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Evaluating Superplasticizer Compatibility in the Production of High-Performance Concrete using Portland Pozzolana Cement CEM II/B-P

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Abstract *- EN CEM II/B-P has potential advantages over CEM I when used to produce concrete. Incorporation of natural pozzolana reduces the amount of clinker used in cement production, hence raw materials, CO_2 emission, and 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 sulfates and acids, and carbonation shrinkage. In addition, additional C-S-H from the reaction of pozzolana and $Ca(OH)_2$ increases long term strength and densification of the pore structure leading to improved durability. This research explores the effect of selected superplasticizers in the production of free-flowing concrete with CEM II/B-P 32.5N targeting high strength. Cube crushing strength above 60 MPa was obtained at 28 days, together with high initial flowability. 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.*

Keywords - *High performance, workability retention.*

I. INTRODUCTION

Mitigating the environmental impact of Portland cement is of great concern 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. Also, the reduced durability of Portland cement concrete due to the reaction with sulfates, acids, atmospheric CO_2, and some reactive aggregates is of concern. These problems are largely resolved by replacing part of the Portland cement with 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 since its discovery and it can be formed into various shapes and sizes depending on the designs adopted. 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.NC is classified as one having cube crushing compressive strength less than 60 MPa at 28 days while HPC is of strengths ranging from 60MPa to 125MPa. UHPC is classified as having a compressive strength of more than 125MPa[4]. HPC and UHPC also exhibit good workability and enhanced durability. Caldarone, et al[5] define high-performance concrete (HPC) as "concrete that is engineered to meet mechanical, durability or constructability properties that exceed those of normal concrete". 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"[6]. The distinguishing properties of HPC include good workability, good workability retention, high strength, and enhanced durability. Neville [7] observes that the production of HPC requires very strict and consistent quality control. For instance, mix design, selection of ingredient materials, batching, and the sequence of feeding and mixing these materials require particular attention. The materials commonly used in the production of HPC include cement, fine and coarse aggregates, supplementary admixtures such as natural pozzolana (NP), fly ash (FA), and silica fume (SF),

and superplasticizer (SP). The use of these supplementary materials reduces the quantity of cement and therefore conserves the environment [8]. For high strength and durability, the water content is kept very low but must provide adequate moisture for the complete hydration of the cementing paste.

Portland-pozzolana cement (PPC) incorporating Portland cement (PC) and NPis widely used owing to its numerous advantages over Portland cement alone[9]. These advantages include higher long term strength resulting from the reaction between pozzolana and $Ca(OH)_2$ released during cement hydration to form additional C-S-H gel, reduced heat of hydration, improved resistance to chemical attack, and low permeability. Hydration of cement and pozzolanic reaction can be summarized as shown in equations (1) and (2).

$$CS + H_2O = C\text{-}S\text{-}H + Ca(OH)_2 \quad (1)$$

$$Ca(OH)_2 + SiO_2 + H_2O = C\text{-}S\text{-}H \quad (2)$$

SP is a high-range water-reducing admixture that has various effects on fresh and hardened concrete properties. Malagavelli and Paturu[10]observed that workability and compressive strength increase with the use of SP. Similarly, a water-binder (w/b) ratio as low as 0.25 can be used to achieve high workability depending on the type of SP added to the concrete[11]. However, SP can also create serious problems in concrete if not properly used[12]. These include bleeding, segregation, and loss of workability. Compatibility between cement and SP should be established as this has a critical effect on workability retention and other properties of concrete. 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. PCEs generally have a comb-like molecular structure that is responsible for the superior dispersion of cement particles while the other three have linear molecular structures[13].

HPC should exhibit good workability and workability retention to allow for moving and placing of the concrete. Neville [7] 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. On the other hand, concrete that does not have good workability is not HPC[14]. Laskar[15] points out that a minimum slump of 100mm with good retention is recommended for HPC. HPC is characterized by high strengths and enhanced durability. In their study,[16] observed that the addition of supplementary cementing materials to concrete improves its long-term durability. Water absorption and electrical resistivity tests are usually carried out to assess the durability of concrete.

