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EFFECTS OF SILICA FUME ON PROPERTIES OF HIGH-STRENGTH CONCRETE

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Abstract— **This paper represents the results of an experimental work on some properties of high-strength concrete containing different levels of silica fume. Silica fume is an ultrafine powder collected as a by-product of the silicon and ferrosilicon alloy production. A certain percentage of silica fume as a cement replacement, can improve some properties of high-strength concrete such as compressive strength, flexural strength durability etc. The main objective of this study was to determine the optimum percentage of silica fume to replace cement in order to improve the properties of hardened high-strength concrete. To fulfill the objective, some properties of concrete containing silica fume were evaluated after 7, 28 and 60 days of curing. Furthermore, comparison between regular concrete and silica fume concrete containing different levels of silica fume content (5%, 10% and 15%) was conducted. The water/binder ratio was kept constant at 0.3 throughout the mixing process. The results of this research work indicate that compressive strength and flexural strength exhibited the highest improvement with 10% and 15% silica fume replacement respectively. This paper can be a useful source of information for other researchers to understand the benefits and adverse effects of silica fume and have an overview of its optimum percentage when dealing with concrete.**

Index Terms— **Silica fume, High-strength concrete, Compressive strength, Flexural strength**

I. INTRODUCTION

Concrete is one of the most important and widely used man-made construction materials. In fact concrete is a composite construction material, composed of cement (commonly Portland cement), coarse aggregate made of gravels or crushed rocks, fine aggregate (sand), and water. Sometimes admixtures are added to give concrete some special characteristics as required. Concrete is an incredibly useful and flexible building material without which modern architecture and construction would not be possible. It can be easily poured into forms and moulds to create different shapes, it quickly hardens to become a durable stone-like material. It is used in buildings, foundations, bridges, footings, roads and many other applications.

Most normal concrete structures deteriorate rapidly especially when they face some challenging environments; consequently, they require costly repairs before their expected service life is reached to end.

In order for a concrete to be good, it must meet two criteria, i.e. concrete has to be satisfactory both in its fresh and hardened state. Concrete in its fresh state must be consistent and cohesive, In other words, consistency of the mix should be such that it can be compacted easily without excessive effort, and also the mix should be cohesive enough so as not to produce segregation with a consequent lack of homogeneity of the finished product. The significant requirements from a concrete in its hardened state are satisfactory compressive strength and adequate durability (Neville, 1995).

Since this research work mainly focuses on the effects of silica fume on the properties of high-strength concrete; therefore it is important to know more about high-strength concrete and silica fume.

A. HIGH-STRENGTH CONCRETE (HSC)

It is a type of high performance concrete (HPC), generally with a specified compressive strength of (40 MPa) or greater. Its production requires more research and attention to quality control than conventional concrete. There are several reasons for using HSC in construction industry, among them requirement for durability and strength of structures, construction of high-rise buildings and long-span bridges, early age serviceability are mentionable.

B. SILICA FUME

Silica fume is also referred to as micro silica or condensed silica fume, but the term silica fume has become generally accepted. It is a by-product of the manufacture of silicon and ferrosilicon alloys from high-purity quartz and coal in a submerged-arc electric furnace (Neville, 1995).

Silica fume is a kind of mineral admixture which gives special characteristics to concrete such as; reduced permeability, improved reinforcement corrosion protection, enhanced resistance against sulfate and chemicals attack, improved mechanical performances, increased tensile and flexural strengths and last but not the least enhanced compressive strength of concrete. Silica fume has been widely used in all over the world, where high strength and durable concrete is required.

II. EXPERIMENTAL DETAILS

A. MATERIALS

The materials used for this research were cement, coarse aggregate, fine aggregate (sand), normal water, superplasticizer (SP) and silica fume (SF).

The type of cement was Ordinary Portland Cement (OPC) for both normal and silica fume concrete. For better result; normal drinking water was used, because it is free from impurities such as oils, acids, alkalis, salts, organic materials and is very effective for concrete. Aggregates of size (5-15) mm were selected as coarse aggregate, and river sand was used as fine aggregate. Two types of admixtures namely, silica fume as partial replacement of cement and superplasticizer, for increasing workability of the fresh concrete, were incorporated in the concrete mixture.

