Sudan University of Science and Technology

College of Graduate studies

Effect of Silica Fume and Steel Fibers on the Hardened Concrete Properties

تأثير دخان السيليكا والألياف الفولاذية على خواص الخرسانة المتصلدة

A Thesis submitted for partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering (Construction Engineering)

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Abstract

This research is aim 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 research includes the replace percent of cement by (silica fume) and Steel fiber, with cement and aggregates (crushed stone and quartz sand).

The effect of adding different percentage (10%,20%,30%) of silica fume on main properties of HPC, i.e., compressive strength, density of concrete and flexural strength was 30%.

The test results revealed that it is possible to produce HPC in Sudan, with compressive strength in excess of 88 MPa using materials which are available at the Sudan, if these are carefully selected and properly mixed in such a way to optimize grain size distribution.

Based on the results of this research, 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 increase concrete density and increase flexural strength is 30% of cement weight.

المستخلص

الهدف من هذا البحث هو إنتاج الخرسانة عالية الأداء في السودان، باستخدام المواد المتوفرة في الأسواق المحلية. تستخدم خلطات التجربة المختلفة للحصول على قوة ضغط تتجاوز 80 ميجا باسكال. يتضمن البحث استبدال النسبة المئوية للأسمنت بواسطة غبار السيليكا والألياف الحديدية، مع الأسمنت والركام (الحجر المسحوق والرمل الكوارتز).

وكان تأثير إضافة نسبة مختلفة (10 ٪، 20 ٪، 30 ٪) من غبار السيليكا على الخصائص الرئيسية للحقل، أي قوة الانضغاط، كثافة الخرسانة وقوة الانثناء كانت 30 ٪.

كشفت نتائج الاختبار أنه من الممكن إنتاج خرسانة عالية الاداء في السودان، مع قوة مضغوطة تبلغ 88 ميجا باسكال باستخدام مواد متوفرة في السودان، إذا تم اختيارها بعناية واختلطت بطريقة مناسبة لتحسين توزيع الحبيبات.

استناداً إلى نتائج هذا البحث، فإن النسبة المثلى من دخان السيليكا اللازم لإنتاج خرسانة عالية الاداء هي حوالي 20٪ من وزن الإسمنت والنسبة المثلى ل غبار السليكا اللازمة لزيادة كثافة الخرسانة وزيادة قوة الانثناء 30٪ من وزن الاسمنت .

DEDICATIONS

I dedicate this work to my father, mother, husband and brothers, for their love, endless support and encouragement.

Also to those who taught us letters of gold and words of jewel of the utmost and sweetest sentences in the whole knowledge. Who reworded to us their knowledge simply and from their thoughts made a lighthouse guides us through the knowledge and success path.

Also to our honoured teachers and professors.

To our truly friends who share us their feelings and hard work, throw our research accomplishment.

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List of Abbreviations

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
HPC	High Performance Concrete
HRWRA	High-Range Water-Reducing Admixture
MDF	Macro-Defect-Free Cement
NSC	Normal Strength Concrete
SCC	Self-Compacting Concrete
RPC	High Performance Concrete
HPC	Ultra High Strength Concrete
HPC	Ultra High Performance Concrete
UHPFRSCC	Ultra High Performance Fiber Reinforced Self-Compacting Concrete
ITZ	Interfacial Transition Zone

Chapter One
Introduction

1.1 Background

Concrete is a commonly used structural material in construction around the world. Over the past decade, some research works have been conducted to examine the effects of cementitious materials that can achieve a higher mechanical performance.

One of the breakthroughs was the development of High Performance Concrete (HPC), which can provide a compressive strength of 50 to 100 MPa **(Washer et al., 2004)**. Recently, Bouygues in France have developed a new generation of ultra-high performance concrete named Reactive Powder Concrete (RPC) in the mid-1990s. It has a typical compressive strength of 150 to 200 MPa, which is four times that of Normal Strength Concrete (NSC).

HPC is recognized as a revolutionary material that can provide a combination of ultra-high strength, high ductility through the inclusion of short steel fiber reinforcement and excellent durability (Wong et al., 2007).

The composition of HPC is coarse aggregate-free which differs from that of ordinary concrete. Instead, fine powders such as quartz sand and crushed quartz, with particle sizes ranging from 45 to 600 μm are used. In fact, it is rather a mortar than an original concrete mixture because there is no coarse aggregate.

The term “reactive powder” reflects the fact that all the powder components in HPC react chemically following casting: cement by conventional hydration; silica fume through pozzolanic reaction with the resulting calcium hydroxide; quartz sand by providing dissolved silica for the formation of further Calcium Silicate Hydrate C-S-H gel; crushed quartz to alter the CaO/SiO_2 ratio and favour the formation of to bermorite and xonolite when HPC is subjected to heat treatment or setting pressure (Lee and Chisholm, 2005) .

The ultra-high mechanical performance of HPC can be explained by:

- Enhancement of homogeneity of HPC by the elimination of coarse aggregates. It was suggested that the maximum size of ingredients of HPC should be less than600 μm **(Shaheen and Shrive, 2006)**.
- Enhancement of compacted density by optimizing the granular mixture **(Richardand Cheyrezy, 1995)**.
- Improved matrix properties by addition of pozzolanic admixtures, i.e. silica fume **(Ma and Schneider, 2002)**.
- Improved matrix properties by reducing water-to-binder ratio **(Ma and Schneider, 2002)**.
- Enhancement of microstructure by heat treatment after hardening **(Shaheen and Shrive, 2006)**.

1.2 Problem Statement:

The usage of High Performance Concrete with high compressive strength in construction applications has been increasing worldwide and will make an impact in Khartoum State due to the limited land area available for construction and the fast growing population as well.

High-rise reinforced concrete multi story buildings are being increasingly used. The large loads in high rise buildings lead to the design of large sections when normal strength concrete is used, but when High Performance Concrete is to be used, small cross sections can be obtained.

Moreover; finally yet importantly, due to bad and unstable political conditions and the continuing wars in Khartoum Strip, strong, relatively cheap, easy to use and locally available repairing and strengthening material should be produced for that purposes.

1.3 Research Significance

There is significant interest in the development of innovative cementitious materials that possess superior properties. A relatively new cementations material, High Performance Concrete (HPC), is recognized as a revolutionary material that can provide a combination of ultra-high strength and excellent durability. However, production of HPC is not yet available in Khartoum and limited research is available in this area. If the HPC, being mixed using local available materials without complicated production process, exhibits good performances comparable to that in foreign countries, then it would be beneficial to study their potential use in the construction industry for future search.

Ordinary concrete includes numerous micro crack that rapidly increase under the applied stresses. These cracks are responsible for the low tensile and flexural strength. Therefore, the production of concrete with a high strength and low permeability is of considerable importance with respect to durability performance.

1.4 Research Objectives

The main goal of the proposed study is to produce High Performance Concrete (HPC) in Khartoum strip using available local materials, and to study its mechanical properties in the hardened stages. This can be achieved through the following objectives:

1. Study the production process of HPC utilizing locally available materials in Khartoum with suitable mixing procedures.

2. Conduct parametric study to determine the effect of mixing steps, silica fume content, filler materials, admixture dosage, and steel fiber.

3. Obtaining the mechanical properties of hardened HPC including compressive strength, hardened density, and flexural strength.

4. Replacement the cement silica fume percentage.

1.5 Methodology

In general, the following methodology was followed:

1. Conduct comprehensive literature review related to the subject of HPC.
2. Selection of suitable local available materials required for producing HPC, including cement, silica fume and steel fibers.
3. Determine mix proportions to produce HPC.
4. Performing physical and mechanical laboratory tests on HPC samples.
5. Results Analyses and draw conclusion.

1.6 Thesis Structure

The research consists of six chapters organized manner:

Chapter One gives a general background about High Performance Concrete, research problem and scope of work, objectives and methodology used to achieve the research objectives. In addition, it describes the structure of the thesis.

Chapter two discusses definition of High Performance Concrete, definitions of curing regimes, advantages of HPC, history of HPC, applications and materials, particle packing and effect of curing, mixing techniques, properties of HPC, micro structures of HPC and mechanisms and processes in early age thermal curing HPC.

Chapter three reviews the materials, which were used in producing Reactive

Powder Concrete and their properties, testing program, equipment used in the testing procedures and methods of curing.

Chapter four illustrates the test results including hardened results, flexural test results.

Chapter five includes the concluded remarks, main conclusions and recommendations drawn from this research.

Chapter Two

Literature Review

2.1 High Performance Concrete

It is a relatively new form of concrete for general applications. The definition of High Performance Concrete was coined by two French scientist in1994 **(Richard and Cheyrezy, 1995; Shaheen andShrive, 2006)**. According to their research, the key characteristics of the material are enhancement of homogeneity by elimination of coarse aggregates, enhancement of the compacted density by optimization of the granular mix, possible application of pressure before and during setting, enhancement of the micro structure by post-set heat-treated and enhancement of the ductility by incorporating short steel fibers.

High Performance Concrete mixes are characterized by high silica fume content and very low water/cement ratio. Coarse aggregate is eliminated to avoid weaknesses of the micro structure, the addition of superplasticizers is used to achieve a low water/binder (cement and silica fume) ratio and heat-treatment (steam curing) is applied to achieve high strength **(Lee and Chisholm, 2005)**.

Owing to the fineness of silica fume and the increased quantity of hydraulically active components, it has been called High Performance Concrete **(Dowd, 1999)**.

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 the applications in prestressed concrete.

2.2 Advantages of HPC

The ultra-high performance of HPC provides many advantages compared to conventional concrete as listed in the following:

1. Superior strengths with very high compressive strength of 100 MPa (approximately two times the strengths of conventional concrete) result in significant savings in dead load. HPC structures may weight only one-third or one-half of corresponding.

Conventional concrete structures. Weight reduction is good in producing more slender transportation structures, reducing overall costs and increasing usable floor space in high-rise buildings **(Rebentrost and Cavill, 2006)**.

2. Superior ductility and energy absorption provide greater structure reliability even under overload conditions or earth quakes **(Dowd, 1999)**; the high energy absorption characteristics of HPC may also allow improved post-elastic response of columns, beam-column joints and shear walls **(Lee and Chisholm, 2005)**.

3. Superior durability which leads to long service life with reduced maintenance. HPC is nearly impermeable, almost no carbonation or penetration of chlorides and sulphates for HPC. The enhanced abrasion resistance provides extended life for bridge decks and industrial floors **(Dauriac, 1997)**; while the enhanced corrosion resistance provides protection to areas with bad or harsh climate conditions such as concentrated rain and snow, and heavy sandstorms **(Ji, et al., 2004)**.

4. Elimination of steel reinforcement bars reduces high labour costs and provides greater architectural freedom. That means it allows nearly limitless

structural member shapes and forms for the architects and designers **(Dauriac, 1997)**.

5. Reduction of thickness of concrete elements results in material and cost savings **(Yazici, et al., 2009)**.

6. A significant amount of unhydrated cement in the finished product provides a self-healing potential under cracking conditions **(Dauriac, 1997)**.

7. The fineness of the HPC product allows high quality surface finishes **(Dauriac, 1997)**.

2.3 Historical Background of HPC

Recent developments of concrete technology have made it possible to produce concrete with compressive strength up to or higher than 50 MPa. These technological advancements were mainly brought about by the developments in chemical and mineral admixtures, particularly superplasticizers and silica fume during 70s and 80s **(Kwan, 2003)**.

In such cases, special high strength aggregate, suitable pressure and heat treatment have to be applied. A value of 810 MPa has been obtained with mixture incorporating steel aggregate **(Richard and Cheyrezy, 1995)**.

Over the years, much research work has been done to produce composite materials with high mechanical performance using cementitious materials. High strength concrete (HPC) columns were first used in the construction of high-rise buildings in the 1970s **(Cyr and Shah, 2002)**. In many developed countries, concrete producers defined high strength concrete as a concrete having a 28-day compressive strength of above 45 MPa when the normal weight aggregate is used **(Shannag, 2000)**.

However, the disadvantages of HPC are that workability would be difficult to define and often declines rapidly with time after mixing; and, high heat evolution of HPC may necessitate the use of low-heat binders and cooling measures to avoid early age thermal cracking **(Wong, 1996)**.

Apart from high strength, civil engineers are now demanding concrete with high performance in other aspects such as high workability, high durability, low heat generation during curing, etc. High performance concrete (HPC) refers to concrete mixtures with a water-to-binder ratio as low as 0.3-0.4, so as to obtain 28-day compressive strength as high as 70-100 MPa or even 1-day compressive strength as high as 45-55 MPa **(Collepardi et al. , 2003)**.

