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DEPARTMENT OF CIVIL AND CONSTRUCTION ENGINEERING

EVALUATING SUPERPLASTICIZER COMPATIBILITY WITH PORTLAND POZZOLANA CEMENT CEM II/B-P IN PRODUCTION OF HIGH PERFORMANCE CONCRETE

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DECLARATION

This Thesis is my original work and has not been presented for a degree in any other university:

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This Thesis has been submitted with our approval as university supervisors:

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Prof. David O. Koteng'

DEDICATION

This Research Project is dedicated to my mother, Justina and my late father, Augustinus both of whom, though certainly never saw the inside of a high school classroom, contended with all manner of hopelessness to make me what I am today.

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ABSTRACT

Portland Pozzolana Cement CEM II/B-P has potential advantages over Portland Cement CEM I when used to produce concrete. The incorporation of up to 35% natural pozzolana reduces the amount of clinker used in cement production, hence raw materials, CO_2 emission, and the energy demand. Moreover, the pozzolana reacts with $Ca(OH)_2$ produced by the hydration of Portland cement thereby mitigating alkali-aggregate reactions, destructive reactions with sulphates and acids, and carbonation shrinkage. In addition, additional C-S-H from the reaction of pozzolana and $Ca(OH)_2$ increases the long term strength and densification of the pore structure leading to improved durability. This research explores the effect of seven locally available superplasticizers in the production of free-flowing high performance concrete with a Portland pozzolana cement CEM II/B-P 32.5N. Compressive, flexural tensile, water absorption and electrical resistivity tests were also carried out on hardened concrete. Four Superplasticizers achieved high initial slump in excess of 200 mm on fresh concrete. However, workability reduced rapidly leading to stiffening within 30 minutes. Such concrete would not allow sufficient time for transportation, placement and finishing, and therefore has limited application. Cube crushing strength in excess of 60 MPa and good indications of durability were obtained at 28 days. In order to unlock the inherent benefits, further research on improving the flow retention of the concrete is necessary.

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ABBREVIATIONS

ACI …… American Concrete Institute

ASTM …….. American Society for Testing and Materials

BSI …….. British Standard Institution

BS EN ……. British Standard European Norm

$Ca(OH)_2$…. Calcium hydrogen oxide

CO_2 ……. Carbon dioxide

C-S-H ……. Calcium Silicate Hydrate

EAC …….. East African Community

FM …….. Fineness Modulus

GGBFS Ground-Granulated Blast Furnace Slag

HPC …….. High Performance Concrete

KS .... Kenya Standard

LOI .... Loss on ignition

MAS ……. Maximum Aggregate Size

MP ……. Modified Phosphonate

MPa ……. Megapascal

PC …….. Portland cement

PCE …….. Polycarboxylate Ether

PH …….. Potential of Hydrogen

PPC ……. Portland Pozzolana Cement

SF …….. Silica Fume

SMF …….. Sulfonated Melamine-formaldehyde

SNF …….. Sulfonated Naphthalene-formaldehyde

SP ……... SuperPlasticizer

UHPC …….. Ultra-high Performance Concrete

W/b ……. Water to Binder

1 INTRODUCTION

1.1 Background to the Study

Mitigation of the environmental impact of Portland cement receives great attention in the production of modern concrete. Of great concern is the high energy consumption in the production of Portland cement clinker and the high emission of CO_2 estimated at one ton for every ton of Portland cement produced. In addition, reduced durability of Portland cement concrete due to the reaction with sulphates, acids, atmospheric CO_2, and with some aggregates is of concern. These problems are largely resolved by replacing part of the Portland cement with a pozzolanic admixtures such as fly ash [1], and metakaolin [2], or the use of alternative binders, primarily geopolymers [3]. EN 197 CEM II/B-P replaces Portland cement clinker with up to 35 % natural pozzolana in the form of volcanic ash or sedimentary rocks.

Concrete is one of the materials that is extensively used in the construction industry. Sinha and Roy [4] observe that the study of concrete is a complete subject by itself and the quality of raw materials used in concrete works vary from one place to another. They argue that a satisfactory concrete is one that exhibits acceptable design properties such as workability, strength, water tightness and durability. According to Mosley et al [5], reinforced concrete is a strong and durable building material that can be formed into various shapes and sizes depending on the designs adopted.

Since its discovery, concrete has gained extensive use in the construction industry. There are three classifications of concrete, namely normal or conventional concrete (NC), high performance concrete (HPC), and ultra (or very) high performance concrete (UHPC), with various ranges of properties. For instance, according to Mehta & Monteiro [6], NC is classified as one having a cube compressive strength of less than 60 MPa at 28 days while HPC is of strengths ranging from 60 MPa to 125 MPa. UHPC is classified as having compressive strength more than 125MPa. HPC and UHPC are also free flowing in the fresh state with a good flowability retention for fast placement by pumping, and have enhanced durability.

The production and use of HPC locally will be a major departure from the common use of concrete of cylinder crushing grades 25, 30 and 35. Koteng' [7] points out that concrete structures in the East African region that are constructed using concrete of these normal grades hardly remain sound up to 20 years owing to deterioration occasioned by chemical attacks. The author cites the deterioration of concrete on Kamburu Dam on River Tana and the Kipevu Oil Terminal in Mombasa and suggests that these problems could have been mitigated through the use of HPC. On the other hand, Cheruiyot [8] argues for the use of high strength concrete in the construction industry in Kenya as this will improve the design and construction standards and is also cost effective in the long run.

Neville and Aitcim [9], point out that concrete of strength of 140 MPa can be routinely produced in some parts of the world. They further observe that the emphasis is now shifting from high strength to HPC. In the production and use of HPC, other properties, besides strength, are considered. These include modulus of elasticity, permeability, durability and resistance to various form of attack. Production of HPC generally require the inclusion of water reducing and strength enhancing materials into the mix which has resulted in a rise in the use of superplasticizers and silica fume (SF).

1.2 Statement of the Problem

Kenya and other East African countries still use a large proportion of concrete of low cube crushing strengths in the order of 25-40 MPa in construction works. This has led to the observed low performance of concrete structures characterized by low resistance to chemical and physical attacks. As a result, the costs of repairs, maintenance and replacement of deteriorated structures are high. Leakages in water containing and retaining structures have also been observed. Further, in designs where normal grade concrete is used, structural elements are of relatively bigger sizes and therefore wasteful on scarce materials. Depletion of sand and other aggregates is a major environment concern worldwide and is compounded by the design of massive structural elements associated with low concrete strengths.

From the above discussions, the construction industry needs to embrace the production and use of HPC. In order to produce high performance concrete, adequate knowledge of the properties and performances of individual ingredients making up the concrete is paramount. This study therefore sought to investigate the effect of superplasticizers on Portland cements intermixed with natural pozzolana in the production of HPC. Such cement is produced to KS EAS 18:2017 Standard and used locally as CEM II/B-P 32.5N Portland pozzolana cement.

1.3 Objectives

1.3.1 General Objectives

To investigate compatibility of superplasticizers with CEM II/B-P in the production of HPC.

1.3.2 Specific Objectives

(i) To investigate the compatibility of various superplasticizers with CEM II/B-P with respect to the workability and workability retention of HPC.

(ii) To investigate durability performance parameters of HPC produced with CEM II/B-P 32.5N.

1.4 Research Questions

(i) Which superplasticizer is the most compatible with CEM II/B-P with respect to HPC workability?

(ii) Can HPC of good durability be produced using CEM II/B-P manufactured by blending PC with locally available natural pozzolana?

1.5 Justification of the Study

The findings of this research will provide information on the potential of the different superplasticizers in the market in producing free-flowing, self-compacting concrete, and the use of natural pozzolana as a cement replacement material in the production of HPC.

1.6 Scope of the Study

The study sought to evaluate the effectiveness of seven super plasticizers in the production of HPC using CEM II/B-P. The effectiveness of the superplasticizers was investigated with respect to workability enhancement and workability retention. Thereafter, a concrete mix design was carried out to produce concrete with minimum compressive strength of 60 MPa at 28 days. Samples were prepared and tests for compressive and tensile strengths, water absorption and electrical resistivity were carried out on the hardened concrete.

1.7 Limitations of the Study

In order to control costs and time, the study focused on only seven super plasticizers and the CEM II/B-P 32.5N. Although there are many natural pozzolana blended cements in the country, the results of the study are reasonably indicative of what can be obtained using similar cements.

2 LITERATURE REVIEW

This chapter spells out theoretical and conceptual frameworks against which ingredient materials were selected, prepared, tested and used in production of the HPC. Properties of these materials and their influence on the performance of HPC are also discussed in this chapter. Further, the chapter highlights findings from other researchers that are handy in explaining observations made in the study.

2.1 History and Use of Concrete

Neville and Brooks [10] broadly define concrete as “any product or mass made by the use of a cementing medium and aggregates”. The cementing medium results from the reaction of cementitious material and water. The production and use of concrete in its various forms can be traced back to the ancient Egyptian, Greek and Roman civilizations. The Egyptians used impure gypsum as cementing material in construction works. The Greeks and the Romans used calcined limestone, sand, crushed stone and/or broken tiles to produce concrete. The Pantheon in Rome is one of the structures built using this ancient concrete.

The use of NC, which is still prevalent in many parts of the world, poses challenges to erection and maintenance of structures, and to the environment. Koteng’ [11] discusses problems encountered with the use of normal concrete citing cases in Kenya. These problems include reduced workability or high water content leading to low strengths of 25-35 MPa, high permeability leading to low resistance to sulphate and acid attacks, use of large structural elements leading to high consumption of cement and aggregates, and high costs of maintenance and repairs to deteriorated structures. The high consumption of cement associated with use of normal concrete leads to high production of cement clinker, thus more CO_2 is released to the atmosphere. CO_2 is an air pollutant and is also responsible for depletion of the ozone layer leading to adverse climate changes. Koteng’ suggests that these negative effects of NP can be mitigated by the production and use of HPC. On the other hand, Mondal and Banerjee [12] observe that conventional concrete is losing its uses to HPC. With concrete ingredients becoming scarce and therefore costly, economic usage of these materials is being embraced in the construction industry. Neville [13] is also of the view that production and use of HPC is bound to grow in the construction industry owing to its superior properties over those of normal concrete.

2.2 High Performance Concrete

According to Caldarone, et al [14], HPC "is concrete that is engineered to meet mechanical, durability or constructability properties that exceed those of normal concrete". Put in other words, "it attains special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing and curing practices" as stated in ACI 232.1R [15]. Neville [13] observes that production of HPC requires very strict and consistent quality control. For instance mix design, selection of ingredient materials, batching, and sequence of feeding and mixing of these materials require particular care to produce HPC of desirable properties.

2.3 Materials for Production of High Performance Concrete

The materials for production of HPC are basically cement, aggregates, water, and admixtures that include superplasticizers and cement replacement materials (CRM). The desired properties for these ingredient materials are briefly discussed hereunder.

