Effect of silica fume on the fresh and hardened properties of high performance concrete

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Abstract

The objective of this study is to investigate the effects of silica fume on the fresh and hardened properties of high performance concrete (HPC). To perform such a study several HPC mixtures are prepared with various silica fume percentages (0 to 15 % by weight of cement, as addition). Fresh properties such as unit weight, slump and air content and hardened properties such as compressive strength, splitting tensile strength, ultrasonic pulse velocity and schmidt hammer are determined by a standard laboratory testing program. The addition of 5 % silica fume to HPC mixes decreased the fresh unit weight when compared with the unit weight of the control mixes. Air content tests showed that the increased silica fume content causes an increase in the entrapped air of the concrete mixes in the fresh state. Silica fume addition improved the splitting tensile strength and compressive strength test results. The tests showed that ultrasonic pulse velocity may have a relationship with concrete density.

Keywords: High performance concrete, silica fume, unit weight, Schmidt hammer, splitting tensile strength.

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1.0 Introduction

High Performance Concrete (HPC) is defined as ‘concrete having desired properties and uniformity which can not be obtained routinely using only conventional constituents and normal mixing, placing, and curing practices’. These properties include: high strength, high toughness, durability, enhanced workability, etc. Generally chemical admixtures include high range water reducers (superplasticizers) are mixed together with silica fume to produce HPC. ACI 363R and other ACI guidelines address some recommendations on placing, compacting and curing of high strength concrete [1,2].

HPC offers the potential for cost savings in construction due to reduced member dimensions, the capability to accommodate rapid construction schedules, and enhanced service life. High strength composites are being increasingly used in strengthening slabs, beams, and columns in bridges and high-rise buildings. However, from a structural perspective, HPC is more brittle than normal strength concrete (NSC). Therefore, failure mechanisms in structural members need to be understood before appropriate design criteria can be developed [2,3].

Some of the important factors for achieving HPC are as follows [3,4,5]:

- A low water to cement ratio, w/c or more strictly, a low water to cementitious ratio, w/c+m, where m is the binder (i.e. fly ash, silica fume, slag, etc.).
- The use of plasticizers or superplasticers is essential to ensuring that adequate workability is obtained at a low ratio of w/c+m without an excessive cementitious material content. Cement particles are absorbed by superplasticizers and exerting an electrostatic repulsion. This results in the dissociation of the cement agglomerates into primary particles with a significant decrease in the viscosity of the cement-water-superplasticizer system. Superplasticizers may also contibute to the decrease in the surface tension of water and to produce lubricating films at particle surfaces.
- Aggregate quality, grading, and maximum size are important factors. Strength of normal weight structural concrete is typically limited by the strength of the cement matrix. For high strength concrete however, it is common that the strength of aggregates to become a limiting factor that should be considered for purposes of concrete mix design along with water to cementitious material ratio.
- The major effect of silica fume to the fresh concrete of HPC is that it increases the cohesiveness of the mix which also makes it to be sticky and immobile. A contributing factor is that silica fume, because of its high fineness, reduces bleeding so that no bleeding water is trapped beneath coarse aggregate particles. As a consequence, the porosity of the interface zone is reduced, means that, voids caused by trapped bleed water are nearly absent, and compared with a mix without containing silica fume.

In this study, the effect of silica fume on the fresh and hardened properties of HPC is investigated by both destructive and non-destructive tests. For this purpose, several HPC mixes having various combinations of silica fume are prepared.

2.0 Materials:

2.1 Water:

Purified water having negligible amounts of deliterious materials is used. The temperature of mixing water during this laboratory study were in the range 18 to 21°C.

2.2 Aggregates:

The geological origin of aggregates is Limestone. Aggregates are crushed and sieved in the quarry according to the required specifications. Tests are carried out according to ASTM standards (American Standards for Testing and Materials) in order to obtain the physical properties of both fine and coarse aggregates, (Table 1).

