THE INTERNATIONAL JOURNAL OF
SCIENCE & TECHNOLEDGE

A Study on the Rheological Properties of High Strength Concrete Incorporating Silica Fume

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Abstract:
Nowadays high strength and high performance concrete are being widely used in various civil engineering practices. Most applications of high strength concrete have been in high rise buildings, long span bridges and some special structural applications. The use of high strength concrete would result in both technical and economical advantage. In high strength concrete it is necessary to reduce the water binder ratio, which in turn will increase the binder content. Superplasticizers are used to achieve the desired workability. There are two types of mineral admixtures which are commonly mixed into the Portland clinker or blended directly with cement nowadays. They can be categorized as crystalline, which are also known as hydraulically inactive additions and pozzolanic which are hydraulically active additions. Silica fume is one of the popular pozzolans used in concrete to get improved properties. The use of silica fume in conjunction with superplasticizers has become the backbone of high strength and high performance concrete. Silica fume is very reactive pozzolan, which is used in concrete because of its fine particles, large surface area and high SiO_2 content. A detailed experimental investigation has been carried out to study the effect of silica fume in conjunction with superplasticizers on some of the properties of fresh concrete. The investigation revealed that by maintaning a constant dosage of high performance superplasticizer along with silica fume, it is possible to maintain a optimum slump value i.e. workability, thereby satisfying most of the modern structural applications.

Keywords: *Compacting factor, fresh concrete properties, silica fume, water binder ratio, workability*

1. Introduction

Concrete production exists around the globe and is one of the leading construction material, essentially man made stone that has become a most versatile and universally recognized tool to build with. Concrete is a widely used structural material which essentially consists of a binder and a mineral filler. It has the unique distinction of being the only construction material which is manufactured actually on the site, whereas other materials are merely shaped and fabricated and eventually assembled at site. Ever since the time of Romans, there has been a continuous effort by the research workers in the field of cement and concrete technology to produce better quality cement resulting in concretes of overall improved quality. The introduction of reinforced concrete as an alternative to steel construction, in the beginning of 20th century, necessitated the development and use of low and medium strength concretes. In keeping with the demands of the nuclear age, high density concrete has been successfully used for the radiation shielding of highly active nuclear reactors. Considerable progress has been achieved in the design and use of structural light weight concretes, which have the dual advantage of reduced density coupled with increased thermal insulation. With the present state of knowledge in the field of concrete mix design, it is possible to select and design concrete capable of resisting heat, sea water, frost and chemical attack arising out of industrial effluents.

When concrete was first adopted as a structural material during the nineteenth century, compressive strength was perhaps the only criterion in the proportioning of a concrete mix. The concept of durability, workability and other factors influencing the mix proportions, as they are understood now, are of comparatively recent origin. The strength of concrete was supposed to improve with the increase in the quantity of cement and with better compaction. High strength concrete refers to concrete that has a uniaxial compressive strength greater than the normal strength concrete obtained in a particular region.

High strength and high performance concrete are being widely used throughout the globe and in the production of these concretes it is necessary to reduce the water/binder ratio with the subsequent increase in the binder content. High strength concrete refers to good abrasion, impact and cavitation resistance. The deterioration and premature failure of concrete structures such as marine structures, concrete bridge deck etc. has lead to the development of high performance concrete. The high performance concrete is defined as the high-tech concrete whose properties have been altered to satisfy specific engineering properties such as high workability, very high strength, high toughness and high durability to severe exposure condition.

Nowadays silica fume is almost invariably used in the production of High Performance Concretes. In future, high range water reducing admixtures (Superplasticizers) will open up new possibilities for the use of such material as partial replacement of cement to produce and develop high strength concrete, as some of them are much finer than cement. The existing literature is rich in information on silica fume concrete and after performing a detail review of the research papers published over the last two decades, the objective of the present study was framed. The present investigation is an effort towards developing a better insight into the isolated effect of silica fume on the different rheological propertiesof silica fume concrete over a wide range of water cementitious material ratio ranging from 0.30 to 0.42 and silica fume replacement percentages of 0, 5, 10 and 15 by weight of total binder with high range water reducing admixtures for optimizing its effect on concrete.

