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Rapid chloride penetration on high performance fly ash incorporated silica fume concrete

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ABSTRACT

Mechanical and durability properties of fly ash incorporated high performance silica fume concretes are discussed with respective to the obtained experimental results. Concrete specimens are prepared at the water-to-binder ratio of 0.28. The effect of inclusion of various percentages of silica fume (4%, 8%, 10% and 12%) on the workability, the Compressive strength and the Rapid chloride penetration, according to ASTM C 1202 are determined and compared with the reference mix in which 12% of fly ash is kept constant as cement replacement material. The consumption of alternative fine aggregate is an accepted step towards solving part of the depletion of natural aggregate and hence sand was substituted with M-sand of 50 %. Total binder content was kept constant as 600 kg/m^3 for all the concrete mixtures. Result show that the combination of 8 to 10 % silica fume and 12% fly ash increase the strength of concrete, but beyond 10% of silica fume with 12% of fly ash combination the compressive strength get decreased. The incorporation of silica fume and fly ash in the concrete mixtures, increased the resistance to chloride ions while an increasing percentage of silica fume in ternary mix and shaped the concretes with very low permeability - high performance.

Keywords- High Performance Concrete (HPC), Fly ash (FA), Silica Fume (SF), Compressive strength, RCPT.

1. INTRODUCTION

One of the commonly used construction material in the world is concrete. Production of concrete consumes more quantity of natural resources, and release of CO_2 into the air and leads to global warming. To increase the sustainability of concrete construction, it is much vital to replace the significant percentage of the ordinary Portland cement (OPC) with the supplementary cementitious materials (SCM). Due to the technical and beneficial advantages, the production of HPC is greatly recommended by the researchers [1]. From an environmental point of view, the use of byproduct and mineral admixture is paramount, since the huge amount of cement production create a lot of pollution related problems. This can be achieved by minimizing the amount of cement by using one or more supplementary cementitious material (SCM) s like fly ash (FA), metakaolin (MK), Ground Granulated Blast Furnace Slag (GGBS), silica fume (SF), alccofine (AF), rice husk ash (RHA) etc., helps in protecting the environment, and preserves cement and save the earth and its resources.

In HPC strength properties and durability characteristics can be improved by adding the cement replacement materials beside with chemical and mineral admixtures. While adding water, each supplementary material holds dissimilar properties and performs in a different way. Fly ash is one of the widely accepted by product material, used in blended cement [2]. Among class C and class F fly ash, class F is low-calcium fly ash, which is formed by burning anthracite or bituminous coal, give the strength of concrete by the nature of filling ability and pozzolanic effect [3]. It reduces the hydration heat and well performing with the durability behaviour when added in concrete as a cementitious material. Though there is a lot of benefit using fly ash, some practical problem still remains as like lower rate of increasing of strength at early stage of aging. This may due to the low pozzolanic reactivity of fly ash. FA has been widely utilized in concrete since it reduces the cost of the materials, conserves energy and resources and reduces environmental problems. The effects of FA on the various properties of concrete have been the subject of numerous investigations such as reported in ACI Committee 226 [3]. At the early stage of concrete the addition of silica fume increases the strength but reduces its permeability [4]. Its Particle size is very small and it can go into the gap available in between the cement particles, hence increases the particle packing behaviour of concrete. The silica fume, also produced high strength concrete when compared to the other cementitious materials. [5]

In India due to lack of availability of ternary cements comprising fly ash and silica fume which are commercially produced in some countries [6],this research intended to expand the knowledge concerning the proper use of these SCMs in concrete to produce HPC. The compressive strength of the ternary concrete was tested and analyzed relative to reference fly ash mixes. Synergy between the several types of cement replacement materials was considered for the excellent performance of the ternary system [7]. The properties of concrete having more than two SCMs were investigated and explained by Anwar et al. (2013) [8]. The main idea of the effort experimented here with is that positive assets of the one type of mineral admixtures could reward the limitations of the other. When the SCMs are added to the concrete, the amorphous silica present in it reacts with calcium hydroxide and (C-S-H) will be formed. This gives strength as well as improving the durability. Inclusion of FA in the binary system decreases the strength at an early stage, but long-term strength increases due to pozzolanic activation of FA at a later stage and sometimes exceeds the OPC concrete. On the other hand, binary mix of OPC with SF concrete shows higher strength at initial age, but the rate of gain of strength decreases with time and similar to OPC concrete. Thomas et al. (1999) confirmed that the combined usage of SF and FA in concrete as a ternary system lead to overall enhancements in mechanical properties [9].

