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EFFECT OF SILICA FUME AND STEEL FIBERS ON HARDENED CONCRETE PROPERTIES

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Abstract

This paper is aimed to produce High Performance Concrete (HPC) in Sudan by using materials, which are available at the local markets. Different trial mixes are used to obtain a compressive strength exceeding 80 MPa. The paper includes the use of mineral admixture (silica fume), steel fiber and Aggregates (Crushed stone and quartz sand).

The effect of adding different amounts of silica fume on main properties of HPC, i.e., compressive strength, density of concrete and flexural strength was investigated. The test results proved the availability to produce HPC in Sudan, with compressive strength in excess of 80 MPa using local materials, if these are carefully selected and properly mixed in such a way to optimize grain size distribution. Based on the results of this paper, the optimum percentage of silica fume necessary for producing HPC is about 20 % of cement weight and the optimum percentage of silica fume necessary for reduce concrete density and producing flexural strength is 30% of cement weight.

Keywords: Silica Fume (SF), High Performance Concrete (HPC).

Introduction

High-Performance Concrete mixes are characterized by high silica fume content and a very low water/cement ratio. Coarse aggregate is excluded to achieve strong microstructure, the addition of super plasticizers is used to achieve a low water/binder (cement and silica fume) ratio and heat-treatment (steam curing) is applied to achieve high strength. Owing to the fineness of silica fume and the increased quantity of hydraulically active components, it has been called High-Performance Concrete [1].

High-Performance Concrete can provide a compressive strength of 50 to 100 MPa. The durability properties of HPC are those of an impermeable material there is almost no penetration of chlorides and sulphates and high resistance to sulphate attack. Resistance to abrasion is similar to that of rock. There is almost no shrinkage or creep, which makes the material suitable for applications in prestressed concrete [2]. Studies on the performance of cementitious products with silica fume are very important, as it is one of the inevitable additives to produce high-performance concrete (HPC). The properties included specific gravity and normal consistency of cement and air content and workability of mortar with different SF contents. Further, strength developments in compression and tension in cement mortars have also been studied at various silica fume contents. silica fume was varied from 0% to 30% at a constant increment of 2.5/5% by weight of cement [3].

Silica fume is used as an admixture in the concrete mix and it has significant effects on the properties of the resulting material. The review paper discusses the effects of silica fume on concrete properties such as strength, modulus, ductility, permeability, chemical attack resistance, corrosion, freeze-thaw durability, creep rate [4].

Another study investigated the impact resistance and mechanical properties of steel fiber-reinforced concrete with water-cement ratios of 0.46 and 0.36, with and without the addition of silica fume. Hooked steel fibers with 60-mm length and an aspect ratio of 80, with three volume fractions of 0%, 0.5%, and 1% were used as the reinforcing

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material. In pre-determined mixtures, silica fume is used as a cement replacement material at 8% weight of cement [5].

Construction and cement industries have many elements responsible for environmental pollution and sustainability issues. These elements include mining of raw materials, manufacturing of aggregates and cement, conveyance of these materials to the construction site, construction wastes. To maintain the quality of the environment, many environmental agencies around the globe are urging cement and aggregate industries to lessen their demands for raw materials. These environmental agencies are inspiring construction industries to utilize recycled aggregates and supplementary cementitious materials [6].

The aim of the study is to assess the coupling effects of silica fume and steel fiber on the compressive performance of recycled aggregate concrete under elevated temperatures. A total number of 90 cylindrical concrete specimens are prepared and tested under axial compression, after heating by elevated temperatures [7].

Fiber-reinforced concrete may be defined as composite materials made with Portland cement, aggregate, and incorporating discrete discontinuous fibers and silica fume. In this paper, an attempt is made at 300 0C to present the results of an experimental investigation carried out on fiber reinforced concrete. While Fiber content was used as (0%, 0.5%, and 1%) by weight of mix and silica fume was used as (0%, 5%, and 10%) by weight of cement. The effect of the addition of silica fume and steel fiber on the various strengths of concrete was studied [8].

