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Synergistic Effect on Ternary Blended Cementitious System

Jasir Thachaparambil

Lecturer, Department of Civil Engineering, SSM Polytechnic College, Tirur, Kerala, India

ABSTRACT

This paper presents a detailed experimental investigation on the synergestic effects on ternary blended cementitious system containing fly ash and silica fume. The experimental programme consisted of three parts, the first part was to obtain the super plasticizer demand for each mix so as to obtain a workability of 110±5%, the second part was to determine the strength and durability properties of the mortar samples having different fly ash and silica fume contents and the third part was to determine the synergy existing in the ternary blends both in terms of durability and strength. Test results have shown that the ternary blended mixtures improved the mortar performance by improving the workability, strength and durability, therefore are applicable. Ternary mixtures performed in accordance with their ingredients; however the degree of improvement that they contribute varies based on the selected dosage and type of SCMs. Synergy between the fly ash and silica fume is the main reason for the outstanding performance of ternary mixtures. The results obtained thus are encouraging for partial replacement.

KEYWORDS: *Synergic action; Ternary blended concrete; Durability; Fly ash; Silica fume; Concrete*

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1. INTRODUCTION

1.1. GENERAL

Cement is the most widely used construction material in the world. Due to the huge quantity of consumption, its performance and environmental footprint on the earth are of great importance. Sustainability and durability have become the major concern of the construction industry.

1.1.1. Environmental Impacts of cement production

Energy consumption is the biggest environmental concern with cement production. Cement production is the most energy intensive of all the industrial manufacturing processes. Including direct fuel use for mining and transportation of raw materials, cement production takes about 1758KWh for every ton of cement.

The industry's heavy reliance on coal leads to especially high emission levels of carbon dioxide, nitrous oxide and sulphur among other pollutants. Thus Portland cement is not only one of the most energy intensive materials of construction but also is responsible for a large amount of greenhouse gas emissions. The world's yearly cement production of 1.6 billion tones accounts for about 7-8% of global loading of carbon dioxide into the atmosphere.

There are two different sources of carbon dioxide emissions during cement production, namely the combustion of fossil fuels to operate the rotary kiln and the chemical process of calcining limestone into lime. Combining these two sources, for every ton of cement production approximately one ton of carbon dioxide is released into the atmosphere. Furthermore, mining large quantity of raw materials, such as limestone and clay, and fuel such as coal, often results in extensive deforestation and top soil loss.

The environmental impact of the construction industry can be reduced through resource productivity i.e. by conserving materials and energy in the cement production and by improving durability of concrete products. Cement conservation is the first step in reducing the energy consumption and greenhouse gas emissions.

One of the efforts to mitigate the environmental issues associated with cement production includes partial replacement of cement with supplementary cementitious materials like fly ash, silica fume, rice husk ash etc. Using supplementary cementitious materials (SCMs) is an effective way of reducing carbon footprint of our cement production.

1.1.2. Durability and quality of structures

Construction industry is becoming increasingly complex and the importance of building structures that are both cost effective and durable has never been higher. Achieving durability in construction should be a very important consideration in the design and construction of new structures. Concrete structures are generally designed for service life of 50 years, but experience shows that in urban and coastal environment many structures begin to deteriorate in 20 to 30 years or even lesser time.

Durability of a structure is its resistance to weathering action, chemical attack, abrasion and other degradation process. Mineral additions have been an important tool to aid durability of concrete structure and thus came the concept of blends.

In recent years, many researchers have established that waste materials like fly ash, blast furnace slag, silica fume, metakaolin, rice husk ash etc. may be used as a partial replacement of cement, which lead to economy and in addition by utilizing the industrial wastes in a useful manner the environmental pollution is also reduced to a great extent and which in turn leads to sustainable development. Blends offer significant advantages over conventional system of Portland cement alone. They can produce stronger and more durable concrete and possess a long and impressive track record. Blends are also suitable for harsh environment where concrete is likely to be exposed to moisture, extreme weather and chemicals. Moreover blends are more environment friendly.

1.2. FLY ASH

Fly ash (FA) is the most widely used supplementary cementitious material in concrete; ASTM C 618-89 defines fly ash as “a finely divided residue that results from combustion of ground or powdered coal”.

It is a byproduct of the combustion of pulverized coal in electric power generating plants. Upon ignition in the furnace, most of the volatile matter and carbon in the coal are burned off. During combustion, the coal’s mineral impurities (such as clay, feldspar, quartz, and shale) fuse in suspension and are carried away from the combustion chamber by the exhaust gases. In the process, the fused material cools and solidifies into spherical glassy particles called fly ash. The fly ash is then collected from the exhaust gases by electrostatic precipitators or bag filters.

Two classes of fly ash are defined by ASTM C 618-89, Class F fly ash and Class C fly ash. The chief difference between these classes is the amount of calcium, silica, alumina, and iron content in the ash. The chemical properties of the fly ash are largely influenced by the chemical content of the coal burned (i.e., anthracite, bituminous, and lignite). Theburning of harder, older anthracite and bituminous coal typically produces Class F fly ash. This fly ash is pozzolanic in nature, and contains less than 20% lime. Class C Fly ash is produced from the burning of younger lignite or sub bituminous coal, in addition to having pozzolanic properties, it also has some self-cementing properties. Class C fly ash generally contains more than 20% lime (CaO).

Fly ash is a finely divided powder resembling Portland cement. Most of the fly ash particles are solid spheres and some are hollow cenospheres. Ground materials, such as Portland cement, have solid angular particles. The particle sizes in fly ash vary from less than 1 μm (micrometer) to more than 100 μm with the typical particle size measuring less than 20 μm. Only 10% to 30% of the particles by mass are larger than 45 μm. The surface area is typically 300 to 500 m^2/kg, although some fly ashes can have surface areas as low as 200 m^2/kg and as high as 700 m^2/kg. For fly ash without close compaction, the bulk density (mass per unit volume including air between particles) can vary from 540 to 860 kg/m^3 whereas with close packed storage or vibration, the range can be 1120 to 1500 kg/m^3. The relative density (specific gravity) of fly ash generally ranges between 1.9 and 2.8 and the color is generally gray or tan.

1.2.1. Pozzolanic action

Class F and Class C fly ashes are commonly used as pozzolanic admixtures for general purpose concrete. During the hydration process of cement, along with the binding gel (C-S-H gel) lime isreleased out and remains as surplus in the hydrated cement. This leached outsurplus lime renders deleterious effect to concrete such as make the concrete porous which in turn give chance to the development of micro cracks, weakening the bond with aggregates and thus affect the durability.

If fly ash is available in the mix, this surplus lime becomes the source forpozzolanic reaction with fly ash and forms additional C-S-H gel having similar binding properties in the concrete as those produced by hydration of cement paste. The reaction of fly ash with surplus lime continues as long as lime is present in the pores of liquid cement paste.

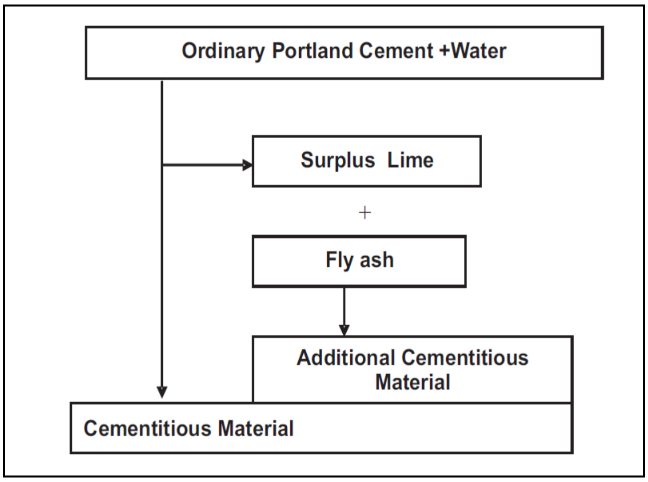

Fig 1.1 Pozzolanic action of fly ash

Fly ash is used in about 50% of ready mixed concrete. Class F fly ash is often used at dosages of 15% to 25% by mass of cementitious material and Class C fly ash is used at dosages of 15% to 40% by mass of cementitious material. Dosage varies with the reactivity of the ash and the desired effects on the concrete.

1.3. SILICA FUME

Silica fume (SF), also referred to as microsilica or condensed silica fume, is a by-product material that is used as a pozzolan. This by-product is a result of the reduction of high-purity quartz with coal in an electric arc furnace in the manufacture of silicon or ferrosilicon alloy. Silica fume rises as an oxidized vapour from the 2000°C (3630°F) furnaces. When it cools it condenses and is collected in huge cloth bags. The condensed silica fume is then processed to remove impurities and to control particle size.

Condensed silica fume is essentially silicon dioxide (usually more than 85%) in non-crystalline (amorphous) form. Since it is an airborne material like fly ash, it has a spherical shape. It is extremely fine with particles less than 1 µm in diameter and with an average diameter of about 0.1 µm, about 100 times smaller than average cement particles. Condensed silica fume has a surface area of about 20,000 m^2/kg. The relative density of silica fume is generally in the range of 2.2 to 2.5. The bulk density of silica fume varies from 130 to 430 kg/m^3.

1.3.1. Silica fume as a supplementary cementitious material

Because of its extreme fineness and high silica content, silica fume is a highly effective pozzolanic material. Silica fume is used in concrete to improve its properties. It has been found that silica fume improves compressive strength, bond strength and abrasion resistance and reduces permeability, and therefore helps in protecting reinforcing steel from corrosion. Silica fume is used in amounts between 5% and 10% by mass of the total cementitious material.

The benefits seen from adding silica fume are the result of changes to the microstructure of the concrete. These changes result from two different but equally important processes. The first of these is the physical aspect of silica fume and the second is its chemical contribution.

Physical contributions

Adding silica fume brings millions and millions of very small particles to a concrete mixture. Just like fine aggregate fills in the spaces between coarse aggregate particles, silica fume fills in the spaces between cement grains. This phenomenon is frequently referred to as particle packing or micro-filling. Even if silica fume did not react chemically, the micro-filler effect would bring about significant improvements in the nature of the concrete.

Chemical contributions

Because of its very high amorphous silicon dioxide content, silica fume is a very reactive pozzolanic material in concrete. As the Portland cement in concrete begins to react chemically, it releases calcium hydroxide. The silica fume reacts with this calcium hydroxide to form additional binder material called calcium silicate hydrate, which is very similar to the calcium silicate hydrate formed from the Portland cement. It is largely this additional binder that gives silica-fume concrete its improved hardened properties.

1.3.2. Applications of silica fume

- 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.

1.4. BINARY AND TERNARY BLENDS

Blends are a mixture of multiple ingredients combined with Portland cement. Blends can be divided into two main categories binary blends and ternary blends. Binary is a mixture of two products i.e. Portland cement and one supplementary cementitious material, whereas the ternary blend is a mixture of three products, Portland cement and two supplementary cementitious materials. The type and proportion of SCMs included in the blends establishes the performance in concrete.

When OPC hydrates C-S-H (calcium silicate hydrate) gelis formed, this glue holds concrete together, However gaps in the glue provide pathways for moisture to penetrate and reduce strength. When

SCMs are added particles pack more tightly within the voids and additional glue forms from the SCM hydration process and result in fewer voids in the matrix thereby less permeability and more strength and durability.

Incorporating a single SCM to improve concrete may have some limitations such as low early age strength, extended curing periods, increased plastic shrinkage cracking etc. The use of appropriately proportioned ternary blends allows the effect of one SCM to compensate for the inherent shortcomings of other, which is termed as the synergistic effect.

1.5. SYNERGY IN TERNARY BLENDED CEMENTITIOUS SYSTEM

Synergy describes the interaction of two or more agents or forces so that their combined effect is greater than sum of their individual effects.

The advantages of using binary blends of either fly ash or silica fume in partial replacement of Portland cement in mortar and concrete is well known. However both materials have certain shortfalls. Silica fume while imparting significant contribution to concrete strength and chemical resistance can create increase in water demand, placing difficulties and plastic shrinkage problems if not properly used. Low calcium fly ash generally provides good resistance to alkali-silica reaction and sulphate attack. However strength development at early ages is typically slower than that in conventional Portland cement systems especially at higher levels of replacement.

But when combined in a ternary system, fly ash compensates for the deficiencies of silica fume and vice versa, silica fume compensates for the deficiencies of fly ash.

In the present study, strength and durability properties of binary and ternary blended mortars of fly ash and silica fume were investigated.

1.5.1. Quantification of Synergy

Thomas *et al*. (1999) proposed an equation to predict the theoretical value for any of the properties of a ternary system and thereby gave a method to quantitatively assess synergy existing in a ternary blended system.

The theoretical value of any predicted property for a mix, [F(15)S(5)] was approximated using the following equation:

$$P_{theor\ 15F/5S} = P_{OPC} + 0.95(P_{15F} - P_{OPC}) + 0.85(P_{5S} - P_{OPC})$$

Where P_{OPC}, P_{15F}, P_{5S} are the values of a given property for OPC, F(15)S(0), and S(5)F(0) mixtures, respectively. 0.95 and 0.85 represent sum of volume fractions of respective OPC and FA in binary mix F (15) S (0) and OPC and SF in mix S(5)F(0).

Then the magnitude of the synergistic effect was calculated from the following equation:

$$S.E = j \times \left(\frac{P_{15F/5S} - P_{theor\ 15F/5S}}{P_{theor\ 15F/5S}} \right) \times 100$$

Where;
S.E = synergistic effect (%)
$P_{15F/5S}$= measured value of a given property for the 15FA/5SF mixture
$P_{theor\ 15F/5S}$ = theoretical value of a given property for the 15FA/5SF mixture
j = 1 for properties to be maximized (compressive strength) and j = -1 for properties to be minimized (rapid chloride permeability and initial sorptivity).

2. LITERATURE REVIEW

2.1. GENERAL

Keeping in view the objectives of the study, a detailed literature survey was conducted, in the domain of both binary and ternary cementitious systems. Large volume of literature is available in the field and a few of them are summarised here.

(1) "Use of ternary cementitious systems containing silica fume and fly ash in concrete", M.D.A Thomas (1999) conducted laboratory studies on durability of concrete that contains ternary blend of Portland cement, silica fume and a wide range of fly ashes.

The results obtained showed that ternary cementitious blends of Portland cement, silica fume and fly ash offer significant advantages over plain Portland cement concrete. The combination of silica fume and low CaO fly ash is complementary; the silica fume improves the early age performance of concrete with the fly ash continuously refining the properties of the hardened concrete as it matures. In terms of durability such blends are vastly superior to plain Portland cement concrete. They found that combinations of 3-5 % silica fume with 20-30% high CaO show satisfactory performance in both ASR and Sulphate expansion tests. They concluded that such combinations produce concrete with generally excellent properties and offset the problems associated with using the increased amounts of high CaO fly ash or silica fume required when these materials are used individually.