HPC is often produced with specifically designed matrices, which contain chemical and mineral admixtures and fiber reinforcement **(Cyr and Shah, 2002)**. The performance criteria of HPC include high strength and elastic modulus, improved toughness and impact resistance, high early-age strength, high durability (including low permeability, resistance to chemical attack and free-thaw damage) and ease of placement and compaction without segregation.

Owing to the rapid advances in concrete technology, special techniques have been used to produce concrete with even higher compressive strengths. Ultra-high strength or ultrahigh performance concrete (UHPC or HPC) is a relatively new cementitious material with compressive strength more than 150 MPa and possesses other perfect properties **(Maand Schneider, 2002)**. Two commonly produced HPCs are macro-defect-free cement (MDF) and High Performance Concrete (HPC).

The main drawback of this concrete was that the mechanical properties was diminished after contact with water, and thus eventually did not have any practical applications **(Cwirzen et al., 2008)**.

RPC is an ultra-high strength super plasticized silica fume concrete characterized by an extremely dense microstructure and with compressive strengths in excess of 200 MPa **(Shaheen and Shrive, 2006)**. Strengths as high as 810 MPa have been recorded by **Semioli (2001)**.

High-strength steel fibers or non-metallic fibers maybe included to improve its ductility **(Rebentrost and Cavill, 2006)**. Application of pressure and heat curing are optional measures designed to enhance the performance **(Richard and Cheyrezy, 1995)**.

HPC was originally developed by Rhodia, Lafarge and Bouygues, the parent company of VSL, and is a registered trademark under the name of Ductal **(Rebentrost and Cavill, 2006)**. **Rebentrost and Cavill (2006)** reported that the durability properties are in multiple folds of magnitude better than current high performance concrete.

2.4 Applications of HPC:

2.4.1 Sherbrooke Footbridge in Canada:

Sherbrooke Footbridge in Quebec in Canada was the world's first major structure to be built with High Performance Concrete (HPC) in 1997 **(Blais and Couture, 1999)**. Spanning 60 m, this precast, prestressed pedestrian bridge is a post-tensioned open-web space HPC truss.

2.4.2 Sunyudo Footbridge in Korea:

The Sunyudo (Peace) Footbridge in Seoul in Korea is the largest HPC Bridge in the world with a single span of 120m **(Rebentrost and Cavill, 2006)**. The bridge contains no ordinary reinforcement. During construction, all segments were prefabricated next to the erection site in the area containing batching facilities, steel form work and heat treatment chamber **(Rebentrost and Cavill, 2006)**.

2.4.3 Sakata-Mirai Footbridge in Japan:

Sakata-Mirai Footbridge in Sakata in Japan does not use any passive reinforcement. It is extremely light with dead weight of only 56 tones, which is approximately one-fifth of the dead load of an equivalent conventional prestressed concrete structure and results in an economic advantage of around 10% **(Jungwirth, 2005)**.

2.4.4 Shepherds Creek Road Bridge in Australia:

The Shepherds Creek Road Bridge in Australia replaces an existing timber bridge. The slab is placed onto a thin permanent precast HPC formwork panels that span between the beams. The beams weigh only 4.2 tons over a length of 15.1 m, compared to about nine tones for a conventional prestressed beam. In addition, the permanent formwork slabs are extremely light and provide a highly durable soffit to the deck **(Rebentrost and Cavill, 2006)**.

2.5 Materials of HPC:

Materials used for producing HPC containing large amounts of binder (i.e. cement). Silica fume, quartz powder …etc. are used as filler materials. Fibers added to improve the mechanical properties.

To ensure and improve the self-levelling and high workability properties, without causing segregation; Large amounts of superplasticizers are to be used

2.5.1 Portland Cement

As the cement content in HPC is generally as high as 700 – 1000 kg/m³ **(Collepardi etal., 2003)**, the choice of cement could be a critical factor affecting the performance of HPC. It is reported that the ideal cement should have a high C3S and C2S (di & tri-calcium silicate) content with very low or zero C3A (tri-calcium aluminate) content **(Kwan, 2003)**. **Lee and Chisholm (2005)** explained that C3A has little intrinsic value as a binding agent and is primarily included in cement due to its role as a flux during the calcination process.

The high cement content of HPC 700 – 1000 kg/m³ compared to 300 – 500 kg/m³ of ordinary concrete would cause the generation of a large amount of heat of hydration during curing and subsequently thermal cracking when the concrete starts to cool down **(Kwan, 2003)**.

Moreover, the large cement paste volume would cause large shrinkage and swelling strains when the moisture condition of concrete changes **(Kwan, 2003)**. This means that the concrete would result in a lower dimensional stability. Therefore, **Kwan (2003)** stated that adding more cement to reduce the water/cement ratio and increase the concrete strength is not the best way to produce concrete with high strength; concrete strength should be increased without significant increase in cement content. **Yazici et al. (2009)** suggested that partial replacement of cement by mineral admixtures could be a feasible solution to overcome these problems in HPC.

When Portland cement is mixed with water, its constituent compounds undergo a series of chemical reactions that are responsible for the eventual hardening of concrete. Reactions with water are designated hydration, and the new solids formed on hydration are collectively referred to as hydration products **(Mindess et al., 2003)**.

In Portland cement, the hydration of tri-calcium aluminate C3A involves reactions with sulphate ions that are supplied by the dissolution of gypsum, which is added to temper the strong initial reaction of C3A with water that can lead to flash set.

2.5.2. Silica fume

Silica fume is known as an admixture to concrete to increase the compressive strength. It is effect material in reducing deleterious alkali silica expansion. Silica fume effect on the properties of fresh concrete also it has a lesser propensity for segregation than concrete without silica fume will not significantly change the unit weight of concrete and increase permeability for plastic shrinkage cracking.

Observation has exhibited that there is a no increase or little increase in strength as for the long term. Silica fume has improved the flexural strength of the concrete. The splitting tensile strength has not exhibited an improvement in the silica fume mixtures. Silica fume is a by-product of silicon metal or silicon-alloy metal factories. Although the silica fume is a waste of industrial materials, it became the most valuable by-product between the pozzolanic materials due to its high pozzolanic property. Actually, silica fume is widely used in concrete or cement as an admixture **(Turkmen, 2003)**.

Concrete materials containing silica fume and found that they have a higher resistance to water transporting with comparison to concrete materials without silica fume. Silica fume is added as it changes the micro structure of the concrete. These changes occur due to two reasons; the first one is the physical aspect of SF, and the second is the chemical contribution. However, the physical aspect of silica fume and chemical contribution is equally important processes **(Tan and Gjorv, 1996)**.

Silica fume leads to changes in the micro structure of the concrete. These changes are consequences of two different but equally important processes; physical aspect of SF, and chemical contribution. The physical phase of this action enhances the void system of cement paste, particularly; the transition zone. The result of this work from SF provides significant improvement in the compressive strength, flexural strength, in addition to other significant improvement in durability and permeability **(Pigeon and Plante, 1989)**.

The mortar that containing silica fume (SF) as a partial replacement for cement has increased its compressive strength. In addition, it was found that silica fume (SF) strengthens the bond between the cement paste and the aggregate. They also added that the partial replacement of cement by silica fume (SF) and the addition of super plasticizer would increase the strength of mortar **(Toutanji and El-Korchi, 1995)**.

The silica fume (SF) has four main functions in the use of concrete technology as follows: **(Gonen and Yazicioglu, 2009)**.

1. Filling the voids between the large class particles (cement).
2. Improving the resistance of concrete and the durability of concrete, by reducing the permeability of the cement paste matrix.
3. Producing secondary hydration with the lime resulting from the primary hydration.
4. Making the concrete more resistant to abrasive forces, and reducing the expansion generated by alkali-aggregate.

Papadakis (1999) reported that concrete containing 18% silica fume by weight of cements enough for total consumption of $Ca(OH)_2$ released from cement hydration. However, considering the filler effect, the optimal share of silica fume is about 30% of cement **(Richard and Cheyrezzy, 1995)**. Therefore, silica fume content in HPC is normally 20-30% of the weight of cement.

2.5.3 Aggregates

Fine aggregates for HPC should be selected to reduce the water demand. Rounded particles are thus preferred to crush rock fines where possible. The silt, clay and dust content of both fine and coarse aggregates should be kept as low as possible.

As most HPC concrete mixes contain a large amount of fine material in the cement (Often greater than 500 kg/m^3), it is accepted practice to utilize slightly coarser grading’s of fine aggregate than is normal for conventional structural concrete (Aitcin, 1998). The finest fractions of the fine aggregate are no longer essential to increase workability or prevent segregation; a coarser grading (fineness modulus 2.7 to 3.0 or BS 882 Class C) (British Standards Institution, 1992) is therefore appropriate. The gratings curve of the fine aggregate should, however, generally be smooth and free of gap grading to optimize the water demand.

The requirements for coarse aggregates have been examined earlier. However, the Particle shape should ideally be equidimensional (i.e. not elongated or flaky) and the grading should once again be smooth with no gaps in the grading between fine and coarse fractions. A maximum aggregate size of 10–14 mm is usually selected (Mehta and Aitcin, 1990a) although aggregates up to 20 mm may be used if they are strong and free of internal flaws or fractures. This can, however, only be evaluated from trial mixes.

As the in Particular significance it may not be possible to achieve the required strength on a project using local aggregate supplies alone. Importation of aggregate supplies or blending materials from a number of sources may be required in order to optimize performance. During the construction of HPC off shore platforms in Norway, a consistent fine aggregate grading was maintained by blending up to eight separate size fractions (Ronneberg and Sandvik, 1990). However, in most cases single sources or blends of two or three sources will be satisfactory.

2.5.4 Quartz sand

Quartz is the major form of pure silica in nature and is a very hard material with hardness of seven on the Mohs scale and density of 2.65 g/cm^3 **(Wikipedia, 2009)**. This can explain the high stiffness of HPC. **Richard and Cheyrezzy (1995)** reported that quartz also offers the advantages of excellent paste/aggregate interfaces, readily available and low cost. They also suggested that the particle size range of quartz sand is between 150 and 600 μm, in order to prevent interference with largest cement particles (80-100 μm).

2.5.5. Steel fibers

The high brittleness is the biggest disadvantage of concretes, especially of very-high strength concrete **(Long et al., 2002)**. It has been reported that the only really practical solution to the brittleness exhibited by all high strength cement-based materials is to incorporate fibers into the matrix **(Huang and Shen, 1983)**. The ductility is enhanced through the incorporation of steel fibers in HPC matrix **(Richard and Cheyrezzy, 1995)**.

addition of small quantities of fibers (in the range of 1-6% by volume) to a concrete mix has relatively little effect on strength; the real purpose of adding fibers is to increase the toughness (the total energy absorbed in breaking a specimen). The steel fibers used are normally 13 mm long with a diameter of 0.15 to 0.2 mm **(Richard and Cheyrezzy, 1995)**.

Richard and Cheyrezzy (1995) stated that the economic optimum corresponds to a ratio of 2% by volume. **Long et al. (2002)** found that the flexural strength to compressive strength ratio increases with the increase in steel fibers content. Moreover, they found that the greater the length to diameter ratio (L/D) of steel fibers, the better the toughness of very-high performance concrete is as shown in Figure 2.1.