The results indicate that with silica fume incorporation, workability of fresh concrete decreases but simultaneously the cohesiveness of the mix increases. Undesirable effects like segregation and bleeding are dramatically reduced.

2. Aims and Objectives

The use of silica fume in combination with a super plasticizer is nowadays a usual way to obtain high strength concrete. The effect of silica fume in concrete have attracted the attention of researchers throughout the world.

Based on the guidelines of the previous work and need for further research to explore the ever expanding field of silica fume concrete, the following objectives are outlined:

- To study the isolated effect of silica fume in concrete keeping other mix design factors almost constant. Cement will be replaced by silica fume over a wide range of water/binder ratios and replacement percentages. As the mix design factors remains almost unchanged, the changes in concrete properties will occur primarily due to silica fume replacements. Since the SPcontents of all the mix will be kept constant, to eliminate the interference of workability, the compaction energy will be varied for obtaining proper compaction. The time of compaction will vary, more for stiff concretes and less for flowing concretes.
- To study the effect of silica fume in fresh mix properties at different water/binder ratios. Silica fume makes the concrete sticky, for determination of workability slump values will be determined.

3. Significance of the Present Research Work

There are many important parameters which needs to be explored in detail. The isolated effect of silica fume in concreteand the optimum silica fume replacement percentage still calls for detailed investigations to ensure the maximum utilization of silica fume in concrete. The present work aims at a deeper insight into the effect of cement replacement by silica fume in concrete over a wide range of water-cementitious material ratios and silica fume replacement percentages.

4. Materials and Procedures

This section describes the characteristics of the materials used in the present investigation. The reason for the selection of the materials are also mentioned.

- Cement: Cement used was 43 Grade Ordinary Portland Cement (Manufacturer's Name- Ultra Tech) conforming to IS:12269-1987. The physical properties as determined in the laboratory are presented in table 1. The chemical analysis results are also shown in table 2.
- Silica Fume: Silica Fume (Grade-920D) was obtained from Elkem India Private Limited, Mumbai, India. The chemical properties of silica fume are presented in the table 3.
- Fine Aggregates: For the production of strong durable concrete, good quality sand should be used. Due to incorporation of silica fume, the volume of fines in the concrete will be high. Use of Zone II sand has been found to be beneficial with regard to workability. Due to scarcity of Zone II sand in this eastern part of India, sand of Zone III as per IS: 383 was used for controlling the workability of resultant mixes.
- Coarse Aggregates: Though aggregates smaller than 12.5 mm is recommended for HSC, 20 mm coarse aggregates are the most commonly used aggregate for the variety of applications in the general concrete construction. Hence to cater for the application in most of the works dealing with HSC, 20 mm graded aggregates have been taken into consideration. 12.5mm aggregates and 20mm aggregates are mixed in the ratio of 50:50 for obtaining maximum packing density.
- Water: Potable Water was used in the present investigations as per IS:456.
- Superplasticizers: Conplast SP-430 manufactured at Bangalore was used as a water reducing agent to achieve the required workability. It is available in brown liquid instantly dispenable in water. Conplast SP-430 complies with IS:9103 and BS:5075 Part-3 and ASTM-C-494 Type "F" as a high range water reducing admixture. It is a SulphonateNapthalene Polymer instantly dispersible in water, having specific gravity 1.22.

The reasons for the selection of the ingredients are discussed below:

a. Cement: Though in the present investigation no particular strength level was targeted, yet, to reach high strength levels, high strength cement having average 28 days strength of 43MPa was used.
b. Coarse Aggregates: For production of high strength concrete smaller size aggregates should be used for effective bond between cement paste and aggregates. Hence 12.5mm aggregates and 20mm aggregates should be used in the ratio of 50:50 to obtain maximum packing density.
c. Fine Aggregates: Zone II sand was used to control the workability of the resultant mixes.
d. Silica Fume: A high quality very active silica fume, supplied by Elkem India Private Limited, Bombay, was used.
e. Superplasticizers: Superplasticizers are almost invariably used in the production of High Strength Concrete with silica fume. Due to incorporation of a considerable amount of silica fume (cement was replaced by silica fume @0 to 15%) a high dosage of superplasticizer was required as silica fume is extremely hydrophilic. Conplast SP-430 (Sulfonated Napthalene Formaldehyde Condensate) was used to improve the cohesiveness and slump.

