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INVESTIGATIONS ON THE MECHANICAL PROPERTIES OF HIGH STRENGTH SILICA-FUME CONCRETE (HSSC) MIXES AT DIFFERENT AGES

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In recent years, some organization increasingly encourages the use of cementitious materials such as fly ash, slag and silica fume. Silica fume is a by-product in the manufacture of ferrosilicon and also of a silicon metal. Lately, some attention has been given to the use of condensed silica fume as a possible partial replacement for cement.

The main objective of this investigation is to study the effect of the binder system containing different levels of silica-fume, as a partial replacement of cement, on the mechanical properties of high strength concrete and particularly, to determine the optimum content of silica-fume that maximize the strength and mechanical performance of HSSC. The work in this research focused on concrete mixes having water/binder ratio = 0.32 and constant total binder content (cement and silica) of 450 Kg/m3. The percentages of silica-fume that replaced cement in this research were: 0.0, 5.0, 10.0, 15.0, 20.0 and 25.0 %. Compressive, splitting and flexural strength tests were carried out at the age of 28, 59, 90,180 and 360 days to identify the mechanical properties of HSSC mixes at different ages. The effect of water/binder ratio on the compressive strength of HSSC mixes has been also examined. The modulus of elasticity of the produced concrete mixes at age of 28 days was determined. Test results of this research indicated that, the partial replacement of silica fume instead of cement in concrete mixes up to a ratio of 15 % effectively improves the mechanical properties of concrete and produces high compressive strength, beyond this limit, the compressive strength significantly decreased.

KEYWORDS: *Silica fume, concrete, compressive, splitting, flexural, modulus of elasticity.*

INTRODUCTION

Silica fume is a fine dust-like material generated during silicon metal and ferrsilicon and related to ferroalloys (e.g., stainless steel) production. Specifically, it is produced by the reaction of high puirty quartz with coal or coke and wood chips in an electric furnace during silicon metal or ferrosilicon alloys production. The glassy, spherical particles are extremely small, measuring less than one micrometer (µm) in diameter, with an average diameter of about 0.1 µm. Silica fume particless are composed primarily of silicon dioxide (usually more than 85 percent) [1].

Silica fume has a tremendous potential in this context and it is well documented that, the use of silica fume in concrete significantly improves the mechanical properties of concrete. Though the literaure is rich in reporting on silica fume concrete, most of the research works are centered on the compressive strength and the technical data on tensile strength is quite limited. They have reported that, it is the general practice of research and designers to alter the mix design of plain concrete (without silica fume) upon the incorporation of silica fume to overcome the adverse effect of silica fume on fresh mix workability. As a result, the isolated effect of silica fume on the properties of concret is yet to be intensively investigated [2-6].

Nowadays high-strength and high-performance concrete are widely used throughout the world and to produce them, it is necessary to reduce the water/binder ratio and increase the binder content. Superplasticizers are used in these concretes to achieve the required workability; moreover, different kinds of cement replacement materials are usually added to them because a low porosity and permeability are desirable.

Silica fume is one of the most popular pozzolanic materials, whose addition to concrete mixture results in lower porosity, permeability and bleeding because their oxides (SiO2) react with and consume calcium hydroxides, which are produced by the hydration of ordinary portland cement. The main results of pozzolanic reactions are: lower heat liberation and strength development, lime-consuming activity and smaller pore size distribution [7-11].

The main objective of this research work is directed towards developing a better understanding on the contribution of silica fume in concrete mixes to characterize its effect on the mechanical properties of concrete as well as to determine its optimum percentage replacement of cement to maximize the concrete efficiency in mechanical properties.

EXPERIMENTAL WORK

High performance concrete mix proportioning has been found to be more critical process than the proportioning of conventional strength concrete mixes. Therefore, laboratory trial batches have been executed in order to obtain the necessary data on the mix design.

The effect of replacing different percentages of silica fume instead of cement on the mechanical performance of hardened concrete mixes has been studied throughout the following experimental program, which mainly consists of six concrete mixes (group I). Each mix of this group has the same constituent materials except of the percentage of silica-fume which varied from 0.0 % to 25 % with a constant water/binder ratio of 0.32, to find out the optimum percentage which may results the great improvement on the mechanical properties of concrete, as shown in table (1).