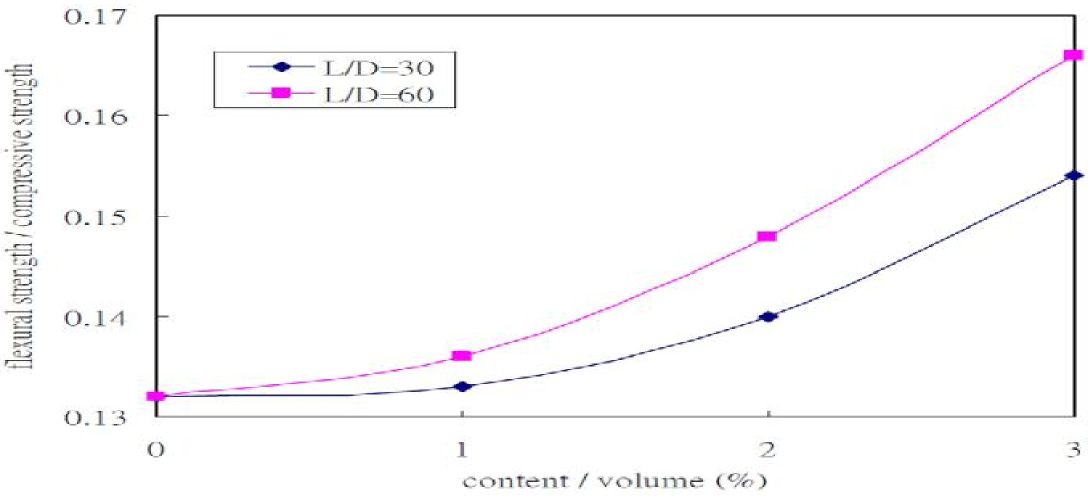


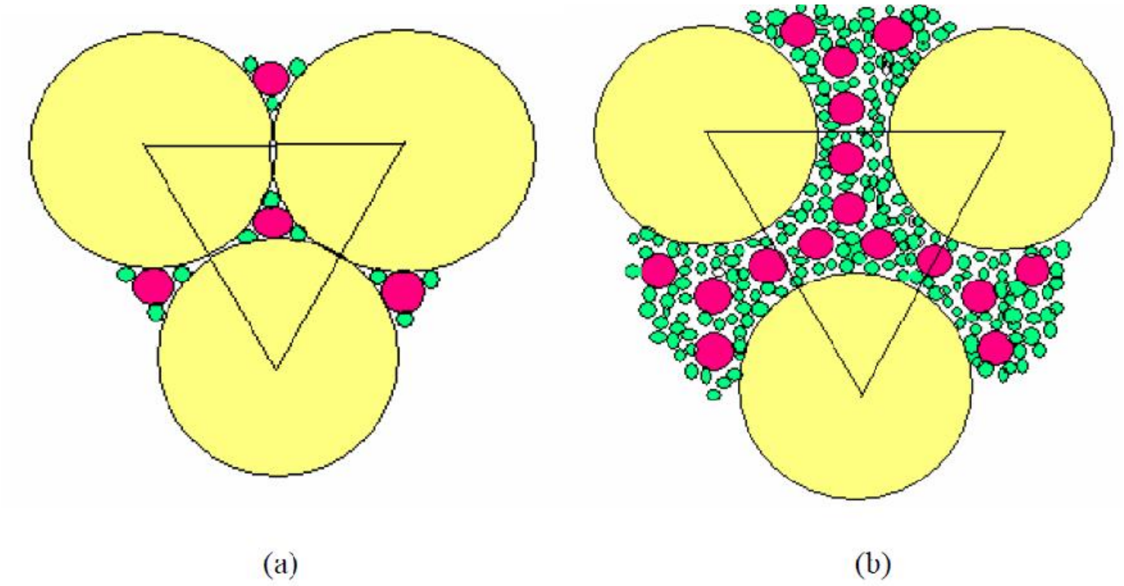
Figure 2.1: The effect of steel fiber on the brittleness of very-high performance concrete (Long et al., 2002)

2.6 Particle Packing

The composition of HPC differs from that of HPC with the absence of coarse aggregates. Instead, fine powders such as quartz sand and crushed quartz, with particle sizes ranging from 45 to 600 µm are used**. Lee and Chisholm (2005)** stated that the performance of HPC strongly depends on the optimization of packing of powder constituents; size classes for granular materials are tightly constrained, with mean particle diameters differing by at least an order of magnitude.

Cyr and Shah (2002) also explained that high strength and low porosity of HPC were obtained by optimizing particle packing. The classic idea of particle packing is based on the "Apollonian" concept **(Vernet, 2004)**; in which smaller particles fill the spaces left between the larger ones. However, he mentioned that the particles cannot move in a concrete made with such a packing arrangement. Therefore, in order to combine high capacity with good workability, it is necessary to increase the proportion of fines to separate the larger particles and allow them to move past each other

(Vernet, 2004) and **(Scrivener and Kirkpatrick, 2008)**. It is illustrated in Figures 2.2 (a) and (b).



Figures 2.2 (a): Schematic of "Apollonian" packing - smaller particles exactly fit into spaces left by larger particles (b): larger particles of the same class are spaced by the smaller ones (Vernet, 2004)

Wong and Kwan (2005) also introduced the concept of packing density and reported that maximization of the packing density by adjusting grading of the whole range of solid particles can improve the overall performance of the concrete mix. For example, quartz powder with a diameter of about 10-50 μm can be used as micro fillers, which can fill the particle size gap between cement particle (80-100 μm) and silica fume (0.1-1 μm) and make the grading curve of the mixture composed of cement, silica fume and quartz powder continuous **(Ma and Schneider, 2002)**. This implies that powder mixture should be composed of a number of classes of granular powder in order to enhance the packing density.

In general, the higher the packing density, the smaller will be the amount of water needed to fill up the voids between the particles and the better will be the performance of the concrete mix **(Kwan, 2003)**.

Similar findings were reported by **Wong and Kwan (2005)** that an increase in packing density of particles would improve the overall performance of concrete, which is summarized in the following:

- Reduction in water demand and thus allowing the use of a lower water/cement ratio for achieving higher strength.
- Reduction in the permeability of the bulk cementitious materials and thus bleeding of fresh cement paste.
- Reduction in the porosity of transition zone by filling up the voids;
- Increase in workability of concrete mix under the same water/cement ratio;
- Improvement in cohesiveness and thus the concrete mix would be less likely to segregate during placing.

2.7 Water-to-binder ratio:

Water demand is the main parameter for assessing the quality of the granular mixture of HPC. That is, the minimum quantity of water which must be added to the powders to obtain fluidification **(Richard and Cheyrezy, 1995)**. Both the strength and workability of a concrete mix depend on the water-to-binder (w/b) (cement + silica fume) or water to cement (w/c) ratio of the mix **(Kwan, 2003)**. W/c ratio is usually replaced by the w/b ratio to account for the incorporation of silica fume and quartz powder to the strength development of HPC **(Liu and Huang, 2008)**.

Lee and Chisholm (2005) found that mixes with insufficient water were stiff and difficult to compact into moulds adequately and results in a hardened concrete with entrapped air voids. Conversely, mixes with a higher w/b ratio were more susceptible to auto genius shrinkage, which would create voids since C-S-H gel (i.e. hardened cement) occupies a lesser volume than the equivalent quantity of dry cement powder and water. They also added that the voids would entrain small air bubbles and thus decrease the strength of concrete. Therefore, an optimal w/b ratio is important in achieving high strength as well as workability.

Wong et al. (2005) found that w/b ratio is the key factor affecting the initial porosity.

They observed that the relative density of fresh pastes increase rapidly with the decrease of w/b. They explained that with the reduction of water in mixtures, the distances between particles become shorter and the porosity of pastes is reduced, and thus the relative density of pastes increases.

2.8 Curing regimes:

There are several definitions for curing in relation to concrete technology, but most of them deal with basic principles and requirements that are similar in many respects. One of the most acceptable definitions by **Neville and Aitcin (1998)** described concrete curing as follows:

Curing of concrete is the process of keeping the appropriate moisture conditions to promote optimum cement hydration immediately after placement. Points given below are general aspects for the curing:

1. Adequate moisture conditions are important because water is necessary for the hydration of cement materials.
2. With insufficient water, the hydration will not proceed and the resulting concrete may not possess the desirable strength and permeability.

3. Curing techniques and curing duration significantly affect curing efficiency.

4. Increasing the effectiveness of curing improves the mechanical and durability properties of concrete.

5. Adequate curing is essential for concrete to obtain strong structural and durability properties.

Curing is the name that is used to enhance the hydration of cement, and consists of control of temperature and of the moisture movement in concrete. Curing keeps concrete saturated as possible, until water-filled space in the fresh cement paste has been filled **(Bamforth et al., 2008).**

Curing leads to better strength development because it allows more water to be made available for the hydration reaction of the concrete's cement paste. Curing improves the ultimate compressive strength and reduces surface dusting. Because of the increase in the rate of evaporation from the fresh mixture and higher concrete temperature, curing problems will be increased when concreting is done in hot weather. Strength and other characteristics of the concrete in hot weather depend on curing time and duration, whether it is cured immediately or during the first few weeks **(Austin et al., 1992)**.

Concrete in its early life shall be cured and protected **(Euro code, 2006)**:

1. To minimize plastic shrinkage.
2. To ensure adequate surface strength.
3. To ensure adequate surface zone durability.
4. From freezing.
5. From harmful vibration, impact or damage.

Curing can produce an effect on the hydration of cements. In performance of concrete structures, the transfer of this benefit is more difficult and variable. The particular performance requirements to resist different unfriendly cases have been considered in the benefits of curing. It is clear from the obtainable demonstration that compressive strength development in structures is one of the properties least sensitive to curing **(Cather, 1994)**.

The curing period consists of two stages; initial and final stage. Initial stage of curing depends on action taken between placement and final finishing of concrete to reduce the loss of moisture from the surface of the concrete. The final stage of curing depends on action taken between the final finishing and termination of curing. The ACI 308 recommended a wet curing period of 7 days for most structural concretes and a period of 14 days for structural concretes containing supplementary cementing materials. Curing is also used quite regularly in the industry. In this method, evaporation of water can be prevented by using polyethylene sheets and curing compounds **(ACI, 1998)**.

If a concrete has insufficient water at the early age, it cannot gain the properties and durability for its long term service. Appropriate curing helps to reduce the porosity and drying shrinkage of concrete, and to achieve higher strength and greater resistance.

Therefore, a suitable curing method such as, water pounding, spraying of water, or covering with wet burlap and plastic sheet is essential in order to produce a strong and durable concrete **(Safiuddin et al. 2000)**.

Steam curing is useful in terms of the early strength in concrete, which is important when additional heat is required to complete the hydration as in the case of cold weather **(Naik, 2005)**. Accelerated curing reduces costs and curing time in the fabrication of pre-cast members.

Concrete derives its strength by the hydration of cement particles. The hydration of cements not a momentary action but a continuing process for a long time and requires water and proper temperature. The rate of hydration is fast to start with, but continues over a very long time at a decreasing rate.

The curing allows the hydration to be continued and consequently, continued gains in concrete strength. In fact, once curing stops the concrete dries out and the strength gains tops **(Mamlouk and Zaniewski, 1999)**.

Many techniques have been developed to prevent evaporation and to provide a good cure for concrete and to investigate the effectiveness of the various curing techniques and their application technologies. The previous knowledge was carefully taken into account, consequently. An extended review of previous research was performed regarding the curing of concrete; some of these researches include the following:

Curing is the name given to procedures used to enhance the hydration of cement as well as to control the temperature and the moisture movement from and into the concrete. More accurately, the objective of curing is to keep concrete nearly saturated as much as possible or totally saturated, up to the water-filled space the fresh cement paste has been filled to the sufficient extent by the products of hydration of cement **(Neville, 1995)**.

General guidance and recommendations to obtain the acceptable strength out of curing were given in **ACI (1979):** Curing is extremely important in the production of high strength concrete. To produce a cement paste with as high solids content as possible, the concrete must contain the absolute minimum content of mixed water. However, after the concrete is in place and the paste structure is established, water should be freely available, especially during the early stages of hydration.

Holland (1989) stated that the beneficial effects of good curing on any type of concrete are generally accepted by all, but the question is still open on how long structural members should be cured to? As shown, the duration requirement in the ACI code for normal strength-gain concrete has historically been a minimum of 7 days, and at least 3 days for concrete. The factors that affect the required duration of curing to attain a certain level of maturity are the curing, temperature, the kinetics of the hydration and pozzolanic reactions of the particular cement materials.

Safiuddin et al. (2000) and **Ramezan et al. (1995)** studies the effectiveness of fly ash or silica fume on the strength of concretes and have found that fly ash is more sensitive to poor curing compared to the control concrete. Results presented effect of curing in Riyadh area of Saudi Arabia. They showed that concrete strength was significantly influenced by the method of curing. It is well known that hydration of cement can take place only when vapour pressure in the capillaries is sufficient. Among the various curing methods that have been used in the Gulf States, one approach is widely practiced. This is a conventional system in which continuous or frequent application of water is maintained through spraying, plastic cover, or wet burlap.

Other systems include the chemical membrane approach in which excessive loss of water is prevented by application of a membrane-forming curing compound to the freshly placed concrete **(Arafah et al., 1995)**.

Assess of effectiveness using different curing methods was studied. The basic principle of this study was to state the degree of hydration that determines the durability of concrete, and the degree of hydration that determines the amount of chemically bound water.

According to them, curing is efficient and able to keep water in the concrete to ensure quantities of chemically bound water and to ensure a high degree of hydration. It was also concluded that it increases the durability problems of concrete to return to early drying, thereby, leads to increase the probability of shrinkage and **cracking (Kern et al., 1995)**.