(2) "Porosity and strength of PFA/SF/OPC ternary blended paste", Khan *et al*. (2000) conducted studies on a ternary blended cementitious system of ordinary Portland cement (OPC)/ pulverised fuel ash (PFA)/ silica fume (SF) for the development of high- performance concrete. Cement pastes covering a wide range of PFA/SF blending proportions were investigated. They found that increase in PFA content was associated with reduction in strength and increase in porosity in comparison with the OPC control paste for all ages investigated. As SF was incorporated as a cement replacement alone, early -age strength was slightly increased and porosity was slightly reduced. However, as PFA was introduced in the ternary blended systems, the strength was reduced and porosity increased. Although none of the ternary blended systems achieved the strength and porosity of the OPC control, these systems are viable when economic and environmental benefits are sought given the level of performance achieved.

(3) "Effects of densified silica fume on the microstructure and compressive strength of blended cement pastes", Rao (2003) reported the influence of silica fume (SF) on various preliminary properties of cement pastes and mortars. Specific gravity, air content and workability decrease as the addition of SF increases. The SF seemed to be an efficient pozzolanic material. It activates the constituents of cement in the early hours of hydration. The air content has been reduced due to its microfillingeffect, which may lead to increase the compressive strength. Quick setting of cement results with higher SF contents. The positive trends have been observed with SF on strength of mortars and soundness. The drying shrinkage of mortar increases as the SF content increases. The optimum SF content for achieving higher strength of mortars was found to be between 15% and 22%.

(4) "Strength, porosity and corrosion resistance of ternary blend Portland cement, rice husk ash and fly ash mortar", **Chindaprasirt*et al.* (2008)** studied the strength, porosity and corrosion resistance of mortars made with ternary blends of ordinary Portland cement (OPC), ground rice husk ash (RHA) and classified fly ash (fine fly ash, FA). The results show that the use of ternary blend of OPC, RHA and FA significantly improves the mortar in terms of strength at the low replacement level and at the later age. The resistance to chloride-induced corrosion of mortar containing pozzolanis significantly improved in comparison to that of OPC mortar. Both FA and RHA are very effective in improving the corrosion resistance of mortars. RHA is slightly more effective than FA. The corrosion resistance of the ternary blend mortar is consistently higher than that of mortar containing single pozzolan. At high replacement of 40% of pozzolan, although the porosity of mortar is increased at the age of 28 days as compared to OPC mortar, the corrosion resistance is significantly improved. This suggests that pore refinement and reduction in calcium hydroxide play important roles in the corrosion resistance of ternary blend OPC, FA and RHA mortar.

(5) "Evaluation of binary and ternary blends of pozzolanic materials using rapid chloride penetration test", Ahmed *et al.* (2009)studied the effect of replacing cement by pozzolanic materials.The materials used were fly ash, blast furnace slag (BFS), and silica fume. The blending was at the increasing levels of 25, 50, and 70% of fly ash or BFS, with or without addition of silica fume at 10% cement replacement to form binary and ternary blends. The results indicated that an increase in fly ash content increased the charge passed in the specimens but the reverse trend was observed with increase in the BFS content in the absence of silica fume. Silica fume alone as well as its ternary blend with 25% fly ash showed lower charge when compared with the control or with the binary blend of cement and fly ash. However, in ternary blends containing fly ash at more than 25%, the presence of silica fume did not cause a reduction in the charge. All ternary blends comprising BFS and silica fume passed lower charges than the respective binary blends. These ternary blends exhibited dense microstructure compared to the corresponding binary fly ash blends. The highest percentage replacement of cement with 70% BFS and silica fume was comparable with the addition of silica fume alone. The results showed that concretes with BFS blends exhibit lower charge passed and higher compressive strength than comparative blends using fly ash.

(6) "Utilisation of fly ash with silica fume and properties of Portland cement- fly ash- silica fume concrete", Nochaiya*et al*. (2009) investigated ternary blends of fly ash, silica fume andPortland cement using an extensive range of mixes: fly ash from 5% to 30%, and silica fume at 2.5%, 5% and 10%.Fresh properties,in terms of the setting time of cement paste and the workability of the ternary blend concrete, were investigated. Compressive strength of the ternary concrete was tested and analyzed relative to both a Portland cement (PC) control and reference fly ash mixes.

From the study it was concluded that water requirement of fly ash pastes with silica fume was found to have higher water demand than the mixes without silica fume and the setting time was found to reduce with increasing silica fume content. The utilization of silica fume with fly ash in concrete was found to increase the compressive strength of concrete mixes. The workability was found to decrease, but still remained similar to or higher than the control mix.

Moreover, the high compressive strength of blended Portland cement –fly ash–silica fume concretes was due to both the filler effect and the pozzolanic reaction of silica fume evidently giving the cement matrix a denser microstructure, thereby resulting in a significant gain in strength. The utilization of fly ash with silica fume not only improve the concrete strength, it allows the use of another by-product (silica fume) which is much finer, with fly ash, each giving its benefit and as a combination allowing more mixture to be used while maintaining good fresh concrete properties. In addition, the use of both by-products would offer ecological benefit as well which help cutting down the use of Portland cement while improving the properties to fly ash concrete.

(7) "Effect of water to binder ratio, air content and type of cementitious materials on fresh and hardened properties of binary and ternary blended concrete" by **Yurdakul*et al*. (2013)** investigated the effect of water-to-binder ratio (w/b), air content, and type of cementitious materials on fresh and hardened properties of binary and ternary blended concrete mixtures in pavements.

In this experimental program, a total matrix of 54 mixtures with w/b of 0.40 and 0.45; nominal air content of 2%, 4% and 8%; and three types of supplementary cementitious materials (SCMs) and one ordinary Portland cement at different combinations was prepared. Binder systems included ordinary Portland cement, binary mixtures with slag cement, Class F and C fly ash, and ternary mixtures containing a combination of slag cement and one type of fly ash.

It was seen that when w/b was kept constant, increasing air content generally had a minor effect on slightly increasing workability. The ternary mixtures slightly retarded the setting time consistent with the effects of their ingredients. Binary and ternary mixtures containing Class C fly ash and slag cement exhibited higher compressive strength than the control mixture. The addition of Class C fly ash in binary mixtures generally showed a lower performance than the ones with Class F fly ash. Ternary mixtures overall performed better than control mixtures as they increased the strength and decreased the permeability.

2.2. OBJECTIVE AND SCOPE OF WORK

Based on the literature reviewed in the previous section, it can be seen that addition of fly ash and silica fume improves the properties of the mortar and concrete. However the benefits of a combination of fly ash and silica fume in improving the strength and durability properties of cement mortar is not well established. In the present study the benefits of combining fly ash and silica fume in cement mortar and the synergy existing in the system were studied. And efforts are made to find an optimum dosage of fly ash and silica fume in a ternary blended system of OPC/FA/SF.

2.2.1. Objective of work

1. To study the strength & durability properties of ternary blended mortar consisting of OPC, FA and SF.
2. To verify whether synergistic effects exist in a ternary blended cementitious system of OPC, FA and SF.
3. To quantify the magnitude of synergy in the OPC/FA/SF system.

2.2.2. Scope of Work

The scope of the study was limited to 1:3 mortar specimens with OPC 53 grade, class F fly ash and silica fume. Water to binder ratio was fixed as 0.5 and the following replacement levels of fly ash and silica fume were used:

- FA: 0%, 15%, 30%
- SF: 0%, 5%, 10%

The compressive strength tests were conducted after 7, 28, 56 and 90 days of water curing. Flexural strength test were conducted on specimens subjected to 28 days and 90 days of water curing. Durability tests are carried out after 3 days of initial water curing (for initial hydration) after which the specimens will be exposed to the respective chemical solution for a time period of 7, 28, 56 and 90 days

3. EXPERIMENTAL PROGRAMME

3.1. GENERAL

The experimental programme consisted of three parts, the first part was to obtain the super plasticizer demand for each mix so as to obtain a workability of 110±5%, the second part was to determine the strength and durability properties of the mortar samples having different fly ash and silica fume contents and the third part was to determine the synergy existing in the ternary blends both in terms of durability and strength.

3.2. MATERIALS

The materials used for the experimental work are ordinary Portland cement 53 grade, class F fly ash, silica fume, M sand, super plasticizer and water.

3.2.1. Ordinary Portland Cement (OPC)

OPC 53 grade, conforming to IS 12269, was used for the experimental work. Laboratory tests were conducted to determine the specific gravity, standard consistency, fineness, initial setting time, final setting time and the compressive strength. All tests were done as specified by IS 4031 (Part 1 to Part 5).The results are as shown in the Table 3.1.The chemical composition of cement was tested at Indian Institute of Technology (IIT) Madras and the results are presented in Table 3.2.

Table 3.1 Properties of Cement

Sl No:	Particulars	Values
1	Grade	OPC 53
2	Specific Gravity	3.15
3	Standard Consistency	31.25%
4	Fineness	4%
5	Initial Setting Time	90 minutes
6	Final Setting Time	270 minutes
7	3rdday Compressive strength	28 N/mm^2
8	7th day Compressive strength	32 N/mm^2

Table 3.2 Chemical composition of cement

Oxide	Content (%)
CaO	63.48
SiO_2	19.13
Al_2O_3	4.26
Fe_2O_3	5.17
SO_3	4.10
MgO	0.67
$P2O_5$	0.62
TiO_2	0.22
Na_2O	0.60
K_2O	1.75

3.2.2. Fly ash

Class F fly ash was used for the experimental work and it was collected from Neptune Ready Mix Concrete plant, Trivananthapuram. The specific gravity the fly ash was found to be 2.08. Fineness of flyash were found out by wet sieve analysis using 45µm sieve.Result is shown in Table 3.3. The chemical composition of fly ash was tested at Indian Institute of Technology (IIT) Madras, and is presented in Table 3.4.Fig 3.2 shows the scanning electron microscope (SEM) images of FA obtained from IIT Madras.

Fig 3.1 Fly ash

Table 3.3 Sieve analysis of Fly ash

Particle retained on 45 micron sieve (%)	Requirement (IS 3812(part1):2003)
30	34

Table 3.4 Chemical composition of fly ash

Chemical Component	% by mass
SiO_2	60.28
Al_2O_3	31.76
Na_2O	2.10
P_2O_5	1.42
SO_3	0.97
Fe_2O_3	0.89
CaO	0.72
K_2O	0.69
TiO_2	0.64
MgO	0.52

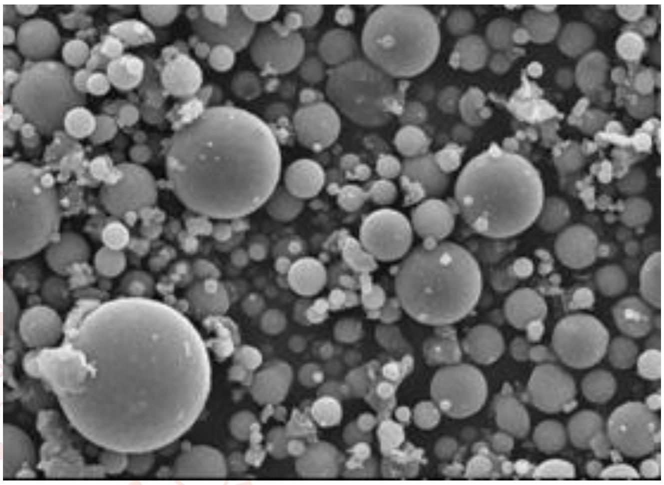

Fig 3.2 SEM images of fly ash

3.2.3. Silica fume

Silica fume used for the experimental work was obtained from ELKEM Materials. From the laboratory tests, thespecific gravity was obtained as 2.2 and density as 0.784 g/cc. Chemical composition of Silica Fume obtained from Indian Institute of Technology (IIT) Madrasis shown in Table 3.5.Fig 3.4 shows the scanning electron microscopic image of SF as obtained from IIT Madras.

Figure 3.3 Silica fume

Table 3.5 Chemical composition of silica fume

Oxide	Content (%)
CaO	2.94
SiO_2	84.28
Al_2O_3	1.54
Fe_2O_3	3.47
SO_3	2.34
MgO	2.09
$P2O_5$	0.60
TiO_2	0.04
Na_2O	1.23
K_2O	1.47

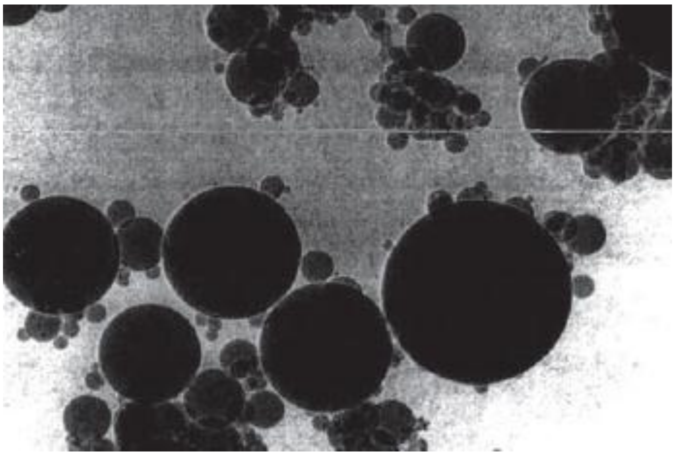

Fig 3.4 SEM image of silica fume

3.2.4. Fine Aggregates

Locally available M Sand was used as fine aggregate. Laboratory tests were conducted, as per IS: 383-1970, to determine the different physical properties of M sand. The details of particle size distribution are given in Table 3.6 and the grading curve is as represented by Fig. 3.3. The properties of fine aggregates are as shown in Table 3.7.