In order to investigate the effect of the water/binder ratio on the compressive strength of the examined concrete mixes, another two groups (II and III) of HSSC mixes having same mix proportions along with water/binder ratios of 0.26 and 0.38 were tested at the age of 28 days for the purpose of comparison with the first group of mixes (group I).

Table (1). Details of concrete mixes.

Group No.	Mix No.	Cement Content Kg/m^3	Silica fume Kg/m^3	Sand Kg/m3	Basalt (1) Kg/m^3	Basalt (2) Kg/m^3	Super-plasticizer Litre/m^3	Water content Litre/m^3
I	1	450.0	0.0	640	640	640	1.5	144
	2	427.5	22.5					
	3	405.0	45					
	4	382.5	67.5					
	5	360.0	90					
	6	337.5	112.5					
II	1	450.0	0.0	640	640	640	1.5	117
	2	427.5	22.5					
	3	405.0	45					
	4	382.5	67.5					
	5	360.0	90					
	6	337.5	112.5					
III	1	450.0	0.0	640	640	640	1.5	171
	2	427.5	22.5					
	3	405.0	45					
	4	382.5	67.5					
	5	360.0	90					
	6	337.5	112.5					

To fabricate the previous concrete mixes, a natural sand, natural basalt type one and two along with different silica fume contents as well as a constant amount of super-plasticizer (Addicrete BVF) were used. Details of physical and mechanical properties of the used sand and two types of basalt are given in table (2). An ordinary portland cement was used in this investigation and the mechanical properties of it are given in Table (3).

Tap water was used in all concrete mixes. Mixing of concrete components was completed by using a horizontal rotating counter flow mixer pan. Prior rotating the mixer pan, the pan mixer was wetted and only the half amounts of the sand, two types of the basalt were added together into the mixer. While rotating, the cement was added into the mixer followed by the rest of the aggregates. The mixing was performed and then, the mixture of the water and superplasticizer were added for the purpose of uniformity.

Table (2). Physical properties of the used sand and basalt.

Property	Test results of sand	Test results of basalt (1)	Test results of basalt (2)
Specific weight (t|m^3)	2.50	2.80	2.79
Volume weight (t|m^3)	1.75	1.71	1.70
Absorption (24 hrs)	0.65% by weight	0.50 % by weight	0.480 % by weight
% of fine materials	1.40 % by weight	0.40 % by weight	0.375 % by weight
Crushing value	-	16 %	16 %
Voids ratio	30 %	38.93 %	39.07 %

Table (3) Properties of the used ordinary portland cement (O. P. C).

Mechanical properties	Test results	E.S.S limits
Specific gravity	3.15	3.15
Fineness %	6.2 %	Max 10 %
Specific surface cm2/gr.	3975	Min 2500
Water demand %	26	Min 25, max 30
Initial setting time (minute)	140	Min 45 min.
Final setting time (minute)	400	Max 10 hr.
Soundness (mm)	1.0 mm	Max 10 mm.
Compressive strength At 3 days Kg/cm^2 At 7 days Kg/cm^2	 280 300	 Min 180 Kg/cm^2 Min 270 Kg/cm^2

The mixing operation was carried out in accordance to the Egyptian Standard Specifications (ESS). Before casting directly, the internal surfaces of the moulds were coated with a thin layer of mineral oil. Fresh concrete was taken from the mixer and poured into the moulds. Mechanical vibration was applied to all concrete moulds. After that, the top surfaces of the specimens were finished and leveled then; the specimens were kept in the laboratory. A standard curing regime was started and continued until the date of testing.

