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Effect of Partial Replacement of Cement with Silica Fume on the Strength & Durability Characteristics of High Performance Concrete Using Silica Fume & Super Plasticizer

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Abstract— The cement content of conventional high strength concrete is generally high which often leads to higher shrinkage and greater evolution of heat of hydration. In special situations a very high compressive strength of concrete is necessary together with sustainability to aggressive environments. Very few studies have been reported in India on the use of silica fume (SF) for development of high performance concrete (HPC). In order to make a quantitative assessment of different cement replacement levels with SF on the strength and durability properties for M90 and M100 grades of HPC trial mixes and to arrive at the optimum level of replacement of cement with SF, investigations were taken. This paper reports on the performance of HPC trial mixes having different replacement levels of cement with SF. The strength and durability characteristics of these mixes are compared with the mixes without SF. Compressive strengths of90MPa and 100MPa at 28 days were obtained by using 10 percent replacement of cement with SF.

Key words: Silica Fume, Concrete

I. INTRODUCTION

According to Nevillie "HPC is a concrete to fulfill specified purpose and no special mystery about it, no unusual ingredients or special equipments have to be used. But to understand the behaviour of concrete and will, to produce a concrete mix within closely controlled tolerances". Incorporation of mineral admixtures like Silica fume acts as pozzolanic material as well as micro fillers, thereby the microstructure of hardened concrete becomes denser and improves the strength and durability properties. Addition of chemical admixtures such as superplasticizer improves the properties of plastic concrete with regard to workability, segregation etc.

II. SIGNIFICANCE & OBJECTIVES

The objective of the present investigation is to investigate the workability, strength and durability characteristics for HPC mixes of grade M90 and M100 by replacing 0, 2.5, 5, 7.5, 10, 12.5 and 15 percent of the mass of cement with SF and using a superplasticizer. Also, an attempt is made to find the optimum cement replacement level by SF for strength and durability characteristics of HPC.Emphasis is given to study the durability characteristics of HPC and the related experiments are discussed in a detailed manner in this paper.

III. EXPERIMENTAL PROGRAMMER

A. *Materials used*

1) Ordinary Portland Cement, 53 Grade conforming to IS:12269-1987.
2) Silica fume as mineral admixture in dry densified form obtained from ELKEM INDIA (P) LTD., MUMBAI conforming to ASTM C-1240.
3) Superplasticizer (chemical admixture) based on Sulphonated naphthalene Formaldehyde condensate - CONPLAST SP430 conforming to IS:9103-1999 and ASTM C-494.
4) Locally available quarried & crushed blue granite stones conforming to graded aggregate of nominal size 12.5mm as per IS:383-1970 with specific gravity 2.82 and fineness modulus 6.73 as Coarse aggregates (CA).
5) Locally available Karur river sand conforming to Grading zone II of IS:383-1970 with specific gravity 2.60 and fineness modulus 2.96 as fine aggregates (FA).
6) Water : Drinking water supplied to Coimbatore city from Siruvani dam for concreting and curing.

B. *Mix Proportions & Preparation of Test Specimens*

Mix proportions are arrived for M90 and M100 grades of concrete based on Absolute volume method of mix design by replacing 0, 2.5, 5, 7.5, 10, 12.5 and 15 percent of the mass of cement by SF and the material requirements per m^3 of concrete are given in Table 1. The ingredients for various mixes are weighed and mixing was carried out using a drum type mixer and casting were done in steel moulds for concrete cubes 150mm size, cubes 100mm size, cylinders 150mm x 300mm, cylinders 100mm x 100mm, beams 100mm x 100mm x 500mm, 152mm diameter x 62.5mm thickness specimens and 70mm x 70mm x 35mm tiles. Curing was done under water for various desired periods.

C. *Details of Experimental Investigations*

1) *Workability & Strength Related Tests*

Workability tests such as slump test, compaction factor test and Vee-Bee consistometer test were carried out for fresh concrete as per IS specifications, keeping the dosage of superplasticizer as constant at 3 percent by weight of binder. For hardened concrete, cube compression strength test on 150mm size cubes at the age of 1day, 3days, 7days, 14days,28days and 56days of curing were carried out using 3000 kN capacity AIMIL compression testing machine as per IS:516-1959. Also, compression strength and split tensile strength tests on 150mm x 300mm cylinders and flexural strength tests on 100mm x 100mm x 500mm beams were carried out on 28 days cured specimens as per IS specifications. The stress-strain graph for HPC is obtained using compress meter fitted to cylinders during cylinder compressive strength test for finding Modulus of Elasticity for HPC mixes.