Table 1: Physical Properties of Aggregates

	Fine	Coarse
Bulk Specific Gravity (dry)	2.69	2.79
Bulk Specific Gravity (ssd)	2.74	2.80
Apparent Specific Gravity	2.83	2.84
Absorption, %	1.78	0.66
Max. Aggregate Size, D_{max} (mm)	---	25
Zone (according to BS)	II	---

2.3 Cement and Silica fume:

Blast Furnace Slag cement is used and corresponds to 32.5 Mpa strength class. The physical and chemical properties of the cement and silica fume used are given in Table 2.

2.4 Superplasticizer:

High Range Water Reducer Admixture (Sikament FFN) is used in this study in order to keep w/b ratio within the specified limits (0.30-0.35) The physical and chemical properties of Sikament FFN are given in Table 2.

Table 2: Physical and Chemical Properties of Cement, Silica Fume and Chemical Admixture

Cement		Silica Fume		Chemical Admixture	
Fineness (cm^2/g)	3191	SiO_2 (%)	97.19	ASTM certification	ASTM-494 Types A & F
% Retained on 90mm	0.72	Al_2O_3 (%)	0.66	Color	Lear straw colored
Standard Consistency (%)	31.77	Fe_2O_3 (%)	0.27	Specific Gravity (g/ml)	1.25 ± 0.05
Initial Setting Time (min)	150.48	CaO (%)	0.77	pH	> 8
Final Setting Time (min)	202.86	MgO (%)	0	Chloride (%)	< 0.1
Flexural Strength (Mpa)	8.28	SO_3 (%)	0.53		
Compressive Strength (Mpa)	42.07	$Na_2O + K_2O$ (%)	0.68		
Linear Shrinkage (mm)	1.83	Loss On Ignition	0.56		
Loss on Ignition (%)	2.19	Specific Gravity	2.17		
Insoluble Residue (%)	1.61				
SO_3 (%)	2.21				

3.0 Mixture Proportioning:

Several HPC mixtures are prepared with various silica fume percentages (0 to 15 % by weight of cement, as addition). The mixes first designed to have a maximum cement content of 550 kg/m^3, and then the designs are repeated for a maximum cement content of 600 kg/m^3. All mixes were prepared with the same workability (Slump: 100±10 mm) and w/b ratio (0.30-0.35), by using Sikament FFN. Table 3 shows the mix proportioning of mix designs prepared.

Table 3: Concrete Mix Proportions

Group #	Water (kg/m^3)		Coarse Agg. (kg/m^3)		Fine Agg. (kg/m^3)		Silica F. (kg/m^3)		SFF (kg/m^3)	
	C:550	C:600	C:550	C:600	C:550	C:600	C:550	C:600	C:550	C:600
Group 1	175.53	180	1140.36	1084.6	645.14	613.60	0	0	7.40	7.20
Group 2	173.25	189	1109.71	1051.1	627.79	594.69	27.5	30	7.66	7.46
Group 3	181.50	198	1079.05	1017.7	610.45	585.550	55	60	7.93	7.80
Group 4	189.75	207	1048.40	984.30	593.11	556.85	82.5	90	8.60	8.13

C:550 = cement content used is 550 kg/m^3
C:600 = cement content used is 600 kg/m^3

4.0 Fresh Properties

Fresh unit weight of all samples are determined but air content test is performed only for mixes containing 600 kg/m^3 cement. For each group first slump is adjusted to 110 ± 10 mm as specified by increasing the amount of superplasticizer. The summarized test results are given in Table 4.

Table 4: Fresh Properties of Mixes

		Group 1	Group 2	Group 3	Group 4
Unit Weight (kg/m^3)	C:550	---	2.540	2.539	2.573
	C:600	2.580	2.489	2.473	2.501
Slump (mm)	C:550	110	100	105	115
	C:600	120	110	115	120
Air Content (%)	C:600	1.78	1.70	1.93	2.10

5.0 Hardened Properties:

Compressive strength test is conducted on 100×100×100 mm cubic specimens at ages 3, 7, and 28 days for all groups. For all ages, 3 specimens were cast having 0.015 m^3 volume. The specimens tested on 28 days are also subjected to non-destructive tests (pundit and schmidt hammer test).

