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Practical Consideration of Using Silica Fume as a Cement Replacement in Concrete

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Abstract: In literature there are many studies dealing with silica fume effect on concrete strength and properties but most of the experimental data available up to day, indicate that there are no radical results or mathematical models which can describe a constant effect. The scatter values of both experimental and numerical methods due to the continuous variety of the physical and chemical characteristics of the concrete components which needs to be investigated for each mix design in fact tests on mix design with variable components and parameters always referred to certain mix design at certain time and place. The present theoretical and experimental study will contribute to the available studies done in the past with new results and comments in particular the mix design physical and chemical properties and the variation of concrete properties when using silica fume and how it influences the concrete mix design, exploring the merits and practical considerations of using such material with recommendations and practical estimation on its utilization. Also, this investigation has been aimed to bring awareness amongst the practicing civil engineers regarding advantages of these new concrete mixes, the performance characteristics of the ready mix concrete become an essential requirement of concrete mix proportions which may include but are not limited to: setting characteristics, material compatibility evaluation, workability, place ability, strength, uniformity, durability and permeability. In general, the high-performance concrete is characterized by a compressive strength in the range of 60-100 N/mm^2 this high value due to: the reduced water/cement ratio (0.40-0.20), compensated with the use of super-water-reducing admixtures. Use of mineral additions, alone or in combination with high pozzolanic activity and/or high specific surface area such as silica fume, slag micro fine, etc. Aggregates of high quality grind (basalt, granite, etc.) capable of ensuring a high intrinsic mechanical strength of the rock and good adhesion at the interface between the stone and cement matrix element.

Key words: Silica fume, transition zone, high performance concrete, concrete parameters, admixtures, pozzolanic activity

INTRODUCTION

Silica fume is an Amorphous light grey silicon oxide powder, obtained by filtering the dust extracted from silicon and ferrosilicon production in an electric arc furnace. Now a days it is widely used in concrete and fiber cement industries. In addition to the pozzolanic properties, silica fume is also very good filler due to its particle size which is 100-150 times finer than cement, so they fill the interstitial voids in the concrete mix and increase particle packing density where packing effect reduces strongly the concrete porosity and permeability. These combined properties lead to an extended life expectancy in aggressive environments, resisting against chloride, acids and sulfates. Silica fume can either be 'addition' (added separately at the concrete mixer) or incorporated into factory-produced composite cement, it also can generally be used with chemical admixtures and it is usually used with a super plasticizer. The bulk density of silica fume depends on the degree of densification in the silo and varies from 150 for un-densified up to 700 kg/m^3 for the densified one. The specific gravity of silica fume is generally in the range of 2.2-2.3 g/cm^3 while the specific surface area of silica fume typically ranges from 15-35 m^2/g. Additionally, silica fume reacts with the free lime which is present in all OPC concretes according to:

$$SiO_2+Ca(OH)_2 = CSH \quad (1)$$

Forming additional quantities of strong-binding CSH (Calcium Silicate Hydrate) gel which is a principal binding component in OPC concrete. By replacing weak-binding lime with more CSH, silica fume significantly enhances the overall compressive strength of the mix. This extra CSH further assists in refining the pore structure of the concrete.

Characteristics of concrete containing silica fume: Each silica fume plant must be accompanied with the product certification which includes most of the characteristics mentioned above because each silica fume patch has to be chosen according to the application required, the mechanical resistance required and the handling equipment available, the quality control must comply with ASTM C1240 (Bayasi and Zhou, 1993).

The micro filler effect is credited with greatly reduced permeability and improved paste-to-aggregate bond of silica fume concrete compared to conventional concrete. However, there is little difference in the moisture absorption (a property different from permeability) of silica fume concrete vs. conventional concrete (Dotto *et al*., 2004).

This good reactivity decreases the concrete permeability, increasing the mix homogeneity preventing the penetration of aggressive agents and the concrete corrosion in aggressive environments. Major applications for silica fume are seen in, high and very high performance concretes, shotcretes, refractory castables and fiber cements (Mehta, 1986).

Concept of transition zone and its effect on the mechanical strength of HPC with silica fume: The transition zone in concrete is a narrow region around the aggregate particles with fewer cement particles and thus more water this is due to the effect magnified by the shearing stresses (Carpinteri *et al*., 2013) exerted on the cement past by the aggregate particles during mixing which tend to cause the water to separate from the cement particles.

Normally this zone is used to measure the quantity and distribution of unreacted cement, pores larger than 0.5 μm and calcium hydroxide. However, in concretes with silica fume the transition zone is much denser.