2.3.1 Cement

According to Sinha and Roy [4] cement is "generally any material with adhesive and cohesive properties which make it capable of bonding mineral fragments into a solid mass of adequate strength and durability". This definition includes Portland cement and other cementing materials such as lime, tars and asphalts. Neville and Brooks [10] trace the use of cement to ancient Roman Empire which adopted the term hydraulic cement to signify its hardening effect when in contact with water. Portland cement (PC) however was discovered and patented by Joseph Aspdin in 1824. The main raw materials for the manufacture of PC are lime, silica, alumina and iron oxide with a little gypsum being added to control the setting of PC when water is introduced. Many types of cement are being produced for various purposes as given in BS EN 197-1:2011 [16]. These are grouped as CEM I, CEM II, CEM III, CEM IV and CEM V.

CEM I Portland Cements contains 95-100% clinker and are suitable where there is no exposure to sulphates while CEM II Portland-Composite Cements are a composite of clinker (65-94%) and other materials such as silica fume, fly ash, natural pozzolana, burnt shale and limestone in various proportions up to a total of 35%. CEM II cement may be made from clinker and only one of these materials. CEM III Blast Furnace Cements are made from clinker (5-64%) and ground-granulated blast furnace slag (GGBFS) (35-95%). GGBFS cements are suitable for use in concrete where protection against sulphate and chloride attacks is required. CEM IV Pozzolanic Cements are made from clinker (45-89 %) and pozzolana (11-55%) and are characterized by low heat of hydration and slow development of strength, though the ultimate strength is not affected. They are suitable for use in large structures and gravity dams. CEM V Composite Cements are made from clinker (20-64%), ground-granulated blast furnace slag (18-31%) and pozzolana (18-31%). They are characterized by low heat of hydration and good resistance to sulphate and chloride attacks.

In Kenya CEM II cement is largely manufactured as CEM II /B-P Portland Pozzolana Cement (PPC) incorporating 21-35 % natural pozzolana and is extensively used in the construction industry. ACI 232.1R [15] defines pozzolan as "a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties".

Abdullahi [17] observes that PPC has gained extensive usage in the construction industry owing to its numerous advantages over Portland cement. These advantages include higher long term strength resulting from continued hydration; reduced heat of hydration; and improved resistance to chemical attack; low permeability and reduced rate of water evaporation owing to the presence of fine pozzolana particles leading to less bleeding, reduced shrinkage and creep. The presence of fine pozzolana particles also improves cohesion of the cement by filling in the spaces between PC particles.

2.3.2 Aggregates

In the production of HPC, selection of aggregates requires utmost attention. Aggregate size and other properties such as shape, mineralogy, surface texture and cleanness have great contribution towards its suitability for production of HPC. Kozul and Darwin [18] found that compressive and flexural strengths are affected by the type, content and crushing strength of aggregates used. On the other hand, Abdullahi [17] concluded that workability of concrete is affected by the type of aggregates, with the river sand producing concrete of higher workability than that produced using crushed quartzite and crushed granite aggregates. Porosity of concrete is influenced by the pore structure of the aggregates used. This also has a bearing on the amount of water to be added to achieve the desired w/b ratio since part of this water is absorbed by the aggregates to reach saturation state. Bulk density of aggregates (loose or compacted) determines the volume of mortar required to fill the spaces between the aggregate particles. As such suitable particle size distribution, fineness modulus and maximum aggregate size (MAS) are critical requirements. In addition, Neville [13] points out that aggregates should be free from deleterious substances and organic impurities as these affect the process of hydration, prevent development of bond between cement and aggregate particles, and may contain sulphates and chlorides that affect concrete durability. It is also desirous to use aggregates that are free from salt contamination as this can cause corrosion of steel and efflorescence in concrete.

2.3.3 Water

Water is a very vital constituent in concrete production as it chemically reacts with cementitious materials to produce a binding paste of desired properties. "The suitability of water for the production of concrete depends on its origin" (EN 1008:2002) [19]. This Standard classifies types of water that may be used in concrete production and their suitability. For instance, potable water is suitable for use in concrete and the same does not need any testing to establish its suitability in this regard. Neville and Brooks [10] state that water which is suitable for use in the production of concrete is also suitable for curing of concrete. On the other hand, Kucche et al [20] concluded that the degree and rate of corrosion of steel increases with a decrease of the pH of water used in concrete production, and so does reductions in compressive and split tensile strengths of concrete. Similarly, a study carried out by More and Dubey [21] reveal that the use of ground water reduces compressive strength of concrete by up to 10%.

Since the extent of cement hydration depends on the amount of water that comes into contact with cementitious material, the quantity of water in the concrete mix must be controlled to achieve the desired properties such as slump, strength and durability of the concrete. As Kumar, et al [22] found, a reduction in w/b ratio causes an increase in compressive strength of concrete. A study carried out by Shamsai et al [23] confirmed a similar correlation between w/b ratio and abrasive strength, with the latter increasing with reduction in the w/b ratio.

2.3.4 Silica Fume

According to ACI 116R [24], SF is a "very fine non-crystalline silica produced in electric arc furnaces as a by-product of the production of elemental silicon or alloys containing silicon". It is ordinarily gray or black in colour depending on whether the material contains some carbon. As Neville [13] observes, SF has extremely fine particles and very high specific surface in the order of 20,000 m^2/kg in comparison with cement whose specific surface is less than 1,000 m^2/kg. This high specific surface makes the material very reactive. In addition, Xu, et al [25] explain that pozzolanic reaction between SF and $Ca(OH)_2$, released in the cement hydration process, produces additional calcium silicate hydrate gel that improves the microstructure of the cement paste. This enhances bonding of ingredient materials and strength of HPC. Since $Ca(OH)_2$ is susceptible to acid attacks, its reduction in the pozzolanic reaction makes HPC less susceptible to the acid attacks. It is also observed that the extremely small particles of SF enter into the spaces between cement particles, thus improving the density of the cement paste and lowers the porosity, hence permeability of HPC.

The Silica Fume Association Users' Manual [26] points out that SF is highly reactive and is usually used in very small quantities with great enhancement properties of concrete. The Manual further spells out guidelines and procedures for proportioning and handling of silica fume in concrete production. On the other hand, Ghudtke and Bhandari [27] found that an optimum value of 28-day compressive strength was achieved with 5-15% replacements of PC with SF. The authors found that replacement of PC beyond 15% resulted in a decrease of compressive strength. Their experiment, however, concluded that workability decreases with increase in the content of SF since the latter has very fine particles that require more water. Similarly, a study by Amudhavalli and Mathew [28] showed that minimum loss of concrete weight and compressive strength due to acid attack occurred at 10% replacement of PC with silica fume. Both of these studies were carried out using PC. When PPC is used in concrete production, the inclusion of silica fume may not produce similar results due to the pozzolan already available in the cement.

2.3.5 Superplasticizers

According to Neville [13], superplasticizers (SPs) are high-range water reducing admixtures. They are water-soluble organic polymers mainly sodium and calcium salts, though the latter are less soluble. Their molecules are long and of high molecular mass resulting from complex polymerization processes. SPs can also be modified by adding copolymers to conventional molecular structures to enhance performance. For specific desired performance, their characteristics can be optimized with respect to the length of the molecules and cross-links. It is advisable that the content of sodium salts be kept within the recommended limits since these salts may interfere with cement hydration and also ignite alkali-silica reaction. On the other hand, the content of impurities should be low to ensure effective performance and reduce harmful side effects.

The four main categories of superplasticizers are sulfonated melamine-formaldehyde condensates (SMF), sulfonated naphthalene-formaldehyde condensates (SNF), modified lignosulfonates (ML), and sulfonic-acid esters and carbohydrate esters. This last category includes polycarboxylate ether (PCE) which has gained remarkable interest in concrete production owing to its enhanced performance. PCE generally have comb-like molecular structure that is responsible for superior dispersion of cement particles while the other three have linear molecular structures. Figures 2.1-2.3 from Rixom and Maivaganam [29] and Figure 2.4 from Sun et al [30] below show molecular structures for SMF, SNF, ML, and PCE. According to Qian and Schutter [31], PCE acts through both electrostatic repulsion as the cement particles become negatively charged and steric repulsion between its non-adsorbing side chains while the other SPs disperse cement particles only by electrostatic repulsion.

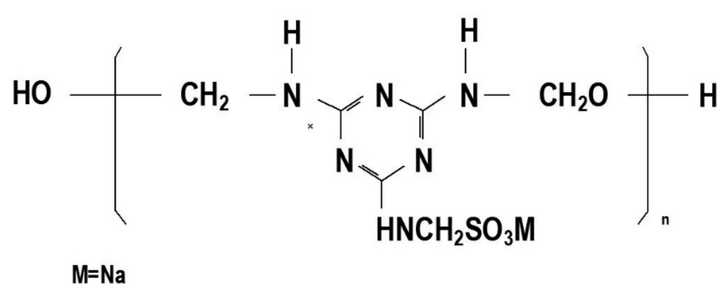

Figure 2.1: SMF Molecular Structure [29]

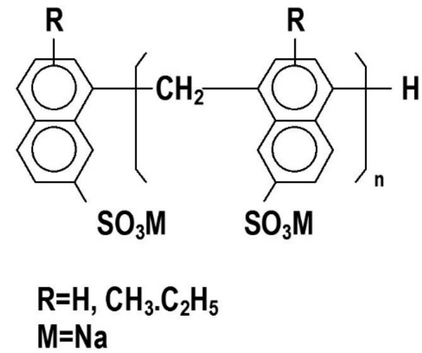

Figure 2.2: SNF Molecular Structure [29]

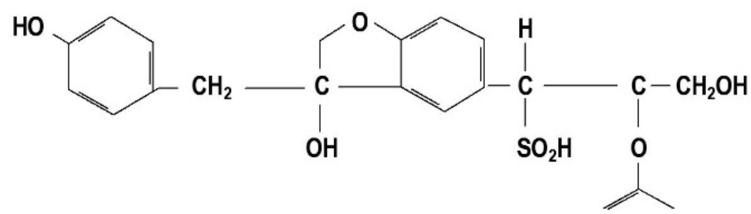

Figure 2.3: ML Molecular Structure [29]

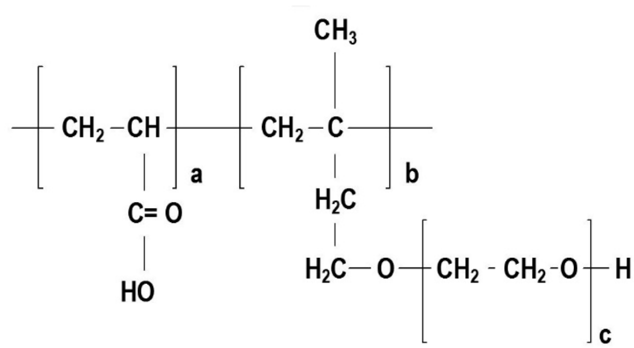

Figure 2.4: PCE Molecular Structure [30]

Neville [13] explains that SP molecules wrap themselves around cement particles and produce high negative charges leading to repulsion of the particles. This repulsion results in deflocculation and dispersion of cement particles, thus high workability with slump between 75-200mm. With the use of SP, concrete of low w/b ratio can be produced with good workability which leads to high strength. SP can reduce w/b ratio by 25-35% with the 24-hour strength increasing by 50-75%. Also high workability with better distribution of cement particles result in better hydration process.