Splitting tensile strength test is conducted on 150×300 mm cylinders at ages 3, 7, and 28 days. For all ages, 2 specimens were cast having 0.025 m^3 volume. The summarized test results for hardened properties of all groups are given in Table 5.

Table 5: Hardened Properties of Mixes

Groups	Compressive Str.(Mpa)						Splitting Tensile Str.(Mpa)			Pundit(µsec)	Schmidt H.(Mpa)
	C:550			C:600			C:600			C:600	C:600
	3	7	28	3	7	28	3	7	28	28	28
Group 1	39.0	46.0	59.7	35.0	48.4	57.8	2.563	3.215	4.570	17.7	40.22
Group 2	39.5	50.5	68.1	32.6	45.0	61.4	2.331	3.906	4.600	18.7	42.18
Group 3	37.7	51.0	66.5	34.9	45.0	63.4	2.868	3.617	3.939	18.8	41.69
Group 4	36.0	51.2	72.3	33.3	44.4	60.0	2.844	3.199	3.578	18.7	43.16

6.0 Discussion and Analysis of Results

6.1 Fresh Properties:

The addition of 5 % silica fume to HPC mixes decreased the fresh unit weight when compared with the unit weight of the control mixes. But further increase the silica fume to 10 and 15 % s an increase in fresh unit weight is observed. However, the unit weight of control mixes for both C:550 and C:600 groups seems to be the maximum (Figure 1). This is due to the decreased amount of aggregates in the mix, because aggregate particles are heavier than the equal volume of silica fume particles (i.e. aggregates have higher specific gravity than silica fume).