The transition zone which is usually, more porous and mechanically weaker than the other two components (rock aggregate and cement), exerts an influence on the properties of the composite material significantly, greater than that which might be expected by its relatively small size.

To better interpret this mechanism which is rather complex, exerted by the transition zone on the mechanical properties (Feldman and Cheng, 1985) (elasticity and durability) of the material, it is appropriate to deepen the description of this area key of the concrete.

In fresh concrete subjected to compaction, around the areas of the lower large aggregate granules a small water bleed will appear, already this situation determines higher water cement ratio (and therefore, a higher porosity) in the transition area with respect to the cement. The formation of the first-crystalline germs of $Ca\ (OH)_2$ which takes place throughout the cementitious matrix due to the effect of hydration of the cement silicates and aluminates is followed by a greater growth of the crystals of these products into the more porous transition zone for the most locally existing water solid ratio. The higher porosity in this area also enables the development of lime crystals oriented more or less parallel to the surface of the aggregate but also easily flaked and then mechanically weaker. So in a matter of several months the porosity of the transition zone would tend to match that of the cement matrix, even when the transition zone is more porous and therefore mechanically weaker of the cement matrix.

In addition to a greater porosity which lasts for several months, consists in the initiation and propagation of micro cracks that damage irreversibly the material. The micro-cracks can form in the transition zone due to any cause of stress which causes a differential movement between the cement matrix and the aggregate with significantly different elastic modulus to each other. In all these circumstances, the transition zone (if there is no prolonged moist curing for a few months and this currently occurs) becomes the place where the various micro-cracks between the aggregate surface and the surrounding cementitious matrix become stronger.

Silica role on concrete chemical properties: When a high amount of calcium hydroxide is present, concrete may be more susceptible to sulfate attack, alkali aggregate reaction or efflorescence. Any pozzolanic material added to concrete alters the hydration reaction pozzolans react with the calcium hydroxide and water to produce more aggregate-binding calcium silicate gel while simultaneously reducing the calcium hydroxide content so the net effect is an increase in overall strength and durability.

The primary reasons are its high percentage of reactive silica and its fine particle size. Silica fume that is used in concrete (ACI Committee, 2003) typically has an SiO_2 content in excess of 85% while fly ashes typically have an SiO_2 content of 30-60%. Note that while fly ash additives will increase the strength of hardened concrete over the course of months as it ages, silica fume additives will increase concrete strength in a matter of days. In addition, the extreme fineness of silica fume when compared to most pozzolans allows it to react almost immediately with the free calcium hydroxide in concrete while conventional pozzolans react more slowly. The behavior of concrete containing silica fume with 85% of may differ from that containing silica fume with 96% of Sio_2. The second mechanism by which silica fume improves concrete is through the so-called "micro filler effect. For many high strength concrete applications, the w/cm ratio will be so low so that there is not enough water to get a measurable slump and still develop a concrete with the desired characteristics to achieve a good concrete workability we have to add admixtures to the mix this is a chemical additive used as a water reducer while adding a superplasticizer will help to bring the concrete to the desired slump. For what concern the aggregate size, generally a high strength concrete does not necessary means that it required small aggregate size (Young and Jennings, 1991) by experience the 19 mm aggregate size is more appropriate.

MATERIALS AND METHODS

Objective: The selection of mix proportions is an art as much as a science. It must be considered that an exact determination of mix proportions by means of tables or computer data generally indicate a scatter results because the materials used are essentially variable and many of their properties cannot be assessed correctly. In fact mix selection requires knowledge of the properties of concrete and experimental data and above all the experience of the expert who conduct the mix design (Bhanja and Sengupta, 2002).

The mix proportions once chosen, cannot expected to remain entirely immutable because the properties of the ingredients (cement, sand, aggregate, water and admixture) may vary from time to time or place to place. As an example to develop high strength concrete mix design, the use of local material under local environment which will be very useful for the structural designers, civil engineers, builders, contractors, ready mix suppliers and precast concrete manufacturers which lead to cost saving and improve safety and push for environment safeguard. As mentioned before, the target is to increase concrete compressive strength and improving its permeability and properties, looking to assess and calibrate some critical parameters.

Test procedure: The 45 samples of which 40 concrete cubes with 150 mm side and 5 Cylinders, diameter 150 mm, length 300 mm were prepared (Table 1). The mixing was done in a mixer machine; cubes were casted and compacted, slump was noted for each of the mixes. The concrete cubes, ten for each type of mix were cured in water. The cubes were tested under nominal conditions. Each water-cured cube was taken from water at the testing age and then rubbed until a saturated surface dry sample was obtained. Silica fume, specified by ASTM C 1240 is replaced in concrete with different percentages, 0, 3, 7, 10% and the hydration periods were 7, 14 and 28 days. All the strength results are the average of the specimens for each concrete mix. The properties of the silica fume used are reported in Table 2.