The experiments of the first group contained the measurements of the compressive strength of the six sets of concrete mixes throughout testing cubes of 10×10×10 cm, (108 cubes in total) at different ages (7, 28, 59, 90, 180 and 360 days). Modulus of rapture of concrete prisms 10 x 10 x 50 cm (90 prisms in total) and splitting strength of concrete cylinders 10 x 20 cm (90 cylinders in total) were determined. The modulus of elasticity of the concrete prisms 10 x 10 x 40 cm, (18 prisms in total) was caculated at the age of 28 days. The same amount of, cementitious materials (cement + silica fume contents = 450 Kg/m3) was used in all test specimens. Test specimens free from silica fume (control mix) were prepared as a base of comparison.

The experiments of the second and third groups include the measurements of the compressive strength for twelve sets of concrete cubes 10×10×10 cm, (36 cubes in total) tested at age of 28 days – see table (1).

TEST RESULTS AND DISCUSSION

The compressive strength results obtained from testing the concrete cubic specimens which, fabricated with different percentage of silica-fume and tested at different ages are recorded in table (4) and plotted against time in figure (1). It can be concluded that, the replacement of silica fume instead of cement in concrete mixes produced higher compressive strength up to a ratio of silica/binder equals to 15 %, beyond this, the compressive strength significantly decreased.

Table (4) Compressive strength values of high strength silica-fume concrete mixes.

Time (Days)	Compperssive strength of concrete cubes (Kg /cm^2)					
	Percentage of silica-fume					
	0.0	5.0	10.0	15.0	20.0	25.0
7	450.0	470	492	513	439	390
28	647	680	700	729	602	546
59	680	704	732	760	632	575
90	703	730	763	800	673	600
180	724	745	793	815	670	594
360	731	754	803	807	665	587

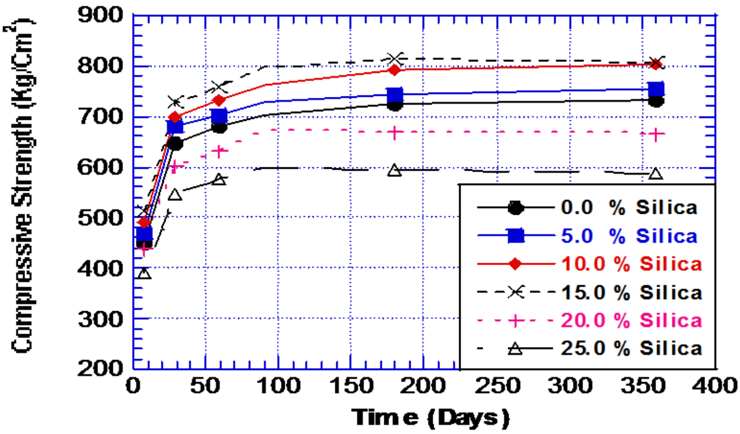


Fig (1) Relationship between the compressive strength of concrete having different ratios of silica-fume and the age of specimens.

Figure (1) emphasizes the fact of increasing the compressive strength with the age of concrete. The increase in strength is found to be very significant up to 90 days. After that, the replacement of silica-fume has more or less no effect on the compressive strength of concrete.

Test results showed that, the compressive strength has been increased by an average value of 13 % for those mixes made of 15% silica. This result is found to be true up to the age of 90 days. This significant increase in the strength can be attributed to the rapid formation of an inhibiting layer of reaction product which, preventing any further reaction of silica fume with calcium hydroxide beyond 90 days.

Increasing silica-fume percentage in concrete mixes from 15 to 20 % causes a considerable decrease in strength by a value of 8 % meanwhile, a reduction of 16 % was resulted when the percentage of silica-fume increased to 25 % when compared with control mix as shown in figure(1). The reason of getting a reduction in strength with high dosage of silica fume replacement may be strongly because the water/binder ratio and the quantity of added super-plasticizer were kept constant which produces dry mixes due to the highly water absorption of silica-fume as well as the effect of reducing cement content in mixes.

The splitting strength results obtained from testing the cylindrical concrete specimens are shown in table (5) as well as illustrated in figure (2). It can be emphasized that, the splitting strength results followed the same trend of the compressive strength for all percentages of silica-fume i.e., the splitting strength has been improved with increasing the % of silica-fume up to 15 %, beyond this limit the splitting strength was found to be decreased. For example, the splitting strength has been increased by a value of 13 % with concrete mixes made of 15 % silica-fume replacement when tested at 28 days meanwhile; the improvement in strength was increased to be 18 % at 90 days.