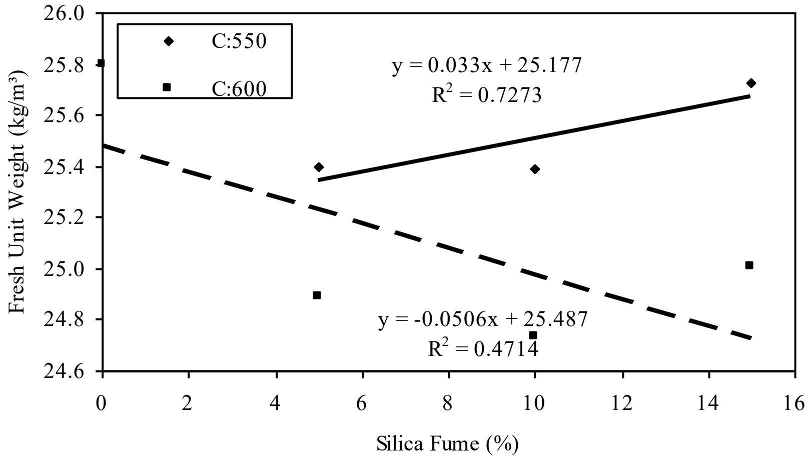

Figure 1. Effect of Silica Fume Addition on Fresh Unit Weight

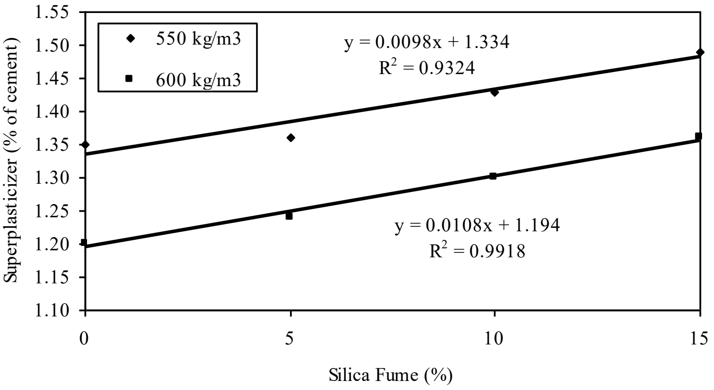

Figure 2. The Increase in the Superplasticizers Dosage with Silica Fume Addition

The large surface area of silica fume particles results in an increased water demand when used in concrete as replacement of cement for the same workability [3,6]. In this study silica fume is not used as a replacement but it is added to the binder portion as a percentage of cement. So, it is obvious that increased amount of fines in the mix will increase the water demand more than in the case explained above for the same workability. However, when the amount of superplasticizer (Sikament FFN) is added within the usual limits, between 1.20 and 1.49 % (calculated as the percentage of cement); it can reduce the initial water film around the aggregate grains irrespective of the type of cement and this could account for the high compactness of the interfacial zone observed in silica fume containing concrete. The increased amount of silica fume in the mixes caused an increase in the need for superplasticizer to keep the slump around 110 ± 10 mm (Figure 2).

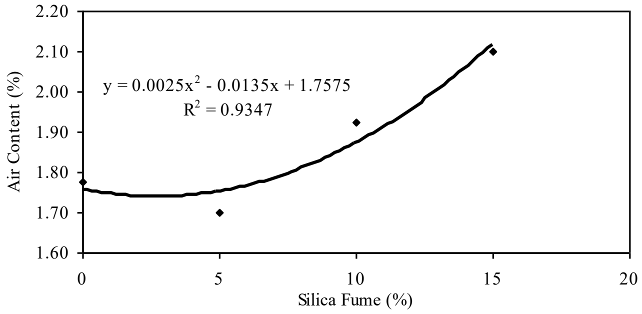

Figure 3. The Effect of Silica Fume Addition on Air Content

The decrease in the need for superplasticizers for C: 600 mixes may be interesting to note because those mixes contain more fines. This may be due to the increase in the amount of water to keep w/b ratio constant and increased plasticity in those mixes. Air content tests showed that increase in silica fume content causes an increase in entrapped air in concrete mixes. This result is compatible with the known disadvantages of using superplasticizers in concrete, which is the increase in the entrapped air. The reason is related with the working mechanism of the superplasticizers within the concrete to decrease the need for water for the same workability. The superplasticizers have the ability to disperse the cement particles by increasing the electrostatic repulsion between the cement particles and this causes the entrapped air to increase, but it should be noted that high dosages of superplasticizers could be used without exceeding the acceptable limits of entrapped air in concrete. The air content for the mixes tested in this study changes slightly from 1.70 to 2.10 % (Figure 3).

6.2 Hardened Properties:

6.2.1 Non-destructive Tests:

Schmidt hammer test is done with type N hammer. A spring-loaded mas has a fixed amount of energy imparted to it by extending the spring to a fixed position; this is achieved by pressing the plungeragainst the surface of the concrete. It is based on the principle that the rebound of elastic mass depends on the hardness of the surface against which the mass impinges This test in fact, is a kind of impact test which relates the rebound number obtained, after that force is applied onto the concrete sample surface. It can only indicate the strength of mortar close to the specimen surface. If there are some aggregates near the surface of the specimen variations may be caused. It can be seen that the compressive strength obtained by Schmidt hammer test is lower than the strength obtained with standard compressive strength test for C: 600 mix groups. This can be due to the range of validity of the Schmidt hammer test which is only defined for strengths lower than 55 MPa that is for NSC. As it is known, in NSC failure and cracking is expected to happen through the cementitious matrix so, what the Schmidt hammer estimates is a true indicator of the overall compressive strength since, it tests the hardened cement paste at the surface. On the other hand, in HSC aggregate is the limiting factor for the compressive strength and the bond between aggregates and the cement paste is the other major parameter affecting the overall strength. And as it can be understood, Schmidt hammer can not test any of these parameters. These doesn’t mean that the surface hardness is independent of the compressive strength but it can be concluded that it may be misleading for the computation of compressive strength for HSC and there is a need for a detailed study to understand the reationship.