B. MIX PROPORTION

The experimental research program was conducted to determine the effect of silica fume on properties of high-strength concrete. Therefore, while performing the experiment, only cement was replaced by different percentages of silica fume, and all the other mix design variables, such as quality and amount of aggregates, water content and superplasticizer were kept constant, if not, they would affect the strength and other properties of the concrete and the aim of present investigation would have been lost. In order to produce high-strength concrete, all those effective ways which can contribute in enhancement of concrete strength must be followed, one of them is to reduce the water-cement ratio (w/c); therefore, for this research the w/c ratio used is 0.3, and the mixing proportion used for the other ingredients (cement, sand, coarse aggregate) is 1.2:1:1.5 respectively.

The total amount of binder, fine aggregates and coarse aggregates were fixed at 700, 596 and 894 Kg/m^3 respectively, based on the mentioned mix proportion. Table 1 shows the materials amount in details. The experimental program included four sets of mixes at different silica fume percentages ranging from 0% (control mix) to 15%. A constant dosage of 2.5% of the total amount of cementitious materials was selected for superplasticizer (SP), because according to (Neville, 2005) the amount of superplasticizer can affect the strength of concrete.

III. TESTING PROGRAM

A. SLUMP TEST

Slump test was conducted according to BS 1881: part 102:1983 for measuring the property of fresh concrete, in other words, to determine the workability/consistency of the fresh concrete. Consequently, all the samples showed true slump (between 0 and 12.5 cm).

B. COMPACTING FACTOR TEST

Compacting factor test was carried out according to BS 1881: part 103:1993 to assess workability of the fresh concrete. The degree of compaction, called the compacting factor, is defined by the ratio of the weight of partially compacted concrete to the weight of fully compacted concrete which is always less than one.

C. COMPRESSIVE STRENGTH TEST

For this study, the specimens in the form of cylinders, were compressed between the platens of a compression testing machine by a gradually applied load. The compressive strength was found by the following equation:

$$f_c = P/A \qquad (1)$$

Where f_c is concrete compressive strength (N/mm^2), P is applied load (N), A is the cross sectional area of the concrete specimen (mm^2). In order to investigate the effects of silica fume on compressive strength of concrete, the compressive strength test was carried out on 100 x 200 mm concrete cylinders in accordance with BS 1881: part 116.

At the ages of 7, 28 and 60 days, three samples of each type of concrete mix (normal concrete and silica fume concrete containing 5%, 10% and 15% silica fume) were tested for compressive strength and the average value was recorded for further analysis.

D. SCHMIDT HAMMER TEST

Also known as rebound hammer test is a non-destructive test which was used to estimate compressive strength of concrete by measuring its surface hardness. This test was conducted according to BS 1881:202:1986 on concrete cylinders at the ages of 7, 28 and 60 days. The result was compared with the result of compressive strength test.

E. FLEXURAL STRENGTH TEST

The flexural strength is expressed as modulus of rapture in (MPa). For this research, flexural strength (modulus of rupture) was determined by center-point loading or three point loading method, during which the concrete beam was placed on two rollers and the entire load was applied on its center. Flexural strength was calculated using the following equation:

$$f_{cf} = 3PL/2bd^2 \qquad (2)$$

where f_{cf} is the flexural strength, P is the maximum applied load by the testing machine, L is the distance between the two supporting rollers (span of the beam) which was determined to be 280 mm for this test, b = 100 mm is the width of the beam, d = 100 mm is the depth of the beam. The test was carried out on 100 x 100 x 350 mm concrete beams at the age of 7, 28 and 60 days. Each strength value obtained is the average of values of three specimens.