Table 3.6 Sieve analysis of Fine aggregate

Sieve size (mm)	Weight retained in each sieve (kg)	Cumulative weight retained (kg)	Cumulative % weight retained	Percentage weight passing	IS Range for zone II
4.75	0	0	0	100	90 – 100
2.36	0.004	0.004	0.4	99.6	75 – 100
1.18	0.317	0.321	32.1	67.9	55 – 90
0.6	0.329	0.65	65	35	35 – 59
0.3	0.267	0.917	91.7	8.3	8 – 30
0.15	0.063	0.98	98	2	0 – 10

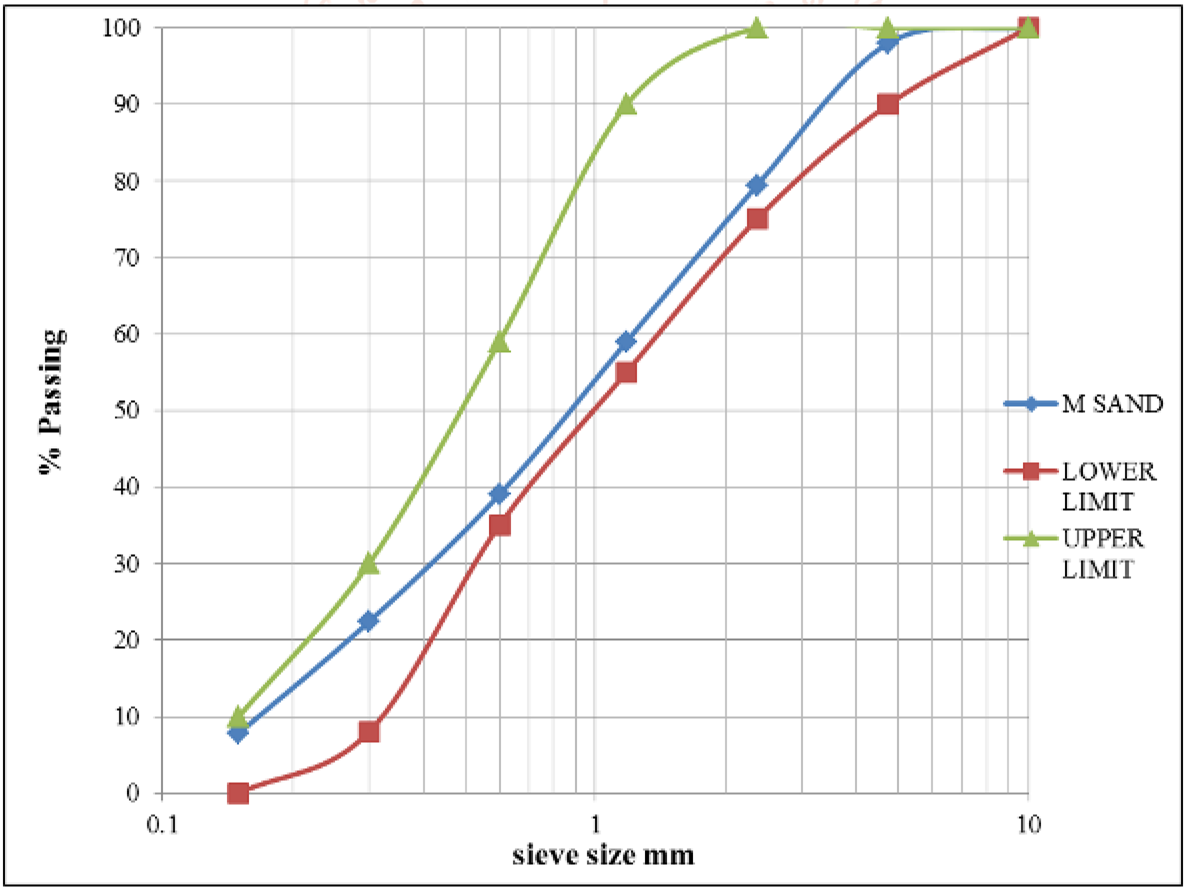

Fig.3.3. Gradation curve of fine aggregate

Table 3.7 Properties of fine aggregate.

Sl. No.	Particulars	Values
1	Specific gravity	2.50
2	Fineness Modulus	3.062
3	Grade	Zone II

3.2.5. Water

Clean and potable water available in the college water supply system was used for the work.

3.2.6. Super plasticiser

Conplast SP430 supplied by M/s Fosroc Chemical (India) Pvt. Ltd was used as superplasticiser. Conplast SP430 is based on SulphonatedNapthalenePolymers and supplied as a brown liquid instantly dispersiblein water. Conplast SP430 has been specially formulated to give high water reductions up to 25% without loss of workability or to produce high quality concrete of reduced permeability. The properties of Conplast SP430 as specified by the suppliers are as shown in Table 3.8.

Table 3.8 Properties of Conplast SP430

Specific Gravity	Typically 1.20 at 20°C
Chloride content	Nil
Recommended dosage	0.7 to 2.0 L/100kg of cement

3.3. MIX PROPORTION AND METHODOLOGY

3.3.1. Mix proportion

Mortar samples were prepared in the ratio 1:3 by weight, i.e. one part of cementitious materials to three parts of fine aggregate.

In this study fly ash and silica fume contents were each expressed as percentage by weight of total cementitious materials. Three fly ash contents namely 0%, 15% and 30% and three silica fume contents 0%, 5% and 10% were adopted for the design of mortar samples. In total there are 9 mixes, one control mix with 0% fly ash and 0% silica fume, two binary mixes of fly ash and OPC, two binary mixes of silica fume and OPC and four ternary mixes. The detailed mix proportions of the mortar samples are tabulated in Table 3.9. The mix numbers are given in the format F(X)S(Y) where F represent fly ash, S represent silica fume and X, Y denotes percentage of fly ash and silica fume in the mix respectively.

Table 3.9 Mix Proportions

SL NO:	Mix	OPC (%)	FA (%)	SF (%)	Type
1	F(0)S(0)	100	0	0	Control Mix
2	F(15)S(0)	85	15	0	Binary Mix
3	F(30)S(0)	70	30	0	Binary Mix
4	F(0)S(5)	95	0	5	Binary Mix
5	F(0)S(10)	90	0	10	Binary Mix
6	F(15)S(5)	80	15	5	Ternary Mix
7	F(30)S(5)	65	30	5	Ternary Mix
8	F(15)S(10)	75	15	10	Ternary Mix
9	F(30)S(10)	60	30	10	Ternary Mix

3.3.2. Methodology

3.3.2.1. Determination of superplasticiser demand

Superplasticiser demand for each mix was determined using flow table test to obtain a workability of 110±5%.

3.3.2.2. Mixing

Cementitious materials, fine aggregates, water and super plasticizer were taken in required proportions and each mortar sample was prepared using a standard mortar mixer. Ordinary Portland cement, fly ash, silica fume and fine aggregates were first dry mixed in the mixer for about three minutes and then water and superplasticizer is added and further mixed for three minutes to get a homogeneous mix.

Fig 3.6 Mortar mixer

3.3.2.3. Casting of specimens

Mortar was cast into cubes, beams and discs. Standard moulds namely, 50mm X 50mm X 50 mm cube moulds, 40mmX 40mmX160mm beam moulds and disc moulds of 150mm diameter and 50mm thickness were used for casting. The mortar mix were filled in the moulds and vibrated using a vibrating table. The surface of the mortar were then finished using a trowel.

3.3.2.4. Curing Regime

All specimens were kept undisturbed for 24 hours and then weighed to obtain their dry weights and subsequently were subjected to water curing until the test ages were reached. The samples for durability studies were transferred to respective acid and sulphate solution after three days of water curing.

Fig 3.7 Curing of mortar specimens

Details of the specimens used for testing are given in Table 3.9

3.4. WORKABILITY OF MORTAR

Workability of mortar is its ease of use measured by the flow of the mortar. Superplasticiser demand for each of the nine mixes, to get a workability of 110±5% were determined by the flow test.

The standard flow tests uses a standard conical frustum shape of mortar with a diameter of four inches. This mortar sample is placed on a flow table and dropped 25 times within 15 seconds. As the mortar is dropped, it spreads out on the flow table. The initial and final diameters of the mortar sample are used to calculate flow. Flow or workability is defined as the increase in diameter divided by the original diameter multiplied by 100.

Figure 3.8 Flow Test

3.5. TESTS CONDUCTED

3.5.1. Compressive strength test

Compressive strength test measures the resistance of samples to gradually applied crushing load. Compressive strength of hardened mortar is the most important of all the properties. Therefore mortar is always tested for its strength before it is used in important works. The test was conducted as per IS 2250-1981, on 50mm x50 mmx 50mm cubical samples in a compression testing machine of capacity 2000KN at a loading rate of 6 N/mm^2.

The test was done for all the nine mixes for determining the 7th day, 28thday, 56th day as well as the 90th day compressive strength. For each test age of these mixes, three specimens were tested. Fig 3.8 shows the details of the test. The maximum load indicated by the testing machine was noted and compressive strength was calculated as;

$$f = \frac{P}{A}$$

Where;
f = Compressive strength (N/mm^2)
P = Maximum Load at failure (N)
A = Cross sectional area (mm^2)

Figure 3.9 Compression Testing Machine

3.5.2. Flexural strength Test

Flexural strength is a measure of tensile strength in bending. Flexural strength testing is carried out on a 40mm x 40mm x 160 mm cement mortar beam. There are two basic flexural tests: the third-point loading and the center-point loading. For the third-point loading test the beam is supported on each end and loaded at its third points and for the center-point loading test the beam is loaded at the middle until failure. The modulus of rupture is then calculated and reported as the flexural strength. The third-point loading test is preferred because, ideally, in the middle third of the span the sample is subjected to pure moment with zero shear. In the center-point test, the area of eventual failure contains not only moment induced stresses but also shear stress and unknown areas of stress concentration. Place the beam in the testing machine as shown in Figure 3.10 with its longitudinal axis normal to the supports. Apply the load vertically at the rate of 50 ±10 N/s until fracture. Three beam specimens for each test age where tested as per ASTM C 78 to determine the flexural strength of all the nine mixes.

Flexural strength was calculated as;

$$\sigma_f = {}^{M}/_{Z}$$

Where;

σ_f =Flexural strength (MPa)

M= Maximum bending moment (Nmm)

Z= Section modulus (mm^3)

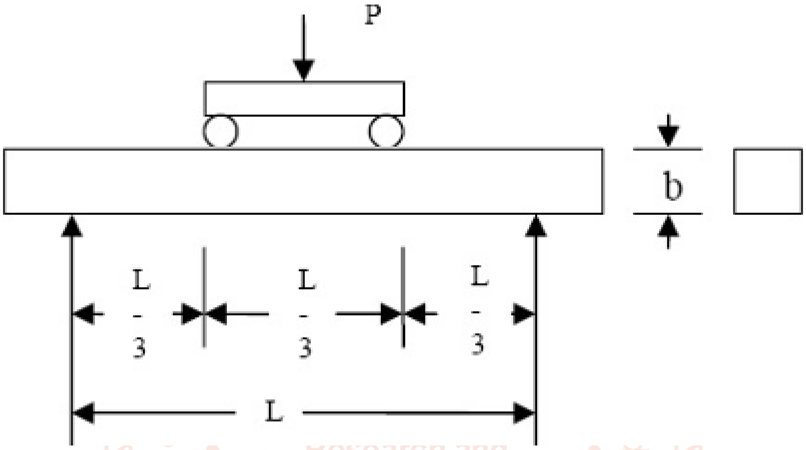

Figure 3.10 Third Point loading method

Fig 3.11 Flexural strength test on mortar beam

3.5.3. Sulphate attack Test

Sulphate attack is one of the most severe environmental deteriorations that affect the long-term durability of concrete. The term sulphate attack denote an increase in the volume of cement paste in concrete or mortar due to the chemical action between the products of hydration of cement and solution containing sulphates. Because of the increase in volume of the solid phase, a gradual disintegration of concrete takes place.

The resistance of mortar specimens against sulphate attack was determined as per ASTM C 1012. 50 mm x 50 mm x50 mm cube specimens were subjected to initial water curing for 3 days and then were transferred to a

20000 ppm sulphate solution prepared by dissolving 52 gm of $MgSO_4.7H_2O$ in one litre of water. After 7, 28, 56 and 90 days of sulphate exposure the effect of sulphate attack was determined from the mass loss and also comparing the compressive strength of the specimens with the strength of water cured specimens. Fig 3.11 shows mortar specimens subjected to sulphate attack.

Fig 3.12 Mortar specimens subjected to sulphate attack

3.5.4. Sulphuric Acid Attack Test

When concrete or mortar samples are exposed to acid solutions (pH less than 6.5) it will result in slow or rapid disintegration of the samples depending on the type and concentration of the acid.

To check the resistance of the mortar mixes against sulphuric acid, mortar cube specimens of size 50mm x 50mm x 50mm were exposed to 3%sulphuric acid solution, after initial water curing of three days. After7, 28, 56 days and 90 days of acid exposure, specimens were tested for compressive strength. The compressive strength of acid cured samples was then compared with the compressive strength of water cured samples, to determine the effect of acid attack. Fig 3.12 shows mortar specimens subjected to acid attack.

Fig 3.13 Mortar specimens subjected to acid attack

3.5.5. Rapid Chloride Permeability Test (RCPT)

Rapid chloride permeability test measures the electrical conductance of mortar samples, which is a measure of resistance of mortar samples to chloride ion penetration.Itwas performed on 100mm diameter and 50mm thick mortar disc specimens, as per ASTM C 1202-94. In RCPT, the disc specimen is fitted between two cells having a hole of 10cm diameter at its center covered by a pocket or reservoir for filling the solution. One of the faces of the specimen is exposed to 3% NaCl solution and the other face is exposed to 0.3 M NaOH solution. Electrode dipped in NaCl will be connected to the negative terminal of the power supply and that of NaOH to the positive terminal. Electrical connections to voltage application and data read out apparatus; i.e. a millimeter is made. 60V dc is applied across the faces continuously for a period of 6 hours and the current between the electrodes is monitored at 30 minutes interval.

The total charge passed is a measure of the electrical conductance of the concrete during the period of the test and is calculated by the formula

$$Q = 900(I_0 + 2I_{30} + 2I_{60} + \ldots.. + 2I_{300} + 2I_{330} + I_{360})$$

Where
Q = charge passed (coulombs)
Io =current (amperes) immediately after voltage is applied,
I_t= current (amperes) at t min after voltage is applied.

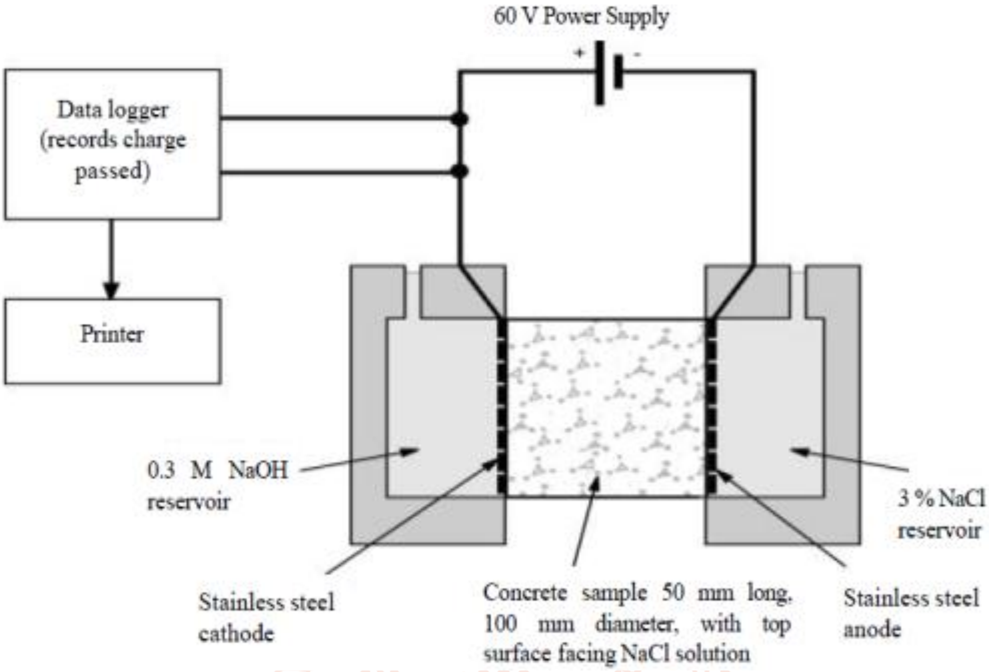

Figure 3.14 RCPT set up

Fig 3.15 RCPT specimen

Fig 3.16 RCPT setup in the laboratory

3.5.6. Sorptivity Test

Water is generally involved in every form of deterioration, and in porous solid, permeability of the material to water usually determines the rate of deterioration. The permeability of a mortar or concrete surface depends on many factors like mixture proportions, presence of chemical admixtures and supplementary cementitious materials, composition and physical characteristics of the cementitious component and of the aggregates, the entrained air content, type and duration of curing, presence of micro cracks, etc.