SP has various effects on the fresh and hardened concrete properties. For instance, Malagavelli and Paturu [32] found that workability and compressive strength increase with the use of SP. On the other hand, Krizova and Novosad [33] found that w/b ratio of between 0.25 and 0.60 can be used to achieve high workability depending on the type of SP added to the concrete. However, Eckert and Carrasquillo [34] pointed out that SP can also create serious problems in concrete if not applied or handled properly. The problems include bleeding, segregation. and loss of workability. Compatibility between cement and SP should be established as this has critical effect on slump retention. The chemical composition of cement has been found to affect the performance of SP. For instance, a high content of tricalcium aluminate (C_3A) reduces the effectiveness of SP. The nature of retarders used in the concrete may also affect the performance of SP.

SP is usually added during mixing of concrete and according to Khadiranaikar [35], there is no stipulated means of determining the required dosage of superplasticizers, but rather a trial and error method can be adopted. Finer cementitious materials require higher dosages of SP for a given workability and vice versa. In their study on compatibility of two brands of SP with PPC, Shrivastava and Kumar [36] found the optimum dosage for the two brands of SP to be 0.9 % and 1.1% of the weight of cement respectively. In summary, a suitable combination of cement and SP dosage that gives desirable performance can only be determined experimentally. They further observed that in as much as SPs are manufactured in compliance with respective standards, their performance is not the same even if the quality and other ingredients of concrete are the same. This holds true even where SPs are of the same chemical family since the performance is influenced by the length of the backbone and side chains in their molecular structures.

2.4 Properties of High Performance Concrete

2.4.1 Workability

Neville [13] defines workability as "the amount of useful internal work necessary to produce full compaction in fresh concrete". He argues that this definition of workability goes beyond that which considers only the ease of placement and resistance to segregation of concrete. He further points out that the major factor affecting workability is water content, especially in non-air-entrained concrete. Workability is also influenced by w/b ratio, with the higher the latter the higher the workability. However, for fixed water content and mix proportions, workability is affected by the maximum aggregate size, grading, shape and texture of aggregates.

In the production of HPC, w/b ratio is usually kept to the lowest level for high strength achievement. This reduction in w/b ratio leads to low workability, therefore to counter this effect, superplasticizers are used in the production of HPC. Malagavelli and Paturu [32] observed that workability increases with the uses of superplasticizers and when used in the right quantity, superplasticizers become handy in slump retention. In other words, they can retard the loss of slump. Chang [37] stated that concrete that does not have a good workability is not HPC. KS EAS 18-1 [38] requires CEM II cements to have initial setting time of more than 75 minutes and the use of SP is expected to extend this initial setting time further. On the other hand, Laskar [39] observes that a minimum slump of 100 mm together with a good workability retention is necessary for for HPC.

2.4.2 Compressive and Flexural Tensile Strengths

One of the reasons why HPC is gaining ground in the construction industry is its higher compressive strength and tensile strengths compared to those for ordinary concrete. Durai et al [40] found that with the use of property enhancers like SF, coupled with lower w/b ratio, these high strengths can be developed at a higher rate. A study by Goyal et al [41] in which PC was replacement with SF of varying quantities resulted in an increase in compressive strength of concrete due to the formation of secondary C-S-H from pozzolanic reaction between SF and $Ca(OH)_2$ released from cement hydration process. They suggest that specifying concrete in terms of its 28-day strength underestimates the benefits of pozzolanic reactions in blended cements.

While observing in their study that pozzolanic reaction began immediately after cement hydration, Osei and Jackson [42] established that replacing cement with pozzolana beyond the optimum quantity resulted in a decrease in the strength of concrete. A research by Tushir et al [43] in which rice husk ash was used as a pozzolana in partial replacement of cement recorded a significant increase in flexural strength of concrete. On the other hand, Amankwah et al [44] found that partially replacing PC with calcined clay pozzolanas improved compressive and flexural strengths, notably at ages beyond 28 days. They also observed that flexural strength increased as compressive strength increased, and vice versa.

2.4.3 Durability

BS 8110 [45] defines a durable concrete element as "one that is designed and constructed to protect embedded metal from corrosion; and to perform satisfactorily in the working environment for the life-time of the structure". Merida and Kharchi [46] found that the loss of strength in NC was three times more than that in HPC when specimens made from these concretes were kept in aggressive sulphate solution for one year. Reddy et al [47] observe that the addition of supplementary cementing materials such as fly ash, SF and blast furnace slag to concrete improves its long-term durability. Two tests are mainly used in evaluating durability of concrete-water absorption and chloride ion penetration. Chloride ion penetration can also be assessed by electrical resistivity tests.

According to Castro et al [48], water absorption test is used to assess the durability of a cementitious system in concrete, and the absorption is influenced by the pores and connectivity of the pore network in the concrete structure. They observe that relative humidity within the concrete structure affects the extent and rate of absorption. While acknowledging that drying the test specimens to 105^{o}C removes water from concrete pores, they point out that this exercise has a potential for causing micro-cracking within the structure, especially if extended beyond the stipulated time and due care is not taken when cooling the samples.

Kurda et al [49] define electrical resistivity as the ratio between the applied voltage and the electric current that flows through a test specimen. In other words, it is the resistance of materials to the electric current passage. It is used to assess risks to chemical attacks to reinforcement steel embedded in concrete. Electrical resistivity is influenced by factors such as aggregate content, binder type, humidity, w/b ratio and age of concrete specimen. The presence of supplementary cementitious materials such as SF in concrete increases its electrical resistivity.

2.5 Mix Design for HPC

Neville [13] points out the appropriate selection of ingredients is paramount in order to produce concrete that meets some required properties. Production and placement costs should also be minimized in the process and as such various aspects should be given critical considerations. For instance, the design should consider minimum properties – workability with slump in excess of 100 mm and slump retention beyond 60 minutes, enhanced compressive strength in excess of 60 MPa and corresponding tensile strength and enhanced durability characterized with very low chloride ion (Cl^-) penetration [6] [13] [37] [39] [50]. Other aspects include economy of production and placing of concrete, costs of quality control, and materials, plant, equipment and labour.

There is no generalized mix design approach for HPC. This is because each structure may require specific concrete properties. Another factor that makes generalized mix design difficult is the influence of other cementitious materials coupled with cement-SP compatibility challenges. In as much as available standards and guidelines on mix designs may be used, experimental approach or trial mixes will complement this process. Adjustments to mix proportions are usually made to achieve the required concrete properties. Yathish [51] lists the data required for mix design to include concrete grade designation; workability (slump) requirement, type of cement to be used, maximum nominal size of aggregate, cement content, content of other cementitious material, water-binder ratio, content of admixtures such as SP, exposure conditions, and method of transportation and placing of concrete.

ACI 211.4R [52] spells out "guidelines for selecting proportions (mix design) for high strength concrete using PC and other cementitious materials". With some adjustments to the proportions of materials, these guidelines can be used for the mix design of HPC using PPC. By contrast, Building Research Establishment (BRE) [53] guidelines are for normal concrete mix designs using cements of strength designations 42.5 MPa and 52.5 MPa as opposed to PPC whose strength designation is 32.5 MPa.

2.6 Summary of the Review and Research Gap

Findings of the previous researchers and other literature reviewed provided necessary information required for investigating the subject matter and meeting of the study objectives. This included discussions on the desired properties of the ingredient materials used in the production of HPC and how these properties affect the performance of HPC. It also spelt out the expected properties of HPC that guarantee long term strength and durability of concrete structures.

The studies undertaken on HPC produced using local materials are limited to CEM I cement. For instance, Cheruiyot [8] investigated the use of stone dust in the production of HPC with a cube crushing strength in the order of 80 MPa. He used Portland Cement CEM I 42.5R and a PCE superplasticizer. His study concluded that locally available stone dust can be used as fine aggregate in the production of HPC. No other local research on HPC could be found. While CEM II/B-P 32.5N cement is extensively used in the production of NC, its use in the production of HPC has not been documented. Moreover, its compatibility with SPs in the local market has not been published. This research attempts to bridge that gap.

2.7 Production of HPC - Conceptual Framework

For ease of visualization, production of HPC is presented in the conceptual framework below.

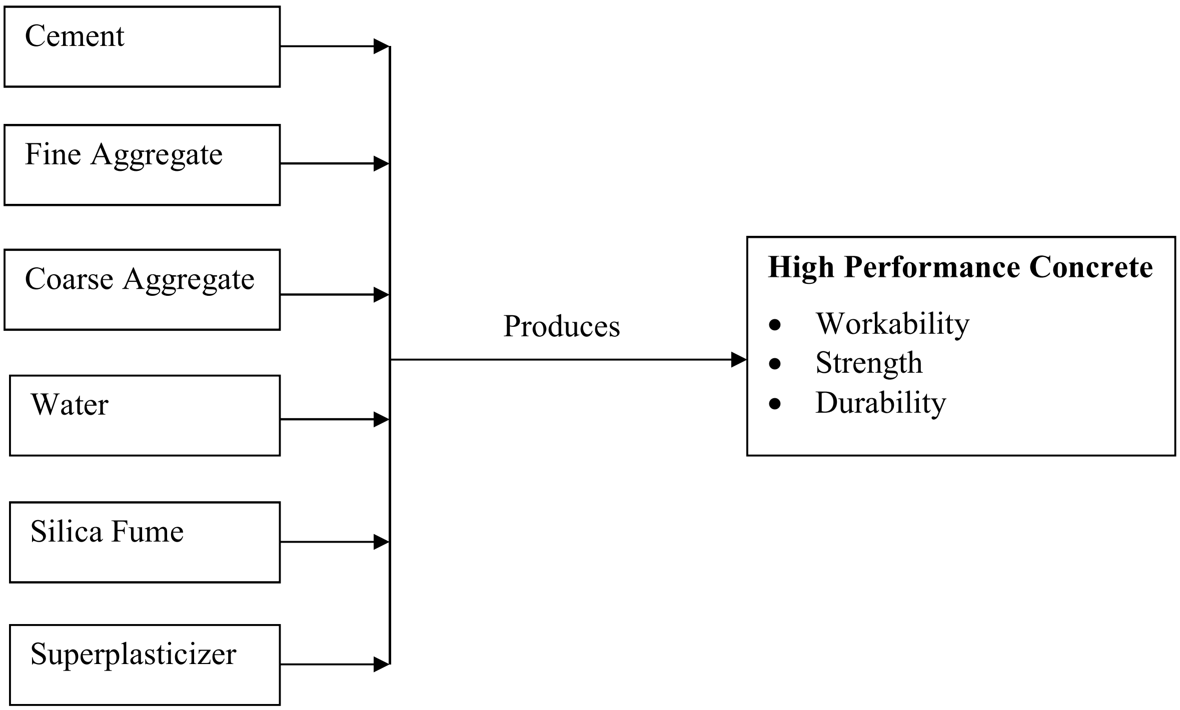

Figure 2.5: Production of HPC - Conceptual Framework

3 MATERIALS AND METHODOLOGY

This chapter presents details of the research design used to achieve the objectives of the study, It discusses how the ingredient materials were sourced, prepared and tested to determine their suitability for the production of HPC. It also describes how the test samples were prepared and handled, including the equipment used at every stage. Further, it guides on data collection and presentation for ease of analysis.

