratio(W/b).

5. Other durability criteria such as permeability, chlorine penetrability may be studied for better understanding of the behaviour of different SCM's.

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APPENDIX-A

Compressive Strength Values of different mixes after 7 and 28 days of water curing.

Sl.no	Mix type	Weight of samples (gm)	Load (N)	C/S area (mm^2)	Compressive strength,7 days (N/mm^2)		Weight of samples (gm)	Load (N)	C/S area (mm^2)	Compressive strength,28 days (N/mm^2)	
					Individual value	Average value				Individual value	Average value
1	**MOPC**	281.66	100000	2500.00	40.00	38.67	287.4	130000	2500.00	52.00	46.67
		279.75	90000	2500.00	36.00		285.86	100000	2500.00	40.00	
		282.02	100000	2500.00	40.00		282.01	120000	2500.00	48.00	
2	**GG30AF5**	257.66	68000	2500.00	27.20	27.20	268.5	84000	2500.00	33.60	33.87
		265.32	66000	2500.00	26.40		270.22	64000	2500.00	25.60	
		261.63	70000	2500.00	28.00		263.5	106000	2500.00	42.40	
3	**GG30AF10**	268.43	90000	2500.00	36.00	37.33	266.18	102000	2500.00	40.80	44.27
		266.51	90000	2500.00	36.00		274.33	110000	2500.00	44.00	
		273.18	100000	2500.00	40.00		270.53	120000	2500.00	48.00	
4	**GG30AF15**	284.98	122000	2500.00	48.80	38.67	270.66	108000	2500.00	43.20	42.40
		267.08	88000	2500.00	35.20		272.21	94000	2500.00	37.60	
		271.56	80000	2500.00	32.00		270.99	116000	2500.00	46.40	
5	**GG50AF5**	272.09	72000	2500.00	28.80	32.00	270.87	90000	2500.00	36.00	34.40
		270.34	82000	2500.00	32.80		266.2	88000	2500.00	35.20	
		271.49	86000	2500.00	34.40		272.59	80000	2500.00	32.00	
6	**GG50AF10**	263.78	80000	2500.00	32.00	29.33	273.42	77000	2500.00	30.80	30.80
		266.66	70000	2500.00	28.00		270.36	82000	2500.00	32.80	
		266.45	70000	2500.00	28.00		271.32	72000	2500.00	28.80	
7	**GG50AF15**	264.06	82000	2500.00	32.80	31.47	266.91	92000	2500.00	36.80	38.93
		267.08	84000	2500.00	33.60		266.42	104000	2500.00	41.60	
		245.19	70000	2500.00	28.00		265.71	96000	2500.00	38.40	

Sl.no	Mix type	Weight of samples (gm)	Load (N)	C/S area (mm^2)	Compressive strength,7 days (N/mm^2)		Weight of samples (gm)	Load (N)	C/S area (mm^2)	Compressive strength,28 days (N/mm^2)	
					Individual value	Average value				Individual value	Average value
8	**GG30SF5**	270.33	90000	2500	36.00	33.33	265.59	60800	2500.00	24.32	23.29
		266.63	84000	2500	33.60		262.88	57200	2500.00	22.88	
		268.68	76000	2500	30.40		280.41	56700	2500.00	22.68	
9	**GG30SF10**	265.54	88000	2500	35.20	34.67	268.86	122000	2500.00	48.80	48.80
		268.39	72000	2500	28.80		264.77	126000	2500.00	50.40	
		274.58	100000	2500	40.00		267.13	118000	2500.00	47.20	
10	**GG30SF15**	265.92	80000	2500	32.00	32.27	260.22	108000	2500.00	43.20	42.93
		266.84	80000	2500	32.00		274.34	106000	2500.00	42.40	
		273.33	82000	2500	32.80		257.93	108000	2500.00	43.20	
11	**GG50SF5**	270.16	52000	2500	20.80	21.61	266.7	96000	2500.00	38.40	38.13
		263.2	62100	2500	24.84		269.8	92000	2500.00	36.80	
		271.13	48000	2500	19.20		276.55	98000	2500.00	39.20	
12	**GG50SF10**	276.24	52000	2500	20.80	20.00	262.58	104000	2500.00	41.60	42.13
		274.8	50000	2500	20.00		273.48	110000	2500.00	44.00	
		266.73	48000	2500	19.20		268.54	102000	2500.00	40.80	
13	**GG50SF15**	266.45	66000	2500	26.40	26.53	258.31	110000	2500.00	44.00	44.93
		264.12	68000	2500	27.20		258.78	102000	2500.00	40.80	
		267.72	65000	2500	26.00		275.45	125000	2500.00	50.00	

APPENDIX-B

Calculation of Water absorption,Apparent porosity and Bulk density of different mixes.

