MECHANICAL PROPERTIES OF HIGH PERFORMANCE CONCRETE USING CONDENSED SILICAFUMES

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ABSTRACT

High Performance Concrete is a recent concept in concrete technology. High performance concrete (HPC) is defined as the concrete which satisfies the special performance and uniformity requirements that cannot always be achieved by using conventional materials, normal mixing, placing and curing practices. The reasons cited for use of HPC in special structures like water storage, high rise buildings, nuclear power plants and earthquake resisting structure etc are due to very low porosity through a tight and refined pore structures of the cement paste, high early strength and continued strength development, improved durability in aggressive environment, reduction in cross sections of structural members, more energy absorption, no repair and retrofitting jobs, increase in life span of the structure and a strong interfacial bonding between the aggregates and the cement paste.

This paper highlights an experimental investigation on the strength characteristics of High Performance Concrete (HPC) mixes, with different replacement levels of cement with Condensed Silica Fume (CSF) of Grade 960–D, where D- stands for silica fume is in the densified form and 960 stands for the grade which is highly used in refractory. The production of HPC Concrete needs the use of chemical and mineral admixtures like superplasticizers and condensed silicafume. The compressive strength of 11095 psi at 28 days with 7.5 percent replacement of Ordinary Portland Cement (OPC) by CSF and 8811 psi at 28 days with 5 percent replacement of Portland Pozzolanna Cement (PPC) with CSF was achieved. Also a maximum compressive strength of 12945psi at 90 days with 7.5 percent replacement of Ordinary Portland Cement (OPC) by CSF and 10986 psi at 90 days with 5 percent replacement of Portland Pozzolanna Cement (PPC) by CSF was observed for a water cementitious *materials ratio 0.32. Micro structural studies like sorptivity test, saturated water adsorption test and porosity were also studied to check the impermeability of High Performance Concrete. Condensed silica fume concrete is more resistance to acids, where a significant damage is observed in plain concrete mix. Ultrasonic pulse velocity test has been carried out in order to check the concrete quality like durability, constructability and strength. The pulse velocity for the concrete mixes was found to be greater than 4570 m/s that fall under the excellent category. Thus, the HPC cubes have excellent quality. Superplasticizers were used for HPC cubes to enhance the workability of concrete mixes.*

KEY WORDS

High performance Concrete (HPC), Condensed Silica fumes (CSF), Ordinary Portland Cement (OPC), Portland Pozzolanna Cement (PPC), Superplasticizers.

INTRODUCTION

High Performance Concrete (HPC) is a recent concept in concrete technology. It is defined as the concrete, which satisfies the special performance and uniformity requirements that cannot be always achieved by using conventional materials, normal mixing, placing and curing practices. HPC has high strength, high durability and high constructability[8, 17]. Condensed Silica Fume (CSF) is a by-product of the ferrosilicon alloy industries and contributes significantly to compressive strength development of concrete because of the micro filler effect and excellent pozzolanic properties of the material. The use of CSF in concrete increases the calcium silicate hydrate (C-S-H) gel formation that is mainly responsible for the high strength, high durability of concrete structures and reduction of pore sizes in the transition zone [2,13].

ADVANTAGES OF HPC

Durability: The increased durability of HPC constitutes the most important contribution to modern concrete construction. The durability of concrete is related to aspects like permeability, alkali silica reaction, resistance against chemical attack etc.

High compressive strength: The high compressive strength of HPC is one of the most striking features. When ordinary concrete find it difficult to exceed strength of 5076 to 5800 psi, HPC reaches 8700 to 14500 psi[13].

Early age strength: HPC exhibits high early age strength. Thus it is possible to achieve a faster re-use of formwork.

Ease of placing: HPC is a high strength flowing (very workable) concrete with superplasticizers and hyper plasticizers. The placement of such concrete is much easier and less costly[2].

Impermeability: HPC being low w/c ratio concrete offers a high degree of impermeability to ingress of water, carbon dioxide and oxygen.[7].

Costs: The increase in cost of HPC is largely balanced by life cycle cost and zero maintenance of structure. Industrial benefits are gained through durability improvements leading to savings in cost[15].