Table (5) Splitting strength results of concrete mixes.

Time (Days)	Splitting strength of concrete cylinders (Kg /cm^2)					
	Percentage of silica-fume					
	0.0	5.0	10.0	15.0	20.0	25.0
28	45.0	47.1	48.3	49.86	40.1	34.55
59	47.0	48.05	50.04	50.98	42.0	36.0
90	48.0	50.5	52.6	55.0	44.9	38.0
180	50.4	51.6	5307	56.02	44.97	37.7
360	50.9	52.2	54.38	55.0	44.33	37.15

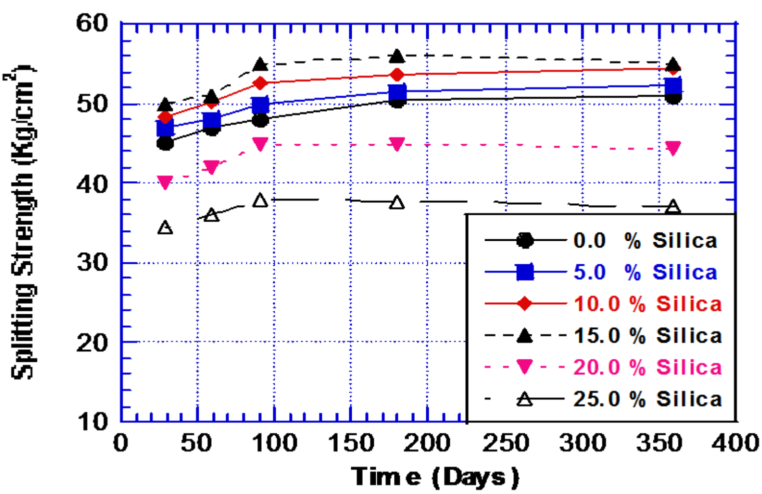


Fig. (2) Relationship between the splitting strength of concrete cylinders made of different ratios of silica-fume and tested at different ages.

The following table (6) comprises the flexural strength results of concrete prisms of the same silica-fume concrete mixes (HSSC) tested at the different specified ages. Figure (3) plots these values of flexural strengths against the age of concrete.

Table (6) Flexural strength results of concrete mixes.

Time (Days)	Flexural strength of concrete cylinders (Kg /cm^2)					
	Percentage of silica-fume					
	0.0	5.0	10.0	15.0	20.0	25.0
28	72.5	77.3	84.1	90.6	82.4	67.7
59	76.01	80.0	87.9	95.02	85.9	71.03
90	80.8	81.9	92.03	98.5	89.8	73.44
180	80.7	84.07	94.0	100.4	93.3	73.7
360	80.1	85.07	93.1	101.4	94.07	72.8

It is of interest to mention that, the flexural strength has been also increased with increasing the % of silica fume up to 15 % following the previous trend of both compressive and splitting strength.

An improvement in the flexural strength of 21% was gained with the concrete mix made of 15 % silica when tested at 28 days meanwhile; the increase was 25 % at 90 days confirming the improvement of strength against age of concrete even with the concrete mixes incorporating silica-fume. However, the flexural strength decreased by about 7% when the silica/binder ratio increased to 25 %, when compared with control mixes.