2) Durability Related Tests

The durability related tests such as Saturated Water Absorption (SWA) test, Porosity test, Sorptivity test, Permeability test, Acid resistance test, Sea water resistance test, Abrasion resistance test and Impact resistance test were carried out on hardened concrete specimens at the age of 28 days of curing.

3) Test for Saturated Water Absorption & Porosity

The water absorption was determined on 100mm cubes as per ASTM C-642 by drying the specimens in an oven at a temperature of 105^{o} C to constant mass and then immersing in water after cooling to room temperature. The specimens were taken out of water at regular intervals of time and weighed. The process was continued till the weights became constant (fully saturated). The difference between the water saturated mass and oven dry mass expressed as a percentage of oven dry mass gives the SWA. The SWA of concrete is a measure of the pore volume or porosity in hardened concrete, which is occupied by water in saturated condition. It denotes the quantity of water, which can be removed on drying a saturated specimen. The porosity obtained from absorption tests is designated as effective porosity. It is determined by using the following formula.

Effective Porosity = (Volume of voids / Bulk volume of specimen) x 100

The volume of voids is obtained from the volume of the water absorbed by an oven dry specimen or the volume of water lost on oven drying a water saturated specimen at 105^{o} C to constant mass. The bulk volume of the specimen is given by the difference in mass of the specimen in air and its mass under submerged condition in water.

4) Test for Modified Sorptivity

Sorptivity measures the rate of penetration of water into the pores in concrete by capillary suction. When the cumulative volume of water that has penetrated per unit surface area of exposure 'q' is plotted against the square root of time of exposure '$\sqrt{t}$', the resulting graph could be approximated by a straight line passing through the origin. The slope of this straight line is considered as a measure of rate of movement of water through the capillary pores and is called sorptivity. In this present study, the test for sorptivity was conducted on 100mm cubes by immersing them in water and measuring the gain in mass at regular intervals of 30 minutes duration over a period of 2 hours.

5) Permeability Test

Permeability is related to the durability of concrete, specially its resistance against progressive deterioration under exposure to severe climate. The tests for permeability were carried out on 100mm x 100mm cylinders as per IS:3085-1965, using a AIMIL Concrete permeability apparatus. Cylinders are kept in permeability mould and tightly packed and sealed. Water pressure was applied at a pressure of 10 kg/cm^2 over cylinders using air compressor. The water percolated through the cylinder specimens was collected in a glass bottle for a period of 100 hours and coefficient of permeability was calculated using the following formula.

Coefficient of permeability,

$$K = \frac{AT}{(H/L)} \tag{1}$$

Where

– Q= quantity of water in milliliters percolating over the entire period of test after the steady state has been reached,
– A= area of specimen face in cm^2,
– T= time in seconds over which Q is measured, and
– H/L= ratio of pressure head to thickness of specimen, both expressed in the same units.

6) Acid Resistance Test

Cubes of 150mm size were weighed and immersed in water diluted with 1 percent of sulphuric acid by weight of water for 45 days continuously and then the cubes were taken out and weighed. The percentage loss in weight and the percentage reduction in compressive strengths were calculated.

7) Sea Water Attack Test

Cubes of 150mm size were weighed and immersed in water diluted with 3 percent of sodium chloride by weight of water for 45 days continuously and then the cubes were taken out and weighed. The percentage loss in weight and the percentage reduction in compressive strengths were calculated.

8) Abrasion Resistance Test

Deterioration of concrete surface may occur due to abrasion by sliding, scraping or action of abrasive materials carried out by water. The tests for abrasion resistance were carried out on specimens of 70mm x 70mm x 35mm size, using Tile Abrasion testing machine. The specimen was kept in the abrasion testing machine after measuring the thickness accurately. The testing machine was allowed to rotate for 300 revolutions by keeping the speed of the machine as 30 rev/min. specimens were taken out and weighed and final thickness were found out.

9) Impact Resistance Test

The tests for impact resistance were carried out on specimens of size 152mm diameter x 62.5mm thickness, using Drop weight testing machine. The specimens were kept on the base plate and centered. A drop hammer weighing 45 N was used to apply the impact load. The number of blows required by dropping a hammer through a height of 457mm to cause the ultimate failure, was recorded.

IV. TEST RESULTS & DISCUSSION

The results of workability, strength and durability related tests are listed in Tables 2,3,4 and 5. The results of strength and durability tests have demonstrated the superior strength and durability characteristics of the concrete mixes containing SF.