Table 1: Properties of Condensed Silica Fume

Components	Percentage (%)
Chemical properties SiO_2	 90-96
Al_2O_3	0.5-0.8
MgO	0.5-1.5
Fe_2O_3	0.2-0.8
CaO	0.1-0.5
Na_2O	0.2-0.7
K_2O	0.4-1
C	0.5-1.4
S	0.1-0.4
Loss of Ignition (LOI)	0.7-2.5
Physical properties	
Specific gravity	2.2
Surface area	20,000 m^2/Kg
Size	0.1 micron
Bulk density	35.96 lb/ ft^3

SCOPE OF INVESTIGATION

A water-cementitious materials ratio of 0.32 was adopted. The effect of different percentages of CSF replacement of cement which is 2.5, 5, 7.5, 10, 12.5 and 15 percent with CSF was studied with OPC and PPC. The quantity of fine aggregate was suitably adjusted for the different replacement levels with CSF. The compressive strength, split tensile strength and flexural strength of the mixes were investigated as per the IS specifications in the laboratory [19]. Also, Durability and micro structural studies has been carried out. Nondestructive test – Ultrasonic pulse Velocity is carried out to check the quality of the concrete like durability, constructability and strength.

MATERIALS USED

Cement: Ordinary Portland Cement (OPC) 53 Grade and Portland Pozzolana Cement
Coarse aggregate: 12.5 mm down size. Fineness Modulus = 5.9
Fine aggregate: River sand Zone II. Fineness Modulus =2.65

Chemical admixture – Conplast SP 337 (Super Plasticizers)
Mineral admixture: Condensed Silica fume, (Imported SiO_2 more than 90%)

MIX PROPORTIONS

There is no specific method of mix design suitable for HPC. The methods adopted for the design of conventional concrete mixes are not directly applicable to HPC. The absolute volume method was used to determine the quantities of different ingredients in calculating the mix proportions. Air content for concrete was assumed as 1%. Unit water and sand percentage were derived considering the properties of coarse and fine aggregate, quantity of condensed silica fume and super plasticizer[5, 10, 14]. In the present study, a HPC mix (M_1) without any mineral admixture is having a compressive strength of 55.25 MPa for OPC and 54.5 MPa for PPC at 28 days age of curing. The chemical admixture used is Sulphonated naphthalene type super plasticizer at 2.5 percent by mass of binder. The mixes M_2, M_3, M_4, M_5, M_6 and M_7 were obtained by replacing 2.5, 5, 7.5, 10, 12.5 and 15 percent of the mass of cement by CSF respectively. The proportions of the mixes are given in table 2.

Table 2 Mix proportioning details of HPC

Mix designation	M_1	M_2	M_3	M_4	M_5	M_6	M_7
CSF in %	0	2.5	5	7.5	10	12.5	15
w-b ratio	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Cement content Kg/m^3	500	487.8	476.2	465.1	454.54	444.44	434.58
CSF content Kg/m^3	0	12.2	23.8	34.9	45.46	55.56	65.22
Total aggregate Kg/m^3	1765	1765	1765	1765	1765	1765	1765
Water lit/m^3	160	160	160	160	160	160	160
Super plasticizer lit/m^3	10.42	10.42	10.42	10.42	10.42	10.42	10.42

MECHANISM OF HPC

Condensed Silica fume improves the properties of concrete by means of pozzolanic action as well as micro filler effect.

Pozzolanic Action: This is a chemical mechanism. CSF because of its extreme fineness and high reactive silica content reacts with the calcium hydroxide, which is liberated during process of hydration and produces calcium – silicate – hydrate (CSH).
Portland cement reaction:

$$2C_3S + 6H \longrightarrow C_3S_2H_3 + 3CH$$

$$2C_2S + 4H \longrightarrow C_3S_2H_3 + CH$$

As a Filler Material: This is a physical mechanism. Because of its spherical shape and small size, CSF disperses easily in presence of super plasticizer and fills the voids between cement particles resulting in well –packed concrete mix. Due to the pozzolanic reaction between CSF and calcium hydroxide in the Portland cement, the large size crystal of $Ca(OH)_2$ is converted to crystal of C-S-H that is dense, leading to reduction of pore size[8]. The improved particle distribution results in reduction of thickness of transition zone, significant improvement of pore structures of the hardened concrete and leads to densely packed stronger and less permeable concrete. The combination of pozzolanic and micro filler action leads to increase in compressive, split tensile, flexural and bond strengths, reduction in bleeding and segregation of fresh concrete. The use of condensed silica fume does not change the unit weight of concrete. Due to low water – cement ratio of the mix, a reduction in volume of large capillary voids of the cement paste matrix would reduce the permeability. Dense packing of the paste matrix is the basis for the superiority of this type of concrete[7, 8].