IV. RESULTS AND DISCUSSION

A. WORKABILITY

Workability is an important property of concrete in its plastic stage. It actually determines the ability of fresh concrete to be placed, compacted and finished without segregation. For this research work, slump and compacting factor tests were conducted. Workability of concrete is directly proportional to the w/c ratio; that is to say, if the ratio is high, the workability of concrete will also be high and vice versa. From the slump test result, it can be seen that the overall workability is low for all the samples, because this research deals with high strength concrete using a low w/c ratio of 0.3. In order to produce high strength concrete w/c ratio must be reduced. A w/c ratio of 0.3 was kept constant throughout the experiment; consequently it increased the compressive strength, meanwhile reduced the overall workability. On the other hand, enhancement of silica fume percentage also caused reduction in workability. **Fig.1** indicates result of the slump test.

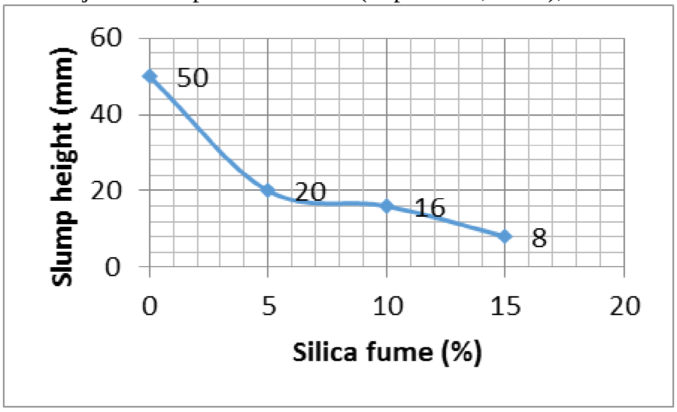


Fig. 1. Slump test result

The highest workability was shown by control mix, while the concrete containing 15% of silica fume resulted in the lowest workability as compared to other concrete mixes. Superplasticizer was used to increase workability of the fresh concrete.

Although both compacting factor and slump tests are used for the same purpose (determination of workability of fresh concrete), it would be better to carry out both, so as to validate each other's result.

The compacting factor test was carried out according to BS 1881: part 103:1983. **Fig. 2** shows a similar result as that of the slump test. It clearly indicates the reduction of workability with the enhancement of silica fume amount.

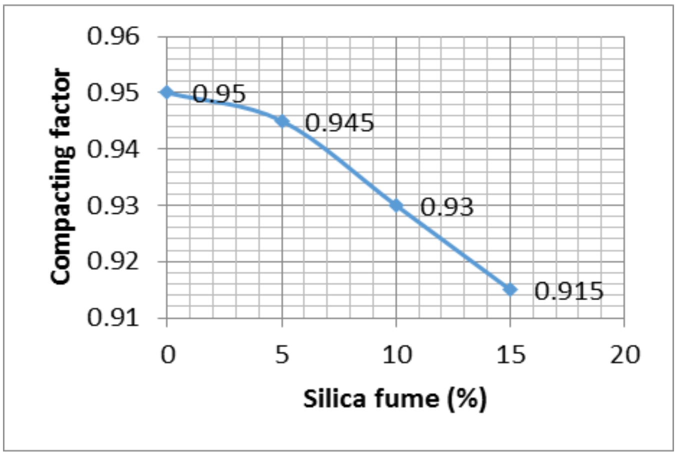


Fig. 2. Compacting factor test result

The value of compacting factor for control mix is the highest, indicating the highest workability, while it decreases with the enhancement of silica fume amount. Concrete containing 15% of silica fume indicates the lowest compacting factor value. The reduction in workability is firstly due to lowering the w/c ratio and secondly due to the enhancement of silica fume. **Table 1** shows the values of compacting factor and slump height.

Table 1
Mix proportion of concrete with and without silica fume

Specimen	Cement	Silica fume		Fine Aggregate	Coarse Aggregate	Water	SP	Slump	Compacting factor
	(Kg/m^3)	%	(Kg/m^3)	(Kg/m^3)	(Kg/m^3)	(Kg/m^3)	%	mm	
SF(0)	700	0	0	596	894	210	2.5	50	0.950
SF(5)	665	5	35	596	894	210	2.5	20	0.945
SF(10)	630	10	70	596	894	210	2.5	16	0.930
SF(15)	595	15	105	596	894	210	2.5	8	0.915

B. COMPRESSIVE STRENGTH

Strength is the most important property of structural concrete because it displays an overall picture of its quality. In other words, among the different strengths of concrete, compressive strength comes first in importance due to concrete is primarily meant to resist compressive stress. High compressive strength of concrete indicates better quality, while poor quality of concrete is the result of its inadequate compressive strength.