A. Workability & Strength related Properties

It was observed that the workability of concrete decreased as the percentage of SF content was increased. The optimum percentage of cement replacement by SF is 10 percent for the above tests for M90 and M100 grades of concrete. This is due to the fact that the increase of strength characteristics is due to the pozzolanic reaction and filler effects of SF. The ratio of cylinder to cube compression strength was found to be 0.81.The flexural strength and Modulus of Elasticity values obtained experimentally are higher and lower than the values calculated by the expression 0.7 $\sqrt{f_{ck}}$ and 5000 $\sqrt{f_{ck}}$ respectively as per IS:456-2000.

B. Durability Related Properties

The results of durability related tests have demonstrated the superior durability characteristics of the concrete mixes containing SF.

C. Saturated Water Absorption, Porosity & Sorptivity

From the test results, it has been observed that the optimum percentage of cement replacement by SF for M90 and M100 grades of concrete is 10 percent for achieving lowest SWA, porosity and sorptivity. It is also to be noted that the SWA, porosity and sorptivity of HPC mixes containing SF are lower compared to that of HPC mix without SF. This is due to the improvement in microstructure due to pozzolanic reaction and micro filler effects of SF, resulting in fine and discontinuous pore structure. The SWA of the concrete mixes was around 1.8 percent. The Concrete Society, UK, classifies the concretes with SWA of around 3 percent as good concretes. This indicates that the performance of HPC mixes developed in the present study could be considered to be good from the point of view of SWA. Taywood Engineering Ltd., (1993) has suggested that good concretes have sorptivity of less than 0.1 mm / $min^{0.5}$. This comparison proves that the HPC mixes developed in the present study could be considered to have shown superior sorptivity performance.

D. Permeability

No percolation of water has been found for M90 and M100 grades of concrete mixes. Immediately after this, the cylinders were removed from the permeability mould and were split to measure the water penetration depth. Water penetration was found to be negligible in all samples of HPC mixes containing SF, whereas for the mixes without SF the depth of water penetration was more. This confirmed that use of SF and low w/b ratio had resulted in almost impermeable concrete.

E. Acid Resistance & Sea Water Resistance

From the results of percentage loss in weight and percentage reduction in compressive strengths, it has been observed that M90 and M100 grades of HPC mixes containing SF were less attacked by acid and sea water compared to the HPC mixes without SF. Hence, HPC mixes containing SF are more durable against acid and sea water attack.

F. Abrasion Resistance & Impact Resistance

The results of average loss in thickness obtained from abrasion resistance test and the average number of drops at failure from the impact resistance test for M90 and M100 grades of HPC mixes showed that the concrete mixes containing SF have higher abrasion and impact resistance. This is due to the formation of stable calcium silicate hydrates (C-S-H gels).

V. CONCLUDING REMARKS

Based on the results of investigation reported in this paper, the following conclusions are made.

- The optimum percentage of cement replacement by SF for M90 and M100 grades of concrete is 10 percent for achieving maximum compressive, split tensile and flexural strengths and Elastic Modulus.
- The IS:456-2000 code underestimates the flexural strength and overestimates the Modulus of Elasticity for HPC.
- Cement replacement level of 10 percent with SF in concrete mixes is found to be the optimum level to obtain lower value of SWA, porosity and sorptivity at the age of 28 days.
- The use of SF and low w/b ratio resulted in practically impermeable concrete.
- Concrete mixes containing SF showed higher values of acid resistance, sea water resistance, abrasion resistance and impact resistance.
- The results of the strength and durability related tests have demonstrated superior strength and durability characteristics of HPC mixes containing SF. This is due to the improvement in the microstructure due to pozzolanic action and filler effects of SF, resulting in fine and discontinuous pore structure.
- Even a partial replacement of cement with SF in concrete mixes would lead to considerable savings in consumption of cement and gainful utilization of SF. Therefore, it can be concluded that replacement of cement with SF upto 10 percent would render the concrete more strong and durable. This observation is in par with the maximum limit of 10 percent for mineral admixture in concrete mixes as recommended by IS: 456-2000.

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Mix	SF (%)	w/b ratio	Cement (kg)	SF (kg)	FA (kg)	CA (kg)	Superplasticizer (lit)	Water (lit)
M90 Grade								
C11	0	0.268	541.0	0	737.1	1070	13.30	140.26
C12	2.5	0.268	527.5	13.5	732.3	1070	13.30	140.26
C13	5	0.268	514.0	27.1	727.4	1070	13.30	140.26
C14	7.5	0.268	500.4	40.6	722.6	1070	13.30	140.26