Particulars	43 Grade OPC used	Requirements as per IS: 8112 – 1989
Standard consistency (%)	34	-
Fineness by		
a) Blaine's method (m^2/kg)	325	Not less than 225
b) Percent retained on 75 μ by wet sieving (%)	5	-
c) Percent retained on 45 μ by wet sieving (%)	30	-
Setting time (minutes)		
a) IST	240	Not less than 30
b) FST	300	Not more than 600
Soundness		
a) By Le- chatelier method (mm)	0.50	Not more than 10
b) Autoclave Expansion (%)	0.095	Not more than 0.8
Specific Gravity	3.15	-

Table 1: Physical Characteristics of cement

Particulars	43 Grade OPC Used
SiO_2 (%)	25.02
Al_2O_3 (%)	6.26
Fe_2O_3 (%)	1.24
CaO (%)	61.82
MgO (%)	2.28
SO_3 (%)	2.44
Na_2O (%)	0.31
K_2O (%)	0.44
TiO_2 (%)	0.14
Loss on ignition (%)	1.06
Lime Saturation factor (L.S.F.)	0.77
Alumina modulus (A.M.)	5.05

Table 2: Chemical Characteristics of cement

Characteristics	Specifications	Result (% by mass)
SiO_2	% min 85.0	88.7
Moisture Content	% max 3.0	0.7
Loss on ignition 975c	% max 6.0	1.8
Carbon	% max 2.5	0.9
>45 Micron	% max 10	0.2
Bulk Density	500-700 Kg/m^3	670

Table 3: Chemical Properties of Silica Fume

5. Experimental Procedure

The present research aimed at investigating the effect of silica fume on the properties of concrete in the fresh and hardened state. Concrete at diffferent water/binder ratio ranging from 0.30 to 0.42 will be prepared. At each water/binder ratio, cement will be replaced by silica fume @0 to 15%. All the concretes will be tested in the freshstates as per relevant Indian Standards and their properties will be determined. Accordingly the effect of silica fume on cement replacements will be determined. The workability of the silica fume concretes depends on a host of parameters. The present investigation is aimed to determine the isolated effect of silica fume on concrete as a result of which the mix variables like quality of ingredients, mix proportions, curing conditions, dosage of SP etc. have been kept constant. The fundamentals of the present investigation is not to arrive at a particular strength or workability but to study the effect of silica fume on the rheological properties of concrete and to determine the optimum silica fume replacement percentage to maintain the desired workability, so as to satisfy most of the modern structural applications. Therefore the effect of cement replacement by silica fume was studied over a wide range of water/binder ratio (0.30 to 0.42) and over a wide range of cement replacements (0-15%).

6. Mixing, Compaction and Curing

The concrete mixing operation was performed in a conventional tilting drum mixer normally used for making high performance concrete due to its enhanced mixing mechanism. Because of importance of thorough mixing the mixer was operated at less than half of its rated capacity. The mixing procedure was as follows —

i) A premixing process i.e. buttering (Neville, 1996) was followed on each day prior to casting.
ii) Half the coarse aggregates were introduced first into the mixer, then the half of the fine aggregates, then the entire cementitious material and finally the remaining fine aggregates and coarse aggregate successively on top.
iii) The ingredients in dry condition were mixed together for one minute.
iv) 70% of the mixing water was then added and mixed for 2 minutes. Subsequently, rest of water uniformly mixed with super-plasticizer was added and mixed for another 3 minutes to obtain a mix having uniform colour and consistency. Super-plasticizer has been thoroughly mixed with water at least 30 minutes prior to casting.