Sl.no	Mix type	Dry weight of samples (gm) (D)	Saturated weight of samples (gm) (W)	Submerged weight of samples (gm) (S)	Water absorption(%)		Apparent Porosity(%)		Bulk density (Kg/m³)	
					Individual value	Average value	Individual value	Average value	Individual value	Average value
1	**MOPC**	250.5	273.88	150.59	9.33	8.28	18.96	16.96	2031.79	2051.05
		255	273.75	150.84	7.35		15.26		2074.69	
		259.15	280.26	153.64	8.15		16.67		2046.68	
2	**GG30AF5**	250.18	258.82	135.13	3.45	3.13	6.99	6.34	2022.64	2023.04
		255.76	264.46	138.18	3.40		6.89		2025.34	
		253.43	259.87	134.48	2.54		5.14		2021.13	
3	**GG30AF10**	255.5	262.51	136.53	2.74	2.86	5.56	5.79	2028.10	2026.51
		241.72	249.3	129.56	3.14		6.33		2018.71	
		259.62	266.61	138.89	2.69		5.47		2032.73	
4	**GG30AF15**	253.21	260.72	134.36	2.97	3.04	5.94	6.11	2003.88	2010.92
		251.84	258.68	133.37	2.72		5.46		2009.74	
		251.04	259.66	135.33	3.43		6.93		2019.14	
5	**GG50AF5**	251.64	259.88	138.45	3.27	3.12	6.79	6.48	2072.31	2077.00
		256.19	264.55	141.51	3.26		6.79		2082.17	
		255.35	262.54	139.57	2.82		5.85		2076.52	
6	**GG50AF10**	246.52	255.3	131.34	3.56	3.95	7.08	7.81	1988.71	1976.66
		236.84	246.88	126.78	4.24		8.36		1972.02	
		246.53	256.54	131.35	4.06		8.00		1969.25	
7	**GG50AF15**	249.24	254.88	131.86	2.26	2.24	4.58	4.55	2026.01	2036.27
		258.17	263.41	137.5	2.03		4.16		2050.43	
		256.83	263.04	136.67	2.42		4.91		2032.37	

Sl.no	Mix type	Dry weight of samples (gm) (D)	Saturated weight of samples (gm) (W)	Submerged weight of samples (gm) (S)	Water absorption(%)		Apparent Porosity(%)		Bulk density (Kg/m³)	
					Individual value	Average value	Individual value	Average value	Individual value	Average value
8	**GG30SF5**	260.09	273.29	146.66	5.08	5.37	10.42	10.98	2053.94	2047.50
		259.37	272.28	146.2	4.98		10.24		2057.19	
		255.18	270.61	144.99	6.05		12.28		2031.36	
9	**GG30SF10**	261.32	272.42	144.63	4.25	4.16	8.69	8.52	2044.92	2047.01
		256.38	266.75	141.49	4.04		8.28		2046.78	
		261.35	272.31	144.78	4.19		8.59		2049.32	
10	**GG30SF15**	258.62	268.62	142.86	3.87	3.82	7.95	7.88	2056.46	2063.36
		256.99	267.14	143.12	3.95		8.18		2072.17	
		257.6	266.97	142.01	3.64		7.50		2061.46	
11	**GG50SF5**	262.69	280.46	150.96	6.76	4.26	13.72	8.77	2028.49	2071.93
		269.23	276.09	148.15	2.55		5.36		2104.35	
		270.22	279.61	149.88	3.47		7.24		2082.94	
12	**GG50SF10**	263.56	272.1	144.93	3.24	3.05	6.72	6.32	2072.50	2074.78
		262.86	270.7	144.9	2.98		6.23		2089.51	
		258.76	266.31	140.84	2.92		6.02		2062.33	
13	**GG50SF15**	262.73	273.07	146.26	3.94	3.61	8.15	7.52	2071.84	2082.69
		263.96	273.43	147.16	3.59		7.50		2090.44	
		265.27	274.07	146.89	3.32		6.92		2085.78	

APPENDIX-C

Calculation of sorptivity coefficient values of different mixes.