This paper evaluates the compatibility of different types of SP with PPC CEM II/B-P 32.5Ncement manufactured to KS-EAS-18-1:2017 which is derived from EN 197, in the production of HPC. CEM II/B-P incorporates up to 35% natural pozzolana. Workability and workability retention in the fresh concrete, strength development, and durability in the hardened concrete are investigated. The results of the research are expected to improve the use of PPC in the production of HPC with better performance than CEM I concrete.

II. MATERIALS AND METHODOLOGY

A. Materials

The materials used in the study were PPC CEM II/B-P 32.5N manufactured in Nairobi to KS EAS 18-1:2017 which conforms to EN 197, river sand of fineness modulus (FM) 2.67, the natural crushed coarse aggregate of maximum aggregate size (MAS) of 12.5mm, silica fume grade NR95D imported from China, seven different superplasticizers SP1 to SP7 available locally, and potable tap water from the Nairobi City mains.

B. Materials preparation and preliminary tests

1) ***Cement:*** The chemical properties of cement were tested at the Kenya State Department of Mining laboratory in Nairobi following KS EAS 148. The result of the tests is given in Table I.

2) ***Fine aggregate:*** Fine aggregate was oven-dried at 105ºC for 24 hours to remove entrained moisture. Several tests were then carried out on the fine aggregate with results as shown in Table II.

3) ***Coarse aggregate:*** Coarse aggregates were oven-dried at 105ºC for 24 hours to remove entrained moisture. The aggregates were then sieved and blended to fall within the limits specified by ASTM C33. The sieve analysis results are shown in Fig. 1. Properties of the aggregates were also determined as shown in Table III.

TABLE I
COMPOSITION OF CEMENT CEM II/B-P

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

TABLE II
PROPERTIES OF FINE AGGREGATE

Fineness modulus	Bulk density (kg/m^3)	Relative density	Water absorption (%)	Organic content (%)
2.67	1,602	2.63	1.37	0.024

TABLE III
PROPERTIES OF COARSE AGGREGATE

Bulk density (kg/m^3)	Relative density	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

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

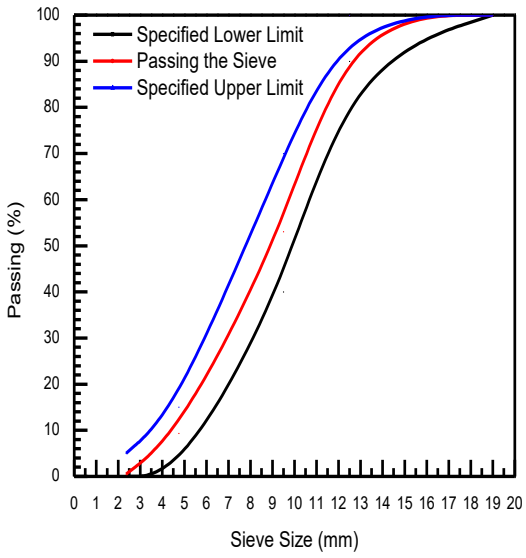

Fig. 1: Coarse Aggregate Sieve Analysis

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. The test results are given in Table IV.

C. 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 compressive cube strength for the HPC was 60MPa (50MPa cylinder crushing strength). The quantities of materials for 1m^3 of concrete were as presented in Table V. Mix 2 contained 5% SF as partial replacement of the cement.

TABLE V
QUANTITIES OF MATERIALS FOR 1M3 OF CONCRETE

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

TABLE IV
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

D. Determination of superplasticizer compatibility

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 1gaccuracy 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 was carried out to produce a uniform paste. Fine aggregate was then added and mixing continued to produce a uniform mortar. Lastly, the 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. The concrete was used to determine the initial slump and slump flow. The concrete was then returned to the mixer and mixing continued and the new slump was determined at 30 min intervals.

E. 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. The proportion for all materials enough to make one mixer load of concrete mix 1were measured out to 1gaccuracy. Concrete was made as described in 2.4 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 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.

F. Compression strength test

One hour prior to testing, the concrete cubes were removed from the saturated lime water, dried using an absorbent cloth, and then left to dry in the open at room temperature. 3No.cubes of a specified age were then successively placed on the testing machine, one at a time and the load was applied at a constant rate of 30-40kN per minute to failure. 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 crushing strength of concrete. A graph of compressive crushing strength against the age of the concrete was plotted.