6.2.2 Ultrasonic pulse velocity (UPV):

The test results showed that UPV has an indirect relationship with concrete density (Figure 4). Denser matrix has less transmit time. It has to be mentioned that the relation between the pulse velocity and the engineering properties of concrete is governed by the bond and pore structures of the mix ingredients and is significantly affected by: the type of aggregate, aggregate/cement ratio, age of concrete, size and grading of aggregate and curing conditions.

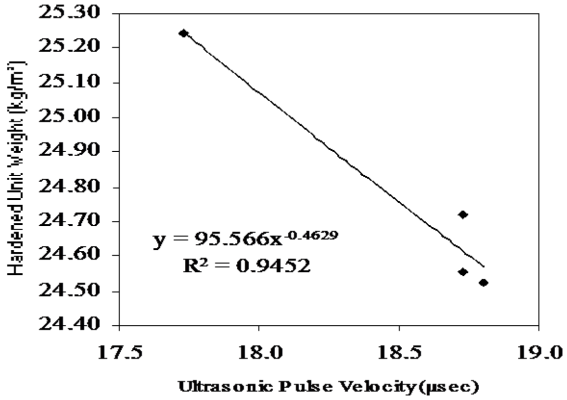

Figure 4. Hardened Unit Weight vs. UPV

6.3 Compressive Strength:

The reasons for the decrease in the compressive strength with increasing cement content can be discussed under two main headings: 1-Hydration of the cement paste, and, 2-Aggregate content.

The cement type used in this study possesses hydration and consequently strength gaining properties very much alike with the Portland blast-furnace (Type IS) cement and Low-heat Portland (Type IV) cement. Its fineness is 319.1 m^2/kg which is within the minimum limits given by the British standards (BS) and Turkish standards (TS) (minimum limits specified; TS:280m^2/kg, BS:275m^2/kg for Type IS, 320m^2/kg for Type IV). These cement classes, possesses low heat of hydration and have good resistance to sulfate attack, aggresive sea water, peaty acids and oils. In the case of high strength concrete with a high early compressive strength, there is a possibility that, because of a limited amount of hydration, the bond between the aggregate and the matrix is not commensurately developed. Consequently, with high strength at early ages, it is possible to have a lower performance than expected [3]. The effect of silica fume addition on strength gaining properties of HSC depends on its pozzolanic activity and ability to improve concrete properties physically by acting as a filler. Pozzolanic activity depends on the cement hydration since, reactive silica reacts with the hydration products to form CSH gel. And the physical effect depends on the overall grading of the concrete constituents.

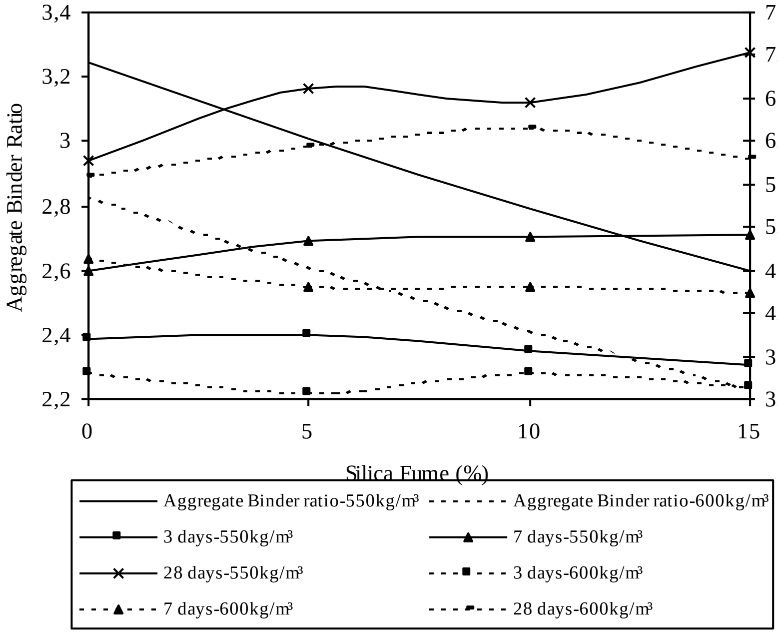

Figure 5. Aggregate/binder ratio and Compressive Strength vs. Silica Fume Addition

It is obvious that aggregate binder ratio is also one of the major parameters, which affects the strength of concrete mixes for both NSC and HSC, and there is an optimum limit for aggregate content, which can give the highest strength for that mix proportioning. Such that further increases in the cement content will not produce an increase in the strength of concrete.