The concrete cover is more prone to lose water because it is sensitive to drying. Curing properties of hardened concrete are affected by the curing conditions and temperature.

Proper curing not only reduces the rate of water evaporation, moreover, it provides a continuous source of moisture for the hydration that reduces the porosity and provides a finer size distribution in the concrete **(Neville and Aitcin, 1998)**. The compressive strength, modulus of elasticity, and flexural strength of concrete will decrease at later ages if curing is neglected in the early age of hydration caused by this compensate the loss **(Aitcin et al., 2000)**.

Houssam and Ziad (1999) investigated the effect of three different methods of curing procedures on the properties of concrete. The methods used were steam curing, air curing and moist curing. They were determined the mechanical properties of concrete such; compressive strength, flexural strength, and permeability.

Although curing is an important aspect in the production of a good concrete, the timing and duration of curing is even more important **(Kovler et al., 2000)**. It is demonstrated that if an interruption happens during the curing, a significant concrete strength could be regained by curing of concrete. Never the less, the detrimental effects resulted from the lack of proper early curing are irreversible, and the strength gained by curing is lower.

Safiuddin et al. (2007) investigated the effect of different curing methods on the properties of micro silica concrete. Three curing methods were used; namely, dry air curing, wrapped curing, and water curing which was applied at 20 ºC to cure the cube and cylinder specimens up to the day of testing. The cube specimens were tested to determine the initial surface absorption of the concrete and hardened density.

Furthermore, cylinder specimens were tested to determine the following parameters; compressive strength, dynamic modulus of elasticity, splitting tensile and rate of moisture movement of micro silica concrete. Researchers also add that, water curing and wrapped curing perform better than dry-air curing; the reason for this phenomenon is that the rate of moisture movement was significant when the specimens were subjected to dry-air curing. Therefore, the hydration process was hindered and consequently affects the compressive strength and other properties of the concrete. Consequently, it was suggested that the concrete that contain silica fume should be cured by water curing to achieve well hardened properties.

2.9 Properties of HPC

2.9.1 Physical Properties

- **Density:**

In general, the HPC produced has a density ranging from 1760 to 2410 kg/m^3 **(Shaheenand Shrive, 2006)**.

On the other hand, **Sadrekarimi (2004)** also found that increase in silica fume content decreases the density. He explained that the space occupied by cement is partly replaced by a relatively lighter powder of silica fume.

- **Workability:**

Shaheen and Shrive (2006) observed that the HPC mix was so thick and viscous that the mixture had zero slump with a water/cement ratio of 0.13.

Liu and huang (2008) proposed a highly flowable reactive powder mortar as a repair material. A flow value as high as 200% was obtained with w/b ratio of 0.3. It is confirmed that workability increases with increased water content **(Lee and Chisholm, 2005)**.

Ma and Schneider (2002) found that the flow ability of HPC was improved with the cement replacement by quartz powder. The result shows that the slump flow increases from 510 mm to 620 mm when 30% cement is replaced by quartz powder. They explained that the incorporation of fine quartz powder reduced the voids in the original mixture.

2.9.2 Mechanical properties

)ا Compressive strength:

HPC has a typical compressive strength of 50 to 100 MPa when mixed and cured at ambient temperatures, and strengths up to 810 MPa have even been recorded by **Richard and Cheyrezy, (1995)**. This was mainly due to the enhancement of homogeneity by the elimination of coarse aggregates; enhancement of compacted density by optimizing the granular mixture and optionally applying pressure before and during setting; improved matrix properties by addition of pozzolanic admixtures, i.e. silica fume; improved matrix properties by reducing water-to-binder ratio; and enhancement of the micro structure by heat treatment after hardening **(Richard and Cheyrezy, 1995).**

Kamen et al. (2007) found that the compressive strength developments of HPC are closely related to the hydration progress. A high strength is reached according to a certain degree of hydration because the material has a low w/b ratio. They explained that the effect was attributable to the initial dense packing of the cement particles, which rapidly provides a small amount of gel required for bonding the hydrating particles. The unhydrated cement and silica fume particles (which act as filler) contribute to enhance the matrix compactness at the micro level and result in an increase of the mechanical properties at the macro level.

Behnood and Ziari (2008) studied the effect of silica fume on the properties of high strength concrete and found that concrete containing silica fume had significantly higher strength than that of ordinary concrete. Similar findings were also reported in the study by **Appa Rao. (2003)**. He explained the strength enhancement is due to the pore size refinement and matrix densification as well as the pozzolanic reaction which reduces the Ca(OH)2 (CH) content. For the application of pressure to increase the compacted density. **Shaheen and Shrive (2006)** added that applying a pre-setting force of between 50 and 100 KN resulted in a maximum compressive strength and any higher values of pressure resulted in lower compressive strength. They explained that the decrease of compressive strength was due to micro cracks induced on the release of pre-setting load.

Modulus of elasticity:

The value of elastic modulus of HPC has a typical value of about 47 GPa **(Rebentrost and Cavill, 2006)**. **Richard and Cheyrezy (1995)** reported that HPC has Young's modulus values exceeding 50 GPa, and it can go up to 75 GPa for those with the highest densities.

2.10 Mix Designs from Previous Research:

Mix designs developed for HPC from previous literatures are outlined in Table 8.5. Most mix designs for HPC are based on the benchmark mix developed by **Richard and Cheyrezy (1994)**. Cement contents range between 28 and 38 percent of the total mix weight, which equates to a mass greater than 650 kilograms per cubic meter of HPC mix.

The 10 percent variation in cement content between mix designs arises through the use of fine powders (silica flour or ground quartz) which enable a reduction in the cement content. Use of either silica flour or ground quartz is dependent on local materials available. Silica fume contents vary between 8 and 10 percent of total mix weight (approximately 20 to 30 percent of cement content) which corresponds to masses of approximately 200 kilograms per cubic meter of HPC mix. Similar to cement, a reduction in silica fume content is enabled through the use of silica flour or ground quartz.

Although not shown in Table 8.5, variations in silica fume types were evident in past mix designs for HPC. These variations are often due to differing carbon, sulphur, and calcium contents and also the retrieval level in the furnace where the silica fume is collected **(Coppola et al. 1996)**. The super plasticiser type and quantity used is highly dependent on the water demand of the binding materials and desired flow of the HPC mix. High range.

2.11 Summary

A review of relevant literature has revealed that the superior material performance of HPC is attributable to a combination of a low water cement ratio, high silica fume content, particle grading optimization of steel fibers. A meticulous mixing rationale is required for the production of HPC. This coupled with the requirement of a dedicated curing regime has generally limited its application to the precast industry where the stringent quality control issues, required for HPC production, can be adhered. These finding where utilized in the investigation for an optimal/consistent HPC mix.

Chapter Three

Constituent Materials and Experimental Program

3.1 Introduction

This chapter presents the experimental program and the constituent materials used to produce HPC associated with this research work. The laboratory investigation consists of tests for hardened concrete.

The tests for hardened concrete included compression tests for strength and indirect tensile tests.

The influence of the silica fumes dosage, cement/ultra-fine ratio and the mixing procedures on the compressive strength concrete together with the workability and density of HPC was studied by preparing several concrete mixes.

The properties of different constituent materials used to produce HPC are discussed such as moisture content, unit weight, specific gravity and the grain size distribution. The test procedures, details and equipment used to assess concrete properties are illustrated in the following sections.

3.2 Characterizations of Constituent Materials

HPC constituent materials used in this research include of Portland ordinary cement, grey silica fume, crushed Quartz,Quartz sand and basalt aggregate, in addition to fiber are used to ensure suitable workability. Proportions of these constituent materials have been chosen carefully in order to optimize the packing density of the mixture.

3.2.1 Cement:

Cement paste is the binder in HPC that holds the aggregate (coarse, fine, micron fine) together and reacts with mineral materials in hardened mass. The property of HPC depends on the quantities and the quality of its constituents. Because cement is the most active component of HPC and usually has the greatest unit cost, its selection and proper use is important in obtaining most economically the balance of properties desired of HPC mixture.

In this research High Strength Portland Cement CEM I 52.2R was used for the production of High Performance Concrete (HPC). The cement met the requirements of ASTM C 150 specifications . The results of physical and mechanical analyses of the cements are summarized in Table (3.1) along with the requirements of relevant ASTM specifications for comparison purposes.

Table (3.1): Cement tests

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

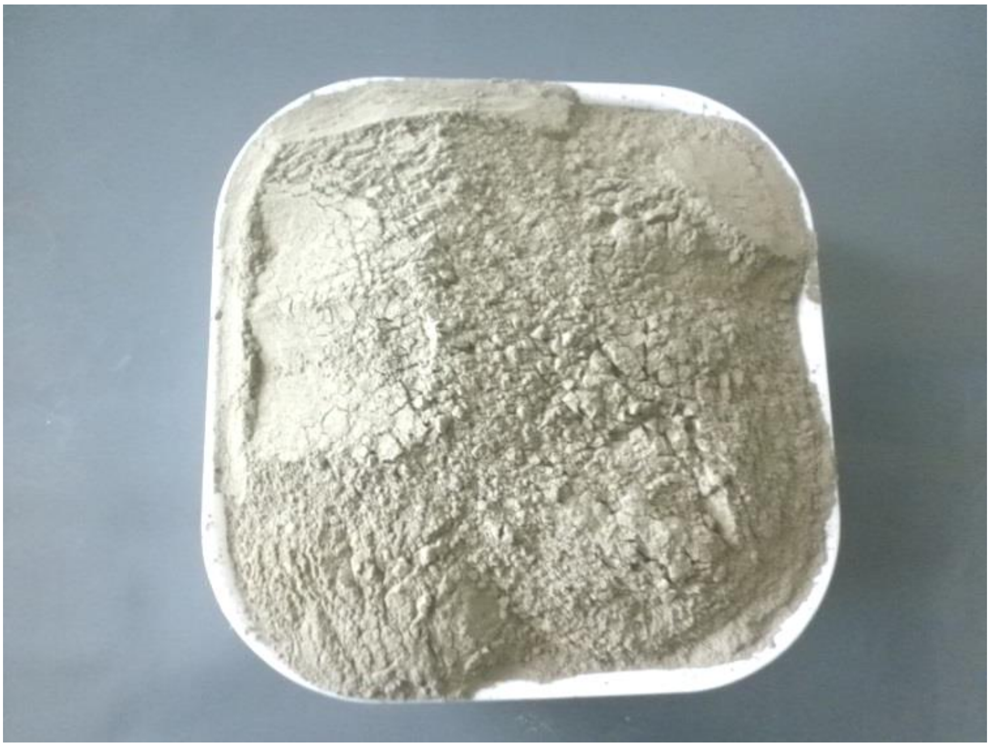


Figure 3.1: Ordinary Portland Cement

3.2.2Silica Fume

Silica fume is a byproduct resulting from the reduction of high-purity quartz with coal or coke and wood chips in an electric arc furnace during the production of silicon metal or ferrosilicon alloys. The silica fume which condenses from the gases escaping from the furnaces has a very high content of amorphous silicon dioxide and consists of very fine spherical particles Silica Fume used in this research (Figure 3.2).

Figure 3.2: Silica Fume.

3.2.3 Aggregates (Crushed stone, quartz sand)

Aggregate is relatively inexpensive and strong making material for concrete. It is treated customarily as inert filler. The primary concerns of aggregate in mix design for High Performance Concrete are gradation, maximum size, and strength. Providing that concrete is workable, the large particles of aggregate are undesirable for producing High Performance Concrete. For producing HPC, selection of very strong aggregate with rough texture is significantly more important the crushed stone (coarse aggregate) . The nominal size ranges from 2.36 to 20 mm and quartz sand (fine aggregate) in the range of 0.6 to 0.3 mm which are locally available in Sudan markets as shown in Figure (3.3). In addition, it is important to ensure that the aggregates are clean, since a layer of silt or clay will reduce the cement aggregate bond strength, in addition to increasing the water demand.