Mix designation	Initial sorptivity coefficient	Average	Secondary sorptivity coefficient	Average	Mix designation	Initial sorptivity coefficient	Average	Secondary sorptivity coefficient	Average
MOPC	2.80E-03	1.63E-03	1.60E-03	1.57E-03	**GG30SF5**	1.10E-03	1.07E-03	1.00E-03	9.67E-04
	9.00E-04		1.50E-03			1.20E-03		1.00E-03	
	1.20E-03		1.60E-03			9.00E-04		9.00E-04	
GG30AF5	1.10E-03	2.03E-03	1.20E-03	1.17E-03	**GG30SF10**	2.20E-03	1.70E-03	1.10E-03	1.03E-03
	2.80E-03		1.20E-03			1.70E-03		1.10E-03	
	2.20E-03		1.10E-03			1.20E-03		9.00E-04	
GG30AF10	1.10E-03	1.37E-03	1.00E-03	1.10E-03	**GG30SF15**	2.10E-03	1.60E-03	1.40E-03	1.23E-03
	1.60E-03		1.10E-03			1.80E-03		1.30E-03	
	1.40E-03		1.20E-03			9.00E-04		1.00E-03	
GG30AF15	3.40E-03	3.17E-03	9.00E-04	8.33E-04	**GG50SF5**	1.40E-03	1.10E-03	8.00E-04	7.33E-04
	3.00E-03		8.00E-04			1.00E-03		6.00E-04	
	3.10E-03		8.00E-04			9.00E-04		8.00E-04	
GG50AF5	3.80E-03	3.80E-03	7.00E-04	7.33E-04	**GG50SF10**	9.00E-04	1.03E-03	7.00E-04	7.33E-04
	3.80E-03		7.00E-04			1.10E-03		6.00E-04	
	3.80E-03		8.00E-04			1.10E-03		9.00E-04	
GG50AF10	2.00E-03	1.77E-03	1.10E-03	1.03E-03	**GG50SF15**	2.90E-03	2.50E-03	1.00E-03	8.67E-04
	2.20E-03		1.00E-03			1.70E-03		9.00E-04	
	1.10E-03		1.00E-03			2.90E-03		7.00E-04	
GG50AF15	1.30E-03	1.17E-03	9.00E-04	9.67E-04					
	1.10E-03		1.00E-03						
	1.10E-03		1.00E-03						