For determination of compressive strength of concrete, two tests (compressive strength and Schmidt Hammer tests) were carried out. Concrete cylinders were put in the testing machine to evaluate their compressive strength by applying axial forces on them until they were crushed. Compressive strength was calculated by dividing the compressive load (N) applied by the testing machine, over the cross sectional area (mm^2) of the cylindrical concrete specimens.

In order to investigate the effects of silica fume on properties of high-strength concrete, the w/c ratio of 0.3 was kept constant throughout the experiment. From **table 2** and **Fig.3**, it can clearly be seen that silica fume increased the compressive strength of the concrete effectively.

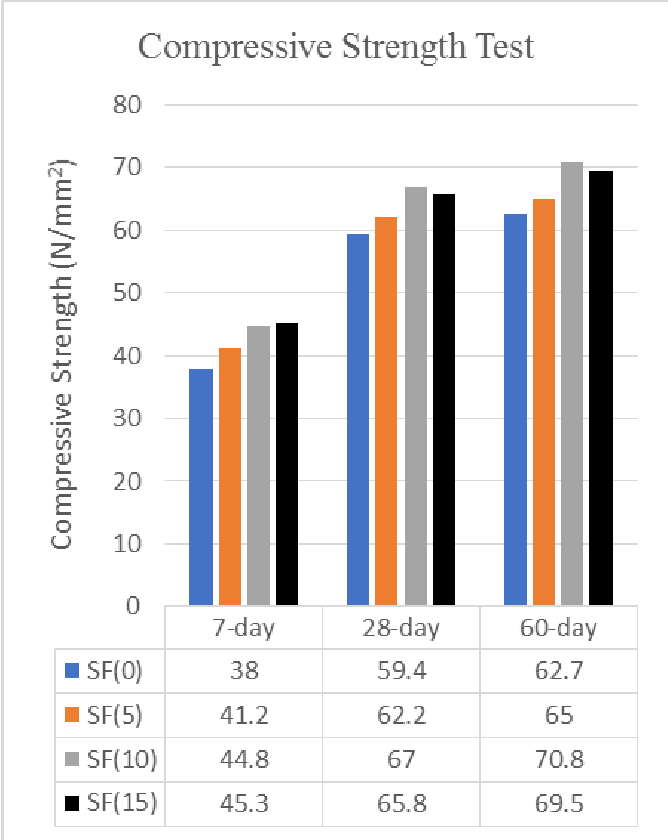


Fig. 3. Compressive strength test result

With the enhancement of silica fume content, the compressive strength increased. The control concrete sample showed the lowest compressive strength, while concrete sample containing 10% silica fume resulted in highest compressive strength as compared to rest of the samples.

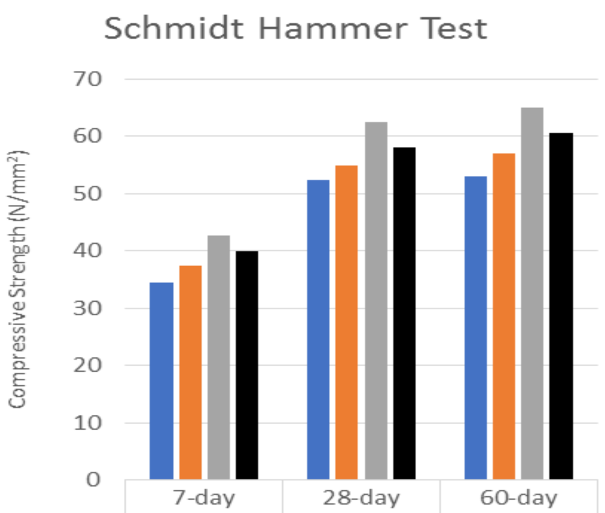
Duval and Kadri (1998) in their research paper found that the compressive strength of concrete increases with the silica fume content up to 20% and reaches a maximum for a 10 to 15% silica fume level.