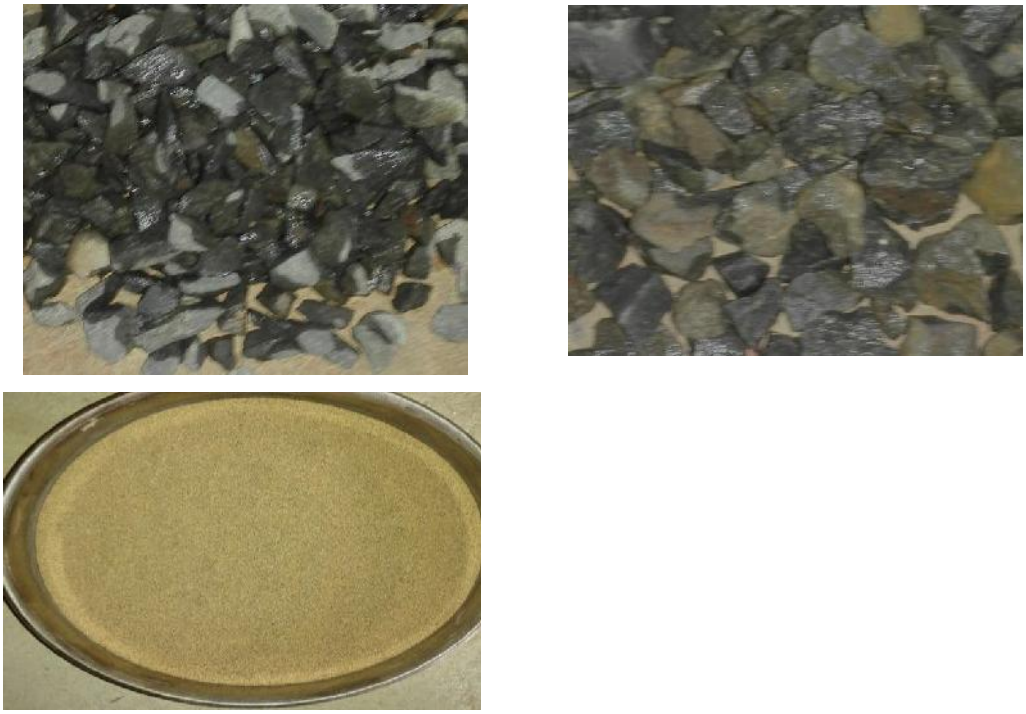


Figure (3.3): Aggregates used in mixture preparations: (a) crushed stone aggregate 3/8"(b) crushed stone aggregate 3/4". (c) Quartz sand with maximum size of 0.6 mm.

3.2.4 Quartz Sand

Aggregate is relatively inexpensive and strong making material for concrete. It is treated customarily as inert filler. The primary concerns of aggregate in mix design for Reactive Powder Concrete are gradation, maximum size, and strength.

Providing that concrete is workable, the large particles of aggregate are undesirable for producing HPC. For producing HPC, the nominal size ranges from 150 to 600 μm for quartz sand (fine aggregate) which are locally available in Khartoum markets (Figure 3.3). In addition, it is important to ensure that the aggregates are clean, since a layer of silt or clay will reduce the cement aggregate bond strength, in addition to increasing the water demand.

Figure 3.4: Quartz sand.

Specific gravity and Unit weight:

The density of the aggregate is required in mix proportions to establish weight volume relationships. The density is expressed as the specific gravity, which is dimension less relating the density of the aggregate to that of water. The determination of specific gravity of quartz sand was according to **ASTM C128-2004**. The specific gravity was calculated at two different conditions which are the dry condition and the saturated surface dry condition. Table 3.2 shows the physical properties of quartz sand. Crushed stone (3/8") and crushed stone (3/4"). The unit weight or the bulk density of the aggregate is the weight of the aggregate per unit volume.

Necessary to select concrete mixtures proportions in HPC. The determination of unit weight was according BS 882-1992 table 4 for grading.

The unit weight or the bulk density of the aggregate is the weight of the aggregate per unit volume. The unit weight is necessary to select concrete mixtures proportions in HPC. The determination of unit weight was according to **ASTM C566-2004**. Table 3.3 illustrate the grading of the quartz sand.

Table 3.2: Physical Property of Quartz Sand used

Property	Value
Specific Gravity	2.61
Unit Weight (t/m3)	1.58

Table 3.3: 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

3.2.5 Water

Drinkable water was used in all concrete mixtures and in the curing of specimens.

Table 3.4: The technical data for the "Sika ViscoCrete - 5930" (source: from supplier)

Type	Property
Appearance	Turbid liquid
Density (kg/l)	1.08 kg/lt. ± 0.005
Basis	Aqueous solution of modified poly carboxylate
Toxicity	Non-Toxic under relevant health and safety codes

3.2.6 Steel fibers

The fibers are used to improve hardened concrete properties and improve the ductility of the HPC. The steel fibers used in this investigation are clean of rust or oil of straight steel wire fibers. The used steel fibers are chopped or cut from steel wires. (Figure 3.5).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/cm3.

Figure 3.5: Steel fibers

3.3 Preparation of HPC

After selection of all needed constituent materials and amounts to be used (mix designs); 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.

Mixing procedure was according following steps:

1) Placing all dry materials (cement, silica fume, quartz sand, Crushed quartz powder and steel fibers) in the mixer pan, and mixing for 2 minutes.

2) Adding water to the dry materials, slowly for 2 minutes

3) Continuation of mixing as the HPC changes from a dry powder to a thick paste.

After final mixing, the mixer is stopped, turned up with its end right down, and the fresh homogeneous concrete is poured into a clean plastic pan.

Figure 3.6: The drum mixer

The casting of all HPC specimens used in this research completed within 20 minutes after being mixed. All specimens were cast and covered to prevent evaporation.

3.4 Equipment and testing procedure

3.4.1 Tests of Hardened Concrete

I. Compressive Strength Test

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

Total number of 36 cubes were manufactured. For each batch of HPC made, 150x150x150mm cube specimens were prepared, as shown in Figure 3.7. 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.

Figure 3.7: Cube specimens

Figure 3.8: Cubes at curing basin

The cubes were stored in water until the time of the test, as shown in Figure 3.8. Before the tests, the specimens were air dried for 10 to 15 minutes and any loose sand grains or incrustations from the faces that will be in contact with the bearing plat of the testing machine are removed. The cubes are placed in the testing machine so that the load is applied to opposite sides as cast and not to the top and bottom as cast.

Therefore, the bearing faces of the specimen are sufficiently plane as to require no capping. If there is appreciable curvature, the face is grinded to plane surface because, much lower results than the true strength are obtained by loading faces of the cube specimens that are not truly plane surfaces.

The compressive strength machine in soil and material laboratory at the IUG was used for determining the maximum compressive loads carried by concrete specimen cubes, as shown in Figure (3.9).

Figure 3.9: Compressive strength test machine

The compressive strength of the specimen, σ comp (in MPa), is calculated by dividing the maximum load carried by the cube specimen during the test by the cross sectional area of the specimen (Figure 3.10).

$$\sigma\ cc = P \backslash A$$

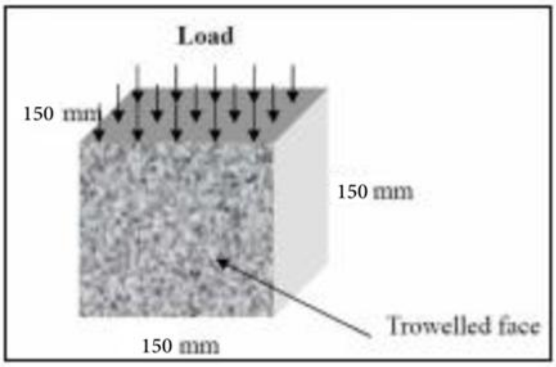


Figure 3.10: Force applied on the 150 mm cube

The compressive strength was determined at different ages 7, 14, and 28 days. At least three of these cubes were tested for each period the mean value of the specimens was considered as the compressive strength of the experiment.

II. Flexural Prism Test

Total number of 3 prisms were manufactured. The flexural strengths of concrete specimens are determined by the use of simple beam with center point loading in accordance to **ASTMC293-1994** as shown in Figure 3.12

The specimens are prisms 100 x 100 x 500 mm. The mold is filled with the concrete in one layer, without compacting. After preparing the specimens, they are covered with plastic sheets for about 24 hours to prevent moisture loss. After 24 hours, the specimens are extracted from the molds and placed in water for curing up to time of test.

At the time of testing, and because the flexural strengths of the prisms are quickly affected by drying which produces skin tension, they are tested immediately after they are removed from the curing basin.

The casted beam specimens to be tested turned on their sides with respect to their position as molded. This should provide smooth, plane and parallel faces for loading. Shown in Figure 3.11.

Figure 3.11: Flexural test specimens (100*100*500mm)

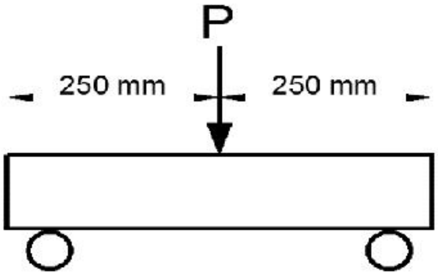


Figure 3.12: Schematic view for flexure test of concrete by centre-point loading

The pedestal on the base plate of the machine is centered directly below the center of the upper spherical head, and the bearing plate and support edge assembly are placed on the pedestal. The center loading device is attached to the spherical head. The test specimen is turned on its side with respect to its position as molded and it is placed on the supports of the testing device.

This provides smooth, plane, and parallel faces for loading. The longitudinal center line of the specimen is set directly above the midpoint of both supports.

The center point loading device is adjusted so that its bearing edge is at exactly right angles to the length of the beam and parallel to its top face as placed, with the center of the bearing edge directly above the center line of the beam and at the center of the span length. The load contacts with the surface of the specimen at the center. If full contact is not obtained between the specimen and the load applying or the support blocks so that there is a gap, the contact surfaces of the specimen are capped.

The specimen is loaded continuously and without shock at until rupture occurs. Finally, the maximum load indicated by the testing machine is recorded.

The flexural strength of the beam, Fr (in MPa), can be calculated by using the following equation:

$$Fsp = \frac{2p}{\pi DL}$$

Where: **P** = maximum applied load indicated by the testing machine;

L = span length;

B = average width of specimen, at the point of fracture;

D = average depth of specimen, at the point of fracture

III. Unit weight:

In this research, the unit weight of the concrete cube specimen is the oretical density. The density is calculated by dividing the weight of each cube by the volume. The same cube specimens that are used to determine the compressive strength was used to determine the density and the tests were carried out according to **ASTM C642-2004**.

3.4.2 Curing Tank:

This special curing tanks have been designed by the author for water curing in accelerated strength concrete. The interior is made from stainless steel.

The electronic controller can provide the curing tank with different thermal gradients for any specific time with a defined temperature value for a complete automatic curing cycle. Figure 3.13 shows the curing tank

Figure 3.13: Curing Tank

3.4.3 Curing methods

Curing is very important to control the rate and extent of moisture loss from concrete during the hydration process. Therefore, it is important to provide sufficient time for the hydration process of the cement to occur during the period in which it is gaining strength. Curing problems are exaggerated when concreting in hot weather, as a result of both higher concrete temperatures and increased rate of evaporation from the fresh mix.

The compressive strength, flexural strength, modulus of elasticity, and other characteristics of concrete in hot atmosphere are thus depend able on its treatment during the first few weeks. The curing period may depend on the properties required for the concrete, the purpose for which it is to be used, and the ambient conditions, i.e. the temperature and relative humidity of the surrounding atmosphere.

Curing must be under taken considering duration of time needed for the concrete to achieve its potential strength. Incomplete curing would cause major defects. These defects will allow the presence of permeability and reduce the compressive strength and they will lead to weaken the durability of concrete. Although there were a lot of research work done on the effect of curing on the HPC, but the effect of delay curing is not investigated. Therefore, this consequently, this will specify the suitable curing method for concrete and will also help to improve the mechanical properties for concrete, as compressive strength, and flexural strength.

After the casting process was completed, the concrete should be prevented from premature drying, and exposing to the normal water curing (Immerse in water) at 25° C until day of testing.