3.1 Materials

The materials used in the study were PPC CEM II/B-P 32.5N manufactured in Nairobi to KS EAS 18-1:2017, river sand of fineness modulus (FM) 2.67 from Machakos County, natural crushed coarse aggregate of maximum aggregate size (MAS) of 12.5mm from a quarry in Mlolongo Machakos County , silica fume grade NR95D imported from China, seven different superplasticizers SP1 to SP7 available locally (Table 3.1), and potable tap water from the Nairobi City mains.

Table 3.1: Superplasticizers

Superplasticizer Identity	Superplasticizer Type	Superplasticizer Brand Name	Recommended Dosage (%)	Manufacturer Dealer
SP1	PCE	Sika Viscocrete 3088	0.4 – 2.0	Sika Chemical Kenya Limited
SP2	PCE	Sika Viscoflow 615 KE	0.2 - 2.0	Sika Chemical Kenya Limited
SP3	SMF	Rheobuild 2000M (BASF)	1.0 - 1.5	BASF East Africa Limited
SP4	SNF	Sikament NNG KE	0.4 - 3.0	Sika Chemical Kenya Limited
SP5	MP	Chryso Optima 100	0.3-5.0	Chryso Eastern Africa
SP6	PCE	Chryso Optima ME40	0.5-2.5	Chryso Eastern Africa
SP7	SNF	Chryso Fluid L	0.6-2.0	Chryso Eastern Africa

3.2 Preparation and Preliminary Tests on Materials

3.2.1 Cement

The chemical properties of cement were tested at the Kenya State Department of Mining laboratory in Nairobi in accordance with KS EAS 148 [54].

3.2.2 Fine Aggregate

Fine aggregate was oven dried at 105^{o}C for 24 hours to remove entrained moisture and sieve analysis was carried out to ASTM C33 [55] at the Technical University of Kenya Concrete Laboratory. Other tests that include bulk density, relative density, water absorption and Organic matter content were also carried out at the Materials Branch Laboratory to determine the suitability of the aggregate in accordance with the requirements of Kenyan Standard KS 95 [56].

3.2.3 Coarse Aggregate

Coarse aggregates were oven-dried at 105^{o}C for 24 hours to remove entrained moisture. The aggregates were then sieved and blended in the ratios of 70%, 10% and 20% for sizes 12.5mm, 9.5mm and 6.3mm respectively to fall within the limits specified by ASTM C33 [55] at the Technical University of Kenya Concrete Laboratory. Other tests that bulk density, relative density, water absorption, Elongation Index, Flakiness Index, Aggregate Crushing Value, Los Angeles Abrasion, Aggregate Impact Value and Sodium Sulphate Soundness were also carried out at the Materials Branch Laboratory to determine the suitability of the aggregate in accordance with the requirements of Kenyan Standard KS 95 [56].

3.2.4 Silica Fume

Chemical tests on silica fume were carried out at the Kenya State Department of Mining laboratory in Nairobi in accordance with KS EAS 148.

3.3 Mix Design

Mix design was carried out to American Concrete Institute Guidelines, ACI 211.4R-08 for high-strength concrete produced using conventional materials and production methods. Since the PPC used in the study contained NP, the lowest partial replacement limitation of 5 % was used for SF. The specified 28 days compressive cube strength for the HPC was 60 MPa (50 MPa cylinder crushing strength). The quantities of materials for 1 m^3 of concrete were as presented in Table 3.1. Mix 2 contained 5% SF as partial replacement of the cement.

Table 3.2: Quantities of Materials for 1m^3 of Concrete

Mix	Coarse aggregate (kg)	Fine aggregate (kg)	Cement (kg)	Silica fume (kg)	Water + SP (kg)
1	1,065	412	648	-	194
2	1,065	412	616	32	194

3.4 Determination of Superplasticizer Compatibility

3.4.1 Preparation of Concrete

Several concrete batches were made using mix 1 with each of the seven SPs. A 0.20 m^3 capacity paddle mixer was used to prepare the concrete. Proportions of each material for enough concrete to fill a cone of bottom diameter 200 mm, top diameter 100 mm, and height 300 mm were measured to 1g accuracy using a digital scale. Water was added to the paddle mixer together with some SP and mixed to disperse the SP. Cement was then added and mixing carried out to produce a uniform paste. Fine aggregate was then added and mixing continued to produce a uniform mortar. Lastly coarse aggregate was added to the mortar and mixing continued to obtain concrete of uniform consistency. SP was added throughout the mixing process to maintain high workability without segregation.

3.4.2 Measurement of Slump and Slump Flow

The freshly prepared concrete was used to determine the initial slump and slump flow in accordance with BS EN 12350-2 [57]. The concrete was then returned to the mixer and mixing continued and new slump was determined at 30 minute intervals. Similarly, slump flows were measured to BS EN 12350-8 [58]. The slump and slump flow for each of the SPs were recorded and presented in a table for analysis.

3.4.3 Analysis of Slump and Slump Flow

The slump and slump flow were analyzed in accordance with ACI 211.4R-08 and findings of relevant previous researches to determine the most compatible SP to be used in the production of HPC. Further, the performance of SPs were observed and explained accordingly.

3.5 Determination of Properties of High Performance Concrete

3.5.1 Preparation and Curing of Test Samples

SP1 was used in the preparation of all test samples owing to its low dosage and the highest initial slump. Proportions of all materials enough to make one mixer load of concrete mix 1 were measured out to 1g accuracy. Concrete was made as described in Clause 3.4 and was immediately used to make 100 x 100 x 100 mm cubes. In total 24 cubes were made, 3 No. each to be tested for compressive strength at 3, 7, 14, 28, 56 and 90 days, and for water absorption and electrical resistivity at 28 days. In addition, 3 No. prisms of size 100 x 100 x 500 mm were made to be tested for flexural strength at 28 days. The process was repeated for mix 2. All samples were covered with moistened paper and left to stand overnight. The next day all samples were demolded and placed in saturated lime water in covered curing tanks until the time of testing. Saturated lime water was used for curing as a precaution against any leaching of lime in concrete by the curing water in accordance with BS1881-111 [59].

3.5.2 Compressive Strength

One hour prior to testing, the concrete cubes were removed from the saturated lime water, dried using absorbent cloth and then left to dry in the open at room temperature. 3 No. cubes of a specified age were then successively placed on the testing machine, one at a time, and load was applied at a constant rate of 30-40 kN per minute to failure in accordance with BS EN 12390-3 [60]. The maximum load at failure was recorded for each of the cubes and the average of the three readings was taken as the failure load. This average load was used to calculate the compressive strength of concrete. A graph of compressive strength against age of the concrete was plotted.

3.5.3 Flexural Tensile Strength

The prisms were removed from the saturated lime water at the age of 28 days, dried using absorbent cloth and then left to dry in the open at room temperature for one hour. 3No. prisms made from mix 1 concrete were then successively placed on the testing machine, one at a time, as shown in Figure 3.1 and diagrammatically in Figure 3.2, and load was applied at a constant rate of 30-40 kN per minute to failure in accordance with BS EN 12390-5 [61]. The maximum load at failure was recorded for each of the prisms. The average of the three loads was taken as the failure load and was used to calculate the flexural tensile strength. The position and mode of failure were noted to confirm conformity of the loading condition to the *Four Point Load Flexural Test (FPFL).*

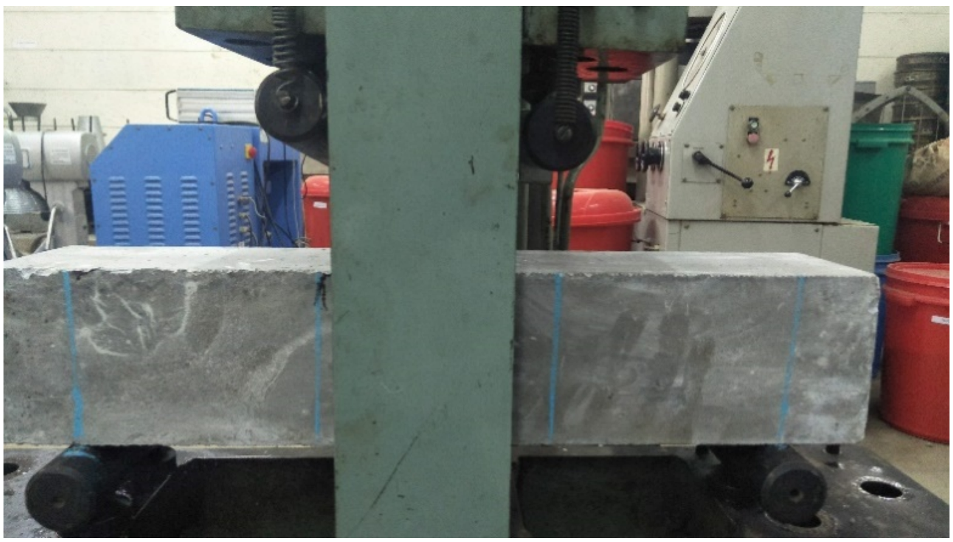

Figure 3.1: Prism on Testing Machine

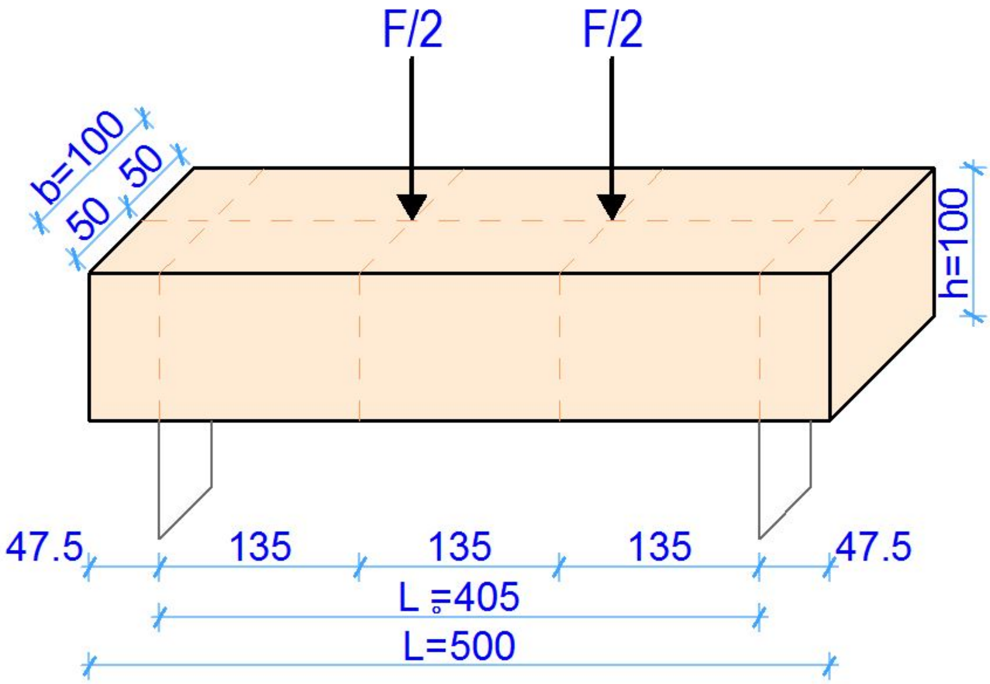

Figure 3.2: Four Point Load Flexural Test

With reference to Arya [62], flexural strength was calculated as shown in Equation 3.1.