Mix designation	**Time**	**0**	**1**	**5**	**10**	**20**	**30**	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
		min	**min**	**min**	**min**	**min**	**min**	**hr**	**hr**	**hr**	**hr**	**hr**	**hr**	**day**	**day**	**day**	**day**	**day**	**day**	**day**	**day**
	Second	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
	√Second	0	8	17	24	35	42	60	85	104	120	134	147	294	416	509	588	657	720	778	831
MOPC	I 1	0	0.068	0.1	0.112	0.12	0.12	0.164	0.2	0.26	0.312	0.364	**0.54**	0.764	1.016	1.264	1.388	1.504	1.552	1.596	**1.64**
	I 2	0	0.048	0.07	0.072	0.08	0.084	0.092	0.1	0.112	0.128	0.152	**0.188**	0.328	0.504	0.696	0.816	0.9	0.984	1.044	**1.14**
	I 3	0	0.068	0.08	0.084	0.088	0.096	0.112	0.12	0.156	0.188	0.204	**0.228**	0.46	0.656	0.864	0.996	1.068	1.152	1.236	**1.284**
GG30AF5	I 1	0	0.012	0.02	0.036	0.06	0.068	0.084	0.1	0.12	0.14	0.148	**0.164**	0.368	0.496	0.628	0.72	0.8	0.884	0.956	**1.016**
	I 2	0	0.024	0.06	0.076	0.116	0.124	0.176	0.240	0.284	0.328	0.388	**0.416**	0.824	0.96	1.112	1.196	1.28	1.34	1.392	**1.456**
	I 3	0	0.02	0.03	0.072	0.084	0.084	0.116	0.18	0.24	0.276	0.3	**0.324**	0.652	0.772	0.916	1.012	1.048	1.112	1.176	**1.212**
GG30AF10	I 1	0	0.064	0.08	0.096	0.108	0.128	0.128	0.15	0.156	0.176	0.204	**0.22**	0.424	0.556	0.628	0.72	0.796	0.848	0.896	**0.948**
	I 2	0	0.016	0.04	0.044	0.064	0.064	0.084	0.12	0.164	0.188	0.22	**0.24**	0.524	0.644	0.756	0.852	0.924	1.016	1.092	**1.108**
	I 3	0	0.072	0.07	0.088	0.116	0.128	0.132	0.17	0.184	0.208	0.228	**0.244**	0.488	0.648	0.776	0.88	0.952	1.028	1.072	**1.124**
GG30AF15	I 1	0	0.036	0.12	0.176	0.204	0.224	0.288	0.36	0.412	0.452	0.5	**0.548**	0.788	0.872	0.976	1.036	1.092	1.148	1.196	**1.24**
	I 2	0	0.04	0.12	0.16	0.2	0.228	0.272	0.34	0.372	0.412	0.436	**0.484**	0.712	0.788	0.896	0.96	1.016	1.056	1.06	**1.112**
	I 3	0	0.02	0.11	0.144	0.192	0.208	0.264	0.33	0.364	0.412	0.444	**0.5**	0.732	0.844	0.924	0.992	1.036	1.084	1.108	**1.136**
GG50AF5	I 1	0	0.052	0.14	0.172	0.248	0.268	0.328	0.4	0.464	0.504	0.556	**0.596**	0.932	1.044	1.104	1.184	1.236	1.264	1.28	**1.3**
	I 2	0	0.056	0.14	0.192	0.244	0.268	0.344	0.42	0.468	0.512	0.564	**0.616**	0.952	1.088	1.192	1.212	1.256	1.276	1.312	**1.324**
	I 3	0	0.068	0.15	0.192	0.24	0.272	0.34	0.42	0.456	0.512	0.564	**0.632**	0.952	1.08	1.208	1.24	1.296	1.336	1.348	**1.356**
GG50AF10	I 1	0	0.076	0.08	0.092	0.092	0.108	0.14	0.2	0.252	0.28	0.292	**0.312**	0.58	0.864	0.96	1.016	1.096	1.136	1.188	**1.236**
	I 2	0	0.036	0.07	0.084	0.092	0.108	0.148	0.22	0.28	0.3	0.308	**0.328**	0.548	0.852	0.952	1.004	1.076	1.1	1.124	**1.148**
	I 3	0	0.012	0.03	0.036	0.044	0.052	0.06	0.1	0.1	0.148	0.152	**0.184**	0.312	0.584	0.68	0.732	0.796	0.824	0.856	**0.88**
GG50AF15	I 1	0	0.012	0.02	0.036	0.048	0.056	0.08	0.12	0.128	0.16	0.18	**0.192**	0.336	0.58	0.68	0.708	0.784	0.804	0.84	**0.88**
	I 2	0	0.036	0.08	0.088	0.092	0.1	0.1	0.12	0.172	0.17	0.18	**0.208**	0.336	0.58	0.704	0.748	0.788	0.812	0.864	**0.916**
	I 3	0	0.056	0.09	0.108	0.124	0.128	0.136	0.15	0.16	0.196	0.2	**0.224**	0.348	0.668	0.752	0.804	0.864	0.892	0.904	**0.928**