3.4.4 Design of higher performance concrete mix:

-B.S.Edition 1975 Revised in1988-B.S 1881
-Cement complying withB.S12(3) and 4027(4) portland 42.5 N/mm2
- Fine and cores aggregate complying with B.S882(5)
-If the specificity of concrete strength in 28 days is 50 N/mm^2 or more the crushed stone must use
-Table of concrete mix design Quantities in w(kg)
-Fresh concrete slump is 30 mm- Aggregate size is 20 mm
-Sand rough and passing in seive 600micron is 25% - 33%

-Charcetristic strength 60 N/mm^2 flow 55 N/mm^2
margin 8.2 N/mm^2
Target strength 63.2 N/mm^2

3.4.5 Mix Design:

Step One: is characteristic strength

–it given 60 N/mm^2

Step Two: is margin from standard deviation downdraft

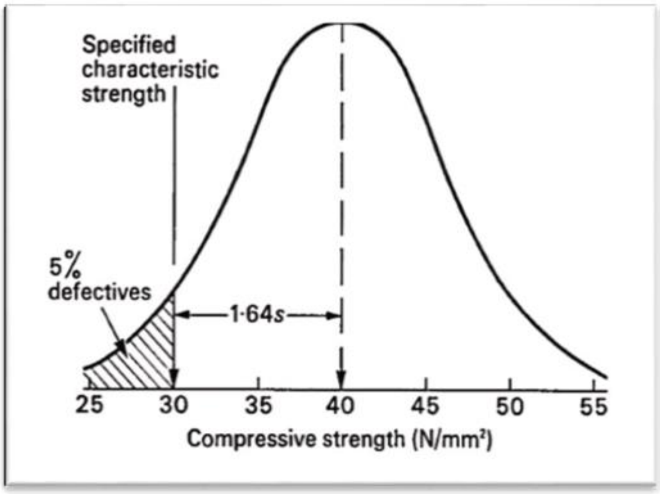


Figure (3.14): Relationship between Standard Deviation and Compressive strength

Table (3.5): K Value

S]	K
10	1.28
5	1.64
1	2.32
2.5	1.96

S=stander deviation 5%

K=a constant –from table 1.64

Margin is K*S = 5*1.64 = 8.2 N/mm^2

Step Three: the master main strength design (targetable strength)

Fm = fc +k.s

60 + 8.3 (an less curve is say max 55 N/mm^2)

Say 63.2 actually 64 N/mm^2

Step four: from cement chart figure 4 down draft

Figure(3.16) – the water ratio give us the 64 N/mm^2

w/c = 0.35

total water is w/c+wabsorbed+Ev haidrat

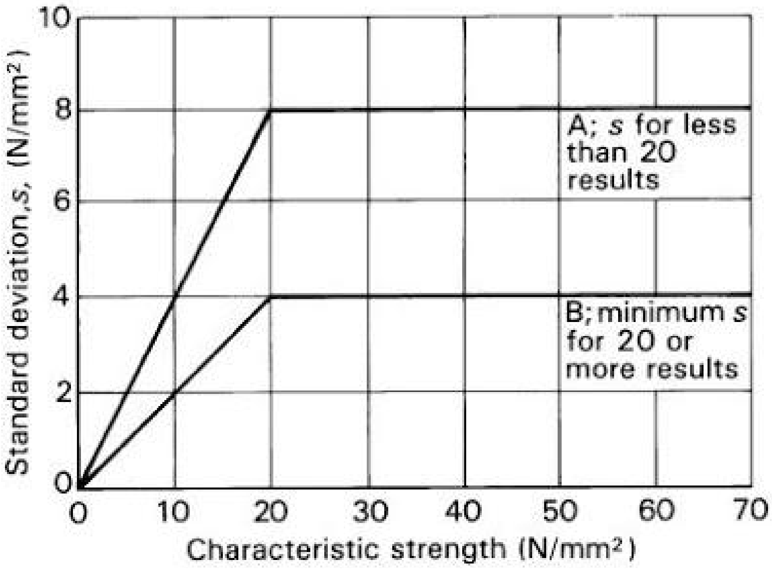


Figure (3.15): Relationship between standard deviation and characteristic strength

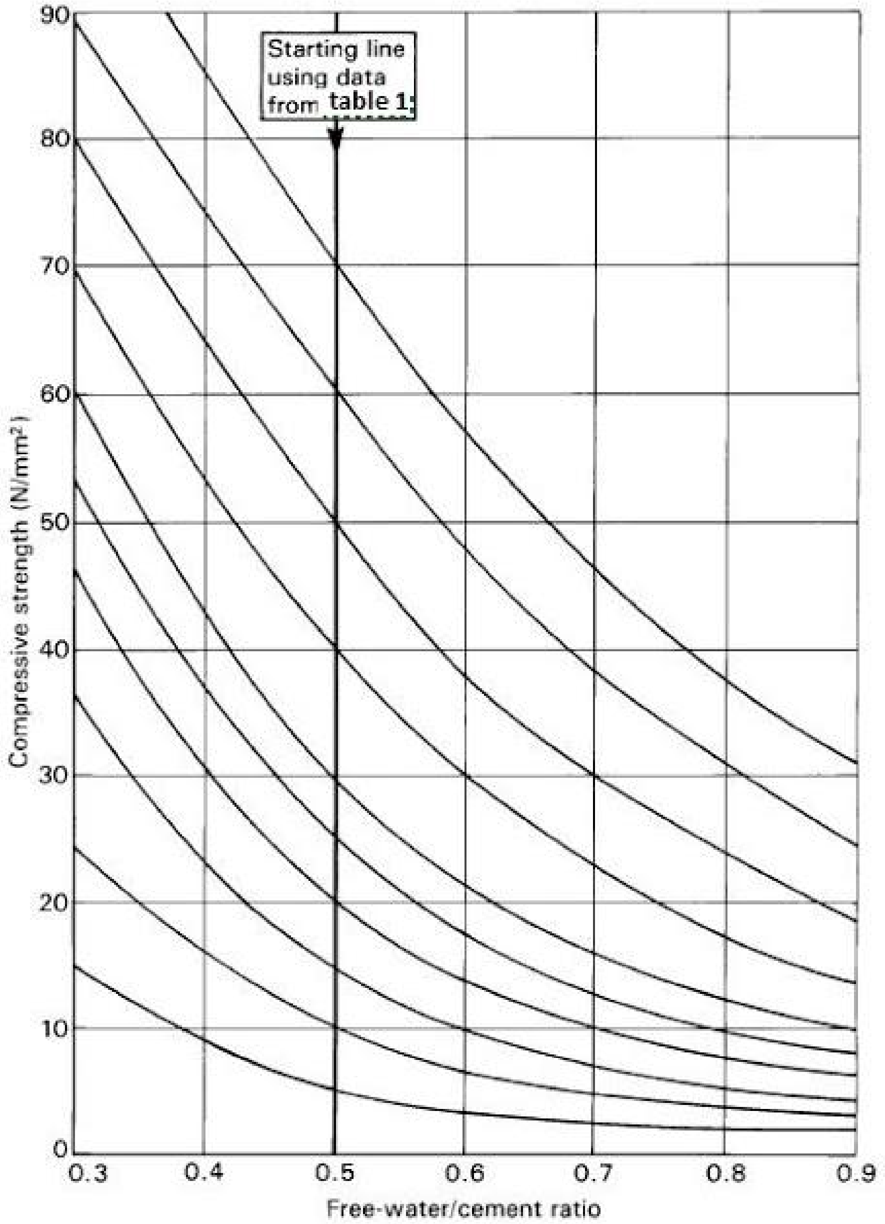


Figure (3.16)Relationship between compressive strength and water/ cement ratio

Step five: is find the weight of water w/c from table (3.6)

Down draft when slump is 30mm and stone crushed - it must be 230 kg/m3

Table (3.6): Approximate free-water contents (kg/m3) required to give various levels of workability

		0-10 >12	10-30 6-12	30-60 3-6	60-80 0-3
Max Size Of Aggregate(mm)	Type of aggregate				
10	Uncrushed	150	180	205	225
	Crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	Crushed	170	190	210	225
30	Uncrushed	115	140	160	175
	Crushed	155	175	190	205

Note: When coarse and fine aggregates of different types are used, the free-water
content is estimated by the expression:
2⁄3Wf+ 1⁄3Wc
where Wf =free-water content appropriate to type of fine aggregate
and Wc =free-water content appropriate to type of coarse aggregate

Step Six: from w/c and water weight above – find cement weight in kg /m3
w/c = water cement ratio

$$230/_{C} = 0.36$$

$$cement = {}^{230}/_{0.36}$$

cement=657 kg/m^3

Step seven: is find wet density concrete mix kg/m3 from the figure(3.17)
2524.33 kg/m3

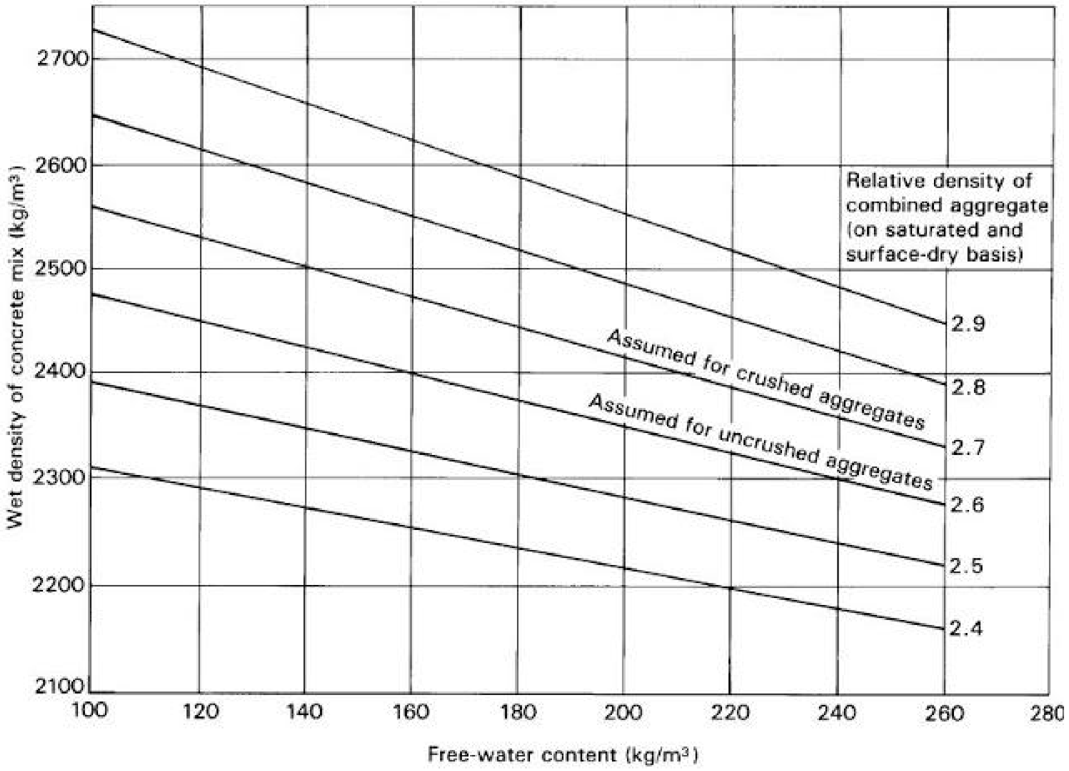


Figure (3.17): Estimated wet density of fully compacted concrete.