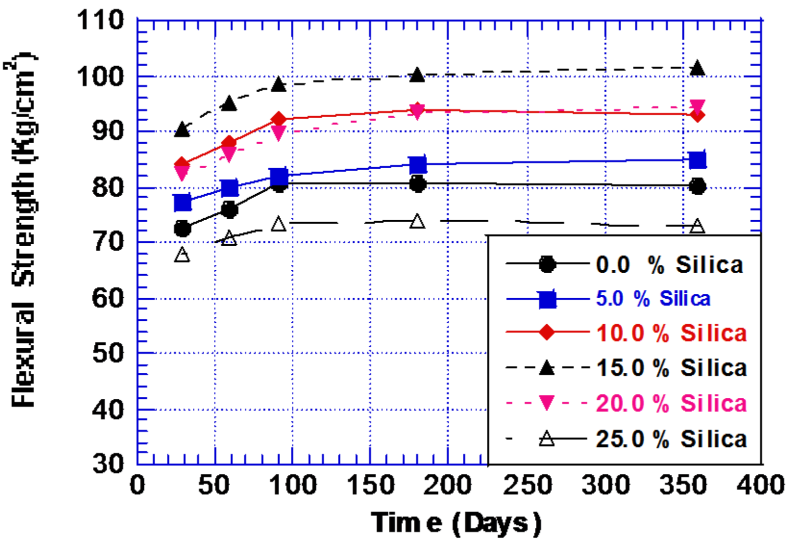
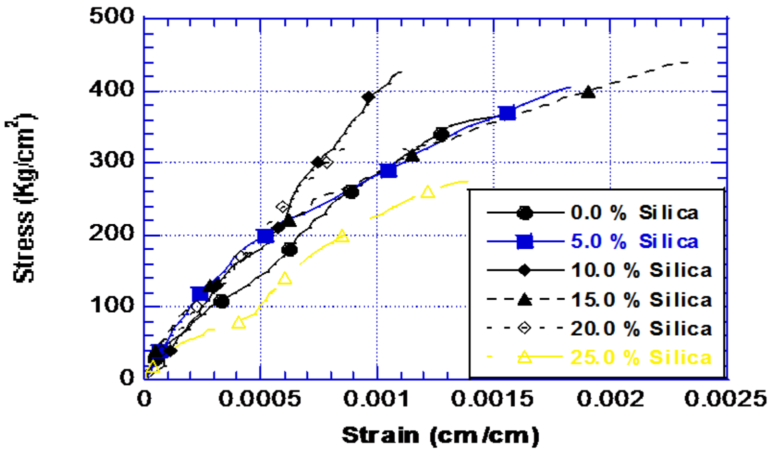


Fig (3) Relationship between the flexural strength of concrete prisms made of different ratios of silica-fume and tested at different ages.

It is important to declare that, the lowest values of flexural strength were obtained from mixes made of silica/binder ratio of 25 %. Therefore, it can be concluded that, silica fume seems to have a more pronounced effect on the flexural strength than the splitting strength i.e., The rate of increasing the flexural strength as a result of using silica-fume in concrete mixes is found to be higher than the increase in splitting strength, this is true at all the percentages of silica-fume in mixes.

The relationship between the stresses and strains of the concrete prismatic specimens made of the six concrete mixes of group (I) and tested at 28 days under static compression is represented in figure (4). The strains in concrete prisms were measured by using an extensometer through two demic points (studs) attached in two opposite sides of the prism surface having spacing between them of 20 cm. The modulus of elasticity was determined for all concrete mixes and the results are recorded in table (7).

It can be resulted that, the modulus of elasticity increases as the percentage of silica-fume increases up to 15 %, which again emphasizes the previous conclusion extracted from the previous results of compression, splitting and flexural strengths. The highest percentage of increase in modulus of elasticity was reported with mixes having 15 % silica-fume and equals to 19 %. Meanwhile, replacement of 25% of cement by silica-fume in concrete mixes causes a decrease in modulus of elasticity by a value of about 15 %, as shown in table (7).



Fig(4) Relationship between stresses and strains for different concrete mixes tested at 28 days.