$$f_{ctm,fl} = \frac{FL_o}{bh^2}$$ **Equation 3.1**

On the other hand, EN 2 [63] estimates flexural strength of concrete beam as in Equations 3.2-3.4.

$$f_{ctm,fl} = (1.6 - h/1000)f_{ctm}$$ **Equation 3.2**

$$f_{ctm} = 0.3f_{ck}^{2/3}$$ **Equation 3.3**

$$f_{ck} = 1.2f_{cu}$$ **Equation 3.4**

where

$f_{ctm,fl}$ is the flexural strength of the beam

F is the maximum load at failure

L_o is the distance between supports

b is the width of the beam

h is the depth of the beam

f_{ctm} is the mean tensile strength of concrete

f_{ck} is the characteristic cylinder strength of concrete

f_{cu} is the characteristic cube strength of concrete

3.5.4 Water Absorption

At the age 28 days, the test samples for Mix 1 and Mix 2 were removed from the saturated lime water and their surfaces dried using absorbent cloth. They were then placed in the oven and dried at 105^{o}C for 72 hours to remove entrained free water. The oven was thereafter switched off, its vents sealed to prevent entry of moisture and the samples were left to cool inside the oven for 24 hours. After cooling, the samples were removed, each weighed and then totally immersed in a bucket of distilled water for 10 minutes. At the end of 10 minutes of immersion, the samples were removed from the bucket, dried with absorbent cloth and each weighed to determine the amount of water absorbed within this period of immersion. They were returned into the bucket for additional 20 minutes, then removed, dried with the absorbent cloth and weighed to determine the amount of water absorbed within the cumulative immersion period of 30 minutes. The same process was repeated to determine the amount of water absorbed at cumulative immersion periods of 60 and 120 minutes. A graph of water absorption against cumulative period of immersion was plotted for the two mixes and comparison of the results made to evaluate the effect of SF on water absorption in accordance with BS 1881-122:2011 [64].

3.5.5 Electrical Resistivity

The test samples were removed from the saturated lime water at the age of 28 days, dried using absorbent cloth and then left to dry in the open at room temperature for one hour. Two holes each of 10mm diameter and positioned 100mm apart were drilled into the concrete to a depth of 20mm. The holes were filled with Potassium Chloride (an electrolyte). The electrodes of the Resistivity Meter (RM) were inserted into the holes and the RM was switched on to trigger electrolysis and flow of electric current through the concrete. Resistivity to the flow of the electric current through the sample was read from the RM and recorded for each sample. These results were interpreted and durability of the concrete assessed in according with AASHTO TP 95 [50]. Figure 3.3 shows electrical resistivity test in progress.

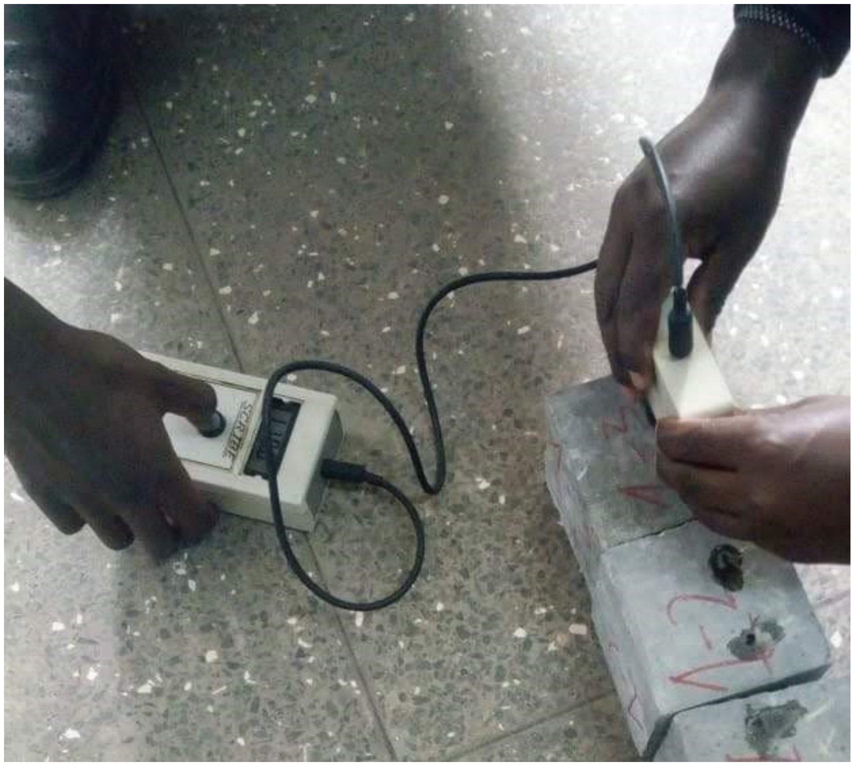

Figure 3.3: Electrical resistivity test in progress

4 RESULTS AND DISCUSSIONS

This chapter presents results of the tests carried out on ingredient materials and other parameters that assess the performance of HPC. These include workability, compressive and flexural tensile strengths, water absorption and electrical resistivity. It also puts forward scientific explanations for the results.

4.1 Material Properties

4.1.1 Cement

Relative density of the cement CEM II/B-P used in the study was determined to be 2.66. The chemical composition of the cement is as shown in Table 4.1.

Table 4.1: Chemical Composition of CEM II/B-P Cement

Element name	Al_2O_3	SiO_2	S	K_2O	CaO	Fe	Others	LOI
Content (%)	4.614	33.002	2.567	2.328	51.219	4.782	1.488	5.480

From the table above, natural pozzolana that typically exists as SiO_2 constitutes 33% of the cement and this is within the upper limit of 35% allowable in KS EAS 18-1 [38]. The SiO_2 reacts with $Ca(OH)_2$ released from hydration of calcium silicate to produce additional calcium silicate hydrate (C-S-H), the gel that binds aggregates together. This in effect increases concrete strength and also densifies the pore structure, hence reduces permeability.

Sulfate content in the cement was found to be 2.57% which is lower than the maximum allowable limit of 3.5% specified by KS EAS 18-1. Sulfate which exists in the form of gypsum ($CaSO_4.2H_2O$) or hemihydrate ($CaSO_4.½H_2O$) or anhydrite ($CaSO_4$) or any mixture of these is added to cement during its manufacture to control setting thereof. The cement did not contain significant quantity of chlorides. If their contents in cement are not kept within acceptable limits, sulfates and chlorides attack reinforcement steel used in concrete structures.

KS EAS 18-1 does not specify the maximum limit of LOI for CEM II. However, it is observed that LOI of 5.48% is higher than the allowable maximum of 5% for CEM I. LOI is a generally accepted test to estimate organic carbon content in cement. High content of organic carbon lowers workability owing to increase in water demand and adsorption of SP onto carbon particles. Furthermore, organic carbon particles come between the C-S-H gel and the aggregates and consequently lower the bonding and strength of concrete.

4.1.2 Fine Aggregate

The sieve analysis results are shown in Figure 4.1. Properties of the aggregates were also determined as shown in Table 4.2.

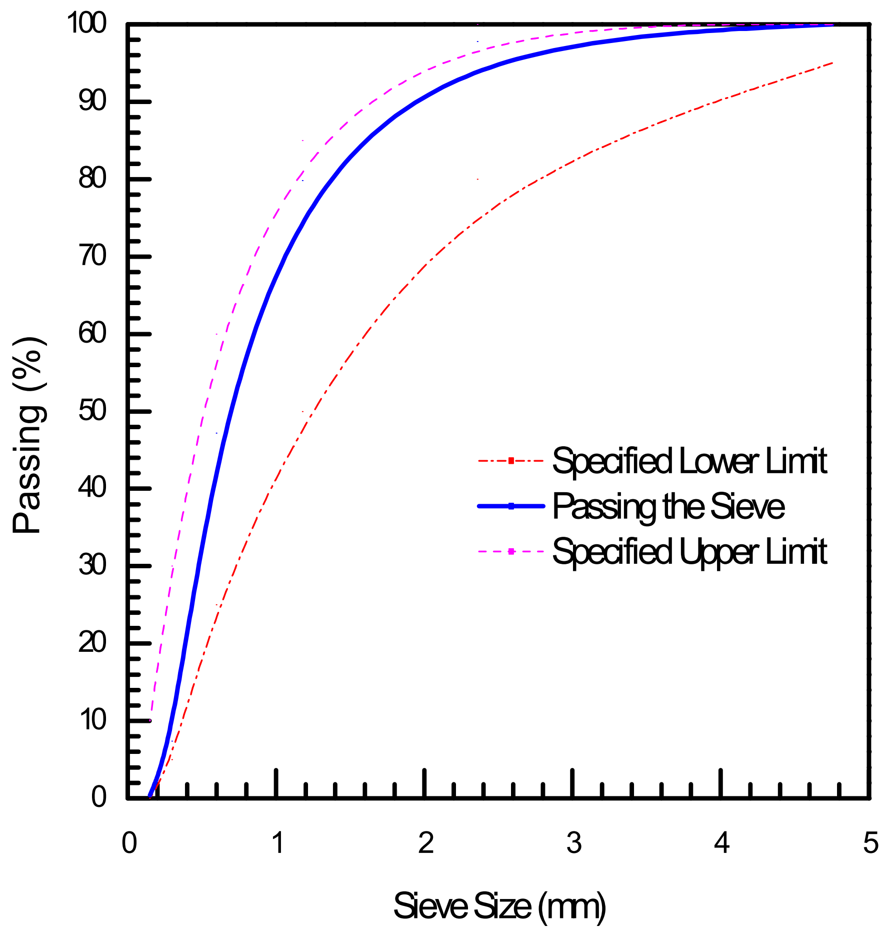

Figure 4.1: Fine Aggregate Sieve Analysis

Table 4.2: Properties of Fine Aggregate

Fineness Modulus (FM)	Bulk Density	Relative Density	Water Absorption	Organic matter Content
2.67	1,602Kg/m^3	2.63	1.37%	0.024%

The Fineness Modulus (FM) of 2.67 was found to be within the ACI 211.4R-08 [52] specified range of 2.5-3.2. However, the material fell more on the finer side of the grading curve and this increases the water demand and lowers workability owing to high specific surface. Also a high dosage of SP is required to enhance fluidity and cohesiveness of concrete. On the other hand, finer aggregate improves the packing of concrete pore structure and therefore reduces permeability.