On the other hand the natural material which is more stable and most commonly used as fine aggregate in the production of concrete is sand. Increasing demands of construction activities need more and more amount of sand. But lots of problems are there in the supply of naturally available fine aggregate. Many countries banned the storage of natural sand and made the way to find other useful materials or byproducts in place of that. This intends to use M- sand in the construction field as a replacement material for natural fine aggregate. This has not only made down the demand of sand from extraction, but also saves landfill space and etc. Hence, while preparing concrete M-sand was used.

However, the effect of a systematic increase in percentage replacement levels of mineral admixtures like SF on mechanical properties and durability property in terms of RCPT on higher binder content has not yet been thoroughly investigated. Jones et al. (1997) examined the durability performance of concrete containing ternary blended binders in comparison to OPC and binary blend of OPC+FA concrete [10]. He explained that the chloride resistance of all the ternary binder concrete is significantly higher than corresponding OPC and binary mixes. Other researchers [Elahi et al. (2010), Khan (2012) and Hariharan et al. (2011)] also reported that ternary blend of OPC+FA+SF has very high resistance to the permeation of chloride ions [11-13]. The work presented here, is the part of the research work dealing via the production and evaluation of ternary cementitious systems, made with FA + SF and the study explores the data to get optimum benefits on a ternary blend cement system having a lower water binder ratio and higher binder content and compare with that of the reference mix made by FA + SF.

2. MATERIALS PROPERTIES AND SPECIMEN PREPARATION

2.1. Materials

The ordinary Portland cement (OPC) -53 grade (Ultra Tech Cement), confirmed to IS12269:1987 [14] was used in this work. Class F fly ash (FA) obtained from the Ennore power plant, mostly composed of silicate glass containing aluminum, iron and alkalies - produced from burning anthracite or bituminous coal (ASTM 618) and silica fume (SF) which is a by product of the smelting process in the silicon and ferrosilicon industry, obtained from ELKEM (India) Ltd, Mumbai were used for production of ternary concrete mixture. Some of their chemical compositions and some physical properties are presented in Table 1.

The fine aggregate used for the production of concrete mixtures consisted of natural sand and manufactured sand in 50:50 proportion of Zone I having a specific gravity of 2.64 and 2.67 respectively. Coarse aggregates of size 20 mm and 12.5 mm with the specific gravity 2.71 and fineness modulus 7.28 for 20 mm and 6.30 for 12.5 mm were used. The w/b ratio and the slump of reference concrete were 0.28 and 110 mm respectively. The same water to binder ratio of 0.28 was used for the other concrete mixes with the slump of 90 to 120 mm. Subsequently, the amount of superplasticiser changed due to the influence of the different levels of binder contents with respect to their water demand. For mixing and curing of concrete, Potable tap water was used. The superplasticiser used to be Varaplast PC 432, ASTM C 494 Type G with the specific gravity of 1.08.

Table 1. Chemical Compositions And Physical Properties Of Binder

Chemical compositions	Cement	Fly ash	Silica fume
SiO_2	21.71	62.44	94.87
Al_2O3	7.58	24.23	0.60
Fe_2O_3	4.67	8.39	0.70
Alkalis ($Na_2O + K_2O$)	0.29	0.36	0.46
LoI	1.94	0.989	0.692
CaO	60.87	2.66	0.10
MgO	0.018	0.89	0.01
Physical properties			
Specific gravity	3.15	2.14	2.2
Standard consistency	27.5%	-	-
Fineness (m^2/kg)	303	300-315	20,000

As the ternary concrete mixture are generally wished-for for conditions where high durability is required [15], the work mainly focused on ternary concrete mixes having total binder content of 600 kg/m^3. In the reference mix (S0), the 12 % of cement was replaced with fly ash and used for comparison purpose. The mix and proportions, details of the concrete containing different percentages of silica fume are given in Table 2. Totally five concrete mixes (S0, S4, S8, S10, S12) were prepared using a mixer machine. The amount of silica fume which replaced cement in this research were 0%, 4%, 8%, 10% and 12% keeping 12% FA constant throughout. Mix Specifications describe the type and replacement level of binders used.