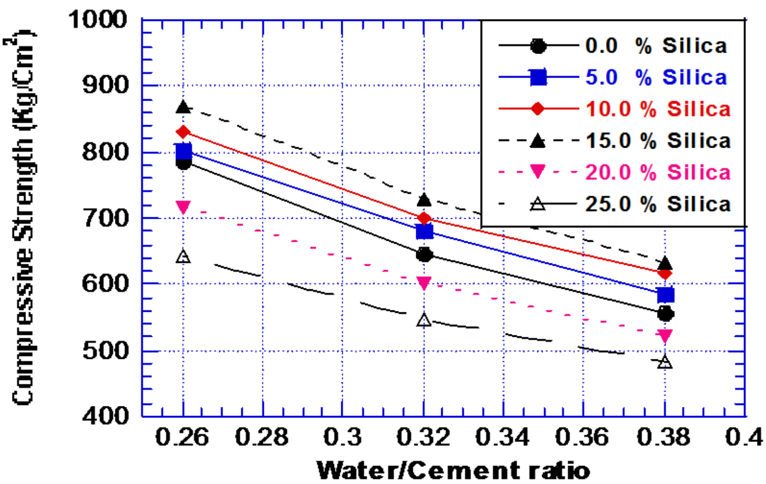
Table (7) Modulus of elasticity results against % of silica of concrete mixes.

Time (Days)	Modulus of elasticity of concrete specimens (Kg /cm^2)					
	Percentage of silica-fume					
	0.0	5.0	10.0	15.0	20.0	25.0
28	320000	342000	364000	381000	353000	273000

The influence of water/binder ratio on the compressive strength of silica-fume concrete mixes is shown in table (8) and also illustrated in figure (5) . It can be noticed that, the compressive strength of silica-fume concrete mixes decreases with increasing the water/binder ratio following the well known fact of decreasing the strength of concrete against water/cement ratio.

Table (8) Effect of water/binder ratio on the compressive strength of concrete Cubes tested at age of 28 days.

Water/binder ratio	Compressive strength of concrete cubes (Kg /cm^2)					
	Percentage of silica-fume					
	0.0	5.0	10.0	15.0	20.0	25.0
0.26	785.1	803.2	831	870	715	642
0.32	647	680	700	729	602	546
0.38	556	586	616	634	520	483



Fig(5) Relationship between the compressive strength and water/binder ratios for different concrete mixes.

The compressive strength was found to be increased by a value of 13 % with concrete mixes made of 15 % silica-fume and water/binder ratio of 32 % when tested at 28 days meanwhile, the increases were 11 % and 14 % for concrete mixes made with water/binder ratios of 0.26 and 0.38 respectively.

A comparative study for the different parameters investigated in this research has been conducted and the results are recorded in table (9) as well as they are shown in the following figure (6). Table (9) contains the % increase in compressive, splitting and flexural strengths as well as the modulus of elasticity for all concrete specimens made of the different percentages of silica-fume and tested at 28 days.

It can be concluded that, the mechanical properties of hardened concrete mixes, in general, has been greatly enhanced by using a percentage of silica-fume as a partial replacement of cement up to 15 %.

Table (9) % increase in strengths and modulus of elasticity made of different Silica-fume/binder ratios and tested at age of 28 days.

Type of Strength	Compressive strength of concrete cubes (Kg/cm^2)					
	Percentage of silica-fume					
	0.0	5.0	10.0	15.0	20.0	25.0
Compressive strength	0.0	5.1	8.19	12.67	-7.0	-15.6
Splitting strength	0.0	4.67	7.33	10.8	-10.8	-23.2
Flexural strength	0.0	6.62	16.0	25	13.7	-6.7
Modulus of elasticity	0.0	6.875	13.75	19.06	10.3	-14.68

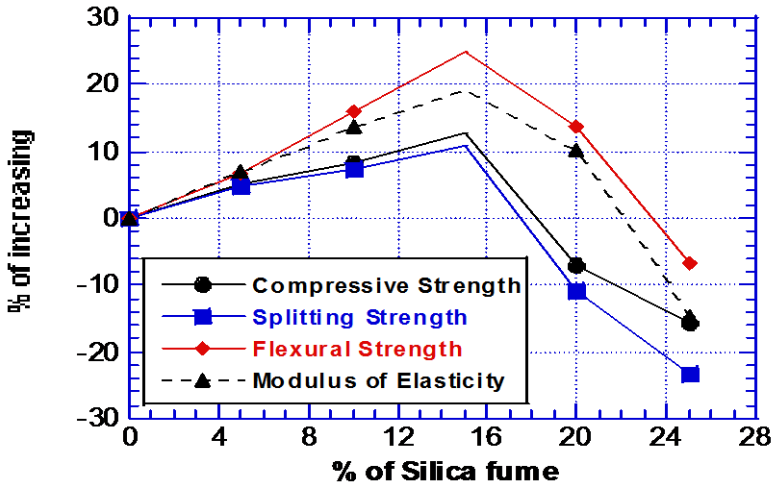


Fig (6) Percentage increase in strengths and modulus of elasticity of concrete mixes against the different percentages of silica-fume.