Step eight: type find the fine and course aggregate weight kg/m3

Correction water = total water

230+8.2 = 238.2.2 kg/m^3

=2524.33-(238.2+657+3%air)= 1619.8 kg/m^3

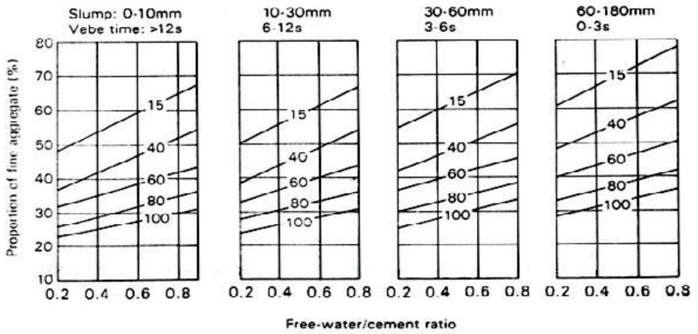
Step Nine: find the sand weight according to passing in sieve 600 micron it must be rough mains between 28% _____ 35% :-

Use 33%

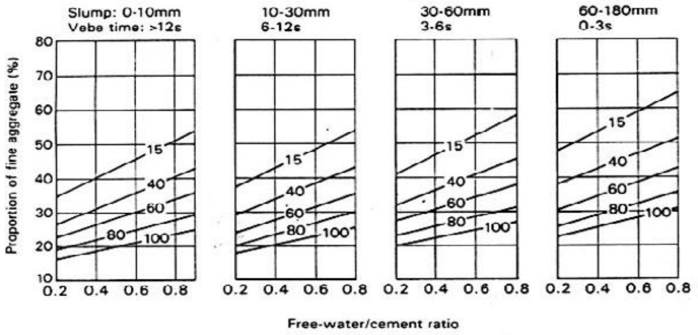
From figure 3.18 and slump 30mm and w/c .36 and sand passing ratio the sand ratio 36%

actually is

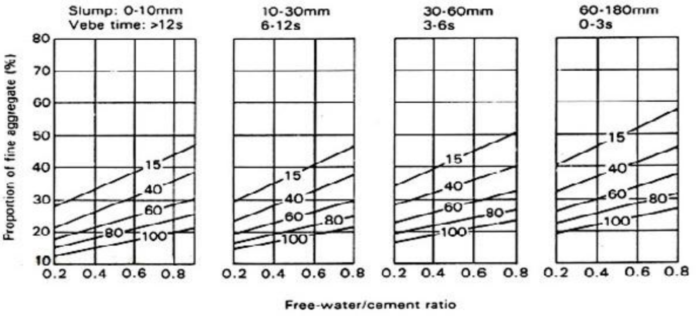
1866*0.36=700.32kg/m^3



Maximum aggregate size: 20mm



Maximum aggregate size: 40mm



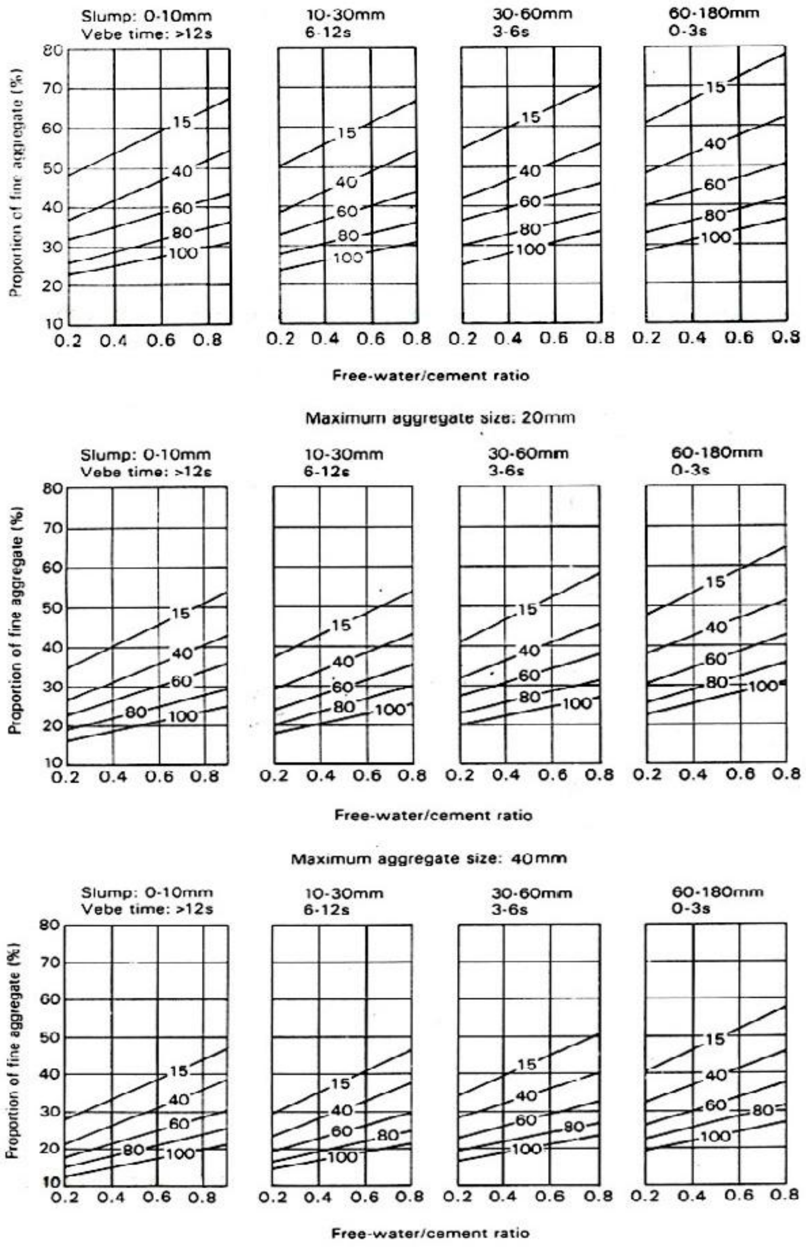


Figure (3.18): Recommended proportions of fine aggregate according to percentage passing a 600 µ m sieve.

Step Ten: stone :
1864.3 – 700.3 = 1164 kg/m^3

Chapter (4)
Test Results and Discussion

4.1 Test Result:

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

Table 4.1 and 4.2 show the mixture proportions and one cubic meter ingredient of the best mix results obtained mixture of HPC. All mixtures details and average results are presented in appendices.

Table 4.1: 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 quartz ¾	1.40
Crushed quartz 3/8	0.75
Steel Fibers	≈ 0.24 (3% of total volume)
Water cement ratio (w/c)	0.36

Table 4.2: 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 quartz ¾	758.55
Crushed quartz 3/8	408.45
Steel Fibers	12.9
Water cement ratio (w/c)	238.2

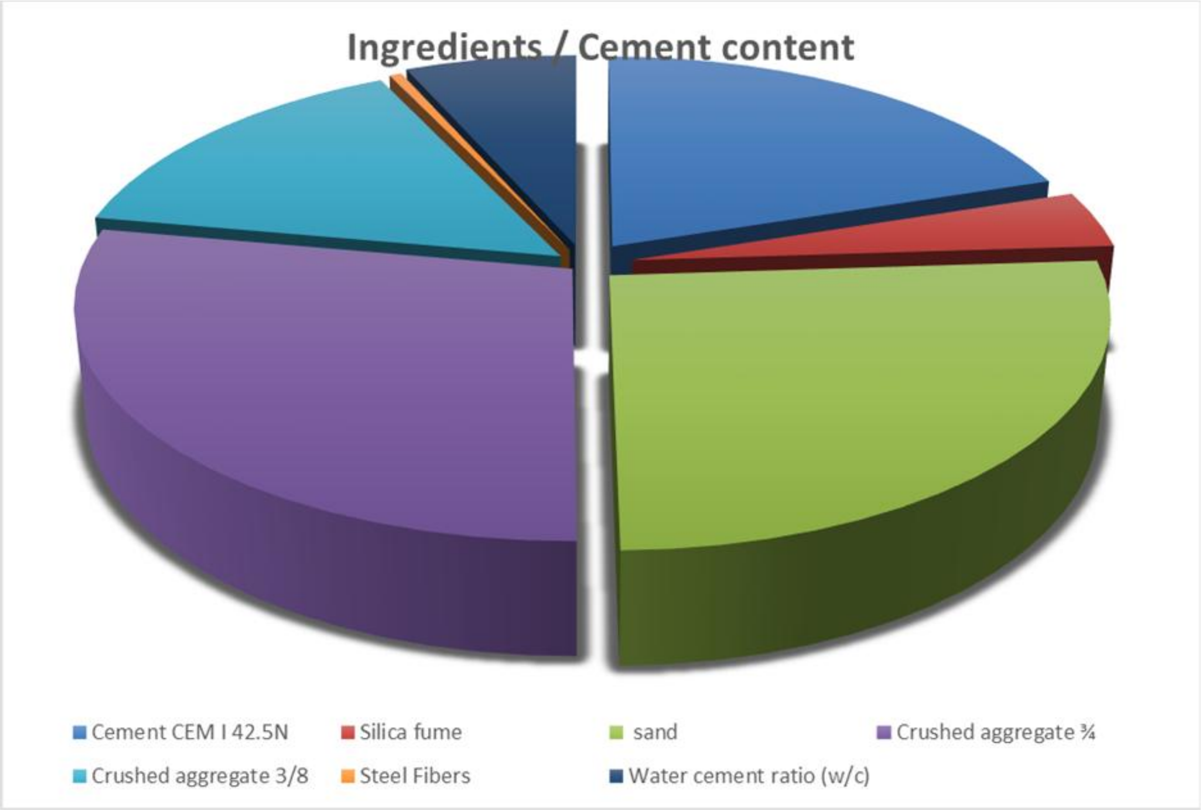


Figure (4.1) Ingrediente/cement content

All mixtures were subjected to fresh and hardened concrete tests in order to be classified as HPC, some mixing ingredients were fixed and the other were variable.

Table (4.3): Mixes design for different silica fume percentage

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

4.2Hardened properties results for Normal Water Curing:

Laboratory tests were conducted to evaluate and study the hardened properties of HPC. Results is the de compressive strength and indirect tens as shown in **Table 4.5:** Hardened properties results of Normal Water Curing strength. Results are summarized in Table 4.4.

Table (4.4): 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

4.2.1 Effects of silica fume and steel fibers on HPC density:

Results is the Density as shown in **Table 4.5** and Figure 4.2 summarizes the effect of silica fume and steel fibers on the HPC density, the results show that the density of concrete decreases when increasing the silica fume content. This can be due the space occupied by cement is partly replaced by a relatively lighter powder of silica fume. However, the density increases when the amount of steel fibers increases.

Table (4.5): 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	2780.40	2760
B	3	2713.8	2763.00	2735
C	3	2705.5	2750.00	2716
D	3	2691.2	2713.00	2704

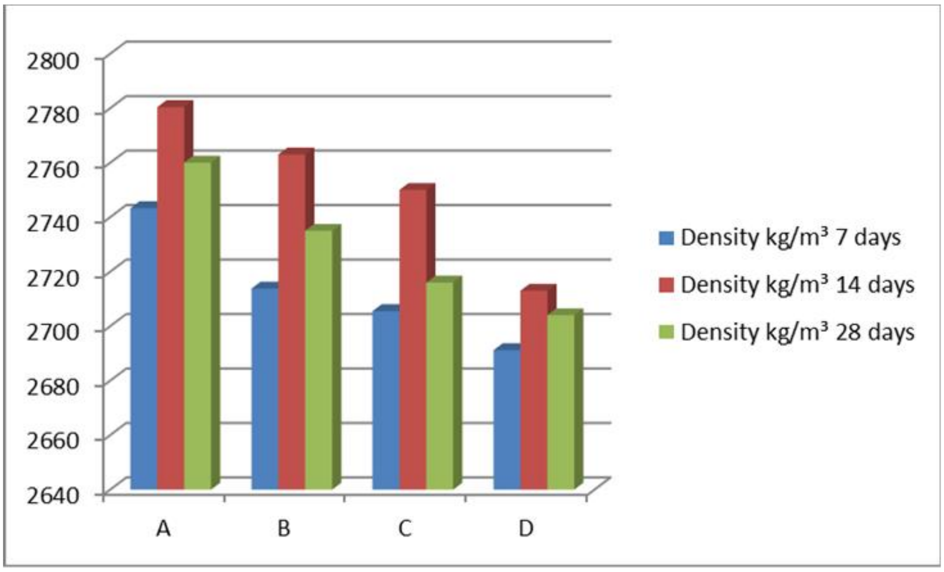


Figure 4.2: Effect of Silica Fume and Steel Fibers on the HPC Density

4.2.2 Effects of silica fume and steel fibers on HPC compressive strength

Results shown in Table 4.4, Figure 4.3,

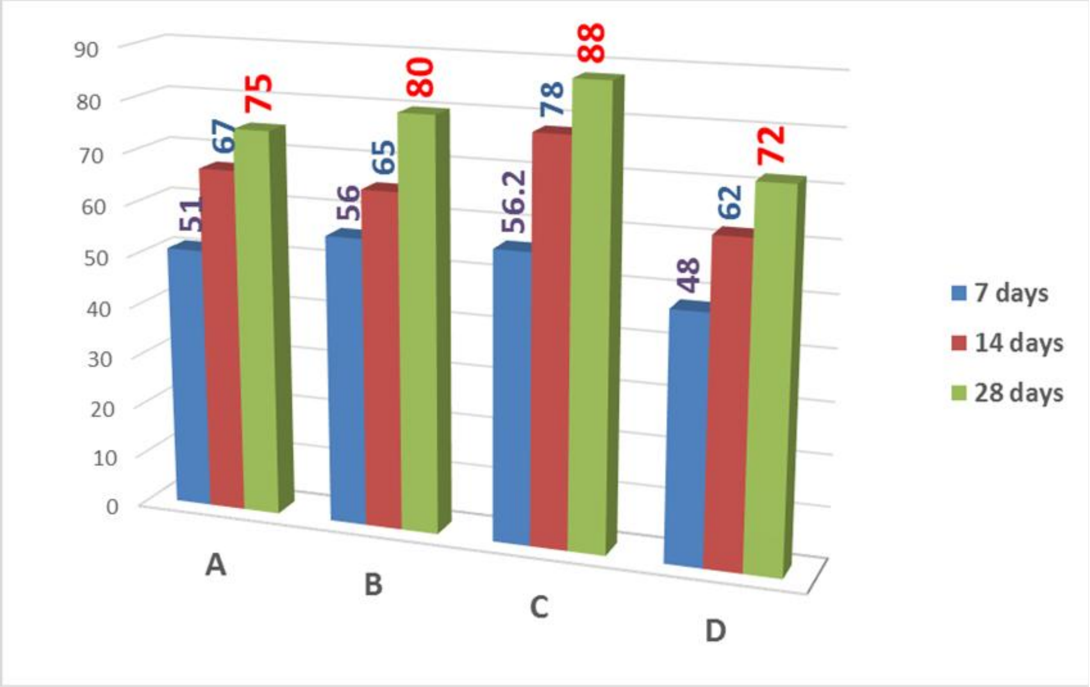


Figure (4.3) Compressive Strength for Experiment

4.2.3 Flexural strength

The results of flexural strength tests for HPC at all curing conditions can be observed in Table 4.6 and Figure 4.4 as shown below:

Table (4.6): Summary of Flexural strength at different ages

Mix	No. of specimens	Flexural strength MPa
		28 days
A	1	14.06
B	1	17.06
C	1	19.31
D	1	22.30

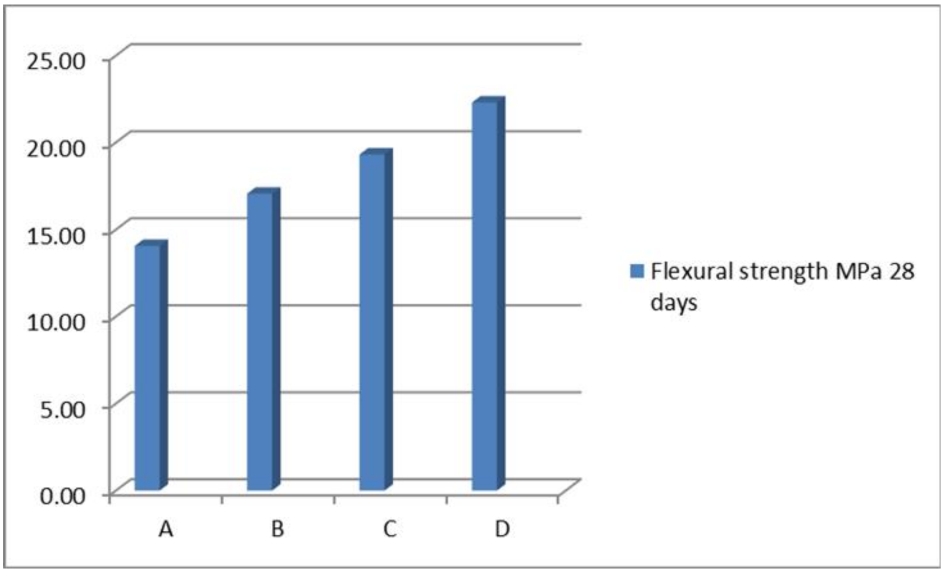


Figure: (4.4) Flexural Strength

4.3 Discussion of Result

A pronounced effect of the using silica fume was observed. The use of 20 % of silica fume as replacement of cement exhibits comparable result 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 research.

The explanation is that the silica fume works in two levels, the pozzolanic reaction and the physical function. The hydration of Portland cement produces many compounds; including calcium silicate hydrates (CSH) and calcium hydroxide (CH). When silica fume is added to fresh concrete, it chemically reacts with the CH to produce additional CSH which improve the bond between the cement and the surface of the aggregate, more ever the silica fume particle can fill the voids creates by free water in the matrix. This function is called particle packing refines the microstructure of the concrete, thus creating a much denser pore structure the benefit of this reacts is twofold; increasing compressive strength and decreasing total pores volume.

Chapter Five
Conclusions and Recommendations

5.1 Introduction

HPC is a relatively new form of concrete for general applications. The main advantage That HPC has over standard concrete is its high compressive strength. Other advantages include low porosity, improved microstructure and homogeneity

The objective of this research was to produce HPC using available materials in Sudan. The experimental phase of this research focused on determining the mechanical behaviour of HPC. The laboratory tests determined the compressive of HPC. The analytical phase of this research focused and elaborated on the Results obtained from the experimental phase.

5.2 Conclusion

Conclusions presented in this section are based on this particular research work. For clarity, the conclusion has been grouped into subsections, focusing on the laboratory test that compression strength. Based on the results of this investigation, the following conclusions can be drawn:

1) The compressive strength

- It is possible to produce HPC in Sudan using materials which are available at the local markets if they are carefully selected and achieving mix composition in grain size distribution that will achieve a minimum compressive strength of 80 MPa at 28days. Such concretes can be produced with Crushed stone, quartz sand and silica fume as the mineral admixture.

2) **The silica fume dosage**

- 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.
- 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%.
- The density of HPC decreases as of silica fume content increases.

M4 **Flexural strength of HPC**

- When the steel fibers content increases, the flexural strength of HPC increases also. For example at silica fume content 30% the flexural strength increase at the 28 days by about 14.05%, 33.65% and 44.85% at steel fiber content
- When silica fume increased from 10% to 20%, the flexural strength of HPC increased, and from 20% to 30% the flexural strength increased.

5.3 Recommendations

Having carrying out this study several suggested 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 micro structure 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.

References

1. Abdul Hussain, S. T. (2013), "Effect of Elevated Temperatures on Compressive and Tensile Strengths of Reactive Powder Concrete", Journal of Engineering and

Development, Vol. 17, No.4, December 2013, ISSN 1813- 7822.

2. ACI (1998) Standard Specification for Curing Concrete. American ConcreteInstitute.

3. ACI 209R-92, 2003, "Prediction of creep, shrinkage, and temperature effect inconcrete structures", ACI Manual of Concrete Practice part 1.

4. ASTM C109, (2004). “Standard Test Method for Compressive Strength of cube Concrete Specimens”. American Society for Testing and Materials Standard PracticeC109, Philadelphia, Pennsylvania.

5. ASTM C128, (2004). “Standard Test Method for Specific gravity and absorption of fine aggregate”, American Society for Testing and Materials Standard Practice C128, Philadelphia, Pennsylvania.

6. ASTM C494, (2004). Standard Specification for Chemical Admixtures for Concrete. American Society for Testing and Materials Standard Practice C494, Philadelphia, Pennsylvania.

7. EUROCODE. (2006). “Execution of concrete structures”. is a Pre standard developed by the European Committee for Standardization.

8. Gonen, T. and Yazicioglu, S. (2009). “The influence of mineral admixtures on the short and long term performances of concrete”. department of construction education, Firat University, Elazig 23119,Turkey.

9. HDR Inc. (2002)."Concrete mixture proportions." HDR Website, HDR Inc.,Omaha

10. Houssam, A. and Ziad, B. (1999). “Effect of curing procedures on properties of silica fume concrete”. Cement and Concrete Research, pp. 497-501.

11. Huang, Z. and Shen, P. (1993). “Experimental study on 200 MPa ultra-high steel fiber concrete”. Concrete, Vol. 3, pp. 3-7.

12. Kamen, A., Denarie, E. and Bruhwiler, E. (2007). "Thermal Effects on Physic Mechanical Properties of Ultra-High Performance Fiber-Reinforced Concrete ".ACIMaterials Journal. Vol. 104, No. 4, PP. 415-423

13. Kwan, A.H.K. (2003). “Development of High Performance Concrete for HongKong”. Materials Science and Technology in Engineering Conference - Now, Newand Next, website available athttp://www.hkpc.org/hkiemat/mastec03_notes/03.pdf.

14. Long, G.C., Wang, X.Y. and Xie, Y.J. (2002). “Very-high-performance concrete with ultra fine powders”. Cement and Concrete Research, Vol. 32, PP. 601-605.

15. Sadrekarimi, A. (2004). "Development of a Light Weight Reactive Powder Concrete". Journal of Advanced Concrete Technology .Vol. 2, No.

Appendices

Appendix A1. Density and Compressive Strength at 7 Days

A:

Mixture	size	area	mass(kg)	Density	load	compressive strength (MPa)
1	0.15*0.15*0.15	22500	8.262	2448	1125	50
2	0.15*0.15*0.15	22500	10.689	3167	1237.5	55
3	0.15*0.15*0.15	22500	8.826	2615	1080	48
mean				2743.3		51

B:

Mixture	size	area	mass(kg)	Density	load	compressive strength (MPa)
1	0.15*0.15*0.15	22500	8.421	2495	1125	50
2	0.15*0.15*0.15	22500	8.492	2516	1417.5	63
3	0.15*0.15*0.15	22500	10.565	3130.5	1237.5	55
mean				2713.8		56

C:

Mixture	size	area	mass(kg)	Density	load	compressive strength (MPa)
1	0.15*0.15*0.15	22500	7.611	2255	1215	54
2	0.15*0.15*0.15	22500	10.938	3241	1305	58
3	0.15*0.15*0.15	22500	8.846	2621.1	1012.5	45
mean				2705.5		56.2

D:

Mixture	size	area	mass(kg)	Density	load	compressive strength (MPa)
1	0.15*0.15*0.15	22500	6.848	2029	967.5	43
2	0.15*0.15*0.15	22500	8.964	2656	1102.5	49
3	0.15*0.15*0.15	22500	11436	3388.5	1170	52
mean				2691.1		48

Appendix A2. Density and Compressive Strength at 14 Days

A:

Mixture	size	area	mass(kg)	Density	load	compressive strength (MPa)
1	0.15*0.15*0.15	22500	8.235	2448	1687.5	75
2	0.15*0.15*0.15	22500	9.281	3167	1462.5	65
3	0.15*0.15*0.15	22500	10.635	2615	13725	61
mean				2780.4		67

B:

Mixture	size	area	mass(kg)	Density	load	compressive strength (MPa)
1	0.15*0.15*0.15	22500	8.235	2440	1395	62
2	0.15*0.15*0.15	22500	9.315	2760	1440	64
3	0.15*0.15*0.15	22500	10.425	3089	1575	70
mean				2763		65.3

C:

Mixture	size	area	mass(kg)	Density	load	compressive strength (MPa)
1	0.15*0.15*0.15	22500	8.573	2540	1642.5	73
2	0.15*0.15*0.15	22500	9.214	2730	1710	76
3	0.15*0.15*0.15	22500	10.06	2980	1912.5	85
mean				2750		78

D:

Mixture	size	area	mass(kg)	Density	load	compressive strength (MPa)
1	0.15*0.15*0.15	22500	8.61	2550	1305	58
2	0.15*0.15*0.15	22500	9.25	2740	1350	60
3	0.15*0.15*0.15	22500	9.619	2850	1530	68
mean				2713.3		62

Appendix A3. Density and Compressive Strength at 28 Days:

A:

Mixture	size	area	mass(kg)	Density	load	compressive strength(MPa)
1	0.15*0.15*0.15	22500	8.944	2448	1620	72
2	0.15*0.15*0.15	22500	9.079	3167	1665	74
3	0.15*0.15*0.15	22500	9.923	2615	1777.5	79
mean				2760		75

B:

Mixture	size	area	mass(kg)	Density	load	compressive strength (MPa)
1	0.15*0.15*0.15	22500	8.2	2430	1665	74
2	0.15*0.15*0.15	22500	9.38	2780	1822.5	81
3	0.15*0.15*0.15	22500	10.11	2995	1912.5	85
mean				2735		80

C:

Mixture	size	area	mass(kg)	Density	load	compressive strength (MPa)
1	0.15*0.15*0.15	22500	8.471	2510	1642.5	85
2	0.15*0.15*0.15	22500	8.978	2660	1710	86
3	0.15*0.15*0.15	22500	10.058	2980	1912.5	93
mean				2716.7		88

D:

Mixture	size	area	mass(kg)	Density	load	compressive strength (MPa)
1	0.15*0.15*0.15	22500	8.978	2660	1530	68
2	0.15*0.15*0.15	22500	8.816	2612	1620	72
3	0.15*0.15*0.15	22500	9.585	2840	1710	76
mean				2704		72

Appendix A4. Flexural Strength:

Mixture	Width (mm)	Depth (mm)	Length(mm)	load (KN)	Flexural (MPa)
A	100	100	50	22.08	14.06
B	100	100	50	26.79	17.06
C	100	100	50	30.33	19.31
D	100	100	50	34.56	22.3