The KS 95 [56] does not specify limits for shell content in aggregates finer than 5mm, neither does it specify requirements for clay owing to unavailability of test locally to determine the clay content. The organic matter content was determined to be 0.024% which is negligible and therefore cannot cause significant adverse effect on the quality of concrete.

Relative Density of 1602 is within the recommended range of 1400-1900Kg/m^3 for sand in accordance with BS EN 1991-1-1 [65] and the material was therefore suitable for production of concrete of acceptable density and rheology. The water Absorption was factored in the determination of the quantities of the water for mixing the concrete and absorption by aggregates to reach saturation state [17].

4.1.3 Coarse Aggregate

The sieve analysis results are shown in Figure 4.2. Properties of the aggregates were also determined as shown in Table 4.3.

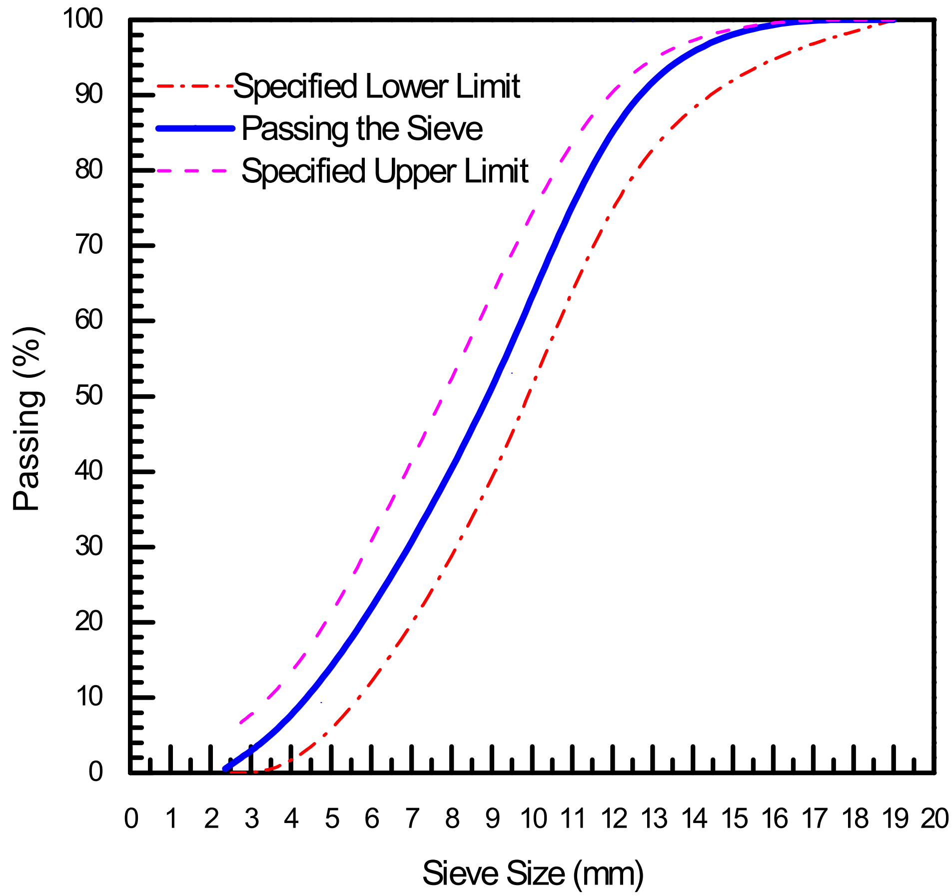

Figure 4.2: Coarse Aggregate Sieve Analysis

Table 4.3: Properties of Coarse Aggregate

Bulk density (kg/m^3)	Relative density (kg/m^3)	Water absorption (%)	EI (%)	FI (%)	ACV (%)	LAA (%)	AIV (%)	SSS (%)
1,527	2.50	2.90	18.4	14.1	17.3	14.6	17.0	0.61

Note
EI = elongation index, FI = flakiness index, ACV = Aggregate Crushing Value, LAA = Los Angeles Abrasion, AIV = Aggregate Impact Value, SSS = Sodium Sulphate Soundness

A well graded coarse aggregate enhances interlocking between the aggregates, compaction and pore structure of concrete [17]. KS 95 [56] does not specify limits for Elongation Index (EI), Aggregate Crushing Values (ACV), Los Angeles Abrasion (LAA) and Sodium Sulphate Soundness (SSS). Neville [13] observes that there is no recognized limits for EI. The FI of

14.1% is lower than the KS 95 [56] specified maximum limit of 40%, thus implying the aggregates are fairly rounded. Round aggregate improves workability of concrete. ACV is only useful when dealing with aggregates whose performance is unknown, particularly when the aggregate is suspected to be of lower strength. Since AIV is a measure of toughness, the material that meets the specified requirements for AIV will also reasonably satisfy requirements for crushing and abrasion properties.

AIV of 17.0% is lower than the KS 95 [56] specified maximum limit of 45% and the aggregate is suitable to produce HPC. Tijani et al [66] concluded that aggregates of high mechanical properties, that include AIV, produce concrete of high compressive strength and the same applies to tensile strength.

Relative Density of 2500 is within the recommended range of 2000-3000Kg/m^3 for normal aggregate in accordance with BS EN 1991-1-1 [65] and the material was therefore suitable for production of concrete of acceptable density and rheology. The water Absorption was factored in the determination of the quantities of the water for mixing the concrete and absorption by aggregates to reach saturation state [17].

4.1.4 Silica Fume

The chemical composition for the silica fume used in the study is shown in Table 4.4.

Table 4.4: Chemical Composition of Silica Fume

Element Name	**SiO_2**	**P_2O_5**	**S**	**K_2O**	**CaO**	**Fe**	**Others**	**LOI**
Content (%)	97.846	0.515	1.071	0.223	0.086	0.093	0.166	3.63

The content of amorphous silicon dioxide (SiO_2) was determined to be 98% which is higher than the recommended minimum content of 85%. As such, the SF contained adequate quantity of SiO_2 needed to react with $Ca(OH)_2$ to form additional C-S-H gel that densifies the concrete pore structure and enhances strength. The quantities of sulfate and chloride contents of 1.071% and 0.086% were negligible and even when combined with those contained in the cement, their overall contents were within the specified limits. The LOI of 3.63% is lower than the maximum limit of 4.0% specified by KS EAS 18-1 and this level of carbonation has no significant effect on the quality of concrete.

4.2 Workability and Superplasticizer Compatibility

Table 4.5 shows the results of the workability tests on mix 1 concrete with the seven SPs as workability aid. It is seen that PCE SP1, SP2 and SP6, and SNF SP4 all gave good initial slump of over 200 mm and a slump flow of over 500 mm. In all these cases, the doses used were within the recommended limits. SMF SP3, Modified Phosphonate (MP) SP5 and SNF SP7 were observed to have a low effect in producing flow in the mix. All the SPs had rapid slump loss within 30 minutes and therefore cannot produce HPC for a large proportion of construction works. Figures 4.3 (a) and (b) show the initial slump and slump after 30 minutes for concrete with SNF SP4. All the concretes were cohesive and exhibited no bleeding or segregation.

Table 4.5: Changes in Slump with Time

Superplasticizer type		Specified dosage (%)	Actual dosage (%)	Changes in slump with time (mm)			Initial slump flow (mm)
				0 (min)	30 (min)	60 (min)	
SP1	PCE	0.4 – 2.0	1.07	265	5	0	650
SP2	PCE	0.2 - 2.0	1.07	260	0	0	650
SP3	SMF	1.0 - 1.5	2.46	65	0	0	0
SP4	SNF	0.4 - 3.0	1.54	235	25	0	535
SP5	MP	0.3-5.0	1.39	60	12	0	0
SP6	PCE	0.5-2.5	1.36	240	0	0	525
SP7	SNF	0.6-2.0	1.50	30	0	0	0

(a) Initial slump flow (b) Slump after 30 min.

Figure 4.3: Changes in slump for mix 1 with SNF superplasticizer SP4

From the results, PCE SPs gave the highest initial slump and this agrees with the study carried out by Chen et al [67] which revealed that PCEs have higher cement dispersing ability, owing to their comb-like structure, than other types of SPs such as SMF and SNF which have linear structures. PCE acts through both electrostatic repulsion as the cement particles become negatively charged and steric repulsion between its non-adsorbing side chains while the other SPs disperse cement particles only by electrostatic repulsion. SNF SP SP7 gave the lowest initial slump and from the technical information provided by the manufacturer, the SP contains synthetic chemicals that may accelerate the setting of concrete at low temperatures and it is therefore recommended to be used for works where concrete is batched and placed under 2 hours. On the other hand, SP4 which is of the same category as SP7 is designed for normal setting concrete.

Despite high initial slump being recorded with four SPs, there was rapid loss of the slump within 30 minutes in all the concrete mixes, thus signifying incompatibility between the cement and the SPs. The rapid loss in flowability hampers transportation, pumping and placing of concrete. This negates the production and use of HPC which is characterized with good initial workability and workability retention over a reasonably long period of time. Neville [13] suggests that a compatible SP should be able to produce concrete with slump retention in excess of 60 minutes and that exhibits a small loss in workability within 5-60 minutes. The CEM II cement used in this study is produced by blending PC with NP mainly in the form of volcanic tuff resulting from previous volcanic activities. Being mined from the ground, NP inevitably contains clay and dust which absorb SP and considerably reduce workability. Chen et al [67] observed that even PCEs, which are the best performing SPs, interact with clay through surface adsorption and chemical intercalation, and this leads to rapid loss of fluidity in concrete. Figure 4.2 shows how PCE side chains get inserted into interlay of clay. Clay also has a tendency of forming into aggregates which become difficult to be uniformly dispersed and this reduces fluidity of concrete.

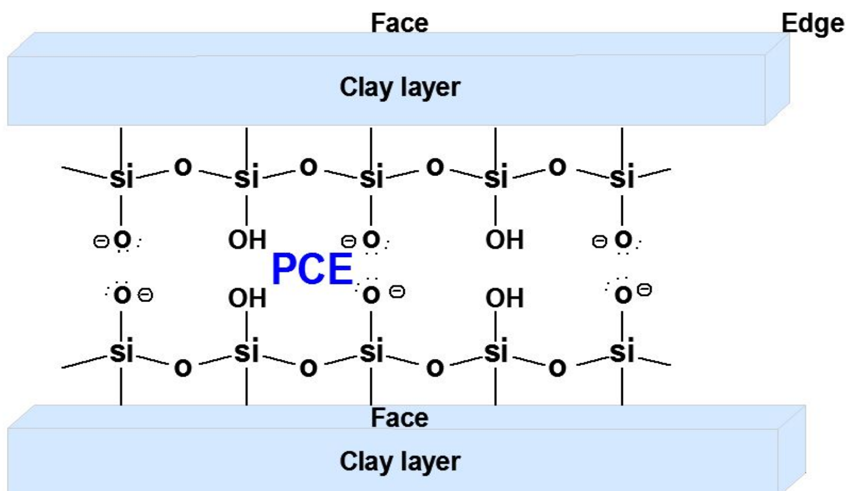

Figure 4.4: Insertion of PCE Side Chain into Clay Interlayers [66]

A study by Aoudjane et al [68] revealed that cement containing NP produced concrete with less workability than that produced using PC. They attributed this to fineness of PPC that requires more water in comparison with PC which is coarser and therefore requires less amount of water. In addition, the high level of carbonation in the cement, as indicated by the high LOI, reduces workability and influences other rheological properties of concrete. Mohebbi et al [69] point out that high content of organic carbon in cement increases water demand in the concrete as water is absorbed by the carbon particles and this reduces workability. Similarly, SP gets adsorbed on the carbon particles and this reduces their effectiveness in dispersing cement particles as desired.