CONCLUSIONS

Based on the present investigation, the following conclusions, with respect to the effect of replacing a part of the cement content in concrete mixes by a certain amount of silica-fume on the mechanical properties of HSSC, are drawn:

1. Incorporation of silica-fume in concrete mixes as a partial replacement of cement up to 15% produces a significant improvement in the mechanical performance and properties of hardened concrete. Compressive, splitting and flexural strengths as well as modulus of elasticity are tremendously enhanced. .
2. Silica-fume is a highly efficient pozzolanic material and has a considerable effect for use in concrete technology. The optimum ratio of using silica-fume instead of cement as a partial replacement is 15 %. It has a great beneficial effect on the mechanical properties of hardened concrete,
3. The percentage increase in strength of concrete mixes containing silica-fume has no significant effect after the age of 90 days,

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دراسة مستفيضة على الخواص الميكانيكية للخرسانة العالية المقاومة والمحتوية على غبار السليكا عند الأعمار المختلفة

فى السنوات الحديثة قام كثير من الباحثين بدراسة تأثير إضافة بعض المواد التى لها خاصية أسمنتية مثل غبار السليكا الناتج بجانب صناعة السبائك الحديدية(silica fume) وكذلك الرماد المتطاير بجانب صناعة الأسمنت (Fly ash) وكذلك اخبث الناتج بجانب صناعة الحديد والصلب (slag) وذلل بغرض تحسين خواص الخرسانة وكذلك تخليص البيئة من بعض المنتجات التى قد تؤدى إلى إضرار بالمجتمع.
الغرض من هذا البحث هو دراسة تأثير إضافة مادة غبار السيليكا بنسب مختلفة وذلك بإحلالها محل الأسمنت من صفر % وحتى 25 % من وزن الأسمنت وذلك لمعرفة النسبة الحرجة التى تودى إلى زيادة مستمرة فى جميع الخواص الميكانيكة للخرسانة. وقد أهتم البحث بدراسة خواص الخلطات الخرسانية والمحتوية على كمية أسمنت = 450 كجم/م3 ونسبة المياة إلى المواد الأسمنتية (أسمنت + سيليكا) = 32 % وتحتوى هذه الخلطات على نسب مختلفة من السليكا وهى صفر % ، 5 % ، 10.0 % ، 15.0 % ، 20.0 % ، 25.0 % وكمية ثابتة من البازلت من النوع الأول والنوع الثانى وكذلك كمية ثابتة من الرمل. وتم دراسة تأثير تغير نسبة المياه إلى المواد الأسمنتية (أسمنت + سيليكا) على مقاومة الضغط للخرسانة العالية المقاومة والمحتوية على غبار السيليكا بنسب مختلفة مع العلم بأنه تم أخذ ثلاث نسب من المياه إلى الأسمنت فقط وهى (0.26 ، 0.32 ، 0.38) وذلك عند عمر 28 يوم من تاريخ الصب.
وقد أثبتت النتائج أنه مع زيادة نسبة السيليكا إلى المواد الأسمنتية تزداد جميع الخواص الميكانيكية للخرسانة العالية المقاومة فى القيمة حتى نسبة 15 % بعد هذه النسبة تقل جميع الخواص الميكانيكية فى القيمة بنسب متفاوتة لكل خاصية على حدة. وكذلك تتحسن الخواص الميكانيكية للخرسانة العالية المقاومة عند نسبة مياه إلى المواد الأسمنتية قيمتها 0.32 عنها عند نسبة 0.38.