This method is intended to determine the susceptibility of an unsaturated mortar specimen to the penetration of water. The water sorptivity test on mortar measures the rate of movement of water through the mortar under capillary suction. It involves measuring the increase in the mass of a specimen resulting from absorption of water as a function of time when only one surface of the specimen is exposed to water. The lower the water sorptivity index, the better is the potential durability of the mortar.

Sorptivity test was conducted as per ASTM C 1585, the test consist of exposing the bottom surface of the sample to water and measuring the increment in mass resulting from absorption of water. Only one surface is exposed to water while the other surfaces are sealed simulating water absorption in a member that is in contact with water on one side only.

The test was conducted on 100mm x 50mm disc specimens, after subjecting to water curing for 28days. The specimens are then oven dried at a temperature of 50°C for 3 days. The oven dried samples are then allowed to cool in the laboratory condition. After weighing the specimens are placed on a support inside a tray with water, in such a way that water level is 1mm to 3 mm above the top of the support device.The flow from the peripheral surface is prevented by sealing it properly with non-absorbent coating.The test setup is shown in Fig 3.16. The mass of the specimen is measured at 0, 60,300,600,1200,1800,3600,7200,10800, 14400 and 18000 seconds after wiping excess water from the bottom surface using a damp cloth.The absorption, *I*, is the change in mass divided by the product of the cross-sectional area of the test specimen and the density of water. For the purpose of this test, the temperature dependence of the density of water is neglected and a value of 0.001 g/mm^3 is used.

$$I = \frac{m_t}{a \times d}$$

Where,
I = normalized absorbed water (mm)
m_t = change in specimen mass at time t (g)
a= area of specimen exposed to water (mm^2)
d= density of water (g/ mm^3)

The initial rate of water absorption or sorptivity (mm/s$^{1/2}$) is defined as the slope of the line that is the best fit to Iplotted against the square root of time (s$^{1/2}$). Obtain this slope by using least squares, linear regression analysis of the plot of I versus time$^{1/2}$.

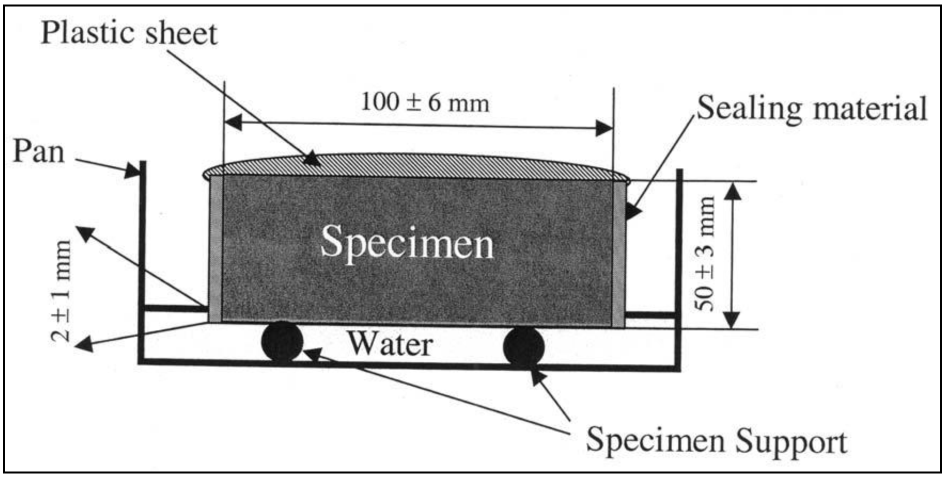

Fig 3.17 ASTM C 1585-04 standard test setup

4. RESULTS AND DISCUSSION

4.1. GENERAL

The strength and durability studies were conducted on all the nine mixes according to the procedures described in the previous chapter. The results obtained were tabulated and a detailed analysis and discussion on the results is presented in this chapter.Each test result plotted in the figures or in the tables is the mean value of results obtained by testing three specimens.The interpretation of the results obtained is based on the current knowledge available in the literature as well as on the nature of results obtained.

4.2. SUPERPLASTICISER DEMAND

Flow table test was conducted for all the nine mixes, to determine the superplasticizer dosage required to obtain a workability of 110±5%. Figure 4.1shows the quantity of superplasticiser required for 1kg of cementitious materials.

It can be seen that as the fly ash content increases superplasticiser demand decreases. This is due to spherical shape and smooth surface of fly ash particles. The smooth spherical fly ash particles act as small bearings to reduce the inter-particle friction in the mixture, thereby improving the workability and decreasing the superplasticiser demand. From the figure it can be observed that an increase in silica fume content increases the superplasticiser demand. This increase in superplasticiser demand or reduced workability is due to extremely fine particle size of silica fume (higher surface area) thus resulting in a greater superplasticiser demand. Ternary mixtures followed the trends of their constituent materials; i.e. for both ternary and binary mixes an increase in fly ash content improves workability and increase in silica fume content decreases workability. Minimum superplasticiser demand is observed for F(30)S(0) mix and F(30)S(5) mix and maximum superplasticiser demand is observed for F(0)S(10)mix.

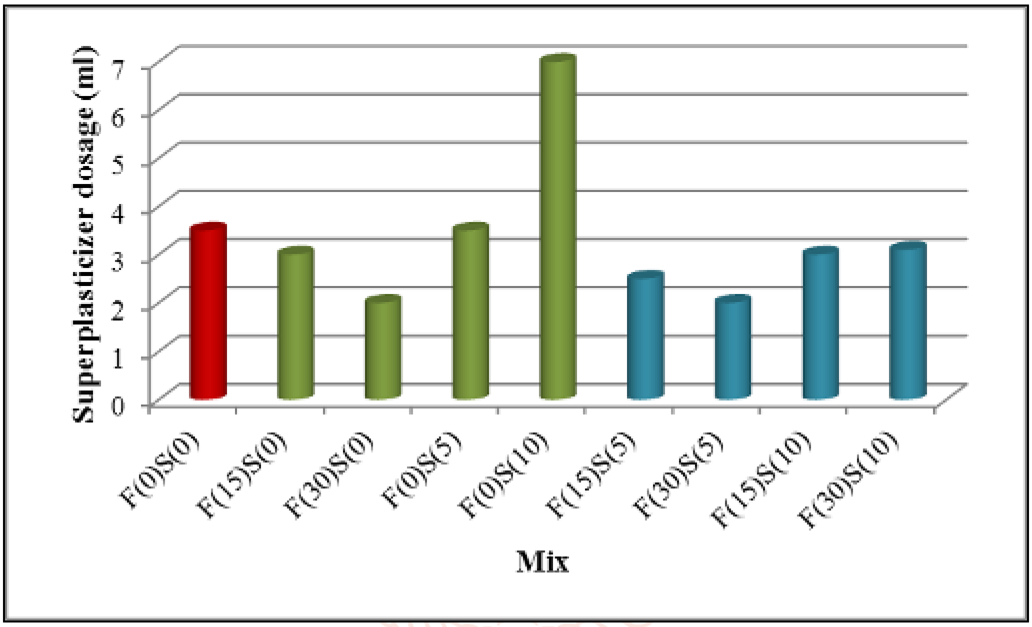

Figure 4.1 Superplasticiser demand for various mixes

4.3. UNIT WEIGHT

After demoulding the specimens, the unit weights of all the nine mixes were measured and the results are as presented in **Table 4.1.**It can be seen that maximum unit weight is obtained for control mix. As expected, the unit weight of the mortars with binary and ternary blends decreased with an increase in FA and SF content due to their low unit weight compared to that of cement. The unit weight of mortars with binary blends of FA/SF varied between 2.29 and 2.42 kg/m^3 whilst the unit weight of ternary blends of FA and SF ranged between2.25and 2.43 kg/m^3.

Table 4.1 Unit weight of various mixes

Mix	Unit weight (Kg/m^3)
F(0)S(0)	2.460
F(15)S(0)	2.420
F(30)S(0)	2.415
F(0)S(5)	2.359
F(0)S(10)	2.290
F(15)S(5)	2.430
F(30)S(5)	2.266
F(15)S(10)	2.310
F(30)S(10)	2.256

4.4. COMPRESSIVE STRENGTH

Compressive strength study was carried out on 50mm x 50mm x 50mm cube specimens at the ages of 7, 28, 56 and 90 days. Three specimens were tested at specified ages for all mixes. Table 4.2 shows the compressive strength values of all the nine mixes at different test ages.

Table 4.2 Compressive strength of different mixes

Mix	Cube Compressive strength N/mm^2			
	7 days	28 days	56 days	90 days
F(0)S(0)	23.20	32.70	40.80	42.00
F(15)S(0)	23.73	36.00	42.70	44.00
F(30)S(0)	21.60	30.80	37.06	37.07
F(0)S(5)	24.30	34.40	41.80	43.70
F(0)S(10)	24.92	34.90	42.60	44.1
F(15)S(5)	22.93	33.20	36.00	37.33
F(30)S(5)	22.67	32.46	35.47	37.20
F(15)S(10)	20.00	37.20	44.00	48.00
F(30)S(10)	18.13	35.02	37.33	38.40

4.4.1. Compressive Strength of Binary Mixes

A. OPC + FA mix

Fig 4.3 shows the compressive strength variationof control mix and binary blends of fly ash and ordinary Portland cement. From the figure it can be seen that fly ash improves the strength at low replacement level and at later ages. F (15)S(0) mix with 15% fly ash, gives better strength than the OPC mix. It may be due to the filler effect and pozzolanic reaction of fly ash. But the increase in strength of F(15)S(0) mix over control mix is significant at later ages only (28 days onwards). It may be attributed to the fact that, the pozzolanic reaction of fly ash is a slow process and hence its contribution to strength development occurs only at later ages.

When the fly ash content is increased to 30% in F (30)S(0) mix, the strength decreases and it is lower than the control mix. It may be due to the fact that at higher replacement levels Portland cement content level will be less which in turn reduces the amount of C-S-H gel resulting from the hydration of ordinary Portland cement.

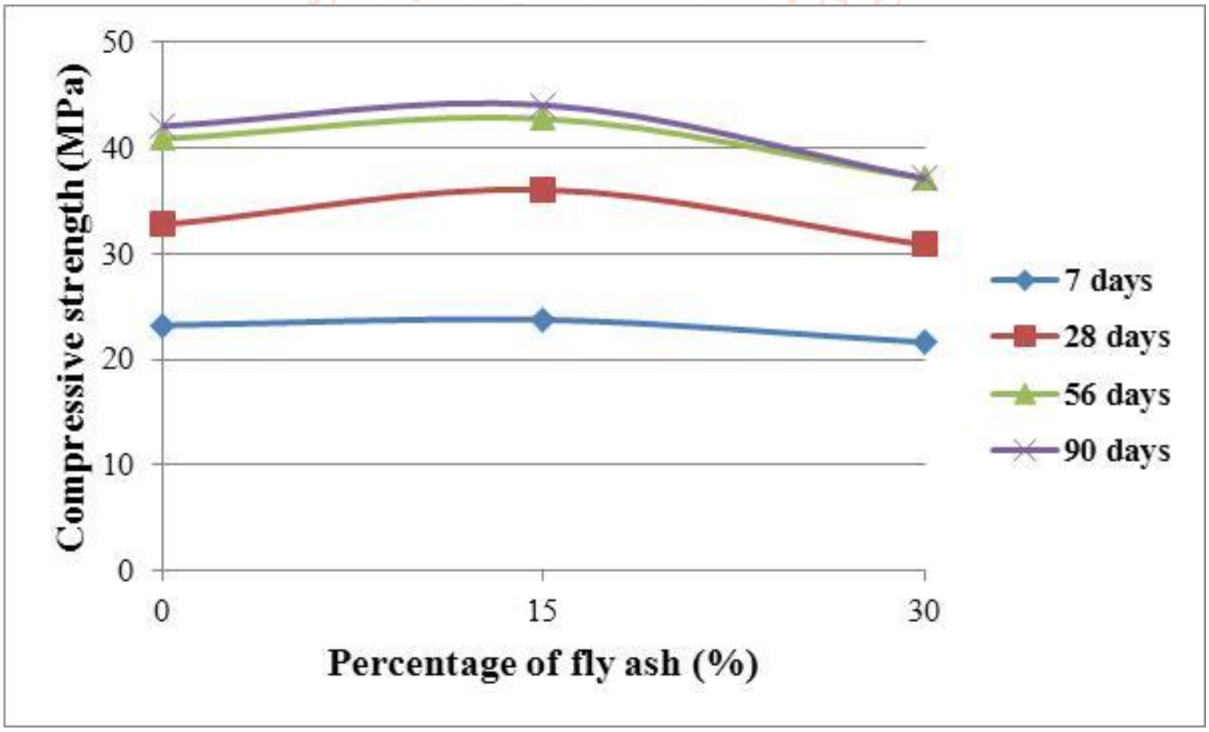

Fig 4.3 Compressive strength development of control and OPC+FA mixes

B. OPC+SF mix

Fig 4.4shows the compressive strength development in control mix and binary blends of OPC and SF. From the plot it is clear that as the silica fume content increases, the compressive strength also increases at all ages. Replacing OPC with SF resulted in strength gain of 4% and 5% in F(0)S(5) and F(0)S(10) mixes respectively at 90 days.

Improvement in compressive strength of mortar with the addition of silica fume may be explained by the chemical and physical effects of silica fume. Chemical effect is due to the pozzolanic reaction of silica fume. Silica fume consume the calcium hydroxide ($Ca(OH)_2$) crystals released from the hydration process, leading to the formation of further calcium silicate hydrate (secondary C-S-H gel) and thus improves the interfacial bond strength between aggregate particles and the matrix. The physical effect can be attributed to the filler effect. Due to its small particle size it gives a denser microstructure, as evident from the scanning electron microscopy image, thereby providing greater strength.

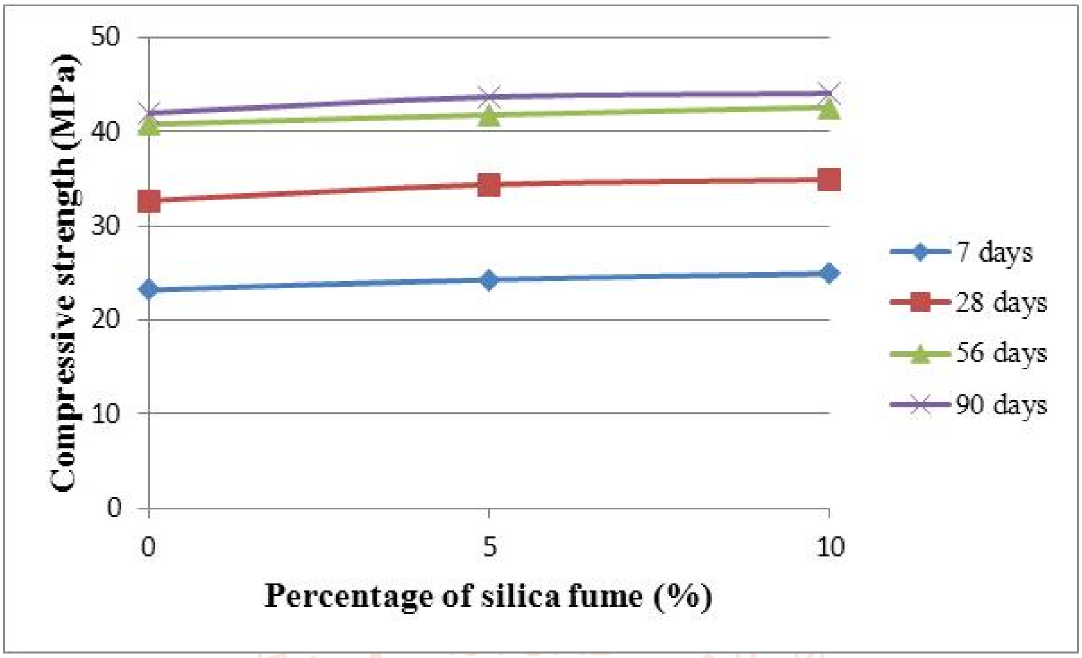

Fig 4.4 Compressive strength development of control and OPC+SF mixes

4.4.2. Compressive strength of ternary mixes

From Fig 4.5 andTable 4.1 it can be seen that the ternary mix F(15)S(10) shows better compressive strength than the control and other binary and ternary mixes. It shows 14.3% increase in strength when compared to the control mix. The behaviour of ternary mixes was in accordance with the trend predicted by the binary mixes. It can be seen that the effectiveness of silica fume in increasing the compressive strength of ternary blends was insignificant in mortar mixes with high fly ash content.