The mixing time was finalized after performing a large number of trials, to obtain good, uniform mix. The sequence of adding the ingredients and the mixing time was fixed for all the mixes.

Immediately after preparing the mix, the specimens were cast and compacted by a Needle vibrator having diameter and length of 25 and 300 mm respectively. The samples were marked with cement paint and covered with wet jute bags properly squeezed so that water do not drop out to prevent the loss of moisture due to evaporation. The specimens were kept in their moulds in a place free from vibration for 24 hours before demoulding. The demoulded specimens were immediately immersed under water in a curing tank maintained at room temperature. Moist curing continued up to 28 days and then the specimens were removed from water and air cured. Specimens to be tested at the age of 7 and 28 days were moist cured until testing. Specimens to be tested at later ages (i.e. 56 days) were submerged in water for 24 hours before testing.

7. Mix Proportions

According to Shah and Ahmad (1994) for proportioning of high strength concretes, mostly purely empirical procedures based on trial mixtures are used and the trial mix approach is best for proportioning high strength concretes. Any mix proportioning method for High Strength Concrete is yet to be universally accepted. The Indian Standard- "Recommended Guidelines for Concrete Mix Design"(IS-10262) is meant for the design of low to medium strength concretes but does not include the design of concrete mixes when pozzolans and admixtures arre used. Therefore for arriving at the reference mix, the basic principles on which high strength concrete mix should bebased were considered and the proportions of a number of mixes incorporating silica fume as reported in the literature were reviewed. Since the strength of silica fume concretes depend on a host of parameters, in order to study the effect of silica fume only, the others were to be kept constant. Hence the mix proportion as well as the dosage of SP were to be kept constant as in the reference mix. For High Strength Concrete the content of cementitious material is higher ranging from 500-650 kg/m^3 (Shah and Ahmad,1994). For the present investigation the binder content will be maintained at 525 kg/m^3. Coarse aggregate and fine aggregate were maintained at a ratio of 60:40 for obtaining the maximum packing density. The detailed mix proportion is presented in the table 4:

Mixes	W/B	Cement (Kg/m^3)	Silica Fume		Aggregates (Kg/m^3)		Water (Kg/m^3)
			%	(Kg/m^3)	Fine	Coarse	
SFC 01	0.30	525	0	0	724.457	1086.686	157.5
SFC 02		498.75	5	26.25	720.598	1080.897	
SFC 03		472.5	10	52.5	716.739	1075.108	
SFC 04		446.25	15	78.75	712.98	1069.48	
SFC 05	0.34	525	0	0	701.945	1052.920	178.5
SFC 06		498.75	5	26.25	698.194	1047.290	
SFC 07		472.5	10	52.5	694.227	1041.340	
SFC 08		446.25	15	78.75	690.368	1035.552	
SFC 09	0.38	525	0	0	679.648	1019.472	199.5
SFC 10		498.75	5	26.25	675.574	1013.361	
SFC 11		472.5	10	52.5	672.144	1008.216	
SFC 12		446.25	15	78.75	667.963	1001.944	
SFC 13	0.42	525	0	0	656.921	985.382	220.5
SFC 14		498.75	5	26.25	653.062	979.593	
SFC 15		472.5	10	52.5	649.203	973.804	
SFC 16		446.25	15	78.75	645.344	968.016	

Table 04: Detailed Mix Proportion

MIX ID:	W/B Ratio:	SLUMP: (mm)	DENSITY: (Kg/m^3)	COMPACTING FACTOR:
SFC:01	0.30	210	2592	0.99
SFC:02		190	2548	0.98
SFC:03		150	2500	0.96
SFC:04		100	2459	0.91
SFC:05	0.34	200	2550	0.99
SFC:06		170	2520	0.98
SFC:07		150	2480	0.95
SFC:08		110	2450	0.90
SFC:09	0.38	210	2540	0.99
SFC:10		190	2500	0.98
SFC:11		160	2458	0.96
SFC:12		120	2430	0.93
SFC:13	0.42	230	2520	0.99
SFC:14		200	2480	0.98
SFC:15		180	2450	0.96
SFC:16		150	2420	0.94