As the hydration process progress, changes take place in the nature of porosity and microstructure of paste; there by decreasing the number of coarse pores of cement – condensed silica fume paste. Hence, the permeability gets decreased[13].

Concrete Structures are also used for storing liquids of which are harmful to concrete. In damp conditions SO_2, CO_2 and other acid fumes present in the atmosphere affect concrete by dissolving and removing part of set cement. In case of HPC, It reduces the effect because of the presence of condensed silica fume.

TEST PROGRAM

A concrete mix with a characteristics mean strength of 8700 psi is designed with an aggregate cement ratio of 3.56 and water cementitious materials ratio 0.32. CSF is used at 0, 2.5, 5, 7.5, 10, 12.5 and 15 percentages by weight of cementations material. For each of the CSF replacement, concrete cube specimens of size 100 x 100 x 100mm, cylinder specimens of size 100 x 200mm and beam specimen of size 100 x 100 x 500mm were cast as per specifications. Three specimens were tested for each variable considered. All the tests were conducted as per Bureau of Indian Standard (BIS) specifications.

Test results and Discussions

Compressive strength

The compressive strength of CSF concrete with OPC and PPC at the ages of 1, 3, 7, 14, 28, 56 and 90days were given in tables 3 and 4. When CSF is added as additional admixture, there is a significant improvement in the strength of concrete because of its high pozzolanic nature to form more CSH gels. It is seen from the tables 3 and 4, that the compressive strength at the early age (1 day) for the CSF based HPC is marginally higher for OPC than PPC because of due to slow pozzolanic reaction. It is observed that the compressive strength increases with increasing age of curing. The maximum cube compressive strength can be seen from table 3 for a mix of 7.5 percent CSF for 28 days that is 11095 psi and at 90 days is 12944.16 psi for OPC concrete. Whereas it is observed in table 4, the maximum cube compressive strength for PPC concrete for 28 days is 8810.73 psi and at 90 days is 10986.22 psi. The maximum compressive strength of concrete in combination with CSF is based on two parameters that are the replacement level and the age of curing. The optimum replacement of CSF for achieving maximum strength in OPC and PPC are 7.5 % and 5% for all the ages of curing.

Split tensile strength

Tests are carried out according BIS 5816-1970 to obtain the splitting tensile strengths for various concrete mixes. The tensile strength of concrete a property that affects both resistance to cracking at prestress release and shear capacity are important with respect to the appearance and durability of concrete structural members. The rate of increase of tensile strength is less for high strength concrete (10877.45-14500 psi) than observed for low strength concrete (3190.71-7976.8 psi). The relationship between the tensile strength and compressive strength at 28 days were studied and concluded that at low compressive strength the tensile strength is as high as 10% of the compressive strength but at higher strength this was about 5%. The split tensile strength of mixes is given in table no. 3 and 4. The split tensile strength at the age of 28 days for OPC varies from 628 to 793.3 psi, whereas in case of PPC the tensile strength varies from 435 to 554 psi. It can be seen that for mix of M_4 shows higher tensile strength for OPC, whereas for PPC the mix is M_3. It is observed that the tensile strength of about 7% of compressive strength for OPC and 6% of compressive strength for PPC.

Flexural strength

Tests are carried out according BIS 516-1959 to obtain the flexural strength for various concrete mixes used. Three beams were cast for each mix tested using two-point loading. The experimental results of flexural strength of OPC and PPC are shown in table 3 and 4. The flexural strength at the age of 28 days for OPC varies from 908 to 1107 psi, whereas in case of PPC the flexural strength varies from 626.54 to 748.37 psi. It can be seen mix of M_4 shows higher flexural strength for OPC, whereas PPC the mix is M_3. It is observed that the flexural strength is about 10% of compressive strength for OPC and 8.5% of compressive strength for PPC.