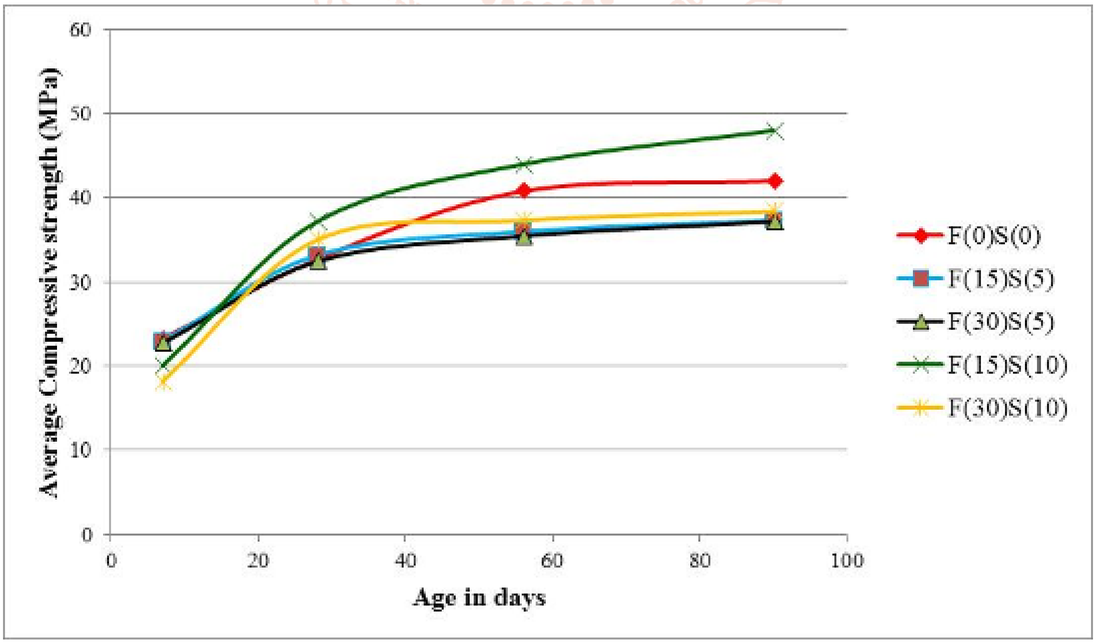

Fig 4.5 Compressive strength development of control and ternary mixes

Fig 4.6 shows the variation of 90 days compressive strength with percentage of cement replaced. From the figure it may be noted that maximum compressive strength is obtained for ternary blend F(15)S(10), with a cement replacement level of 25%. When the replacement level is increased beyond 25% the compressive strength decreases.

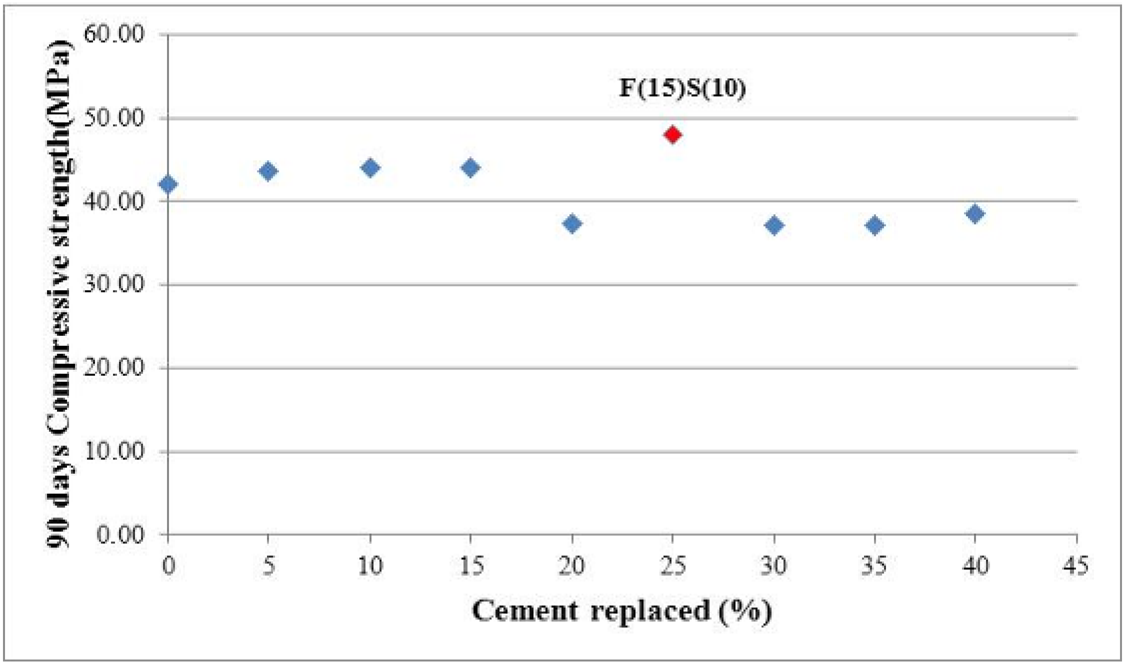

Fig 4.6 Compressive strength Vs percentage of cement replaced

4.5. FLEXURAL STRENGTH

Beam specimens of size 40mm x 40mm x 160 mm were tested for determining the flexural strength of the nine mixes. Fig 4.7 shows the variation of flexural strength for all the mixes. From the figure it can be seen that all the ternary mixes gives superior performance when compared to the control and binary mixes. It may be due to the filler effect and increased pozzolanic action by the addition of silica fume and fly ash. Maximum flexural strength of 12.85MPa is obtained for mix F(15)S(10).From the figure it is evident that better performance of ternary mixes is evident at later ages, because the pozzolanic reaction of fly ash is a slow process and hence its contribution to strength development occurs only at later ages.

Fig 4.8 shows the rate of strength development in different mixes. From the Fig 4.8 it can be clearly seen that rate of strength development in ternary mixes is greater than the control and binary mixes, and maximum value is obtained for F (15)S(10).

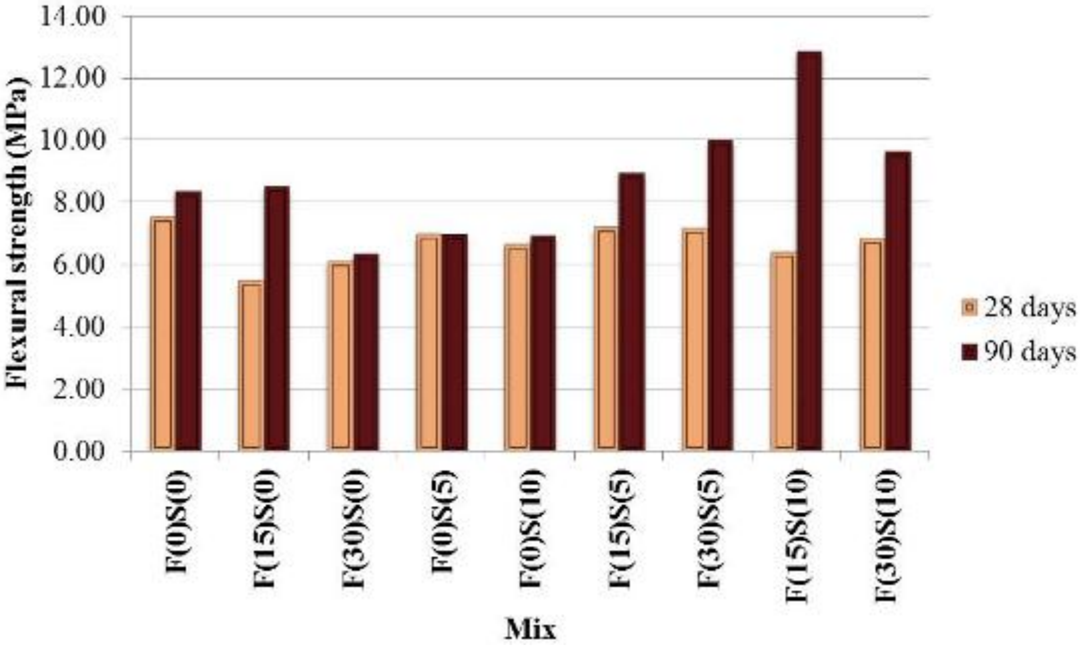

Fig 4.7Flexural strength of various mixes

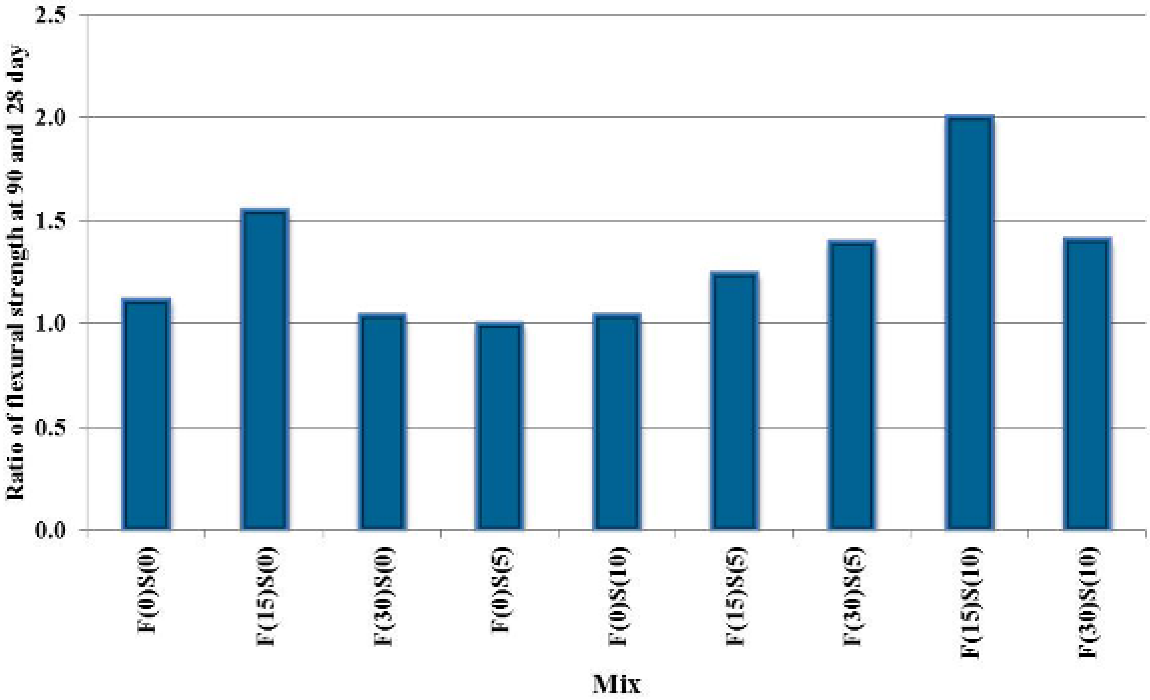

Fig 4.8Rate of increase in flexural strength with age

4.6. SULPHATE ATTACK TEST

The resistance of mortar specimens against sulphate attack was determined on cube specimens of size 50mm x 50mm x50mm, immersed in sulphate solution. After exposure to sulphate solution, white patches were found on the surface of mortarspecimens. The compressive strength variation of the specimens subjected to sulphate attack is as shown by Fig 4.9, Fig 4.10 and Fig 4.11. From Fig 4.9it can be seen that compressive strength of sulphate cured samples increases as fly ash content increases. Similarly from Fig 4.10 it is seen that an increase in silica fume content results in increase in compressive strength of sulphate cured samples. From Fig 4.11 it can be seen that all the ternary mixes show better sulphate resistance when compared to the OPC control mix.

The superior performance of blends may be due to reduced permeability and pozzolanic action. When supplementary cementitious materials like fly ash and silica fume are added, particles pack more tightly, hence there will be lesser voids, which in turn reduce permeability and improve sulphate resistance. Moreover pozzolanic reaction of silica fume and fly ash produces additional C-S-H gel or bond which grows into the capillary spaces that remain after hydration and improves the strength of matrix against sulphate attack. Maximum sulphate resistance is observed for F(15)S(10) mix. The 90 days strength of F(15)S(10) mix is 41.86MPa, which is about 15% greater than OPC control mix.