Table 05: Fresh Concrete Properties

8. Results and Discussions

In the present study, a detailed investigation was performed on the properties of fresh concrete over a range of water binder ratio. Silica Fume was used as a partial replacement of cement at different levels varying from 0 to 15%. Various test has been performed to determine the properties of these concretes and the result has been discussed as follows:

9. Fresh Concrete

In the fresh state, the mixes were closely examined by visual observations and consistency of the mixes were determined. Since silica fume concretes are sticky and the investigation was carried out for a wide range of water cementitious materials ratio and binder contents, workability of the mixes varied over a wide range, from highly flowing concrete to concrete suffering from segregation and bleeding. Hence, to get a better idea of concrete consistency both slump and compacting factor tests were performed as per IS:1199. The slump was measured in mm and its type was also noted. The C.F. values have been calculated according to the following formula:

$$\text{C.F.} = \frac{\text{Weight of partially compacted concrete}}{\text{Weight of fully compacted concrete}}$$

The fresh concrete density was also determined for all the mixes.

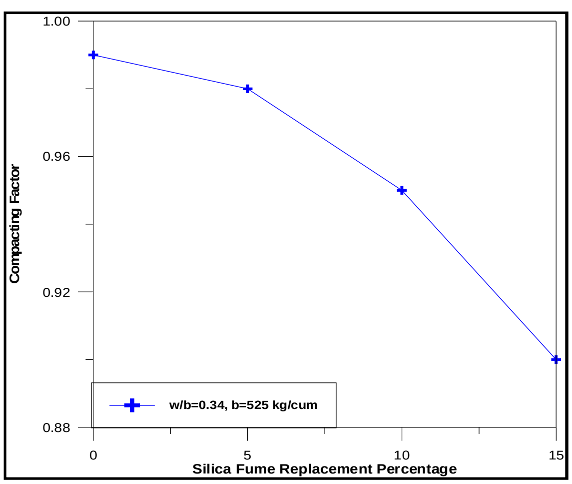

Figure 1 A: Variation of Compacting Factor for w/b ratio=0.34

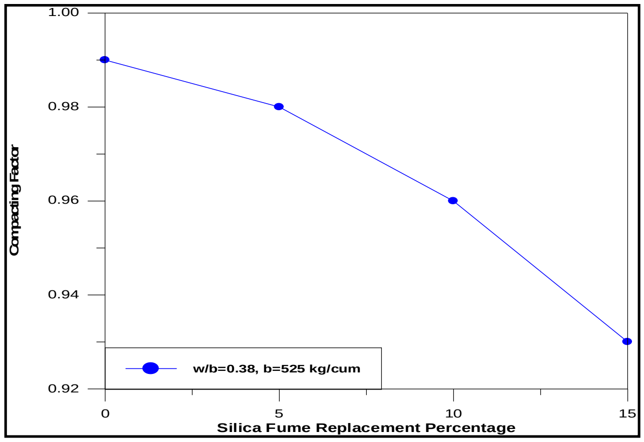

Figure 1 B: Variation of Compacting Factor for w/b ratio=0.38

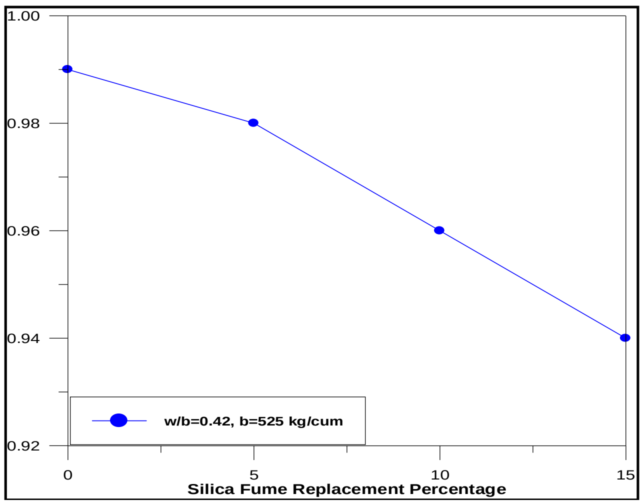

Figure 1 C: Variation of Compacting Factor for w/b ratio=0.42

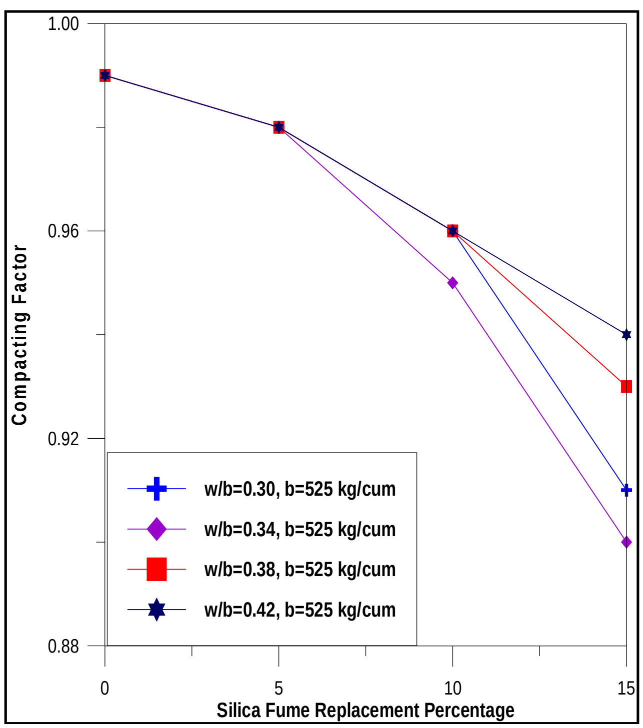

Figure 1D: Variation of Compacting Factor with Silica Fume Replacement Percentage for Different w/b ratios.

9.1. Results

In the present investigation, 16 different concrete mixes have been studied. Each mix had to be cast a number of times and the average values of the rheological properties have been tabulated in table 05. In all the cases, immediately after completion of mixing, concrete were closely inspected by visual observation to assess the quality, consistency and uniformity of the mix. For measuring the workability, slump and CF tests were performed and the average value of these observations is presented in Table 05.