Concrete components weight and volume are reported in Table 3. The superplasticizer used is Master-Glenium® 51 with dosage 1 L per 100 kg of cement (cementations material) Master-Glenium 51 is an innovative admixture based on modified Poly-Carboxylic Ether (PCE) polymers. The product has been primarily developed for the use in the concrete industry where the highest durability and performance is required, increasing Initial and final compressive strength and decrease the risk of shrinkage and creep. W/b ratio used is 0.39 (maintained constant) and according to ACI 211.1 recommendation referred to slump and aggregate size in use and according to Abraham's low where the concrete compressive strength R, increases when w/c ratio decreases according to:

Table 1: Tested specimens

Specimen	Size	No.
Cube	150×150×150 mm	40
Cylinder	Diameter-150 mm, length 300 mm	5

Table 2: Silica fume propriety

SiO_2 (min.)	Cl (max.)	CaO (max.)	MgO (max.)	LOI (max.)	Moisture (max.)	Bulk Density
85%	3%	3%	6%	3%	3%	550-700
Min	Max	Max	Max	Max	Max	KG/M3

Table 3: Material weight and volume

Material	kg/m^3	Specific gravity	Volume (m^3)
Weight of water	185.25	1.00	185.25/1000
Weight of cement	475.00	3.14	475/3.14 = 151.3/1000
Weight of coarse agg	1076.00	2.66	1076/2.66 = 404.5/1000
Entrapped air			2/1000
Total			743/1000

$$R = K_1/K_2^a \tag{2}$$

Where, K_1, K_2 are two constant depending on time and temperature respectively. Cement (OPC) 43 grade was used.

At this point to define the composition of the concrete in terms of kg/m^3 of water (w), cement (c) and Aggregate (i), mathematically. Note w/c ratio, c is calculated while the volume of aggregate (V_i) is determined by means of a simple volume balance, subtracting from one m^3 of concrete, the volume of water (V_a), cement (V_c) and air (V_a') according to:

$$V_i = V_{tot}\left(1m^3\right) - V_c - V_w - V_a' \tag{3}$$

Based on the values, reported in Table 3, transforming the weight in volume and calculate the fine aggregatevolume, we define the concrete density as: Total = 743/1000 kg/m^3. Fine aggregate = 1000-743 = 257 257×2.62 = 673.34 say 673 kg/m^3. Plasticizer = 4.89 L, water = 185.25-4.89 = 180.36 Lit, say 180.5 Lit, W/c = 0.39. Table 4 indicates the composition of the mix design Fig. 1-3.

Table 4: Concrete mix design proportion

Samples	W/b	Cement	Fine agg.	Coarse agg.	Water	Superplasticizer M. Glenium 51	Silica fume
C0	0.39	475.00	673	1076	180.5	4.89	00.00
C1	0.39	460.75	673	1076	180.5	4.89	14.25
C2	0.39	441.75	673	1076	180.5	4.89	33.25
C3	0.39	427.50	673	1076	180.5	4.89	47.50