C15	10	0.268	486.9	54.1	717.8	1070	13.30	140.26
C16	12.5	0.268	473.4	67.6	713.0	1070	13.30	140.26
C17	15	0.268	459.9	81.2	708.2	1070	13.30	140.26
M100 Grade								
C21	0	0.25	580.0	0	705	1070	14.26	139.56
C22	2.5	0.25	565.5	14.5	700	1070	14.26	139.56
C23	5	0.25	551.0	29	694	1070	14.26	139.56
C24	7.5	0.25	536.5	43.5	689	1070	14.26	139.56
C25	10	0.25	522.0	58	684	1070	14.26	139.56
C26	12.5	0.25	507.5	72.5	679	1070	14.26	139.56
C27	15	0.25	493.0	87	674	1070	14.26	139.56

Table 1: Details of HPC Trial Mixes for M90 Grade

Properties	C11	C12	C13	C14	C15	C16	C17
Silica Fume (%)	0	2.5	5	7.5	10	12.5	15
CubCube compressive strength (MPa),							
1 day	26.40	32.66	34.33	36.14	40.26	39.54	37.74
3 days	42.62	48.22	49.86	54.52	61.34	55.82	54.62
7 days	57.16	62.84	68.42	72.86	76.93	72.36	69.84
14 days	65.54	71.53	74.22	78.66	87.36	83.74	82.66
28 days	74.24	82.20	84.64	91.77	99.86	95.28	92.32
56 days	82.85	91.64	94.35	101.98	110.74	104.22	101.36
Cylinder comp. strength (MPa), 28 days	59.48	64.65	67.52	73.64	80.66	75.26	74.54
Split tensile strength (MPa), 28 days	5.30	5.84	6.12	6.38	6.60	6.24	6.15
Flexural strength (MPa), 28 days	7.90	8.40	8.70	9.2	9.90	9.40	9.10
Elastic modulus (GPa), 28 days	34.5	37.5	38.1	39.8	40.8	39.3	38.8
Slump (mm)	49	46	44	40	35	24	15
Compaction Factor	0.91	0.90	0.88	0.86	0.84	0.81	0.78
Vee-Bee degrees (secs)	13	16	17	18	19	38	46

Table 2: Strength Related Properties of HPC Mixes for M90 Grade

Properties	C21	C22	C23	C24	C25	C26	C27
Silica Fume (%)	0	2.5	5	7.5	10	12.5	15
Cube compressive strength (MPa),							
1 day	28.59	34.37	36.00	39.41	44.74	44.59	41.19
3 days	45.78	52.74	52.89	59.56	67.11	62.07	60.89
7 days	62.37	68.74	73.63	80.15	84.75	80.15	78.07
14 days	71.41	76.88	80.88	85.04	97.19	93.33	92.00
28 days	83.11	89.04	93.89	100.80	110.66	105.33	102.67
56 days	91.68	98.40	103.2	110.75	122.10	114.23	111.75
Cylinder comp. strength (MPa), 28 days	65.64	69.43	74.92	80.70	89.64	83.75	82.62
Split tensile strength (MPa), 28 days	5.81	6.41	6.89	7.16	7.53	7.41	7.31
Flexural strength (MPa), 28 days	8.60	9.00	9.40	9.60	10.40	9.80	9.40
Elastic modulus (GPa), 28 days	38.0	39.0	39.5	41.4	41.5	40.8	40.9
Slump (mm)	30	28	27	25	25	18	15
Compaction Factor	0.86	0.85	0.83	0.82	0.81	0.78	0.75
Vee-Bee degrees (secs)	15	17	18	18	20	55	64

Table 3: Strength Related Properties of HPC Mixes for M100 Grade

Properties		`C11	C12	C13	C14`	C15	C16	C17
Silica Fume (%)		0	2.5	5	7.5	10	12.5	15
Saturated water absorption (%)		1.72	1.48	1.34	1.26	1.16	1.19	1.25
Porosity (%)		2.73	2.47	2.30	2.18	2.10	2.14	2.22
Sorptivity (mm/min $^{0.5}$)		0.0473	0.0251	0.0234	0.0210	0.0185	0.0194	0.0216
Permeability (cm/sec)		nil	nil	nil	nil	nil	Nil	Nil
Acid resistance	Loss in Wt. (%)	2.84	1.31	1.20	1.11	1.02	0.94	0.86
	Loss in comp. st. (%)	12.74	4.85	4.38	3.92	3.33	3.05	2.90
Sea water resistance	Loss in wt. (%)	2.44	1.12	1.02	0.94	0.88	0.81	0.76
	Loss in comp. st. (%)	9.20	3.64	3.25	3.14	3.01	2.78	2.49

Impact resistance	Average number of drops at failure	210	234	239	243	259	268	289

Table 4: Durability Related Properties of HPC Trial Mixes of M90 Grade

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