9.2. Discussions

The aim of the present study was to investigate the concrete properties on the effect of cement replacement by silica fume over a wide range of water binder ratios. In the following sections a detailed study of the effect of these variable on the fresh concrete properties is presented.

9.3. Effect of Cement Replacement by Silica Fume on Consistency

The relative proportion of the concrete mixes including the SP content was kept almost constant, only cement was replaced by silica fume. Hence the mix character varied over a wide spectrum- from flowing concrete to concrete suffering from high bleeding and segregation. But the concrete suffering from bleeding and segregation improved drastically with silica fume incorporation. The workability of the concrete mixes decreased tremendously with the increasing percentage of silica fume replacement, starting from 5% of cement replacement. At water cement ratio of 0.34, the control concrete was a flowing one. At 5% silica fume replacement, the cohesiveness of the mix increased. But at 10% there was a considerable reduction in workability, which got reduced at evenhigher percentage of silica fume i.e.15%. At water cement ratio of 0.34, the slump values at 0%(control), 5%, 10% and 15% silica fumes were 200, 170, 150 and 110 respectively. Incorporation of silica fume turns the concrete sticky and hence there is a change in workability. At water cement ratio of 0.38, the control concrete was a highly flowing one. But with the addition of 5% silica fume the mix character improved considerably and with even higher percentages of silica fume replacement a very cohesive concrete mix was obtained. Concrete with a very high percentage of silica fume exhibited a bluish ash colour. At water cement ratio of 0.42 the control concrete suffered from segregation and bleeding. But as a result of the incorporation of the silica fume a stable mix was obtained at 15% silica fume replacement.