Table 3 Properties of HPC mixes of OPC

Properties	M_1	M_2	M_3	M_4	M_5	M_6	M_7
Compressive strength (psi)							
1 day	1776	2212	2828	3843	2937	2284	2140
3 days	5185	5800	6055	6454	5946	5584	4714
7 days	6128	6273	6526	6890	6672	6418	6326
14 days	7433	7723	8267	9246	7795	6925	6672

28 days	8013	8484	8666	11095	8883	8557	8194.3
56 days	9935	10150	10840	12110	11313	10260	9070
90 days	10551	10805	11566	12945	11830	11060	10152
Split tensile strength (psi) 28 days	65	66	68	80	69	66	63
Flexural strength (psi) 28 days	93	94	100	111	95	92	91
Young's modulus (x10^3 psi) 28 days	5391	5549	5607	6342	5675	5570	5450
Workability (CF)	0.85	0.83	0.825	0.81	0.78	0.73	0.69
Vee-Bee (seconds)	17	19	20	21	23	28	35

Table 4 Properties of HPC mixes of PPC

Properties	M_1	M_2	M_3	M_4	M_5	M_6	M_7
Compressive strength (psi) 1 day	1160	1378	1632	1560	1232	1088	943
3 days	2140	3190	4242	3808	3046	2538	1922
7 days	5004	5910	6563	5838	4575	4242	3626
14 days	6092	7143	7505	6750	5910	5258	4605
28 days	7910	8300	8810	7040	6418	5838	5185
56 days	8810	9029	9072	8086	7070	6527	6309
90 days	9060	9465	10986	10232	9500	8810	8593
Split tensile strength (psi) 28 days	435	453	554	500	489	466	444
Flexural strength (psi) 28 days	650	669	749	720	692	670	626
Young's modulus (x10^3 psi) 28 days	5353	5487	5652	5050	4824	4615	4336
Workability (CF)	0.84	0.82	0.805	0.75	0.72	0.70	0.64
Vee-Bee (seconds)	16	18	23	30	34	38	43

Durability

When Concrete is exposed to aggressive environment containing chlorides, sulphates and chemicals, leads to deterioration of concrete and are measured in terms of loss of weight of concrete. To study the acid resistance of concrete, the cube specimens of concrete is cured for 28 days and then immersed in 2.5% of HCl and 2.5% H_2SO_4 of solution up to 90 days. It is observed in table no 5 that the increase in percentage of CSF decreases the loss of weight in concrete.

Table 5 – Durability- Acid Resistance Test Results

CSF (%)	Loss of weight in % 2.5% HCl solution.	Loss of weight in % 2.5% H_2SO_4 solution.
0	3.51	3.07
2.5	2.09	1.92
5	1.85	1.73
7.5	1.78	1.58
10	1.64	1.35
12.5	1.43	1.18
15	1.30	1.01

Micro structural Properties

The micro structural properties of HPC like saturated water absorption, porosity and sorptivity was studied. According to BIS and ASTM specifications, the sorptivity results were compared with Taywood engineering (1993) to check the quality of concrete. The HPC mixes show good quality.

Table 6 Micro Structural Related Properties – OPC

CSF (%)	Saturated water absorption (%)		Porosity (%)		Sorptivity (mm/min$^{1/2}$)	
	28 days	90 days	28 days	90 days	28 days	90 days
0	4.12	3.58	3.95	3.42	0.143	0.089
2.5	3.67	3.23	3.54	3.09	0.122	0.076

5.0	3.33	2.98	3.22	2.89	0.122	0.069
7.5	1.002	0.94	0.992	0.85	0.0304	0.028
10.0	1.242	1.12	1.23	1.06	0.0456	0.035
12.5	1.43	1.26	1.41	1.18	0.0687	0.056
15.0	3.13	2.98	3.036	2.76	0.117	0.087

Table 7 Micro Structural Related Properties - PPC

CSF (%)	**Saturated water absorption (%)**		**Porosity (%)**		**Sorptivity** (mm/min$^{1/2}$)	
	28 days	**90 days**	**28 days**	**90 days**	**28 days**	**90 days**
0	2.986	2.44	2.9	2.21	0.054	0.045
2.5	2.46	2.29	2.19	2.01	0.0396	0.0358
5.0	1.85	1.78	1.82	1.69	0.0243	0.0212
7.5	2.88	2.35	2.78	2.21	0.0912	0.083
10.0	2.98	2.67	2.8	2.52	0.1	0.094
12.5	3.14	2.86	3.1	2.67	0.1065	0.109
15.0	4.57	3.12	4.37	2.96	0.122	0.116