Table 2. Details Of Mix And Proportion

Mix ID	Mix Specification	Proportion of binder (kg/m^3)			Super plasticiser (kg/m^3)
		Cement	Fly ash (FA)	Silica fume (SF)	
S0	Reference mix CF12 (Cement + 12%FA)	528	72	0	2.90
S4	CFSF4 (Cement+12%FA+4%SF)	504	72	24	3.0
S8	CFSF8 (Cement+12%FA+8%SF)	480	72	48	3.40
S10	CFSF10 (Cement+12%FA+10%SF)	468	72	60	3.80
S12	CFSF12 (Cement+12%FA+12%SF)	456	72	72	4.0

MIX : Coarse Aggregate: 904 kg/m^3, Fine Aggregate: 738 kg/m^3, water: 168 kg/m^3, W/B=0.28

2.2. Preparation of specimens

- Measure all the mix ingredients in the proportions and make sure that all the accessories are moist (mixing drum, trowels, mixing trays, and rods). In addition, make sure that there is no standing water in mixing drum or pans.
- Place the coarse aggregate into the mixing drum and add silica fume with some of the water and mix for 1 ½ minutes
- Add the Portland cement and fly ash and mix for an additional 1 ½ minutes.
- Add the fine aggregate and use the remaining water to wash in chemical admixture added at the end of the batching sequence. Mix for 5 minute, rest for 3 minute, and mix for 5 minute. Moreover, ensure that it cannot be over mixed.

For the silica fume to be effective first, the agglomeration that make up the densified silica fume must be broken down and second the silica fume must be distributed uniformly throughout the concrete. After production of each concrete mix, the required specimen were cast according to standard procedure. The specimen were demoulded after the initial one day protection and were water cured until the time of testing.

3. EXPERIMENTAL PROGRAM

3.1 Workability And Strength Test

Experimental program has planned to provide sufficient information for ascertaining the optimum ternary combination of FA and SF in high performance concrete. Workability tests in terms of slump were carried out on fresh concrete as per IS: 1199 -1959 specifications. The results of the tests were furnished in Table 3. To evaluate the behaviour of HPC of ternary system, compression strength test on 150 mm size cubes at the age of 7 days and 28 days of curing were carried out as per BIS: 516-1959, using 3000 KN capacity compression testing machine. For each test for each mix, three specimens were tested and the average were reported in Table 3.In order to compare the performance of ternary mixtures with the OPC+FA binary blends the strengths of CF12 mix at a specified age were taken as reference value and expressed as 100%. The relative strength values of the ternary blends are shown in Table 3.

Table 3: Results Of Slump Value And Compressive Strength

Mix ID	**Mix Designation**	**Replacement Level of silica fume (%)**	**Slump value in mm**	**Compressive strength of cube (Mpa)**		**Relative Compressive strength (%)**	
				7 days	28 days	7 days	28 days

SO	CF12	0	110	68.32	74.14	100	100
S4	CFSF4	4	120	67.88	75.23	97.89	101.47
S8	CFSF8	8	110	69.32	87.95	96.96	118.63
S10	CFSF10	10	100	74.73	89.90	109.38	121.26
S12	CFSF12	12	90	62.26	78.20	91.13	105.48

3.2 Rapid Chloride Penetration Test

The Rapid Chloride ion Permeability Test (RCPT) ,for durability study was performed to find out the resistance of various mixtures to chloride –ion penetration in accordance with ASTM C1202 [16] using concrete disc of size 100 mm diameters and 50 mm thickness. After 28 days of curing, the concrete specimens were subjected to RCPT test. A 50 mm thick specimen is cut from the sample using the cooled diamond saw. The side of the cylindrical specimen was coated with epoxy, and after the epoxy is dried, it was put in a vacuum chamber for 3 hours. The specimen was vacuum saturated for 1 hour and allowed to soak for 18 hours. It was then placed in the test device. The left-hand side (–) of the test cell is filled with a 3% NaCl solution. The right-hand side (+) of the test cell is filled with 0.3N NaOH solution. The system was then connected and a 60 volt potential was applied for 6 hours. Readings (Current) were measured at every 30 minutes up to 6 hours. At the end of 6 hours, the sample was removed from the cell and the amount of coulombs passed through the specimen is calculated using the following formula.

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

Q = charge passed (coulombs),

Io = current (amperes) immediately after voltage is applied and

I_t = current (amperes) at t min after voltage is applied.

The experimental setup is shown in Figure 1. From the results using current and time, chloride permeability was calculated in terms of Coulombs at the end of 6 hours. A smooth curve through the data is drawn in a graph plotted with current (in amperes) versus time (in seconds) and the area underneath the curve was calculated to obtain the charge passed during the 6-hours test period. The total charge passed is a measure of the electrical conductance of the concrete during the period of the test and were mentioned in the Table 4 and Table 5.