Another work aims to study the effect of steel fiber shape, length, diameter, and aspect ratio on the mechanical properties of slurry infiltration fiber reinforced concrete. This study comprised of casting and testing three groups of specimens with a 6% fiber volume fraction [9].

Environmental protection, conservation of natural aggregate resources, shortage of waste disposal land, and high construction and demolition waste disposal levy prior to disposal is the principal factors responsible for growing interest in the use of construction and demolition waste as aggregates in the production of concrete. These aggregates are known as recycled aggregates [10].

The effect of silica fume on the properties of high-strength fiber-reinforced concrete was carried out using silica fume at two different percentages and with three different hooked-end fibers, namely, 30/0.50, 60/0.80, and 50/0.60 length/diameter (mm/mm). Fibers were added to concrete in three different percentages of 0.5, 1.0, and 2.0% by volume of concrete [11].

The study of self-compacting concrete specimens produced by silica fume, metakaolin, fly ash, and steel fibers was carried out. The main objective of the research is to obtain ductile self-compacting high-strength concrete, which flows under its own weight and homogeneity while completely filling any formwork and passing around congested reinforcement [12].

The effect of the replacement of fine aggregates by waste rubber fibers on the impact resistance of concrete has been assessed. Silica fume has also been considered as a replacement for cement. Six replacement levels of rubber fiber (0%, 5%, 10%, 15%, 20% and 25%) and three replacement levels of silica fume (0%, 5% and 10%) have been considered for three different water-cement ratios [13].

Steel fiber reinforced concrete is a new construction material with good tensile strength, fracture toughness, and ductility. Although many aspects of steel fiber reinforced concrete have been investigated extensively, the size effects on the structural strength of members remain largely preoccupancy [14].

As a requirement for structural design, experimental investigations were carried out to investigate mechanical properties of reactive powder concrete [15].

Another work aims to investigate the effects of replacing cement with silica fume in the reinforced self-compacting concrete with recycled steel fiber and study its mechanical properties and impact resistance. To characterize mechanical properties and impact resistance, 144 specimens with different fiber volume fractions of 0.25%, 0.5%, and 0.75% were experimentally tested [16].

Several types of industrial byproducts are generated. By the utilization of industrial byproducts, silica fume is produced by the smelting process in the silicon and ferrosilicon. Silica fume is very effective in the design and development of high-strength high-performance concrete [17].

Paper Objectives

The paper aimed to produce High-Performance Concrete (HPC) in the Khartoum strip using available local materials and to study its mechanical properties in the hardened stages. This work can be performed through the following objectives:

1. Make HPC using available materials in Khartoum with suitable mixing procedures.
2. Conduct experimental work to determine the effect of mixing steps, silica fume content, crushed stone, quartz sand, and steel fiber.
3. Determine the mechanical properties of hardened HPC including compressive strength, hardened density, and flexural strength.

Methodology and Experimental Testing

In general, the following methodology was followed:

1. Review comprehensive literature related to the subject of HPC.
2. Selection of suitable local materials required for HPC, including cement, silica fume, and steel fibers.
3. Select suitable mix proportions to produce HPC.
4. Conduct physical and mechanical laboratory tests on HPC samples.
5. Analyzing results of laboratory tests and drawing conclusions.

This section presents the experimental work and the constituent materials used to produce HPC associated with this work. The laboratory work was conducted for hardened concrete. Tests of hardened concrete include compression and indirect tensile tests.

Characterizations of Constituent Materials

HPC constituent materials used in this paper include Portland ordinary cement, grey silica fume, Quartz sand, and crushed stone, in addition to fiber are used to ensure suitable workability. Constituent materials proportions are chosen carefully in order to optimize the packing density of the mixture. The requirements of relevant ASTM specifications for cement are illustrated in **Table 1**.