Mix designation	**Time**	**0**	**1**	**5**	**10**	**20**	**30**	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
		min	**min**	**min**	**min**	**min**	**min**	**hr**	**hr**	**hr**	**hr**	**hr**	**hr**	**day**	**day**	**day**	**day**	**day**	**day**	**day**	**day**
	Second	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
	√Second	0	8	17	24	35	42	60	85	104	120	134	147	294	416	509	588	657	720	778	831
GG30SF5	I 1	0	0.012	0.04	0.044	0.064	0.076	0.1	0.11	0.132	0.148	0.16	**0.184**	0.384	0.608	0.676	0.74	0.792	0.828	0.916	**0.996**
	I 2	0	0.02	0.03	0.052	0.068	0.08	0.092	0.1	0.104	0.152	0.192	**0.216**	0.664	0.92	1	1.072	1.104	1.128	1.188	**1.28**
	I 3	0	0.004	0	0.024	0.036	0.044	0.056	0.07	0.076	0.104	0.116	**0.144**	0.304	0.508	0.612	0.66	0.716	0.744	0.8	**0.864**
GG30SF10	I 1	0	0.044	0.08	0.096	0.116	0.132	0.176	0.22	0.244	0.288	0.312	**0.36**	0.708	0.984	1.076	1.168	1.232	1.256	1.304	**1.352**
	I 2	0	0.064	0.08	0.092	0.12	0.136	0.156	0.18	0.216	0.24	0.268	**0.3**	0.568	0.852	0.932	1.024	1.084	1.132	1.118	**1.236**
	I 3	0	0.068	0.08	0.08	0.104	0.128	0.128	0.14	0.144	0.168	0.192	**0.248**	0.38	0.6	0.652	0.704	0.756	0.8	0.856	**0.908**
GG30SF15	I 1	0	0.076	0.14	0.144	0.148	0.172	0.208	0.25	0.268	0.3	0.336	**0.392**	0.676	0.96	1.032	1.132	1.188	1.224	1.268	**1.296**
	I 2	0	0.056	0.1	0.104	0.124	0.132	0.168	0.18	0.212	0.248	0.276	**0.324**	0.564	0.896	1	1.092	1.16	1.192	1.248	**1.312**
	I 3	0	0.032	0.05	0.06	0.076	0.092	0.096	0.11	0.116	0.128	0.14	**0.164**	0.3	0.56	0.604	0.684	0.74	0.788	0.84	**0.908**
GG50SF5	I 1	0	0.044	0.06	0.064	0.068	0.12	0.124	0.15	0.164	0.18	0.208	**0.24**	0.436	0.66	0.712	0.752	0.8	0.868	0.888	**0.916**
	I 2	0	0.06	0.07	0.092	0.092	0.108	0.12	0.13	0.148	0.16	0.172	**0.188**	0.308	0.492	0.528	0.548	0.576	0.608	0.636	**0.692**
	I 3	0	0.04	0.04	0.052	0.06	0.072	0.096	0.11	0.124	0.132	0.136	**0.164**	0.364	0.592	0.628	0.648	0.684	0.764	0.804	**0.852**
GG50SF10	I 1	0	0.012	0.02	0.032	0.04	0.06	0.064	0.08	0.096	0.116	0.124	**0.136**	0.328	0.544	0.604	0.64	0.656	0.7	0.724	**0.768**
	I 2	0	0.024	0.05	0.052	0.056	0.068	0.092	0.1	0.128	0.148	0.156	**0.172**	0.34	0.532	0.564	0.588	0.6	0.648	0.676	**0.724**
	I 3	0	0.024	0.02	0.048	0.048	0.064	0.092	0.12	0.132	0.148	0.156	**0.168**	0.412	0.68	0.72	0.744	0.796	0.872	0.908	**0.98**
GG50SF15	I 1	0	0.016	0.07	0.092	0.116	0.164	0.216	0.28	0.316	0.364	0.392	**0.432**	0.804	1.156	1.216	1.244	1.3	1.3	1.404	**1.456**
	I 2	0	0.016	0.04	0.056	0.064	0.092	0.132	0.15	0.18	0.208	0.224	**0.256**	0.556	0.812	0.868	0.892	0.944	0.98	1.032	**1.104**
	I 3	0	0.036	0.08	0.1	0.144	0.176	0.256	0.29	0.332	0.392	0.412	**0.444**	0.808	1.116	1.144	1.176	1.196	1.228	1.256	**1.296**

APPENDIX-D

Change in weight and observed compressive strength values of different mixes after H_2SO_4 exposure for 56 days.