This apparently is not due to having fully developed the strength of the concrete but to having reached the limit of the bonding potential of that cement-aggregate combination [7,8].To study this behavior in fact, it’s needed to keep the aggregate contents constant with increasing cement content but in this study aggregate contents decreased with increasing binder content due to the mix design procedure, (Figure 5). This limit cannot be seen from the test results but the explanation of relative decrease in the strength in C: 600 mixes with the same theory will not be a false solution. As seen in the Figure 4, the decreases in the strength in very early ages by silica fume addition for both C: 550 and C: 600 mixes is caused by the lack of development of bonding between the aggregates and the paste. The paste-aggregate bond characteristic (properties of the interfacial, or transition zone) greatly affects the overall strength of the concrete.

6.4 Splitting Tensile Strength:

Splitting tensile strength tests were performed only for C: 600 set of samples. And it is found that the specimens tested were much more sensitive against the increase in cementitious material content (i.e, silica fume), such that an optimum content of 5 % silica fume addition gave the maximum splitting tensile strength for 28 days. For the other cases (3 days and 7 days), silica fume addition improved the splitting tensile strength. These results are compatible with the compressive strength test results. Cement paste itself have very low resistance to tensile forces and the increased cementitious matrix in samples having silica fume contents 10 % and 15 % seems to have a decrease in their splitting tensile strength compared to the control samples and samples having 5 % silica fume.

The results were compared with the compressive strength test results and the proposed relations in the literature. Carasquillo, Nilson, and Slate reported the following relation between the splitting tensile strength and compressive strength which is presented on the Figure 6. The compressive strength test results corresponding to the splitting tensile strength test result were converted to the equal cylinder compressive strengths by multiplying their cubic strength with 0.82 [1,8].As it can be seen from the figure, the test results were compatible with the previous findings.

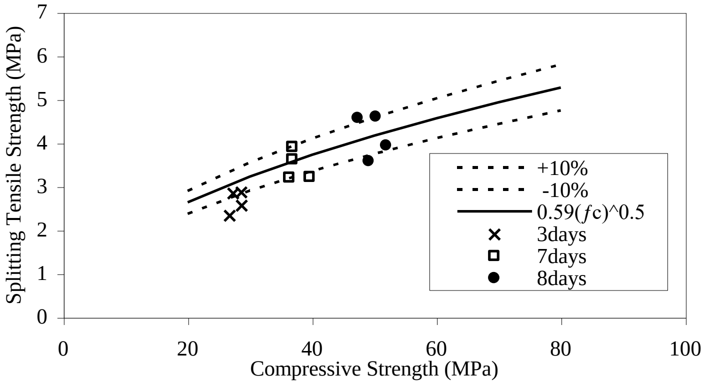

Figure 6. Relation Between Splitting Tensile Strength and Compressive Strength

7.0 Conclusions

Based on the experimental study, the following conclusions can be drawn:

- The decrease in the compressive strength in very early ages by silica fume addition for both C: 550 and C: 600 mix groups were due to the lack of development of bonding between the aggregates and the paste.

- It is found that the specimens tested under the splitting tensile strength were much more sensitive against the increase in cementitious material content (i.e, silica fume), such that an optimum content of 5 % silica fume addition gave the maximum splitting tensile strength for 28 days.

- The compressive strength obtained by Schmidt hammer test is lower than the strength obtained with standard compressive strength test for C: 600 mix groups. This might be due to the range of validity of the Schmidt hammer test which can only defined for strengths lower than 55 Mpa (that is for NSC). Also, failure mechanisms of NSC and HSC which are quite different to describe such a relationship.

8.0 References

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