Table 1: ASTM Specifications for Cement

Type of test		Ordinary Portland Cement	
		Results	BS EN 197-
Setting time (Vicat test) hr. : min	Initial	1 hr. 35 min	> 60 min
	Final	3 hr. 5 min	
Normal Consistency (%)		26.5	
Mortar compressive strength (MPa)	3-Days	18.2	Min. 10
	7-Days	29.8	
	28-Days	42.6	Min 42.5 max 62.5

The nominal size of coarse aggregate ranges from 2.4 to 20 mm and quartz sand (fine aggregate) in the range of 0.3 to 0.6 mm which are locally available in Sudan markets. A physical property of quartz sand is determined as shown in **Table 2**. The grading of the quartz sand is illustrated in **Table 3**.

Table 2: Physical Property of Quartz Sand Used

Property	**Value**
Specific Gravity	2.61
Unit Weight (t/m^3)	1.58

Table 3: Grading of The Quartz Sand Used

Sieve size(mm)	0.600	0.300	0.150	0.075
% Passing	100	37.60	1.00	0.20

The steel fibers used in this paper are clean from rust or oil of straight steel wire fibers. The steel wires are cut into the desired length around 13 mm, and diameter 0.25 mm, with length/diameter ≈ 52, Tensile strength ≈ 277 MPa, and density of 7.8 g/cm^3.

After the selection of all needed constituent materials and amounts to be used, all materials are weighted properly. Then mixing with a power-driven tilting revolving drum mixer started to ensure that all particles are surrounded with cement paste and silica fume and all the materials and steel fibers should be distributed homogeneously in the concrete mass.

Tests of Hardened Concrete

A significant portion of this paper focused on the behaviors of HPC cube specimens under compressive loading. The compressive tests were all completed nominally according to **ASTM C109-2004** standard test method for cubes.

Numbers of 36 cubes were manufactured. For each batch of HPC made, 150x150x150mm cube specimens were prepared. The cubes were filled with fresh concrete without compacting, after preparing the specimens; cubes were covered with plastic sheets for about 24 hours to prevent moisture loss.

A total number of 3 prisms (100 x 100 x 500 mm) was manufactured. The flexural strengths of concrete specimens are determined by the use of simple beam with center-point loading with accordance to **ASTMC293-1994**. The mold is filled with the concrete in one layer, without compacting. In order to prevent moisture loss of the specimens, they are covered with plastic sheets for about 24 hours. After 24 hours, the specimens are extracted from the molds and placed in water for curing up to the time of the test.

Comparison of Results and Discussion

A series of tests were carried out on the concrete specimens to study and evaluate the mechanical properties of hardened High-Performance Concrete. This paper discusses the results obtained from 3 different tests adopted in the testing program. Results include unit weight, compressive strength, and flexural strength tests.

Tables 4 & 5 show the mixture proportions and one cubic meter ingredient of the best mix results obtained mixture of HPC. Four mixes designed for different silica fume percentages were illustrated in **Table 6**. Mix A was taken as the basic reference for comparison purposes.

Table 4: Best Mixture Proportions of HPC by Weight of Cement

Material	**Ingredient / Cement Content**
Cement CEM I 42.5N	1.00
Silica fume	0.36
Sand	1.29
Crushed aggregate ¾	1.40
Crushed aggregate 3/8	0.75
Steel Fibers	≈ 0.24 (3% of total volume)
Water cement ratio (w/c)	0.36

Table 5: One Cubic Meter Components of HPC Mixture

Material	**Ingredient / Cement Content**
Cement CEM I 42.5N	524.60
Silica fume	131.4
sand	700.30
Crushed aggregate ¾	758.55
Crushed aggregate 3/8	408.45
Steel Fibers	12.9
Water cement ratio (w/c)	238.2

Table 6: Mixes Design for Different Silica Fume Percentage

Material	Mix A (kg/m³)	Mix B (kg/m³)	Mix C (kg/m³)	Mix D (kg/m³)
Cement CEM I 42.5N	657	592	524.6	459.9
Silica fume	0	10	20	30
Silica fume replacement level	0	65.7	131.4	197.1
Sand	700.3	700.3	700.3	700.3
Crushed aggregate ¾	758.55	758.55	758.55	758.55
Crushed aggregate 3/8	408.45	408.45	408.45	408.45
Steel Fibers	12.9	10	9.6	8.85
Water cement ratio (w/c)	238.2	238.2	238.2	238.2

Laboratory tests were conducted to evaluate and study the hardened properties of HPC. Results of the compressive strength were illustrated in **Table 7**.