Table 4.3 Compressive strength of different mixes exposed to sulphate attack

Mix	Compressive strength (N/mm^2)			
	7 days	28 days	56 days	90 days
F(0)S(0)	18.00	26.40	31.20	36.27
F(15)S(0)	22.40	30.40	35.20	36.60
F(30)S(0)	24.80	30.40	36.00	37.00
F(0)S(5)	20.53	28.00	37.00	38.93
F(0)S(10)	20.00	28.00	39.20	41.06
F(15)S(5)	22.67	26.80	36.00	35.73
F(30)S(5)	23.20	29.86	34.40	36.00
F(15)S(10)	23.73	33.60	37.60	41.86
F(30)S(10)	20.26	29.60	36.00	36.53

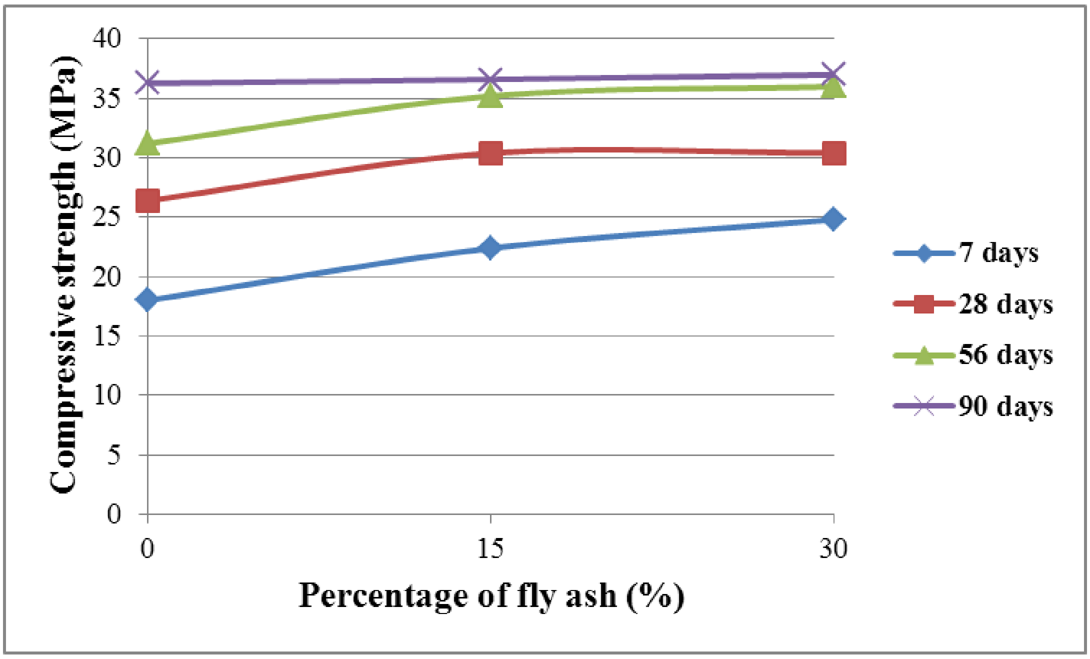

Fig 4.9 Compressive strength development of control and OPC+FA mixes subjected to sulphate attack

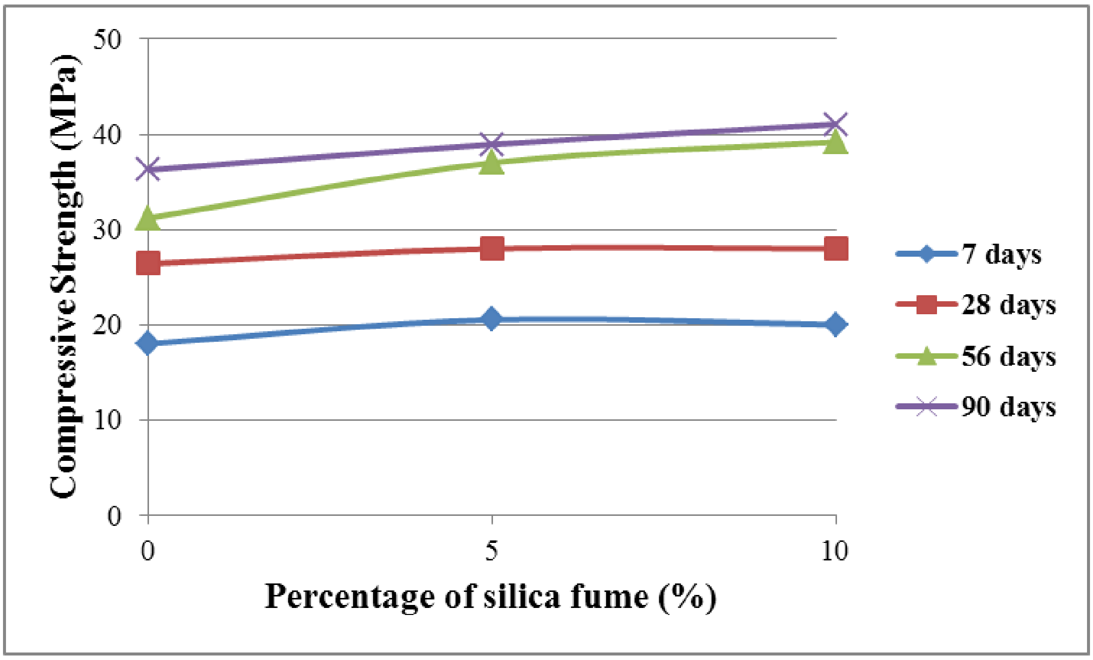

Fig 4.10 Compressive strength development of control and OPC+SF mixes subjected to sulphate attack

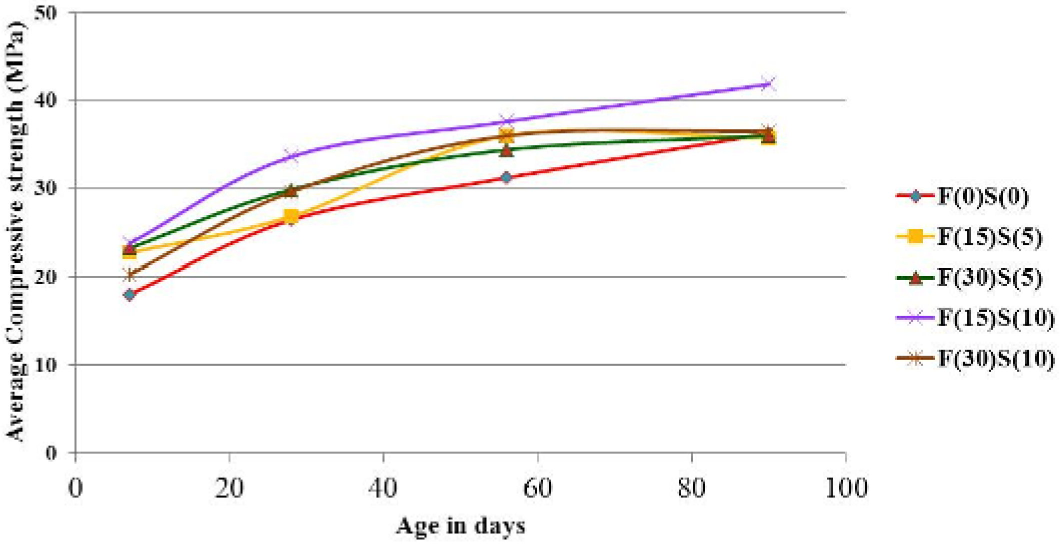

Fig 4.11Compressive strength of control and ternary mixes subjected to sulphate attack

The reduction of compressive strength due to acid attack was expressed in the form of strength deterioration factor (SDF).Fig 4.12 shows the SDF of different mixes when immersed in sulphate solution for 90 days.The results indicate that at higher levels of fly ash, strength deterioration under sulphate attack is less. It mayalso be noted that SDF value of all ternary mixes were less than the control mix. This higher resistance to sulphate attack might be because of the dense impermeable nature of the ternary mixes, due to the reduction of micro pores in the matrix on the addition of FA and SF. The binary mix F(30)S(0) suffers minimum strength loss when subjected to sulphate attack.

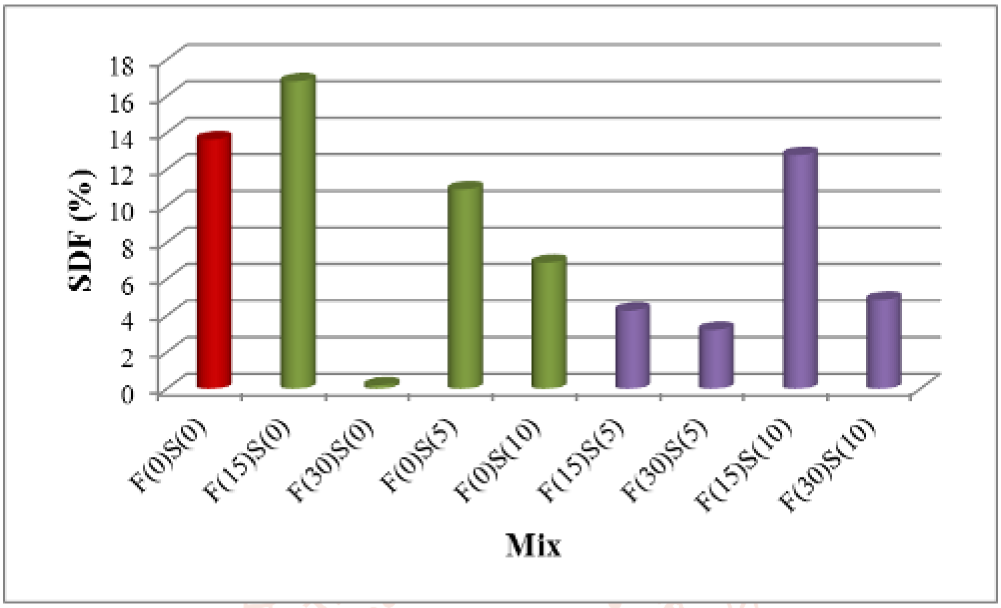

Fig 4.12 SDF values for various mixes when subjected to sulphate attack

4.7. SULPHURIC ACID ATTACK TEST

Table 4.4 shows the compressive strength of different mixes subjected to sulphuric acid attack. Fig 4.13 shows the compressive strength of control and binary mix containing fly ash after sulphate exposure. From the figure it can be seen that at 7, 28 and 56 days there is no commendable increase or decrease in the compressive strength with the addition of fly ash i.e. Binary blends give almost same result as that of OPC control mix. This may be due to the slow reaction rate of fly ash. At 90 days, mix with 15% fly ash shows better acid resistance when compared to the control mix; it may be attributed to the reduced permeability due to the addition of fly ash. But when fly ash content is increased further to 30% the strength decreases. This reduction in strength at 30% fly ash content may be due to deficiency of ordinary Portland cement in the mix.

Fig 4.14 shows the compressive strength development of control mix and binary blends of OPC and SF. From the figure it can be seen that incorporation of silica fume does not improve the acid resistance. When subjected to acid attack the binary blends of silica fume showed reduced strength when compared to OPC mix. Fig 4.15 shows the behavior of ternary blends under acid attack. It can be seen that at later ages (56 days onwards) ternary mix F(15)S(10) showed better acid resistance than the control mix. All other ternary mixes showed poor acid resistance when compared to the control mix.

Table 4.4 Compressive strength of various mixes subjected to acid attack

Mix	Compressive strength (N/mm^2)			
	7 days	28 days	56 days	90 days
F(0)S(0)	22.93	29.60	32.80	37.86
F(15)S(0)	22.93	28.53	32.80	43.20
F(30)S(0)	23.20	28.00	32.00	36.20
F(0)S(5)	24.00	27.20	30.40	34.26
F(0)S(10)	23.20	28.00	32.00	36.00
F(15)S(5)	21.86	22.40	31.20	34.93
F(30)S(5)	22.40	17.87	29.60	36.40
F(15)S(10)	25.06	24.80	34.93	43.20
F(30)S(10)	18.93	34.93	33.60	35.46

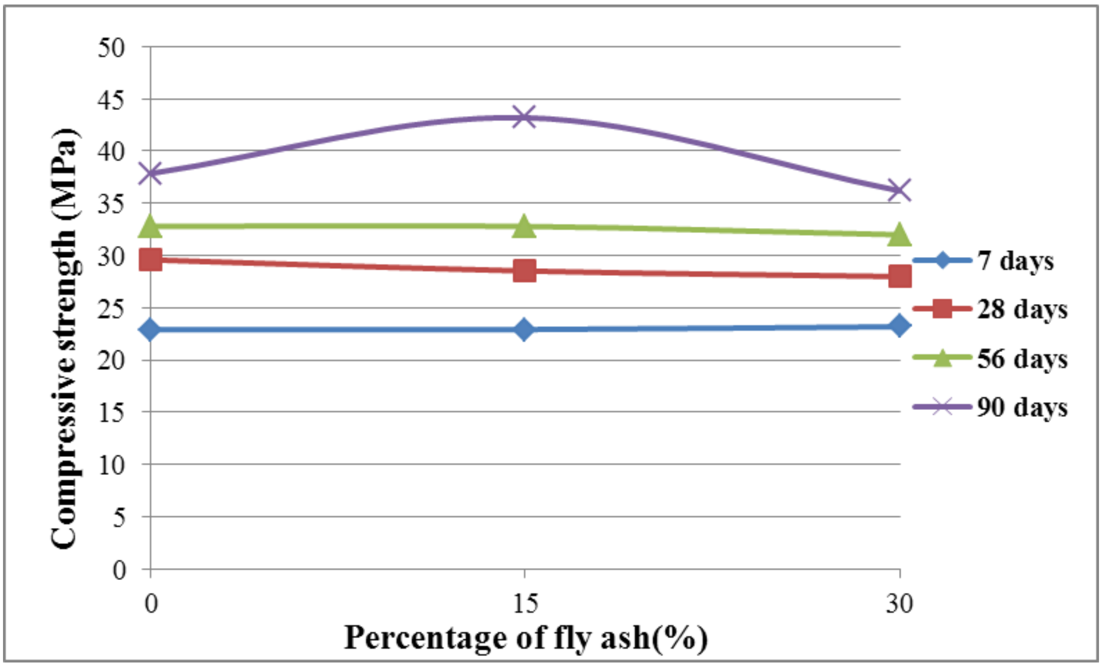

Fig 4.13 Compressive strength of control and OPC+FA mixes subjected to acid attack

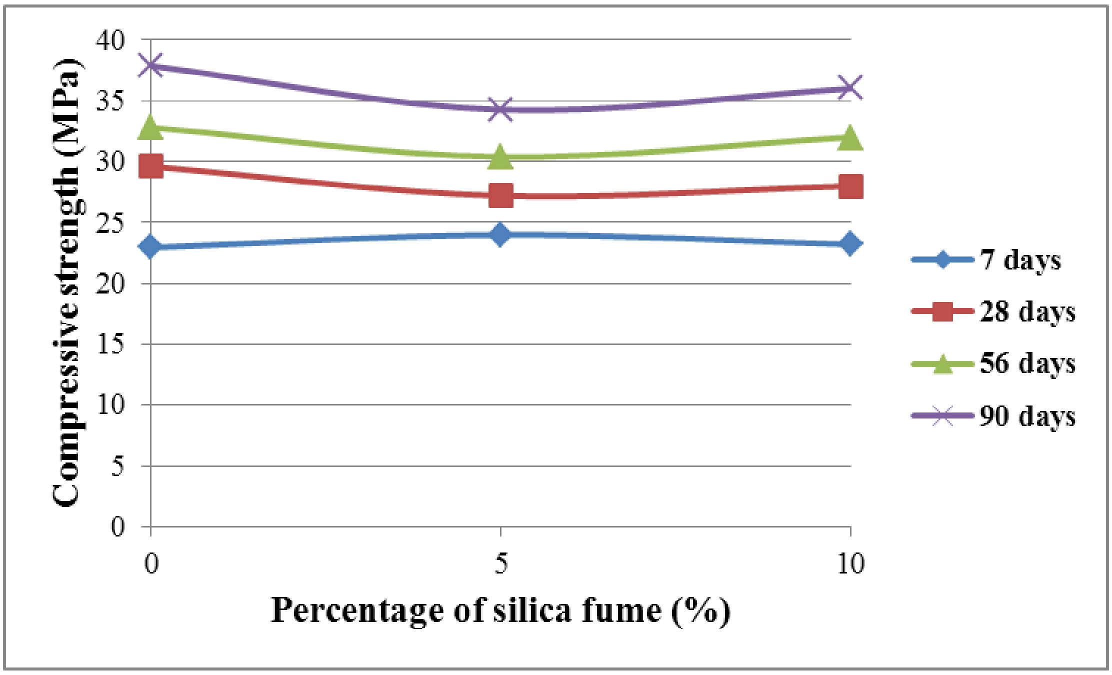

Fig 4.14 Compressive strength of control and OPC+SF mixes subjected to acid attack