Based on the above observations, SP1 was selected for use in the production of HPC owing to its low dosage and the highest initial slump of 265 mm. This initial slump exceeds the target slump of 100 mm considered in the mix design. It, however, did not achieve the target slump retention of 60 minutes.

4.3 Properties of High Performance Concrete

4.3.1 Compressive Strength

The development of compressive strength for both mixes 1 and 2 is shown in Figure 4.5. It is observed that both mixes show similar strength up to 28 days. Beyond 28 days the mix without silica fume shows better strength with a strength difference of 6 MPa at 90 days. Moreover, the curve for mix 2 starts to level off after 28 days with decrease in strength beyond 56 days. In both cases, 28-day cube strength in excess of 60 MPa was achieved, which is within the HPC range of 60 – 125 MPa. It is further observed that both mixes produce high early strengths in excess of 35 MPa at 3 days and 50 MPa at 7 days. With this enhanced strength, there can be reduction in the quantity of reinforcement steel where concrete structure is designed to resist compressive forces.

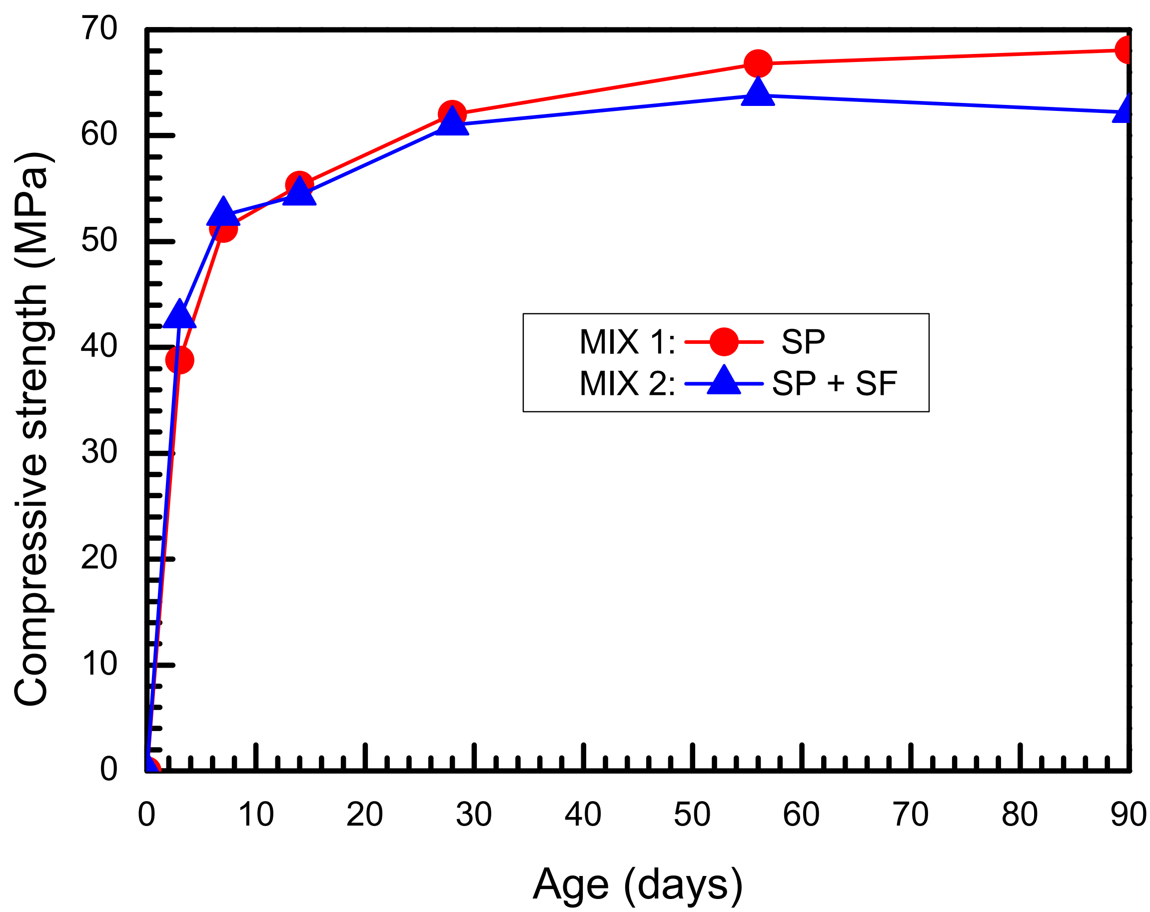

Figure 4.5: Development of Compressive Strength with Age

There is remarkable gain in strength within the first 3 days of curing. This is attributed to the hydration of calcium silicates in PC to form C-S-H gel and release $Ca(OH)_2$. Neville [13] observes that this fast and exothermic reaction takes place with the first three days after mixing of concrete. There is no significant difference in strength between the two mixes from 7 to 28 days. During this period, strength development is both from continued hydration of PC and pozzolanic reaction of SF and NP with $Ca(OH)_2$ released from hydration of PC. With strengths within these ages being reasonably the same for the two mixes, explanations given by Goyal et al [41] may hold. In their study, the authors found that replacing cement by a percentage greater than the optimum tends to lower the efficiency of mineral admixtures with reduction in strength. They argue that the pozzolanic reaction starts becoming lime controlled instead of being pozzolana controlled. In other words, it depends on the quantity of $Ca(OH)_2$ being released from the cement hydration. In this case the addition of SF in mix 2 increases the concentration of pozzolana beyond the optimum level. The rate of pozzolanic reaction is thus being controlled by the rate of release of $Ca(OH)_2$ rather than the reactivity of SF. From 28 days, a steady gain in strength is observed in mix 1 as expected due to continued pozzolanic reaction with time as additional binding C-S-H gel is formed. The gain in strength also resulted from use of SP that effectively dispersed cement particles, thus facilitating formation of C-S-H gel uniformly throughout the concrete. This improved compaction, cohesion, and strength of concrete. The use of SP enabled reduction in w/b ratio and this increased strength. The use of well graded coarse aggregate with high mechanical properties (low AIV) also enhanced the strength [13] [31] [32] [66].

However, for mix 2, there is a decrease in strength from 64 MPa to 62MPa between 56 and 90 days signifying breakage of bond in the structure of concrete. A similar observation was made by Ghudtke and Bhandari [27] who found that replacing PC with SF beyond the optimum quantity resulted in a decrease in compressive strength of concrete. This is attributed to autogenous shrinkage in hardened concrete occasioned by self-desiccation. Holt [70] points out that this is a major concern in HPC with compressive strengths in excess of 50 MPa and low w/b ratio attributing this to localized drying within concrete pore structure due to decrease in relative humidity. Water is drawn out of the capillary pore spaces between solid particles leading to shrinkage and micro-cracks in the cement matrix, and hence loss in strength. Wu et al [71] also confirm that autogenous shrinkage is more pronounced in HPC with w/b ratio lower than 0.4 and containing supplementary cementitious materials such as SF that increase water demand. It is apparent that despite the test specimens being cured in water, this water could not adequately penetrate the densified pore structure and reach the inner core of the concrete, leading to low relative humidity in this region that resulted in self-desiccation.

4.3.2 Flexural Tensile Strength

Figures 4.6(a) and (b) below show failure of the prisms under FPFL. The failures occurred within the middle third of the loaded length where there is maximum bending moment as expected. Table 4.2 shows the results of flexural tensile strength tests carried at 28 days on prisms made from mixes 1 and 2 compared with theoretically calculated values from EN 2 [63]. The flexural strengths determined from the experiment are 12 % of their respective compressive strengths and 18 % higher than those calculated from EN 2 due to pozzolanic reactions that enhanced strength. The strength was further enhanced by the use of SP that facilitated uniform hydration of cement and enabled reduction of w/b ratio [13] [32] [33].

(a) Failure of prisms in flexure **(b) Location of failure**

Figure 4.6: Prism failure under loading

Table 4.6: Beam Flexural Strengths

Concrete mix	Cube strength (MPa)	Experimental flexural strength (MPa)	Calculated flexural strength EN 2 (MPa)
1	62	7.3	6.2
2	61	7.3	6.2

Since flexural strength is the same for both mix 1 and mix 2, it is evident that the replacement of the CEM II cement with SF does not enhance the flexural strength at 28 days. A similar observation was made for compressive strength.

4.3.3 Water Absorption

Figure 4.5 shows water absorption for concrete mixes 1 and 2 at 28 days as measured against time. Within the first 10 minutes, water absorption for the two mixes is reasonably the same as water penetrates the relatively loose outer surface of the concrete. However, as time increases, there is less rate of absorption in mix 2 pointing to a denser pore structure. This is attributed to physical packing as SF particles which are very fine filled the spaces between the cement and aggregates.