Table 7: Summary of Mean Compressive Strength at Different Ages

Mix	No. of specimens	Compressive Strength MPa		
		7 days	14 days	28 days
A	3	51	67.00	75
B	3	56	65.30	80
C	3	56.2	78.00	88
D	3	48	62.00	72

Results of the mean density were presented in **Table 8.** The effect of silica fume and steel fibers on the mean density was presented graphically in **Figure 1** and the results show that the density of concrete decreases when increasing the silica fume content. This can be due to the space occupied by cement being partly replaced by a relatively lighter powder of silica fume.

Table 8: Summary of Mean Density Strength at Different Ages

Mix	No. of specimens	Density kg/m³		
		7 days	14 days	28 days
A	3	2743.3	2780.4	2760
B	3	2713.8	2763.0	2735
C	3	2705.5	2750.0	2716
D	3	2691.2	2713.0	2704

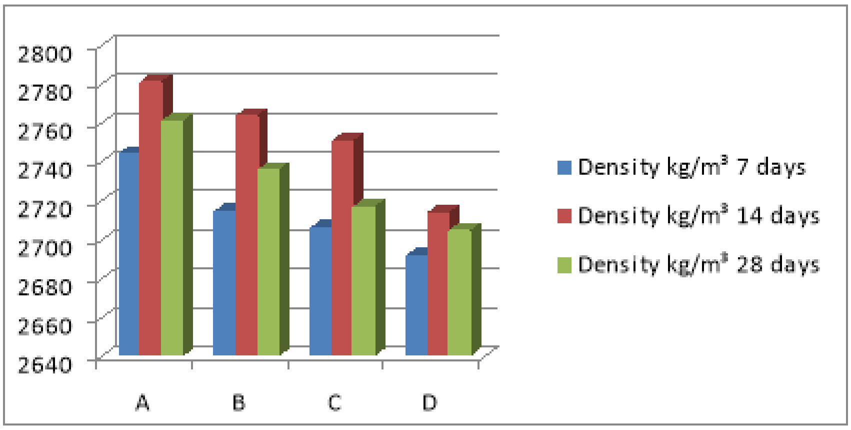

Figure 1: Effect of Silica Fume and Steel Fibers on the HPC Density

The effect of silica fume and steel fibers on HPC compressive strength was graphically illustrated in **Figure 2**. The results of flexural strength tests for **HPC** can be observed in **Figure 3**.

The effect of using silica fume was observed. The use of 20 % of silica fume as a replacement of cement exhibits comparable results with the mixture containing 0 % silica fume. The increase in the silica fume content effectively increased the compressive strength of concrete. The compressive strength of the concrete specimens for 20 % silica fume replacement was up to 80 MPa, which met the target compressive strength for this paper.