Table 8 Quality of concrete suggested by Taywood engineering[19]

Concrete quality	**Sorptivity** (mm/min$^{1/2}$)
Good	<0.1
Acceptable	0.1 to 0.2
Poor	>0.2

Ultra Sonic Pulse Velocity test (NDT)

The ultrasonic pulse velocity test is used to check the quality of the HPC cubes. Tests were carried out for both OPC and PPC, HPC cubes. A maximum and minimum pulse velocity of 5780.35 m/sec and 5555.56 m/sec was observed for OPC. But for PPC, it was 5586 m/sec and 4784.69m/sec, which falls under the excellent category. Table 9 gives the pulse velocity ratings as suggested by Leslie and Cheesman.

Table 9 Suggested Pulse Velocity of Concrete by Leslie & Cheesman[20]

Pulse Velocity m/sec	General Conditions
> 4575	Excellent
3660 – 4575	Good
3050 – 3660	Questionable
2135 – 3050	Poor
< 2135	Very Poor

Table 10 Pulse Velocity of the HPC cubes

CSF (%)	Distance traveled (m)	Time taken to travel (t x 10^{-6} seconds)		Pulse velocity (m/sec)	
		OPC	PPC	OPC	PPC
0.0	0.1	18.0	20.9	5555.56	4784.69
2.5		17.5	18.2	5714.29	5494.51
5.0		17.4	17.9	5747.13	5586
7.5		17.3	18.9	5780.35	5291
10.0		17.8	19	5618.00	5263.16
12.5		18.6	19.5	5376.34	5128.21
15.0		18.0	20.1	5555.56	4975.12

CONCLUSIONS

Based on the experimental investigation, the following conclusions are drawn within the limitation of test results.

Compressive strength

- The use of CSF is one of the constituent for the production of HPC. The cube compressive strength studies indicate that the optimum percentages of CSF are 7.5% and 5% for OPC and PPC concrete.

- The compressive strength of CSF concrete increases with increase in age of curing.
- The use of CSF in concrete improves the early strength for OPC concrete whereas slow strength gain in case of PPC concrete.

Split tensile strength

- The rate of increase of split tensile strength with compressive strength is less.
- The ratio of tensile strength to compressive strength decreases with increase in compressive strength.
- The tensile strength does not increase significantly with increase CSF content.

Flexural strength

- OPC concrete with CSF attains greater flexural strength than that of PPC concrete.
- The flexural strength calculated, using BIS 456:2000 is found always lower compared to the test results.
- The durability of silica fume concrete are more resistance to H_2SO_4 and HCl where a significant damage is observed in plain concrete mix, the addition of silica fume has shown a significant improvement.

Micro structural studies

- This test is carried out to identify the impermeable nature of the silica fume concrete for 28days & 90 days.
- A very low SWA percentage obtained for 7.5% of silica fume for OPC was 1.002% for 28 days &1.35% for PPC, for 90 days OPC was 0.94% & for 90 days PPC was 1.78 %.
- The porosity of concrete for OPC of 28 days is 0.992%, whereas for PPC is 1.82%, for OPC of 90 days 0.85%, whereas for PPC 1.69 % as the strength gets decreased above the optimum replacement the porosity gets increased due to the inefficient packing of cementitious materials in the transition zone.
- Sorptivity of concrete for OPC of 28 days is 0.0304 mm/min$^{1/2}$, whereas for is PPC 0.0243 mm/min$^{1/2}$. For OPC 90 days is 0.028 mm/min$^{1/2}$, whereas for PPC is 0.0212 mm/min$^{1/2}$.

Non- destructive test

- The ultrasonic pulse velocity test is used to find the quality of concrete like durability, constructability with good finish and strength.
- Leslie & Chessman specified the suggested pulse velocity of concrete as pulse velocity of greater than 4575 m/sec then that concrete comes under excellent category.

- The high pulse velocity of concrete for 7.5% of silica fume for OPC was 5780.35 m/sec & for 5% of silica fume for PPC was 5494.51 m/sec. this falls under the excellent category.

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