G. Tensile strength test

The prisms were removed from the saturated lime water at the age of 28days, dried using an absorbent cloth, and then left to dry in the open at room temperature for one hour. 3No.prismsmade from mix 1 concrete was then successively placed on the testing machine, one at a time, as shown on Fig. 2 and load was applied at a constant rate of 30-40kN per minute to failure. 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 the same was used to calculate the flexural tensile strength. The position and modes of failure were also noted to confirm conformity of the loading condition to the*Four Point Load Flexural Test (FPFL).*

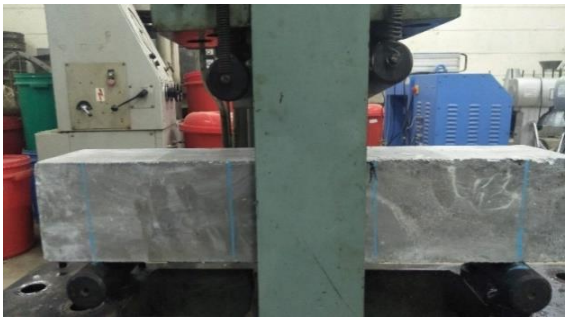

Fig. 2: Concrete Prism on Testing Machine

H. Water absorption test

At the age of 28 days, the test samples for Mix 1 and Mix 2 were removed from the saturated lime water and their surfaces dried using an absorbent cloth. They were then placed in the oven and dried at 105ºC for 72 hours to remove entrained free water. The oven was thereafter switched off, its vents sealed to prevent the 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 an 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 a cumulative period of immersion was plotted for the two mixes and a comparison of the results made to evaluate the effect of SF on water absorption following BS 1881-122:2011.

I. Electrical resistivity test

The test samples were removed from the saturated lime water at the age of 28days, dried using an 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 the durability of the concrete was assessed according to AASHTO TP 95. Fig.3 shows the electrical resistivity test in progress.

Fig. 3:Electrical Resistivity Test

III. RESULTS AND DISCUSSION

A. Effects of superplasticizers on workability

Table VI shows the results of the workability tests on mix 1 concrete with the seven SNPs as workability aid. It is seen that PCE SP1, SP2 and SP6, and SNF SP4all gave a 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) SP5and 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 a workable HPC. Fig. 4 (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.

(a) Initial slump flow (b) Slump after 30 minutes

Fig. 4: Changes in a slump for mix 1 with SNFsuperplasticizer SP4

From the results, PCESPs gave the highest initial slump and this agrees with the study carried out by[17] 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-absorbing side chains while the other SPs disperse cement particles only by electrostatic repulsion[18] 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

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TABLE VI
CHANGES IN SLUMP WITH TIME

Superplasticizer type		Specified dosage (%)	Actual dosage (%)	Changes in a 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

Despite the high initial slump being recorded with four SPs, there was a 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 by good initial workability and workability retention over a reasonably long period. Neville[7] is of the view that a compatible SP should be able to produce concrete with slump retention over 60minutes 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[17] 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. Clay also tends to form into aggregates which become difficult to be uniformly dispersed and this reduces the fluidity of concrete.

A study by[19] revealed that cement containing NP produced concrete with less workability than that produced using PC. They attributed this to the 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[20] point out that the 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.

B. Compressive strength

The development of compressive strength for both mix 1 and 2 is shown in Fig. 5. It is observed that both mixes show similar strength for up to 28 days. Beyond 28 days the mix without silica fume shows better strength with a strong difference of 6MPa at 90 days. Moreover, the curve for mix 2 starts to level off after 28 days with signs of a decrease in strength beyond this age. In both cases,28-day cube strengths over 60 MPawas achieved, which are within the HPC range of 60 – 125 MPa.It is further observed that both mixes produce high early strengths over 35MPa at 3 days and 50 MPa at 7 days.