Sl.no	Mix type	Weight of samples before immesion (4% H_2SO_4) (gm)	Weight of samples after immesion (4% H_2SO_4) (gm)	Change in weight (%)		Load (N)	C/S area (mm²)	Compressive strength (N/mm²)	
				Individual value	Average value			Individual value	Average value
1	**MOPC**	282.16	269.81	4.38	4.81	50000	2500.00	20.00	21.07
		281.78	270.95	3.84		54000	2500.00	21.60	
		277.8	260.54	6.21		54000	2500.00	21.60	
2	**GG30AF5**	260.6	256.73	1.49	3.07	40000	2500.00	16.00	14.93
		269.69	261.39	3.08		36000	2500.00	14.40	
		273.97	261.24	4.65		36000	2500.00	14.40	
3	**GG30AF10**	277.21	254.33	8.25	5.06	56000	2500.00	22.40	17.87
		271.91	264.18	2.84		36000	2500.00	14.40	
		269.65	258.61	4.09		42000	2500.00	16.80	
4	**GG30AF15**	278.08	238.48	14.24	9.07	34000	2500.00	13.60	14.13
		258.52	244.79	5.31		36000	2500.00	14.40	
		272.84	251.97	7.65		36000	2500.00	14.40	
5	**GG50AF5**	278.08	265.69	4.46	3.10	24000	2500.00	9.60	9.33
		258.52	252.42	2.36		24000	2500.00	9.60	
		272.84	266.07	2.48		22000	2500.00	8.80	
6	**GG50AF10**	277.15	271.44	2.06	3.10	40000	2500.00	16.00	14.67
		279.41	270.57	3.16		35000	2500.00	14.00	
		268.98	258.05	4.06		35000	2500.00	14.00	
7	**GG50AF15**	267.51	278.16	-3.98	-4.07	65000	2500.00	26.00	24.93
		266.12	278.02	-4.47		62000	2500.00	24.80	
		266.07	276.08	-3.76		60000	2500.00	24.00	

Sl.no	Mix type	Weight of samples before immesion (4% H_2SO_4) (gm)	Weight of samples after immesion (4% H_2SO_4) (gm)	Change in weight (%)		Load (N)	C/S area (mm²)	Compressive strength (N/mm²)	
				Individual value	Average value			Individual value	Average value
8	**GG30SF5**	273.2	220.28	19.37	22.18	25000	2500.00	10.00	11.07
		274.61	218.15	20.56		30000	2500.00	12.00	
		270.7	198.67	26.61		28000	2500.00	11.20	
9	**GG30SF10**	265.78	254.29	4.32	4.95	42000	2500.00	16.80	16.80
		273.84	256.22	6.43		42000	2500.00	16.80	
		276.45	265.14	4.09		42000	2500.00	16.80	
10	**GG30SF15**	269.59	268.23	0.50	-1.82	40000	2500.00	16.00	17.07
		264.5	271.28	-2.56		48000	2500.00	19.20	
		269.97	279.14	-3.40		40000	2500.00	16.00	
11	**GG50SF5**	273.08	278	-1.80	-0.64	45000	2500.00	18.00	16.67
		259.52	254.6	1.90		40000	2500.00	16.00	
		271.06	276.49	-2.00		40000	2500.00	16.00	
12	**GG50SF10**	275.43	262.84	4.57	3.00	50000	2500.00	20.00	20.00
		271.87	265.69	2.27		52000	2500.00	20.80	
		267.87	262.09	2.16		48000	2500.00	19.20	
13	**GG50SF15**	273.49	296.61	-8.45	-8.87	50000	2500.00	20.00	20.00
		262.98	287.94	-9.49		48000	2500.00	19.20	
		265.04	288.04	-8.68		52000	2500.00	20.80	

Change in weight and observed compressive strength values of different mixes after $MgSO_4$ exposure for 56 days.