Table 4. Chloride Ion Penetrability Based on Charge Passed (as per ASTM C1202)

Charge Passed (coulombs)	**Chloride Ion Penetrability**
>4,000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very low
<100	Negligible

Fig1: RCPT test set –up and apparatus used in this study

4.TEST RESULTS AND DISCUSSION

4.1. Water demand and Workability of Fresh Concrete

To maintain good workability and to have a slump of about 90 to 120 mm, the dosage of superplasticizer necessary for mixes containing different percentage of binder is shown in Table 2. From the results, it is clear that for a given slump value, the mixes incorporating higher silica fume content tend to require higher dosages of superplasticizer compared to lower SF content in the ternary Mix.This indicates the water demand variation of all mixtures. In ternary blend mixes of OPC+FA+AF, the SP doses were higher than the binary mixes of OPC+FA . FA act as small ball bearings owing to spherical particles hence the demand of SP is lower in binary mix of OPC+FA. On the other hand, due to very fine particles of SF , specific surface area increases and hence, SP dosage increases because of the more demand of water, that makes some of the superplasticiser being adsorbed on its surface. SF concrete exhibitated more cohesiveness than ordinary Portland cement concrete. All the mixes have shown satisfactory performance in relation to bleeding and segregation. It is well agreed with other finding, Jahren (1983) [17] .

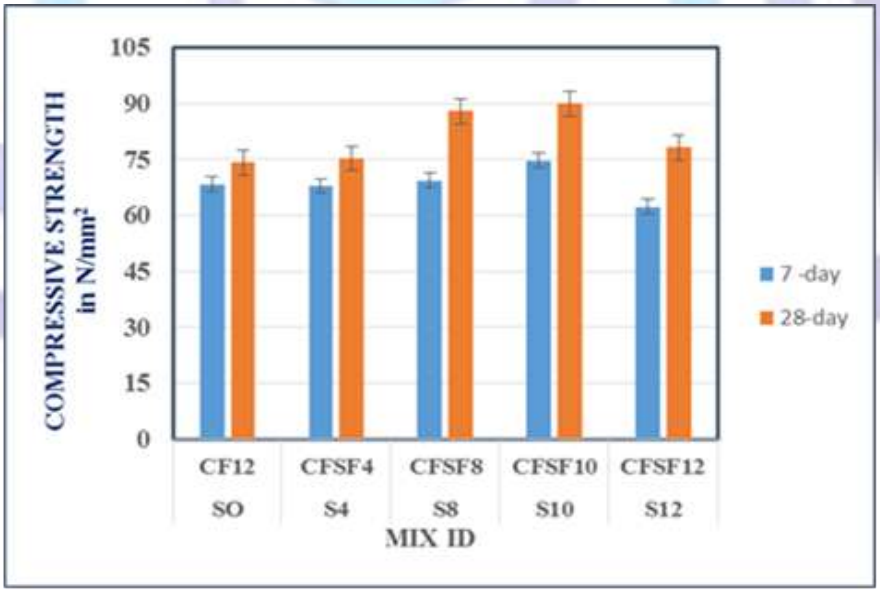

Fig 2: Effect of variation of silicafume on compressive strength of ternary mixes

4.2 Compressive Strength of Concrete Cube

The compressive strength of CF12 mix (reference concrete) attain the strength of 68.32 MPa and 74.14 MPa at 7 days and 28 days respectively shows high strength concrete,in which cement is replaced with 12% of fly ash and act as binary system. Nevertheless, due to continued pozzolanic reactivity, the fly ash concrete might have developed greater strength at later ages, which was more than that of the concrete without fly ash. [18] . Other four mixes produced with 12% of fly ash and different proportions of silica fume (4%, 8%, 10% and 12%) were specified as CFSF4, CFSF8 , CFSF10 and CFSF12 respectively. These ternary blend concrete having FA and SF combination results improvement in early strength at 7 days and strength development at 28 days as shown in figure 2. This maybe because in the hydration process, the fly ash provides sufficient lime to react with the pozzolans. More lime inhibit the process of hydration, but is still adequate to offer the required design strength. It has been observed that at the age of 28 day, the maximum compressive strength of cube obtained for the mix CFSF10 was 89.90 MPa. However,beyond 10% SF for ternary combination the 28 day strength was decreasing but it was higher than the reference mix. Hence, the optimum replacement level of silica fume for ternary cementitious mix was within 8 to 10%. The pozzolans added being finer than the cement fills the pores and voids in the concrete thereby increasing the compressive strength. The inclusion of SF shows early gaining of strength and that of fly ash shows a long term attainment of strength. Hence, the ternary system enhance better strength behaviour than binary system.The strength improvement is marginal for low SF content concrete because to cover the surface of all coarse aggregate particles the volume of silica fume is inadequate. As the SF amount is increased up to 10% , packing behavior also increased due to the improvement of the interfacial bond between the aggregate – cement matrix. It can be concluded that due to the action of amorphous silica available in the silica fume particles, strength enhancement of the concrete took place by both pozzolanic and physical actions.