But based on this research study, concrete with 10% silica fume achieved more compressive strength than 15% silica fume, while the difference between them is not much.

It is mentionable that there is a huge difference in strength between concrete samples at the age of 7 and 28 days, but at the age of 28 and 60 days, the strength difference is very less. The reason is that concrete obtains maximum of its strength within 28 days of the curing time and after that the strength development in concrete becomes very slow.

Mazloom, et all. (2004) in his research paper found that the compressive strength development of concrete mixtures containing silica fume was negligible after the age of 90 days; however, there were strength increases in the control concrete even after one year and the reason behind this can be attributed to the rapid formation of a layer which prevents reaction of silica fume with calcium hydroxide beyond 90 days. And in case of the control concrete, hydration is at a less advanced stage and strength still shows significant increases. This shows that silica fume increases the early age strength of concrete.

Similar to the compressive strength test, Schmidt hammer test results show enhancement in concrete strength as the number of curing days and amount of silica fume content increased. On the other hand, a small difference can be seen in the results of the two tests i.e. the overall strength values obtained in case of Schmidt test are slightly less than the values obtained by compressive strength test for the same specimens. The reason for this difference can be the fact that, Schmidt hammer test is an indirect way of measuring the strength, as it simply gives an indication based on the surface properties, while in compressive strength test; the specimen is pushed axially till it is crushed. Therefore, there is a bit difference in the results of the two tests. Considering **Table 2** and **Fig.4**, the results obtained by this test indicate that with enhancement of the amount of silica fume content, compressive strength of the concrete increased and similar to compressive strength test, the highest compressive strength was shown by concrete containing 10% silica fume content and the lowest compressive strength was exhibited by control mix.



	7-day	28-day	60-day
SF(0)	34.5	52.4	53
SF(5)	37.5	55	57
SF(10)	42.6	62.5	65
SF(15)	40	58	60.5

Fig. 4. Schmidt Hammer test result

C. FLEXURAL STRENGTH

It is a well-known fact that concrete is strong in compression but weak in tension; therefore, to increase the tensile strength of concrete, it is reinforced either by using steel bars or some certain types of admixtures in the concrete mixture. Flexural strength is the limit of a material to withstand flexural stress without failing. The specimen subjected to flexural stress, faces both tension and compression behavior because of bending moment. In other words, upon applying the load, the specimen will bend; consequently the inner part of the specimen on which the load is applied will face compression, while the outer part will face tension.

For this research study, silica fume was used to investigate its effect on the flexural strength of concrete. Flexural strength test was conducted on 10 x 10 x 350 mm beams at the ages of 7, 28, 60 days. The result of the test can be seen in **Fig.5** and **Table 2**.

The flexural strength almost follows the same trend as the compressive strength. The result of the test shows that at the age of 7 days, the flexural strength is very less and gradually increases by the time being. The 28-day flexural strength is considerably much higher than that of 7-day, on the other hand, the difference between 28-day and 60-day flexural strength is very less and almost negligible. The flexural strength ranges from (2.34 to 5.8 N/mm2), (6 to 9.7 N/mm2) and (6 to 10 N/mm2) for specimen at ages of 7, 28 and 60 days respectively. Silica fume could significantly increase the flexural strength of the concrete. It is mentionable that silica fume concrete is stronger in tension comparing to control concrete mix, and the flexural strength kept on increasing as the silica fume content increased.

Bhanja and Sengupta (2005) in their research paper found that by keeping the other mix design parameters constant, silica fume incorporation in concrete results in significant improvements in the flexural strength of concrete, along with the compressive strength. They also added that the optimum 28-day flexural strength has been obtained in the range of 15% to 25% silica fume replacement.