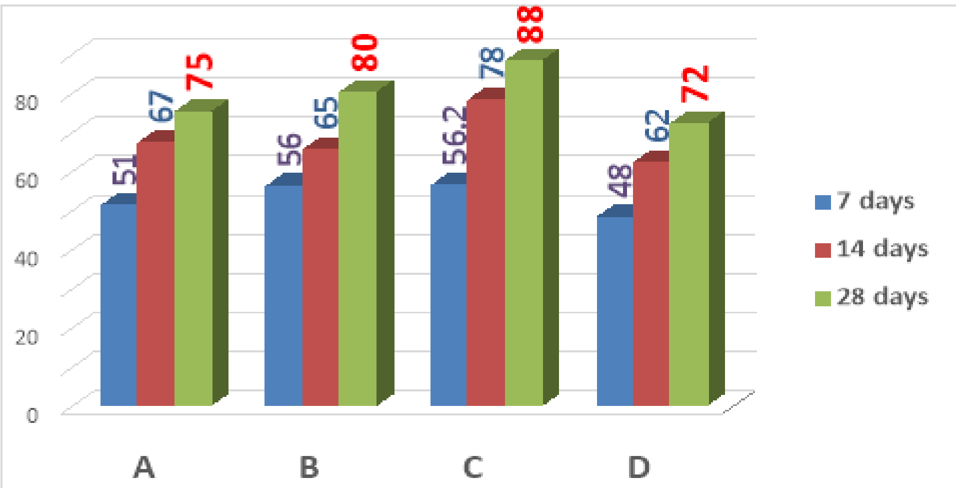

Figure 2: Compressive Strength for Different Concrete Mixes

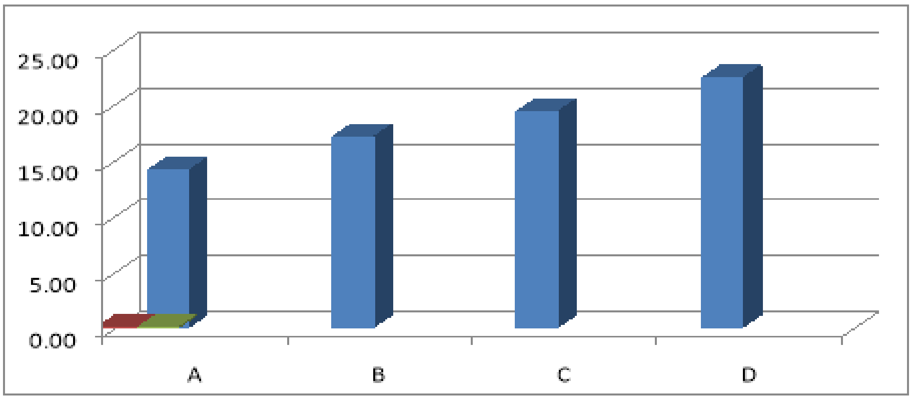

Figure 3: Flexural Strength Test for Different Concrete Mixes

It is found that the silica fume works as a Pozzolanic reaction and physical function. The hydration of Portland cement has produced some compounds such as calcium silicate hydrates (CSH) and calcium hydroxide (CH). The silica fume chemically reacts with the CH to produce additional CSH in order to improve the bond between the cement and the surface of the aggregate. Moreover, the silica fume particle fills the voids. This action enhances to increase the compressive strength of concrete and decrease total pores volume.

Conclusion

The conclusions presented were based on this particular research work. They have been drawn as follows:

1. It was concluded that the production of HPC in Sudan is available at the local markets if materials are carefully selected and achieving mix composition in grain size distribution that will achieve a minimum compressive strength of 80 MPa at 28 days. Such concretes can be produced with crushed stone, quartz sand, and silica fume as the mineral admixture.
2. The use of the silica fume effectively increases the compressive strength of the concrete due to the improvement in the bond between the cement and the surface of the aggregate through the chemical reaction between silica fume and the CH resulting from the hydration of cement.
3. The use of silica fume is necessary for the production of HPC. The cube compressive strength studies indicate that the optimum percentage of silica fume is about 20%.
4. The density of HPC decreases as silica fume content increases.
5. The silica fume content increases, the flexural strength of HPC increases also. For example, at silica fume content 30% the flexural strength increases at 28 days by about 21%, 37%, and 59 % for Mixes B, C and, D respectively in comparison reference Mix A.

Recommendations

Suggested recommendations for further research can be summarized as follows:

1. The influences of cement type and fine aggregate and silica fume aspect ratio on the mechanical property of HPC need to be taken into consideration.
2. The effect of fibers (Steel, Carbon, Propylene, and Glass) and polymers (Epoxy, SPR) addition on the mechanical properties of HPC need to be taken into consideration for further research.
3. Effect of curing on the microstructure of HPC will be a very important study for future researches.
4. The influences of aggregate shape and surface on the mechanical property of HPC need to be taken into consideration.
5. The influences of cement type and steel fibers aspect ratio on the mechanical property of HPC need to be taken into consideration.

Conflict of Interest

There is no conflict of Interest between the authors of this manuscript.

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