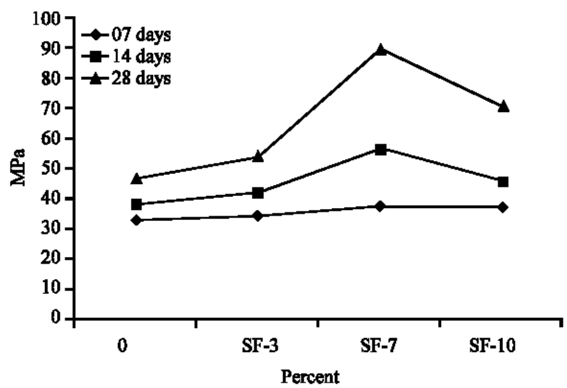

Fig. 1: Compressive strength vs. silica fume percentage

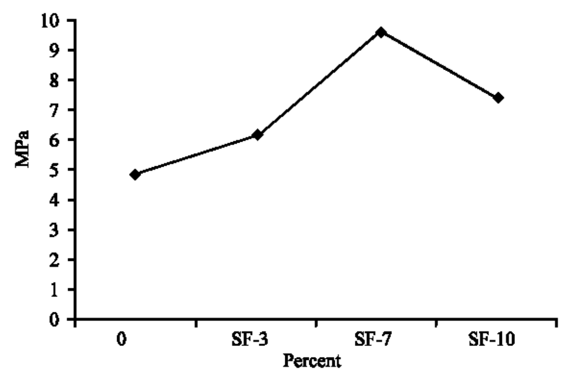

Fig. 2: Split tensile strength vs. silica fume percentage

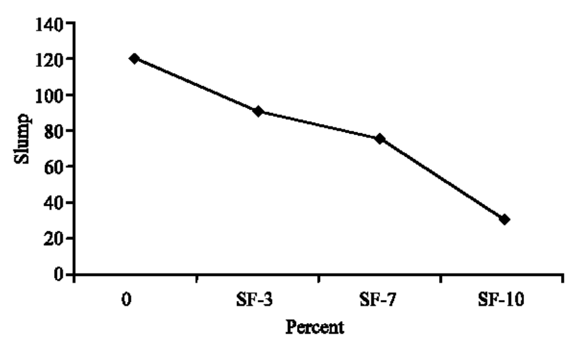

Fig. 3: Slump vs. silica fume percentage

RESULTS AND DISCUSSION

Tests result: From Table 5 there is significant improvement in compressive strength. It is evident that

Table 5: Compressive strength tests at 7, 14 and 28 curing days

	Average compressive strength			
Days cured	(0% S.F)	(3% S.F)	(7% S.F)	(10% S.F)
7	30.44	31.44	35.04	34.59
14	35.63	39.56	54.96	43.41
28	44.00	51.85	88.89	69.48

Average compressive strength

Table 6: Split tensile strength values

Samples No.	Tensile strength at 28 days
C0	4.81
C1	6.09
C2	9.48
C3	7.36

Table 7: Slump test values

Samples	Slump (mm)
C0 (0%)	120
C1 (3%)	90
C2 (7%)	75
C3 (10%)	30

maximum compressive strength is attained when ilica fume replacement level is 7%. Beyond this level compressive strength decreases. The maximum 28 days compressive was 88.89 N/mm^2 when added level was 7%.

Table 6 indicates a marginal increase in split tensile strength. The maximum 28 days split tensile strength was 9.48 N/mm^2 when added level was 7%. Table 7 indicates that the highest workability was seen when silica fume level is zero while the concrete containing 10% of silica fume resulted in the lowest workability as compared to other concrete mixes.

Table 8 indicates the compressive strength of three samples at 28 days, compared with Table 5 the values are mostly the same at 28 days. The important issue was found in the second and 3th specimens where with same cement quantity, the water cementous ratio has major effect on increasing the concrete compressive strength more than the effect of silica fume. In Table 9, the silica fume dosage reaches 135 kg/m^3 (more than 30% of cement) while the very high additive dosage (more than 6% on the cement and silica fume) allows reduce the water/cement ratio to 0.26 and the water/(cement+silica fume) ratio to 0.19. Just to make maximum use of the principle of extreme densification were waived obtaining a fluid mixture by limiting the consistency to that of moist earth (slump 30 mm) to reduce any possibility of bleeding

Table 8: Compressive strength tsest with variable, W/cm ratio

Mixture	Cement	Fly ash kg/m^3	SF kg/m^3	SF %	W/cm	Comp. 28 days
1	475	59	24	4	0.29	86
2	390	-	27	6	0.35	56
4	390	-	30	7	0.37	44

Table 9: An example mix design of 110 MPa

OPC 43	410
Silica Fiume	135 kg/m^3
Superplasticizer	35 kg/m^3
Quartzite 0-1 mm	710 kg/m^3
Granite 4-15mm	1155kg/m^3
Water	100 kg/m^3
W/c	0.26
W/b (cement+silica fume)	0.19
Slump	30 mm

in the compacting stage and favor, therefore, the formation of an adhesive bond in the transition zone between the cement matrix and aggregate.

CONCLUSION

Cement replacement by silica fume in concrete indicate: a significant reduction of porosity, permeability, carbonation and alkali silica reaction. Evidence improvement in chemical resistance, abrasion resistance reinforcement corrosion resistance and freeze resistance; it must be noted that "increasing silica fume quantity doesn't implicate the increases in compressive strength generally" this depends only on the concrete mix design; all improved properties due to the addition of micro silica (compressive strength, permeability and workability) are seen only at certain level which depends strongly on w/cm ratio, fineness of the aggregate and the superplasticizer type and quantity, beyond that level, more percentage of added silica fume shows no further improvement for these properties. This limit of silica fume percentage is not constant because it depends on the concrete components and its mix design. A major effect of silica fume in concrete is the improvement of the aggregate matrix bond as indicated in the transition zone effect.

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