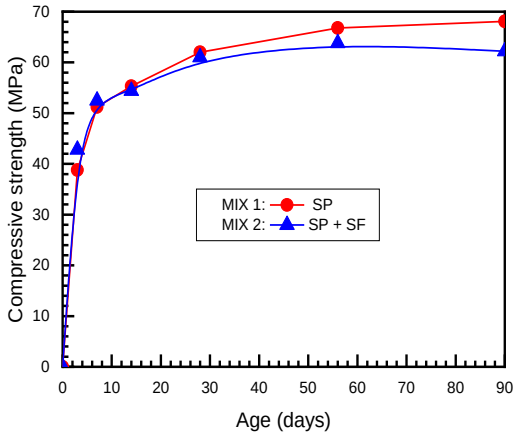

Fig. 5: Development of compressive strength with age

There is a 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[7] observes that this fast and exothermic reaction takes place with the first three days after the 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 cement, and pozzolanic reaction of SF and NP with

$Ca(OH)_2$ released from the hydration of PC With strengths within these ages being reasonably the same for the two mixes, explanations given by[21] hold. In their study, they found that replacing cement by a percentage greater than the optimum tends to lower the efficiency of mineral admixtures with a 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 the use of SP that effectively dispersed cement particles, thus facilitating the formation of C-S-H gel uniformly throughout the concrete. This improved compaction, cohesion, and strength of concrete. The use of SP enabled a 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[7],[10],[11],[22].

However, for mix 2, there is a decrease in strength from 64MPa to 62MPa between 56 and 90 days signifying breakage of bond in the structure of concrete. A similar observation was made by[23] 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[24] points out that this is a major concern in HPC with compressive strengths above 50MPa and low w/b ratio attributing this to localized drying within concrete pore structure due to a 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[25] also confirm that autogenous shrinkage is more pronounced in HPC with a 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 the low relative humidity in this region that resulted in self-desiccation.

C. *Flexural tensile strength*

Fig. 6 (a) and (b) below show the failure of the prisms under FPFL. The failures occurred within the middle third of the loaded length where there is a maximum bending moment as expected. Table VII 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. The flexural strengths determined from the experiment are 12% of their respective compressive strengths and 18% higher than those calculated from EN 2due 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[7],[10],[11].

(a) Failure of prisms in flexure

(b) Location of failure

Fig. 6: Beam failure under loading

TABLE VII
FLEXURAL STRENGTH

Concrete mix	Cube strength (MPa)	Experimental flexural strength	Calculated flexural strength
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.

D. *Water Absorption*

Fig. 7 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.

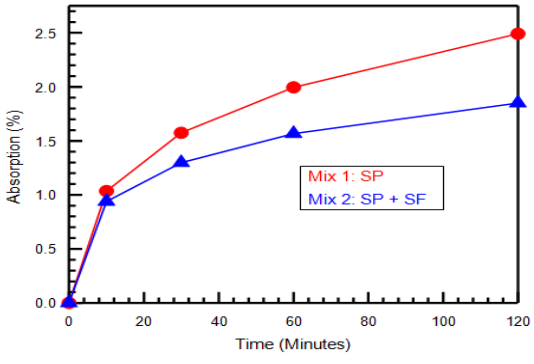

Fig. 7: Changes in water absorption with time

Zhang and Zong[26] explain water absorption process in terms of surface sorptivity and internal sorptivity. Surface sorptivity takes place immediately a specimen is immersed in waterwhile 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[27] 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.

E. Electrical Resistivity

Table VIII 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 TP95, 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. 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 VIII
ELECTRICAL RESISTIVITY

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

Azarsa and Gupta[28] view the ER of concrete as its capability to withstand the transfer of ions that are subjected to an electric field through its pore structure, which is handy in assessing the penetration of Cl^- into the concrete. On the other hand, it was found that there is no practical relationship between permeability and compressive strength of concrete[26]. This explains the observed converse relationship between compressive strengths and durability parameters for the two concrete mixes.

IV. CONCLUSIONS

The following conclusions can be derived from the study:

(i). CEM II/B-P 32.5N conforming to EN 197 can be used to produce concrete with strength in the HPC range and with electrical resistivity in excess of 70 kΩ-cm which indicates a good level of durability.

(ii). PCE and specific brands of SNF superplasticizers can produce high flowability in the concrete when used within the recommended dosage, but the loss of flowability is rapid with stiffening of the mix occurring within 30 minutes.

(iii). Incorporating SF in the mix improves the densification of the concrete but harms the long-term development of strength with significant loss of strength beginning to occur after 28 days.

(iv). The rapid loss of workability renders the concrete inapplicable for most practical purposes unless for very quick castings.

(v). Further research should focus on improving flow retention to allow adequate time for transporting, placing, and finishing the concrete before setting.

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