This research study indicates that the SF(0) and SF(15) obtained the lowest and highest flexural strengths respectively

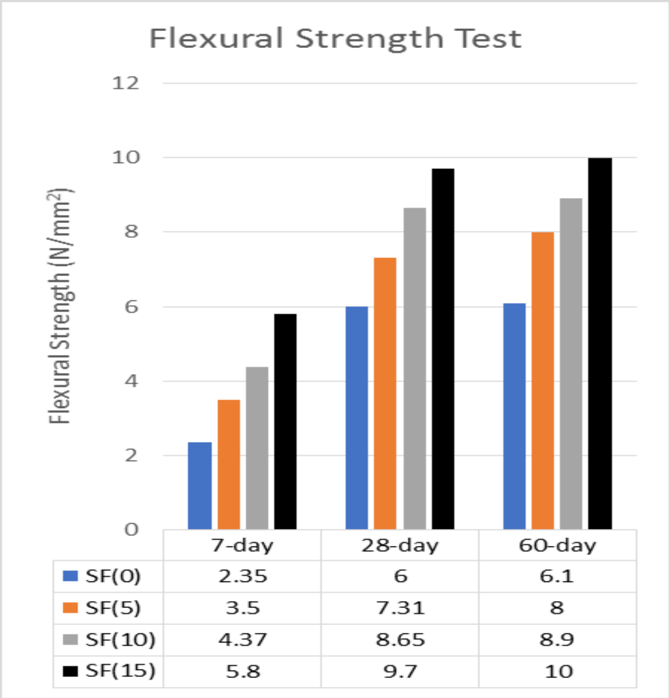


Fig. 5. Flexural strength test result

Table 2
Results of compressive strength and flexural strength tests of hardened concrete

Specimen	Compressive strength by machine (N/mm^2)			Compressive strength by Schmidt Hammer (N/mm^2)			Flexural Strength (N/mm^2)		
	7-day	28-day	60-day	7-day	28-day	60-day	7-day	28-day	60-day
SF(0)	38	59.4	62.7	34.5	52.4	53	2.35	6	6.1
SF(5)	41.2	62.2	65	37.5	55	57	3.5	7.31	8
SF(10)	44.8	67	70.8	39.6	61.5	62.8	4.37	8.65	8.9
SF(15)	45.3	65.8	69.5	41	62	63.5	5.8	9.7	10

V. CONCLUSION

It is a general fact that most normal concrete structures deteriorate rapidly, especially when they face some challenging environments and they require costly repairs before their expected service life ends. Therefore, in order to be able to solve such problem, it is required to use all those effective techniques to improve quality of concrete mixture.

The result of this experiment and related laboratory tests showed that in general, silica fume incorporation in concrete as a partial replacement of cement significantly improved quality of the concrete. Based on this research work, by using 0 - 15% silica fume as replacement of cement in high-strength concrete the following points can be concluded:

- The overall workability of the fresh concrete was low to some extent because a low water/cement ratio (w/c = 0.3) was used and the slump loss further increased with the enhancement of silica fume content.
- It was found that up to 10% cement may be replaced by silica fume without harming the concrete workability.
- The high-strength concrete showed a rapid compressive and flexural strength development between 7 and 28 days, while between 28 and 60 days the development rate reduced. It is due to the fact that concrete gains maximum of its strength within the first 28 days.
- Concrete containing 10% silica fume replacement achieved the highest compressive strength followed by 15% silica fume replacement with a small difference.
- A small differences can be seen in the results of Schmidt Hammer and compressive strength tests i.e. the strength values obtained by the former are slightly less than the later one. The reason is that, Schmidt hammer test is an indirect way of measuring the strength, as it simply gives an indication based on the surface properties, while in compressive strength test, the specimen is pushed axially till it is crushed, therefore the results cannot exactly be the same.
- Flexural strength test showed a significant increase in the flexural strength of the concrete with the enhancement of the silica fume content. Based on the flexural test result, concrete with 15% silica fume content achieved the highest flexural strength.

It is mentionable that silica fume incorporation in the concrete mix significantly improved the properties of concrete such as, compressive and flexural strengths. Based on this research work, 10% and 15% silica fume content as replacement of cement were found to be the optimum amount for significantly enhancement of compressive strength and flexural strength respectively. Further studies may be carried out to find the effects of silica fume on reduction of concrete permeability. According to some researchers, silica fume can significantly reduce concrete permeability and enhances its durability.

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