Sl.no	Mix type	Weight of samples before immesion (4% H_2SO_4) (gm)	Weight of samples after immesion (4% H_2SO_4) (gm)	Change in weight (%)		Load (N)	C/S area (mm²)	Compressive strength (N/mm²)	
				Individual value	Average value			Individual value	Average value
1	**MOPC**	284.91	284.67	0.08	-0.29	132000	2500.00	52.80	49.07
		288.8	293.18	-1.52		120000	2500.00	48.00	
		284.82	283.25	0.55		116000	2500.00	46.40	
2	**GG30AF5**	265.14	265.35	-0.08	-0.15	110000	2500.00	44.00	48.67
		273.18	273.71	-0.19		130000	2500.00	52.00	
		261.97	262.45	-0.18		125000	2500.00	50.00	
3	**GG30AF10**	276.3	277.1	-0.29	-0.12	146000	2500.00	58.40	57.07
		272.32	272.46	-0.05		142000	2500.00	56.80	
		269.08	269.13	-0.02		140000	2500.00	56.00	
4	**GG30AF15**	272.23	273	-0.28	-0.23	78000	2500.00	31.20	36.53
		275.79	276.17	-0.14		98000	2500.00	39.20	
		270.13	270.82	-0.26		98000	2500.00	39.20	
5	**GG50AF5**	272.23	271.49	0.27	-0.42	94000	2500.00	37.60	37.87
		275.79	275.08	0.26		94000	2500.00	37.60	
		270.13	275	-1.80		96000	2500.00	38.40	
6	**GG50AF10**	278.94	278.26	0.24	0.46	150000	2500.00	60.00	57.07
		281.44	279.76	0.60		142000	2500.00	56.80	
		268.52	267.05	0.55		136000	2500.00	54.40	
7	**GG50AF15**	267.75	268.66	-0.34	-0.37	115000	2500.00	46.00	46.00
		268.29	269.1	-0.30		118000	2500.00	47.20	
		271.26	272.55	-0.48		112000	2500.00	44.80	

Sl.no	Mix type	Weight of samples before immesion (4% H_2SO_4) (gm)	Weight of samples after immesion (4% H_2SO_4) (gm)	Change in weight (%)		Load (N)	C/S area (mm^2)	Compressive strength (N/mm^2)	
				Individual value	Average value			Individual value	Average value
8	**GG30SF5**	279.77	280.46	-0.25	-0.10	105000	2500.00	42.00	48.00
		273.53	273.56	-0.01		130000	2500.00	52.00	
		265.34	265.47	-0.05		125000	2500.00	50.00	
9	**GG30SF10**	269.72	272.19	-0.92	-1.08	120000	2500.00	48.00	47.20
		269.95	272.83	-1.07		118000	2500.00	47.20	
		267.27	270.61	-1.25		116000	2500.00	46.40	
10	**GG30SF15**	263.38	263.58	-0.08	-0.073	136000	2500.00	54.40	50.13
		271.97	272.14	-0.06		120000	2500.00	48.00	
		264.01	264.22	-0.08		120000	2500.00	48.00	
11	**GG50SF5**	271.92	271.77	0.06	0.086	100000	2500.00	40.00	46.00
		271.36	271.02	0.13		130000	2500.00	52.00	
		274.22	274.01	0.08		115000	2500.00	46.00	
12	**GG50SF10**	278.83	279.7	-0.31	-0.08	115000	2500.00	46.00	50.00
		274.22	274.02	0.07		125000	2500.00	50.00	
		272	272.01	0.00		135000	2500.00	54.00	
13	**GG50SF15**	260.73	262.77	-0.78	-0.83	96000	2500.00	38.40	37.87
		270.93	272.76	-0.68		94000	2500.00	37.60	
		268.78	271.58	-1.04		94000	2500.00	37.60	

APPENDIX-E

Change in weight and observed compressive strength values of different mixes after thermal exposure.

Sl.no	Mix type	Weight of samples before exposure (gm)	Weight of samples after exposure (gm)	Weight loss (%)		Load (N)	C/S area (mm²)	Compressive strength (N/mm²)	
				Individual value	Average value			Individual value	Average value
1	**MOPC**	279.29	254.1	9.02	8.24	20000	2500.00	8.00	8.27
		284.13	260.7	8.25		20000	2500.00	8.00	
		288.02	266.52	7.46		22000	2500.00	8.80	
2	**GG30AF5**	271.52	245.96	9.41	9.995	40000	2500.00	16.00	14.67
		265.52	238.05	10.35		32000	2500.00	12.80	
		267.36	240.02	10.23		38000	2500.00	15.20	
3	**GG30AF10**	271.18	243.8	10.10	10.28	32000	2500.00	12.80	14.13
		270.19	242.42	10.28		36000	2500.00	14.40	
		268.72	240.58	10.47		38000	2500.00	15.20	
4	**GG30AF15**	279.91	256.19	8.47	8.32	48000	2500.00	19.20	18.67
		279.09	256.5	8.09		48000	2500.00	19.20	
		275.48	252.36	8.39		44000	2500.00	17.60	
5	**GG50AF5**	263.05	237.82	9.59	9.79	24800	2500.00	9.92	9.99
		256.86	231.44	9.90		24900	2500.00	9.96	
		263.11	237.08	9.89		25200	2500.00	10.08	
6	**GG50AF10**	271.19	247.14	8.87	8.80	36000	2500.00	14.40	14.13
		266.69	243.95	8.53		34000	2500.00	13.60	
		279.32	254.14	9.01		36000	2500.00	14.40	
7	**GG50AF15**	269.69	247.19	8.34	8.22	34500	2500.00	13.80	12.85
		268.12	246.02	8.24		30700	2500.00	12.28	
		271.72	249.76	8.08		31200	2500.00	12.48	