Figure 02(A, B, C, D & E) exhibits the variation of slump. From the figure it is observed that as the silica fume content is increased, a decrease in workability occurs. At higher replacement levels the concrete turned more cohesive and a highly stable mix was obtained. Silica fume increases the cohesiveness of the mix and turns it sticky. The values of the fresh density of concrete indicate that as the silica fume content increases, the fresh density of concrete decreases.

9.4 General Observations

Slump test is very sensitive for flowing mixes, Most of the concrete mixes were cohesive, flowable and free from segregation. The slump values of all the mixes lie between 100-210 mm indicating a very high degree of workability as per IS 456-2000. The slump values of 5% silica fume replacement was very close to control, but the slump value of 10% silica fume was reduced considerably. Again with the addition of high percentage of silica fume i.e. 15%, the slump value was dramatically reduced.

The values of the fresh density of concrete indicate that as the silica fume content increases, the fresh density of concrete decreases. On calculation, it is observed that the average density of control and silica fume concretes are about 2550 kg/m^3 and 2475 kg/m^3 respectively.

Control concrete at, water cement ratio of 0.38 and 0.42 have exhibited high bleeding, but with the incorporation of silica fume the mix character improved considerably and highly stable and cohesive mix was obtained with reduced bleeding.

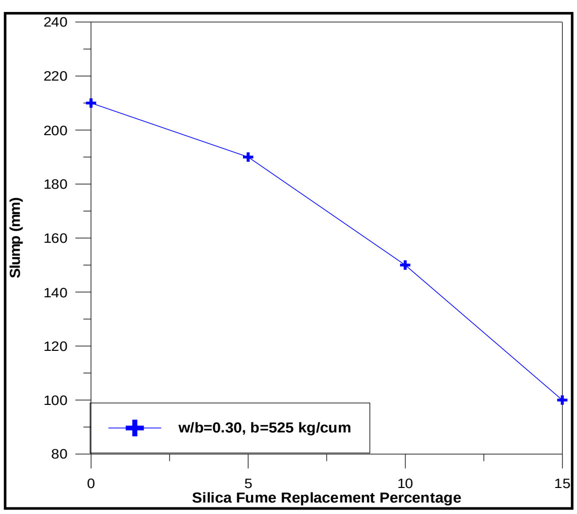

Figure 2 A: Variation of Slump for w/b ratio=0.30

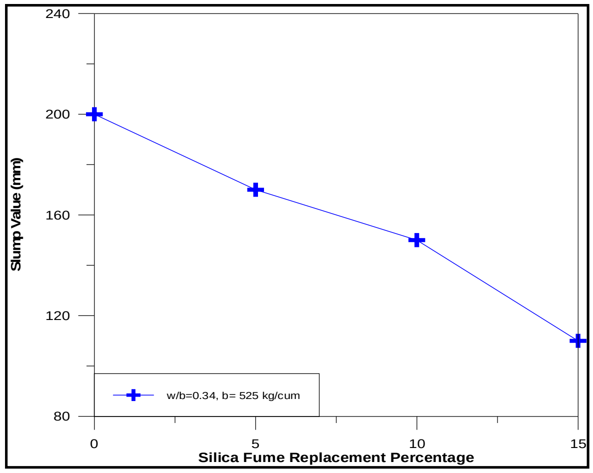