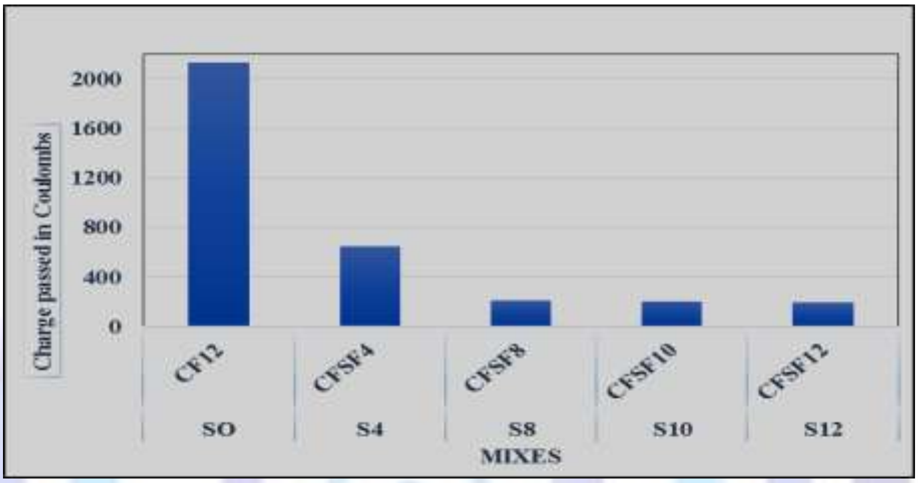

Fig 3: Chloride penetrating rate of ternary mixes having various percetage of silicafume

4.3 Rapid Chloride Permeability Test

The relationship between chloride penetrating rate and the charge passed by coulombs is given in Table 5 and figure 3. For reference concrete, the average charge passed was found to be 2128 and for silica fume mixed concrete the maximum charge passed was 648 after 28 days of curing. The charge passed for reference concrete has shown higher values than other ternary concrete mixtures. As per ASTM C1202, the value obtained for ternary concrete mixtures were graded under the category “very low”. As such, it is indicating lesser permeability concrete. The important observation is that addition of silicafume definitely reduces the pores of concrete and makes the concrete impermeable. Thus, the charge passed through the concrete mixture containing SF and FA can be used as a measure of the overall conductivity of concrete rather than as a measure of the resistance of concrete to chloride penetration. The charge passed was shown related to the compressive strength of SF and FA concrete; the compressive strength increases linearly with the charge passed decreasing

Table 5. Results for Rapid Chloride Ion Penetrating Test

S. No	Mix ID (Mix designation)	Charge passed in Coulombs	As per ASTM C1202 Chloride penetrating rate
1	SO(CF12)	2128	Moderate
2	S4(CFSF4)	648	Very Low
3	S8(CFSF8)	209	Very Low
4	S10(CFSF10)	201	Very Low
5	S12(CFSF12)	192	Very Low

6. CONCLUSION

The following conclusions were drawn based on the investigation carried out on the reference binary mix and ternary blended HPC mixes.

1.Water demand of ternary concrete mixtures was increased slightly while increaing the percentage of silicafume.

2. The High performance concretes with ternary system counteract the drawbacks of binary blended concretes.

3. In concrete using the ternary blend of FA+SF, the replacement level of OPC with the combination of 12% FA and 10% SF showed higher cube strength than the reference mix for 28 day. This significant improvement in the compressive strength of concrete may be because of the high pozzolanic nature and void filling ability of the silica fume .

4.This research indicates that the maximum strength can be attained at the percentage replacement of silica fume lie between 8 to 10%.

5. Whereas for 28 day, CFSF12 ternary mix with 12% SF, the strength get decreased but almost for all of the tested specimens 28 –day strength are greater than 100 %.

6.Ternary mixtures based on silica fume and fly ash had excellent durability performance interm of very low chloride ion penetration value at the age of 28 day.

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