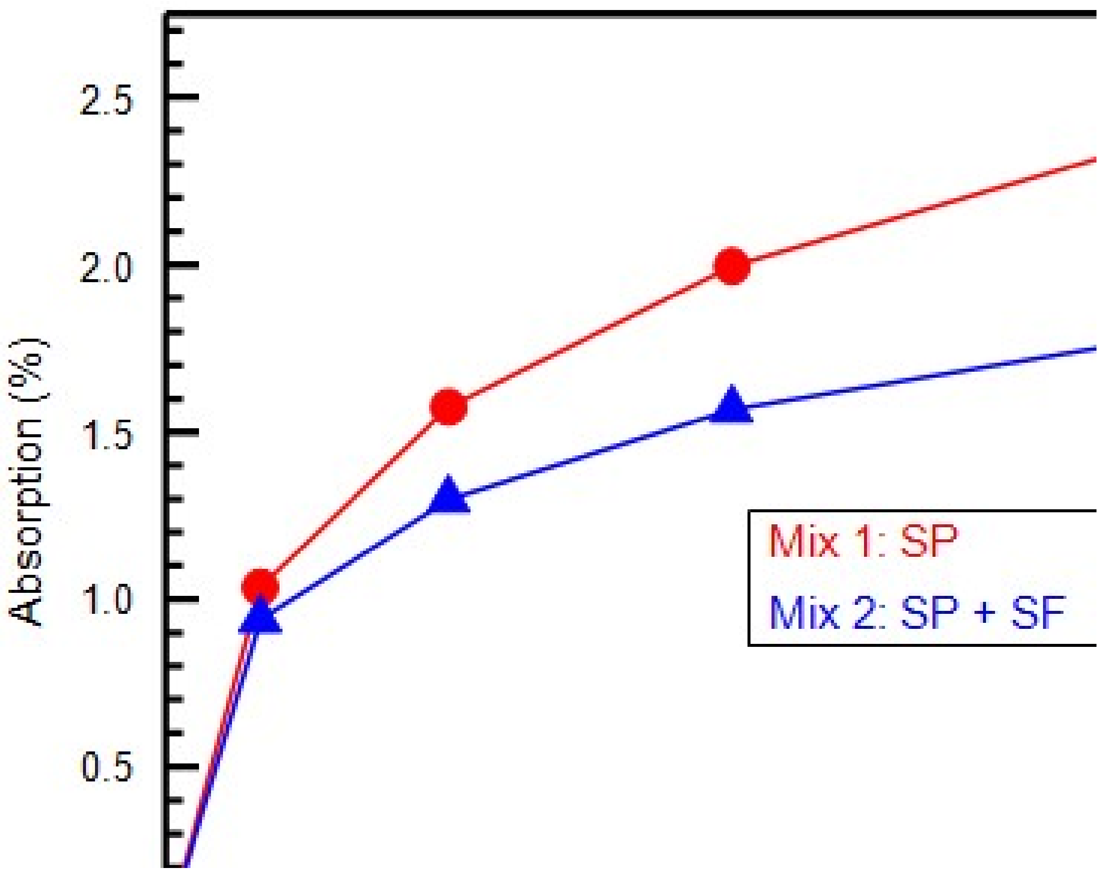

Figure 4.7: Changes in Water Absorption with Time

Zhang and Zong [72] explain water absorption process in terms of surface sorptivity and internal sorptivity. Surface sorptivity takes place immediately a specimen is immersed in water while internal sorptivity progresses with time. They define sorptivity as the index of moisture transportation into unsaturated specimen. They however found no clear relationship between sorptivity and compressive strength. This explains the observations made that mix 1 has slightly higher compressive strength than mix 2 and also a higher water absorption. The authors concluded that sorptivity is influenced by capillary suction of water through pore spaces between solid particles in concrete and not by the strength of concrete.

De Schutter and Audenaert [73] carried out a study to evaluate water absorption of concrete as a measure for resistance against carbonation and chloride migration. Their study considered concrete mixes with 28-day water absorption of between 3-6.5 %. They concluded that concrete with low water absorption indicates a densified pore structure that enhances resistance to chemical and adverse environmental attacks, hence durable structures with low costs of maintenance and replacement.

4.3.4 Electrical Resistivity

Table 4.3 shows the electrical resistivity (ER) of the two mixes, with mix 2 with 5 % SF showing a marked higher ER. ER is a measure of the rate at which ions move through the concrete. According to AASHTO TP 95, ER of 37 to 254 kΩ-cm is associated with very low Cl^- penetrability which is indicative of a good level of pore density and therefore enhanced durability. This level of durability enhances long term performance of the concrete. The partial replacement of the CEM II cement with 5 % SF increased ER by more than 25 % due to increased densification of the pore structure of the concrete.

Table 4.7: Electrical Resistivity

Concrete Mix	Electrical Resistivity (kΩ-cm)
1	70.4
2	88.6

Azarsa and Gupta [74] view ER of concrete as its capability to withstand the transfer of ions that are subjected to an electric field through its pore structure, which helps in assessing the penetration of Cl^- into concrete. On the other hand, Zhang and Zong [72] found that there is no practical relationship between permeability and compressive strength of concrete. This explains the observed converse relationship between compressive strengths and ER for the two concrete mixes.

5 CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the findings of the study, the conclusions drawn and the recommendations made based on the study findings.

5.1 Conclusions

The following conclusions can be derived from the study:

i. PCE and specific brands of SNF superplasticizers are able to produce high flowability in the concrete when used within the recommended dosage, but loss of flowability is rapid with stiffening of the mix occurring within 30 minutes.

i. The rapid loss of workability renders the concrete inapplicable for most practical construction purposes unless for very quick castings.

ii. For the mix design adopted in the study, Portland pozzolana cement CEM II/B-P 32.5N can be used to produce concrete with strength in the High Performance Concrete range and with water absorption below 2.5 % and electrical resistivity in excess of 70 kΩ-cm both of which indicate a good level of durability.

iii. Incorporating silica fume in the mix improves the densification of the concrete but has negative effect on the long-term development of strength with significant loss of strength beginning to occur after 28 days.

5.2 Recommendations

5.2.1 Recommendations from this Study

i. Use of Portland pozzolana cement CEM II/B-P 32.5N together with properly selected aggregates and a suitable superplasticizer to produce concrete with enhanced strength and durability that improve quality of structures. The concrete produced, however, only suitable for quick casting due to rapid loss of workability.

ii. Cement replacement materials such as silica fume need not be used with CEMII/B-P 32.5N as these are likely to lower the long term strength of concrete.

5.2.2 Recommendations for future studies

In order to exploit the inherent advantages of CEM II/B-P over CEM I, future research should focus on extending the workability retention of CEM II/B-P concrete incorporating a workability enhancing admixture.

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APPENDICES

APPENDIX A: PRELIMINARY TESTS ON MATERIALS

A1: Fine Aggregate (River Sand) Sieve Analysis

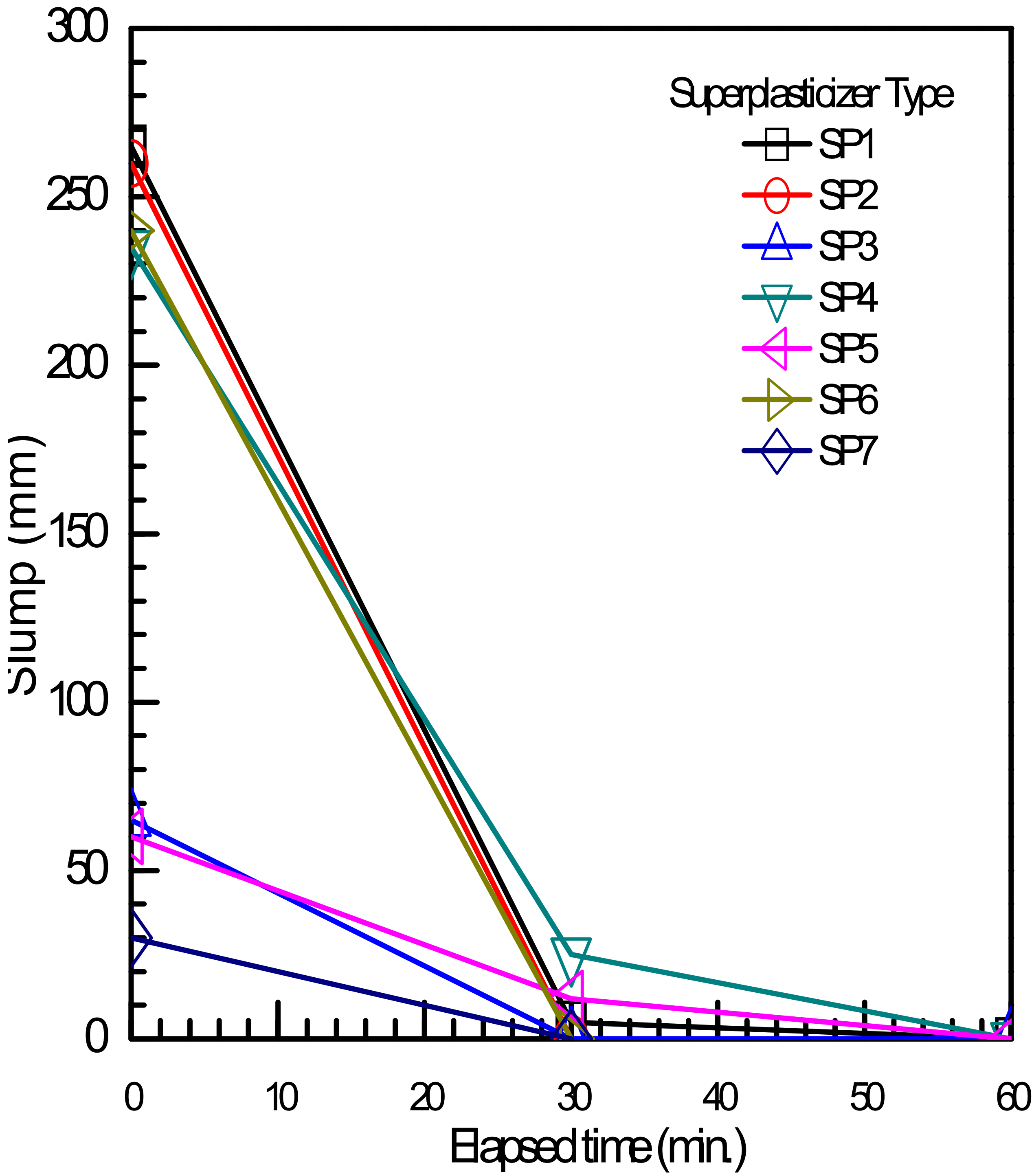
ASTM Sieve (mm)	Retained (g)	Cumulative Retained (g)	Cumulative Retained (%)	Cumulative Passing (%)	Material Specification Lower Limit (%)	Material Specification Upper Limit (%)
4.75	0.000	0.000	0.00	100.00	95	100
2.36	0.022	0.022	2.20	97.80	80	100
1.18	0.180	0.202	20.20	79.80	50	85
600	0.326	0.528	52.80	47.20	25	60
300	0.398	0.926	92.60	7.40	5	30
150	0.070	0.996	99.60	0.40	0	10
Pan	0.004	1.000	100.00			
Total	**1.000**					
Fineness Modulus, FM (Sieves 4.75, 2.36, 1.18, 600, 300,150) =					**2.67**	

A2: Coarse Aggregate Sieve Analysis

ASTM Sieve (mm)	Retained (g)	Cumulative Retained (g)	Cumulative Retained (%)	Cumulative Passing (%)	Material Specification Lower Limit (%)	Material Specification Upper Limit (%)
19	0.000	0.000	0.00	100.00	100	100
12.5	0.000	0.000	0.00	100.00	90	100
9.5	1.810	1.810	45.25	54.75	40	70
4.75	1.899	3.709	92.73	7.27	0	15
2.36	0.273	3.982	99.55	0.45	0	5
Pan	0.018	4.000	100.00	0.00	0	0
Total	**4.000**					

APPENDIX B: TESTS ON CONCRETE

B1: Results of Slump Test on Fresh Concrete



B1: Results of Compressive Strength Test on Hardened Concrete

Concrete Mix	Age (Day)/Cube Crushing Strength (MPa)						
	0	**3**	**7**	**14**	**28**	**56**	**90**
Mix 1: CEM+FA+CA+SP	0	39	53	55	62	64	68
Mix 2: CEM+FA+CA+SP+SF	0	43	53	56	61	64	62

CEM-Cement, FA-Fine Aggregate, CA-Coarse Aggregate, SP-Superplasticizer, SF-Silica Fume

APPENDIX C: JOURNAL PAPER

C1: Author's Certificate from SSRG-IJCE

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