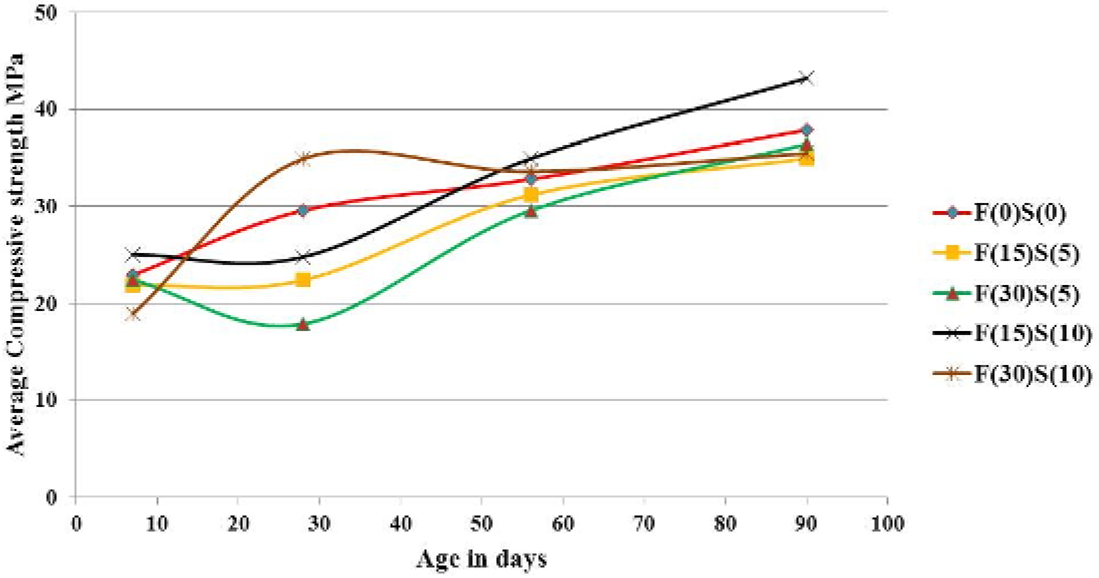

Fig 4.15Compressive strength of control and ternary mixes subjected to acid attack

The reduction of compressive strength due to acid attack was expressed in the form of strengthdeterioration factor (SDF).Fig 4.16 shows the SDF of different mixes when immersed in acid solution for 90 days. It may be noted that the binary mix F(15)S(0) suffers minimum strength loss when subjected to sulphuric acid attack. The SDF value of all ternary mixes was less than the control mix. This higher resistance to sulphate attack might be due to reduced permeability of ternary mixes due to denser microstructure. It may also be noted that binary blends of SF suffered maximum strength loss.

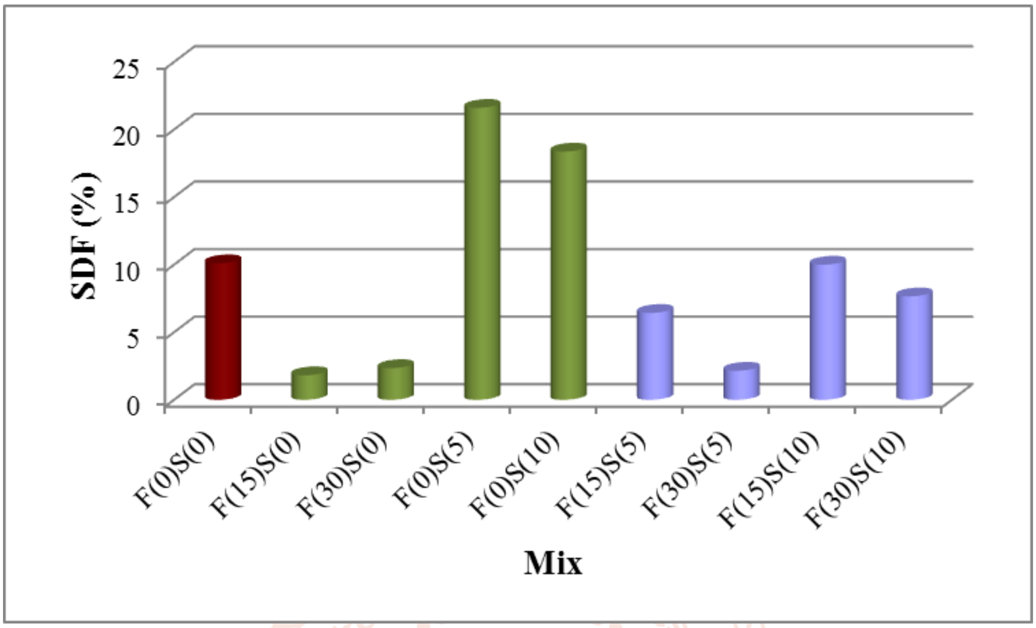

Fig 4.16 SDF values for various mixes when subjected to sulphuric acid attack

4.8. Rapid Chloride Permeability Test (RCPT)

The details of charge passed through different mixes are shown in Table 4.5.Fig 4.17 shows the variation of total charge passed with fly ash content and Fig 4.18 shows variation of total charge passed with silica fume content. It can be seen that an increase in fly ash content and silica fume content, in respective binary blends of fly ash and silica fume, results in increase of resistance to chloride ion penetration.

Fig 4.19 shows the variation of total charge passed in different mixes. It may be noted that ternary blends showed higher resistance to chloride ion penetration when compared to both control and binary mixes. Highest amount of charge is passed through control mix and least charge is passed through ternary blend F(30)S(10) mix. Thus the results clearly indicate that addition of fly ash and silica fume in mortar mixes reduces the chloride permeability. The reduced charge in the ternary and binary blends may be attributed to finer pore sixe distribution when compared to control mix. This results in decreased capillary porosity, which in turn increases resistance against chloride ion penetration.

Table 4.5Chloride Permeability of Different Mixes at 90 days

Mix	Total charge passed (Coulombs)
F(0)S(0)	751.86
F(15)S(0)	653.67
F(30)S(0)	383.58
F(0)S(5)	647.46
F(0)S(10)	501.66
F(15)S(5)	364.77
F(30)S(5)	274.95
F(15)S(10)	201.51
F(30)S(10)	141.84

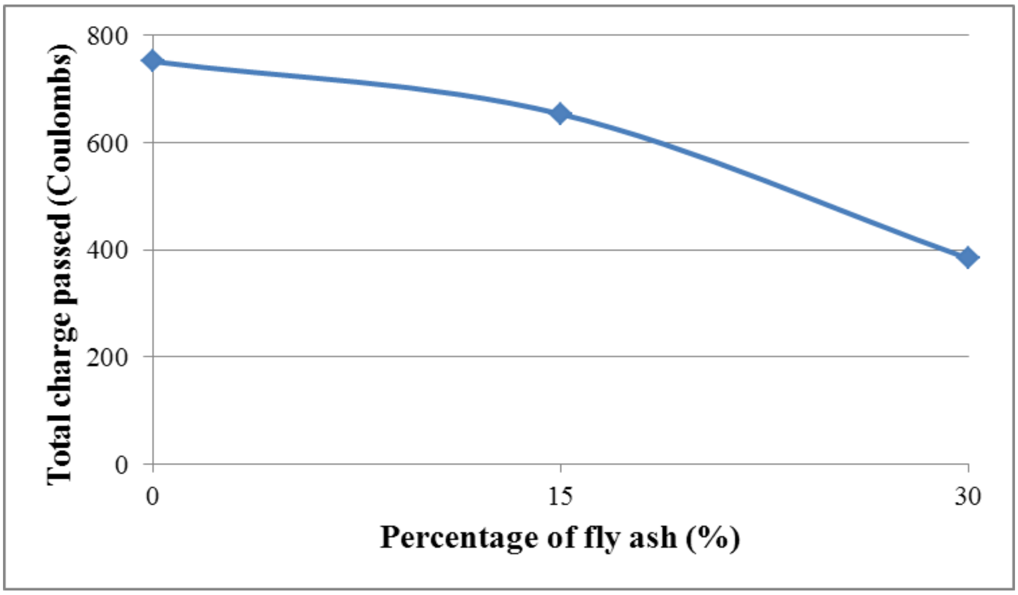

Fig 4.17 Total charge versus Percentage of fly ash

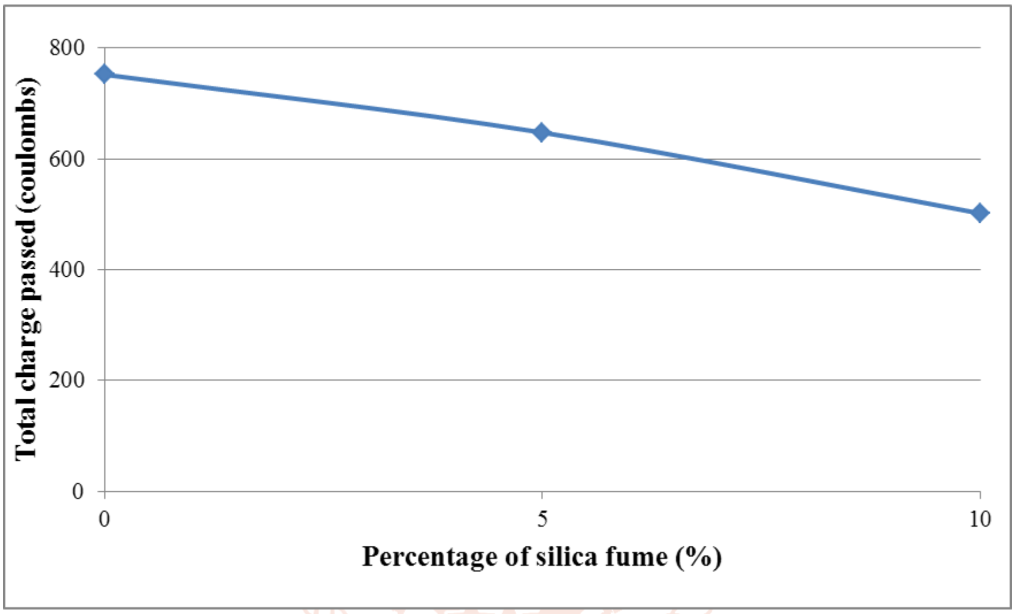

Fig 4.18 Total charge versus Percentage of silica fume

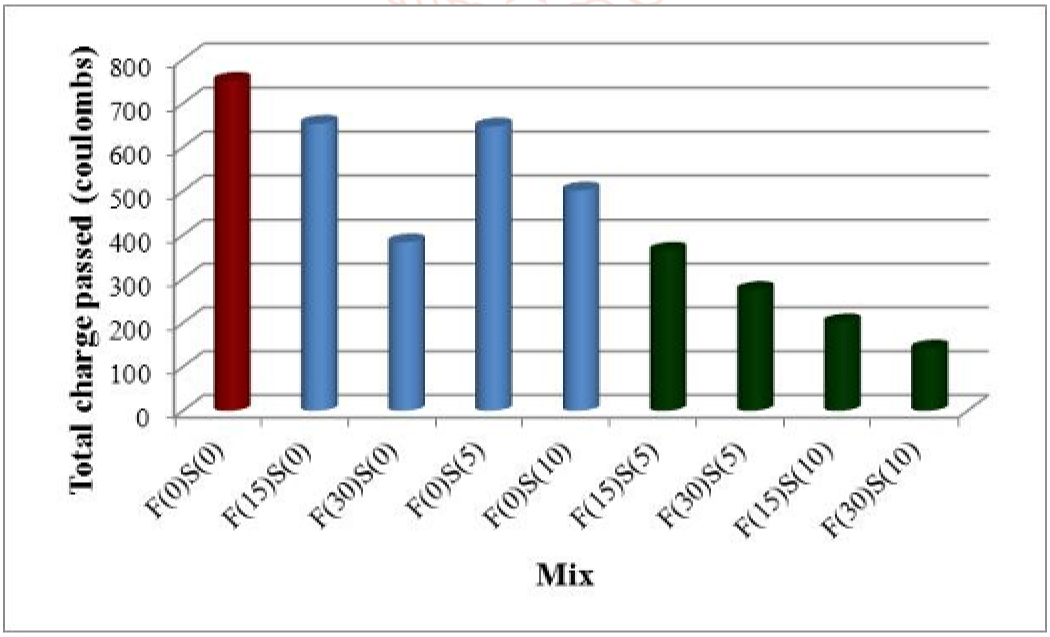

Fig 4.19 Total charge passed through different mixes

Fig 4.20 shows the variation of total charge passed through the specimens with the initial current observed during the commencement of the test.

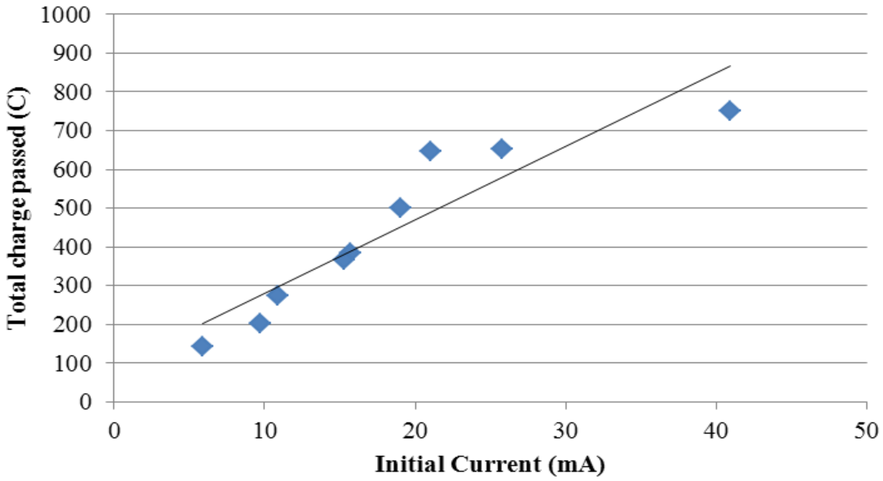

Fig 4.20Total Charge passed vs. Initial Current at 90 days

4.9. SORPTIVITY TEST

Sorptivity test was conducted on 100mm x 50mm disc specimens after 28 days of water curing, as explained in the previous chapter. Absorption of water (I) by all the mixes, in the first six hours was measured. Absorption measurements are then plotted as a function of square root of time. Sorptivity is taken as the slope of the curve (I vs.√t) during first six hours. The sorptivity values of all the nine mixes are presented in Table 4.6.

From Fig 4.21 it can be seen that binary and ternary mixes gave superior performance when compared to the control mix. Control mix exhibited a maximum sorptivity of 0.0085mm/s$^{1/2}$, and minimum sorptivity of 0.0041mm/s$^{1/2}$ was obtained for ternary mix F(30)S(5). On an average sorptivity of binary blends of fly ash was 36% lesser than control mix and sorptivity of binary blends of silica fume were 32% lesser than control mix. Sorptivity of ternary blends decreased on an average of 41% over the control mix.

Thus the results indicate that inclusion of fly ash and silica fume reduces the water absorption of mortar specimens. This may be due to the filler effect of fine fly ash and silica fume particles, which makes the water passage harder. When fly ash and silica fume are added particles pack more tightly with lesser voids, thereby reducing permeability and sorptivity.