Figure 2 B: Variation of Slump for w/b ratio=0.34

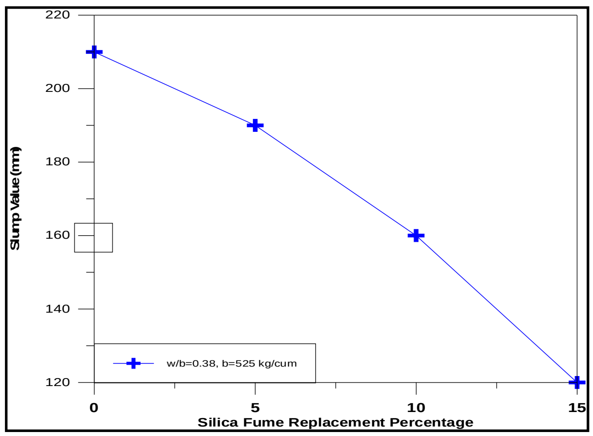

Figure 2 C: Variation of Slump for w/b ratio=0.38

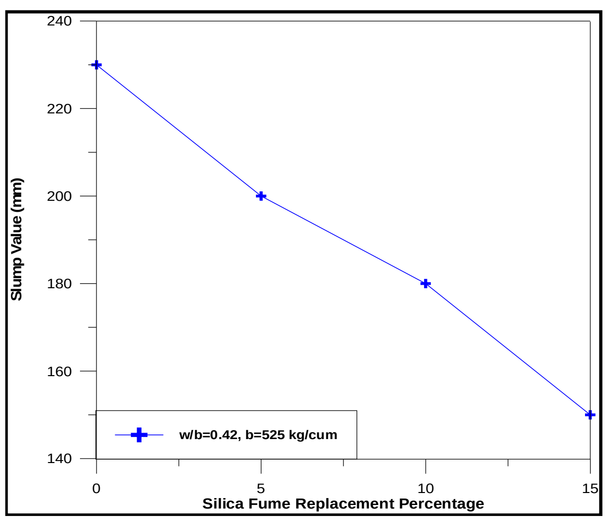

Figure 2 D: Variation of Slump for w/b ratio=0.42

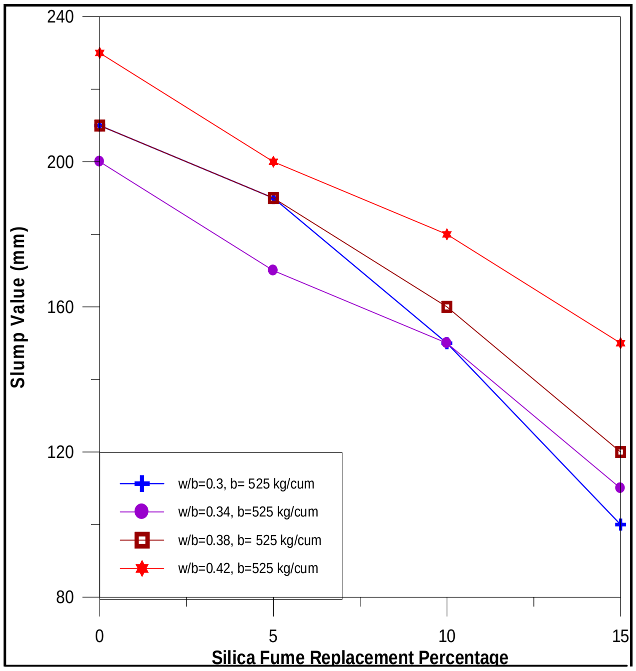

Figure 2 E: Variation of Slump with Silica Fume Replacement Percentage for Different w/b ratios.

10. Conclusions

From the above observation it can be concluded that silica fume affects a number of properties of fresh concrete.

1. For all water cement and binder content, the workability of the concrete mix reduced dramatically with the increase in the silica fume replacement percentage.
2. As the amount of silica fume used in a mix increases, the cohesiveness of the mix increases and the mix becomes sticky.
3. Superplasticizer dosage was kept constant (2.5%). Hence no effect of SP dosage on slump variation.

In a nutshell, the following points may be highlighted:

Silica Fume incorporation in concrete:

1. Increases the water demand and reduces the workability.
2. Increases the cohesiveness of the mix. At higher silica fume contents the mix becomes sticky.
3. Reduces bleeding.
4. Prevents segregation.
5. Reduces the fresh density of concrete.
6. Large replacement percentage can cause a change in the colour of the mix.

11. Acknowledgement

The authors are thakful to the Mani Group for the supply of high quality Micro Silica from Elkem India Pvt Limited. Also our sincere gratitude to Fosroc Chemicals for providing us high performance superplasticizers named conplast sp-430.

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