Sl.no	Mix type	Weight of samples before exposure (gm)	Weight of samples after exposure (gm)	Weight loss (%)		Load (N)	C/S area (mm²)	Compressive strength (N/mm²)	
				Individual value	Average value			Individual value	Average value
8	**GG30SF5**	272.99	248.76	8.88	8.76	32000	2500.00	12.80	13.87
		269.28	245.3	8.91		38000	2500.00	15.20	
		274.82	251.43	8.51		34000	2500.00	13.60	
9	**GG30SF10**	262.12	238.9	8.86	8.45	32000	2500.00	12.80	12.53
		265.76	244.26	8.09		30000	2500.00	12.00	
		263.81	241.64	8.40		32000	2500.00	12.80	
10	**GG30SF15**	261.23	235.88	9.70	9.42	28000	2500.00	11.20	10.93
		269.46	243.47	9.65		26000	2500.00	10.40	
		263.89	240.38	8.91		28000	2500.00	11.20	
11	**GG50SF5**	271.66	246.76	9.17	9.27	28000	2500.00	11.20	10.67
		274.24	246.23	10.21		26000	2500.00	10.40	
		265.67	243.24	8.44		26000	2500.00	10.40	
12	**GG50SF10**	276.21	251.75	8.86	8.81	28000	2500.00	11.20	11.47
		275.85	251.22	8.93		30000	2500.00	12.00	
		268.03	244.88	8.64		28000	2500.00	11.20	
13	**GG50SF15**	272.28	246.57	9.44	9.64	26000	2500.00	10.40	11.20
		267.71	241.05	9.96		32000	2500.00	12.80	
		275.3	249.09	9.52		26000	2500.00	10.40	

APPENDIX-F

Strength Deterioration Factor(SDF) and Residual compressive strength values of different mixes after H_2SO_4 and $MgSO_4$ exposure for 56 days.

Sl.no	Exposure condition	Mix type	Compressive strength		S.D.F(%)	Residual compressive strength(%)	Exposure condition	Compressive strength		S.D.F(%)	Residual compressive strength(%)
			After 28days(MPa)	After H_2SO_4 exposure (MPa)				After 28days(MPa)	After $MgSO_4$ exposure (MPa)		
1	H_2SO_4	MOPC	46.67	21.07	54.85	45.15	$MgSO_4$	46.67	49.07	-5.14	105.14
2		GG30AF5	33.87	14.93	55.92	44.08		33.87	48.67	-43.70	143.70
3		GG30AF10	44.27	17.87	59.63	40.37		44.27	57.07	-28.91	128.91
4		GG30AF15	42.4	14.13	66.67	33.33		42.4	36.53	13.84	86.16
5		GG50AF5	34.40	9.33	72.88	27.12		34.40	37.87	-10.09	110.09
6		GG50AF10	30.8	14.67	52.37	47.63		30.8	57.07	-85.29	185.29
7		GG50AF15	38.93	24.93	35.96	64.04		38.93	46	-18.16	118.16
8		GG30SF5	23.29	11.07	52.47	47.53		23.29	48	-106.10	206.10
9		GG30SF10	48.8	16.8	65.57	34.43		48.8	47.2	3.28	96.72
10		GG30SF15	42.93	17.07	60.24	39.76		42.93	50.13	-16.77	116.77
11		GG50SF5	38.13	16.67	56.28	43.72		38.13	46	-20.64	120.64
12		GG50SF10	42.13	20.00	52.53	47.47		42.13	50.00	-18.68	118.68
13		GG50SF15	44.93	20.00	55.49	44.51		44.93	37.87	15.71	84.29