Table 4.6Sorptivity of various mixes

Mix	Sorptivity (mm/s$^{1/2}$)
F(0)S(0)	0.0085
F(15)S(0)	0.0052
F(30)S(0)	0.0056
F(0)S(5)	0.0066
F(0)S(10)	0.0049
F(15)S(5)	0.0045
F(30)S(5)	0.0041
F(15)S(10)	0.0043
F(30)S(10)	0.0042

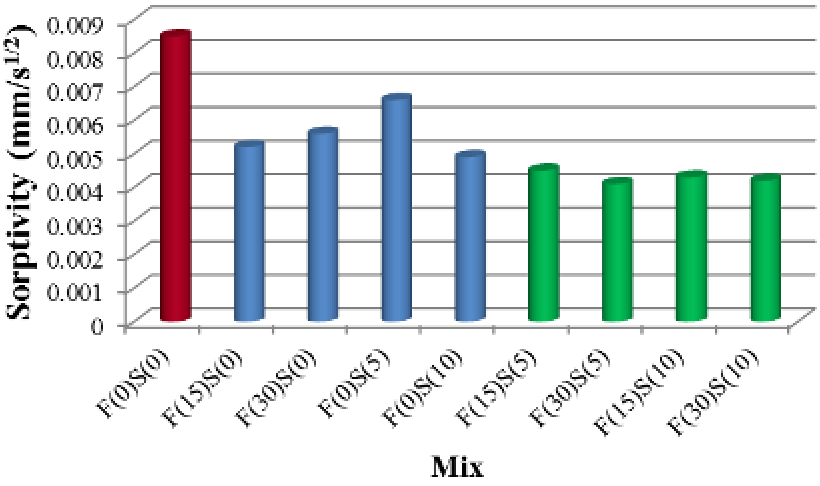

Fig 4.21Sorptivity of various mixes

4.10. QUANTIFICATION OF SYNERGY

The theoretical values of the strength and durability properties of ternary mixes were calculated using the equation described in the previous chapter and the magnitude of synergistic effect (S.E) was calculated using the equation:

$$S.E = j \times \left(\frac{P_{actual} - P_{theor}}{P_{theor}}\right) \times 100$$

Where SE is the synergistic effect (%), P_{actual} is a measured value of a given property, $P_{theor}$is a theoretical value of a given property and j = 1 for properties to be maximized (compressive strength) and j = -1 for properties to be minimized (rapid chloride permeability and initial sorptivity).

Figure 4.22 shows the synergistic effect in the development of 90 days compressive strength of the ternary blends. From the figure it may be noted that the ternary mix F(15)S(0) which gave superior compressive strength when compared to the control and binary mixes showed a maximum synergy of 5.3%. The SE values for all other ternary blends are typically negative, implying lack of any synergistic effect.

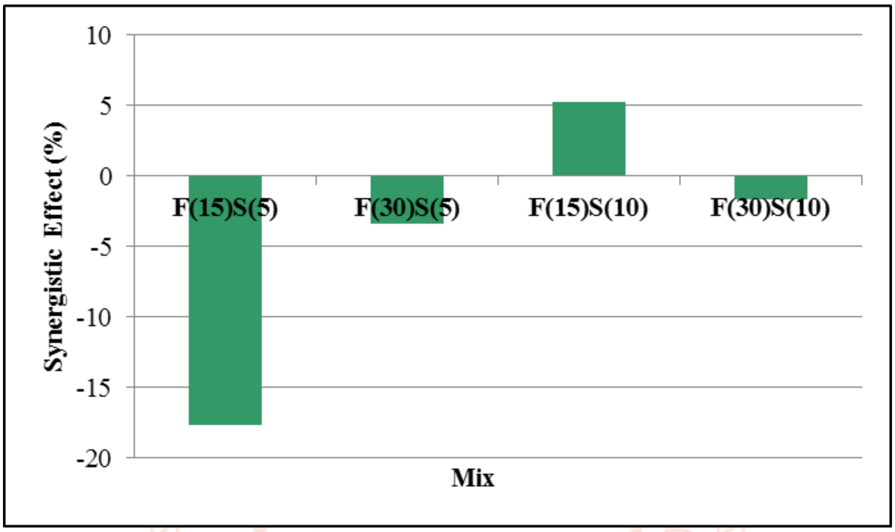

Fig 4.22 Synergistic Effect Vs Mix for 90 days compressive strength

Fig 4.23 shows the values of S.E for 90 days flexural strength of various ternary blends. It can be seen that all the ternary blends showed positive synergy. F(30)S(5) mix showed a Maximum S.E value of 82%.

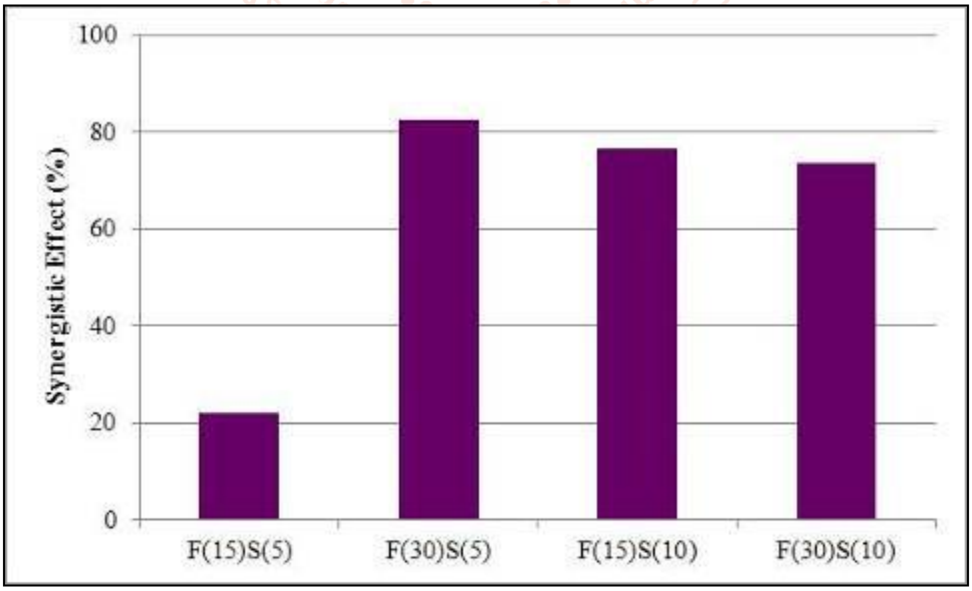

Fig 4.23Synergistic Effect Vs Mix for 90 days Flexural strength

Figure 4.24 shows the synergistic effect in the development of 90 days compressive strength of the ternary blends subjected to sulphate attack and acid attack. It can be seen that when the ternary mixes were subjected to sulphate attack only mix F(15)S(10) showed positive synergy. Under acid attack all the ternary mixes except F(15)S(5) showed positive synergy.

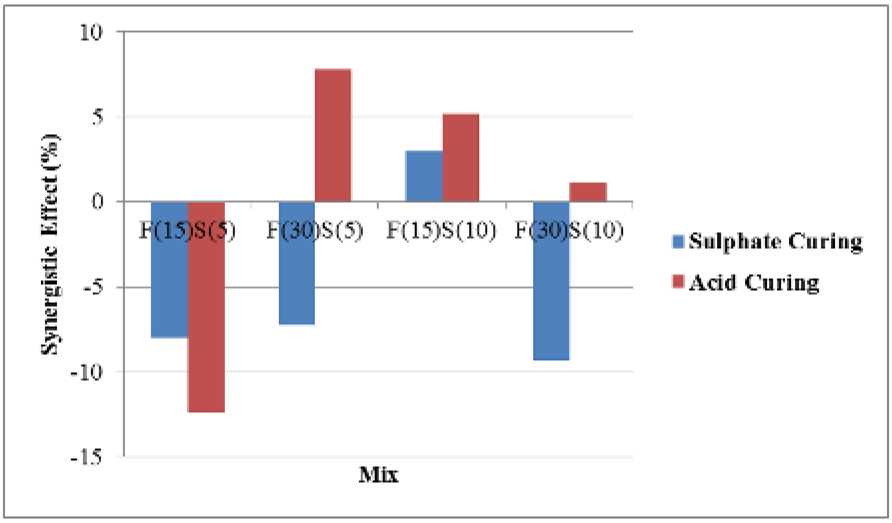

Fig 4.24Synergistic Effect versus Mix

Figure 4.25 shows the values of S.E for resistance to chloride ion penetration (RCP) of various ternary blends. It may be noted that all the ternary blends gave a positive S.E value. This implies that the excellent resistanceto chloride ion penetration observed for the ternary mixes is attributable to the synergistic interaction taking place between fly ash and silica fume. Maximum S.E value is obtained for F(15)S(10) mix.

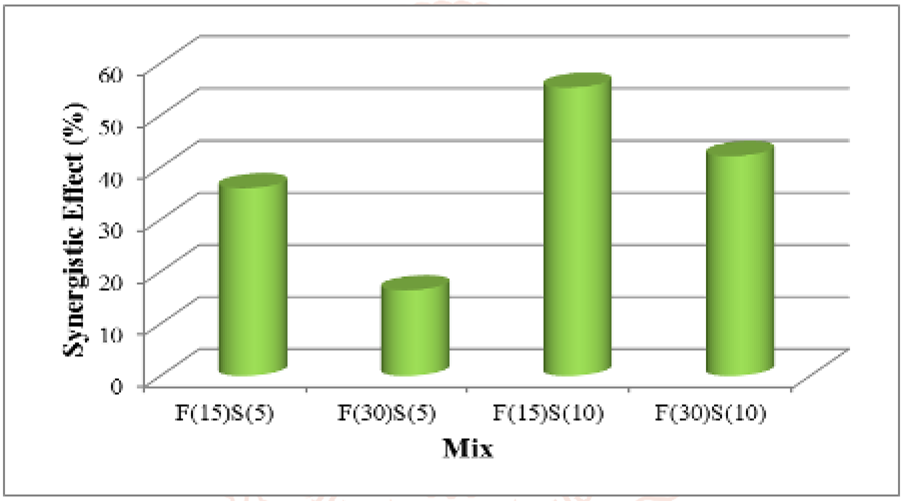

Fig 4.25 Synergistic Effect versus Mix for RCP

Fig 4.26 shows the values of S.E for sorptivity of various ternary blends. It may be noted that the ternary blend with least sorptivity showed maximum positive synergy of 7.2%. All other ternary blends showed negative synergy.

This however, does not necessarily imply that these mixes performed poorly. Quite the opposite the mix F(15)S(5) performed better than the control and binary mixes.

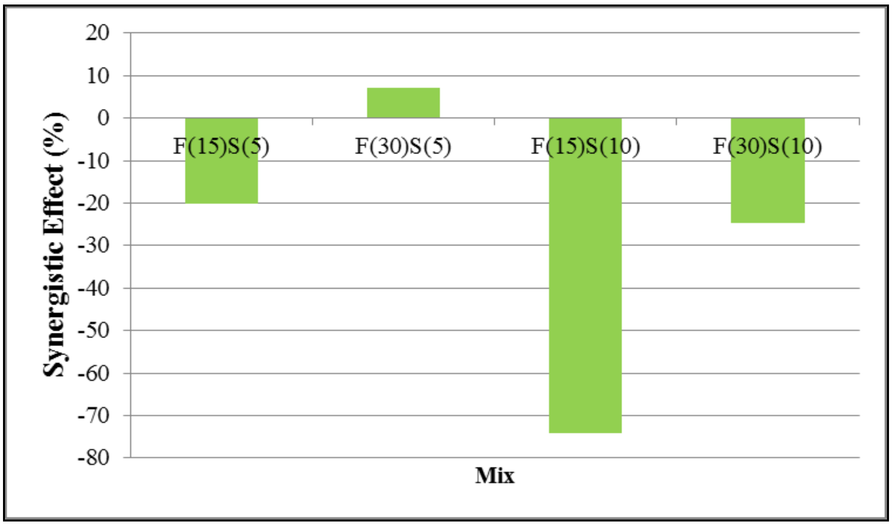

Fig 4.26 Synergistic Effect versus Mix for sorptivity

5. CONCLUSION

5.1. GENERAL

An investigation was carried out on the strength and durability properties of mortars with binary and ternary blended cementitious materials. Two kinds of supplementary cementitious materials namely fly ash and silica fume were blended with ordinary Portland cement to produce mortar for testing. The effects of binary and ternary blending of fly ash and silica fume with ordinary Portland cement were studied. A subsequent objective of the study was to verify and quantify synergistic effects in a ternary cementitious system containing fly ash, silica fume and ordinary Portland cement. The conclusions drawn from the present investigation based on the limited observations made during the study period and the scope for the future work are presented in this chapter.

5.2. CONCLUSIONS

Test results have shown that the ternary blended mixtures overall improved the mortar performance by improving the workability, strength and durability, therefore are applicable. Ternary mixtures overall performed in accordance with their ingredients; however the degree of improvement that they contribute varies based on the selected dosage and type of SCMs. The following conclusions are made based on the results:

- At constant water binder ratio, superplasticiser demand decreases with increase in fly ash content and increases with increase in silica fume content, i.e. fly ash improves workability and silica fume decreases workability.
- Maximum dry unit weight is obtained for control mix. The unit weight of the mortars with binary and ternary blends decreased with an increase in FA and SF content.
- Fly ash improves the compressive strength only at low replacement level and at later ages.
- Increase in silica fume content increases compressive strength at all ages.
- Maximum compressive strength was obtained for ternary mix F(15)S(10). It showed a 14.3% increase in 90 days compressive strength when compared to control mix.
- When the cement replacement level is increased beyond 25%, compressive strength decreases.
- All ternary mixes showed better flexural strength when compared to control and binary mixes. Maximum flexural strength was obtained for ternary mix F (15) S(10).
- Increase in fly ash content and silica fume content increases the compressive strength of mortar specimens subjected to sulphate attack.
- Under sulphate attack all ternary blends outperformed control mix, they suffered minimum strength deterioration when compared to control mix. Maximum compressive strength was obtained for F(15)S(10) mix.
- The compressive strength of control mix and binary blends of fly ash, subjected to acid attack are comparable at 7, 28 and 56 days of acid exposure. At 90 days binary mix with 15% fly ash showed greater compressive strength when compared to control mix.
- Incorporation of silica fume does not improve acid resistance.
- Addition of fly ash and silica fume increases the resistance to chloride ion penetration. Maximum resistance to chloride ion penetration was reported for ternary mix F(30)S(10) mix.
- Inclusion of SCMs like fly ash and silica fume reduces the water absorption of mortar specimens. Minimum sorptivity was obtained for ternary mix F (30)S(5).

5.3. SCOPE FOR FUTURE WORKS

- Effect of variation in mix composition can be studied by changing the fly ash content and the silica fume content.
- Effect of variation of water binder ratio on the strength and durability properties of ternary blends may be studied.
- Additional tests may be conducted to determine the effect of ternary blending on carbonation rate.
- The investigation may be extended to ternary blending of ordinary Portland cement, fly ash and silica fume in concrete.
- Petrographical study on the mineral formation of different ternary blends during hydration may be studied.
- The effect of quaternary blends on strength and durability parameters can be investigated.

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