And., Intl.,J., Appl Sci., Eng., Tech, Vol 03, No 02, July 2023
e-ISSN: 2797-0442

Influence of Corn Cob Ash-Silica Fume Blend on the Mechanical and Durability Properties of Concrete

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Abstract— This research explored the feasibility of corn cob ash-silica fume blend in the production of pozzolanic cement to produce High-Performance Concrete. The cement in concrete was partially replaced by corn cob ash-silica fume blend in 5,10,15 and 20% by weight of cement and was compared to a control mix of 0% replacement. An intelligent mix design, Densified Mix Design Algorithm (DMDA), was used to effectively reduce both water and cement content. In order to create high strength and workability, a polycarboxylate-based super plasticizing admixture was utilized in conjunction with a low water binder ratio of 0.35. Compressive strength was appraised to determine the mechanical properties at days 3,7,14,28 and 56 to determine the optimum percentage replacement and compared to the control at the specific ages. With the optimum percentage replacement, the flexural test was investigated at 28 days. Water absorption and electrical resistivity tests were also investigated as potential indicators of durability. All of the blends that included corn cob ash and silica fume produced a higher strength than the control except 15 and 20%, with 10% replacement yielding a cube strength of 61 MPa at day 56.

Keywords: Corn cob ash, Densified Mix Design Algorithm, High performance, Pozzolanic cement, Silica fume

1. Introduction

Cement consumption has increased as a result of the requirement for a socioeconomic infrastructure to support the creation of wealthy societies as a result of rapid population development [1]. Concrete has been largely and actively used over time due to its desirable mechanical and durability properties, its fire resistance, its simplicity in application and its widespread availability.

The process of manufacture of cement is energy-intensive, leads to overexploitation of limestone reserves and as a result of its high carbon footprint, it contributes immensely to the global carbon (IV) oxide. Furthermore, cement suffers reduced durability because of its ability to react with acids, sulphates and atmospheric carbon (IV) oxide (CO_2). As a result of cement's susceptibility to chemical attacks, reinforcement steel bars ultimately suffer from corrosion [2]. Adoption of new concrete types that can meet the requirement for better durability and mechanical qualities can address these issues in significant part. In addition, high-performance concrete (HPC) adaptation has been required due to the incorporation of new building processes, sensitivity to environmental issues, and sophistication in structural designs.

Concrete that satisfies a unique set of performance and uniformity characteristics that are not always consistently achievable using customary mixing, pouring, and curing procedures is referred to as high-performance concrete (HPC) [3]. Although the components of HPC are fundamentally the same as those of ordinary concrete, the proportions have been planned and built to deliver great strength and durability, reducing maintenance and extending lifetime. Due to its strong early strength, speedy service delivery will be facilitated by its quick concrete laying, which will ultimately facilitate faster

Received: July 14, 2023, Revised: August 01, 2023, Accepted: August 12, 2023
https://doi.org/10.25077/aijaset.v3i2.86

construction while maintaining structural integrity. Additionally, high strength ensures the adoption of reduced structural member sizes, which then ensures that construction materials are used sparingly. HPC produced from pozzolanic materials will ensure durable concrete since it will have excellent resistance to chemical attack, be less permeable and ultimately have a reduced need for maintenance.

This study used an intelligent mix design to explore the influence of corn cob ash (CCA)-Silica Fume (SF) blend in the production of HPC. Corn cob is the core portion of corn and is one of the largely produced staple agricultural food in Sub-Saharan Africa. It is locally used as a source of fuel; firewood, as chicken feed and sometimes as manure. The ash generated from this cob is normally dumped in low-level areas and landfilling which causes environmental problems. Corn cob is one of the agricultural waste products that can be considered for reuse in various ways. Corn cob can be reused as a pozzolanic material since it is rich in silica and hence classified as an SCM [4]. Corn cob ash has to be treated by burning in controlled temperatures at 850ºC to tap into its pozzolana. Previous studies carried out tests on corn cob ash and its possibility to be utilized in as a partial alternative for cement [5][6][7].
CCA is a supplementary cementitious material (SCM), which means it can help concrete's fresh and hard characteristics by partially replacing cement. The inclusion of silica fume modifies the characteristics of concrete, which enhances the bond between the paste and the particles and, ultimately, lowers the degree of porosity of the concrete [8]. A superplasticizer (SP) will also be utilized to enhance workability by modifying the natural rheology of concrete and controlling the setting time.

Conventional concrete design mix prepared with the nominal mix design classes of class 20, 25, 30 or even 35 have proven to be limited in terms of strength offered. This means that for the design of high-rise structures, with high loads computed, large structural member sizes are required. Previous studies [6][5] partially replaced cement using CCA while applying nominal mix design and found a strength of 25.18 MPa and 34.3 MPa by day 28.

This research is aiming to produce a pozzolanic cement that is HPC using CCA-Silica fume blend with a target strength of 60 MPa by day 56. By using an intelligent mix design, DMDA, reducing the water binder ratio, using a superplasticizer to enhance workability and silica fume to increase overall strength. Additionally, since CCA is a SCM, its pozzolanic nature will significantly reduce the amount of clinker required which will then ensure sustainability and overall protection of natural reserves.

2. Materials and Methodology

2.1 Materials

Portland cement CEM 1 42.5 N, corn cob ash, river sand, naturally crushed coarse aggregates, silica fume, superplasticizer, and potable tap water from Nairobi City mains were the materials utilized in the study.

2.2 Materials Preparation and Preliminary Tests

2.2.1 Cement

The cement used in the study was Portland cement CEM 42.5 N manufactured locally to KS EAS 18-1:2017, which meets the standards of European standard EN 197. The chemical composition was tested at the Kenya State Department of Mining laboratory in Nairobi, and the results are captured in Table 1.

AIJASET – Vol. 03, No. 02, July 2023. 93-104
https://doi.org/10.25077/aijaset.v3i2.86

Table 1. Chemical Compositions of Fine Materials by Weight

Oxides	Cement	Silica fume	Raw CCA	CCA after burning
Silicon dioxide (SiO_2)	20.359	96.216	26.318	27.186
Aluminium oxide (Al_2O_3)	5.134	0.000	2.693	0.000
Iron (III) oxide (Fe_2O_3)	3.252	0.099	3.732	3.764
Calcium oxide (CaO)	63.276	0.169	5.177	3.442
Potassium oxide (K_2O)	0.529	0.163	41.239	40.939
Magnesium oxide (MgO)	0.000	2.713	7.609	10.284
Phosphorus pentoxide (P_2O_5)	0.439	0.142	6.605	8.348
Titanium dioxide (TiO_2)	0.189	0.018	0.454	0.982
Manganese oxide (MnO)	0.025	0.027	0.121	0.321
Sulfur trioxide	2.734	0.389	0.000	0.000
Loss on ignition (LOI)	-	-	-	-
SiO_2+Al_2O_3+Fe_2O_3	-	-	32.742	30.95

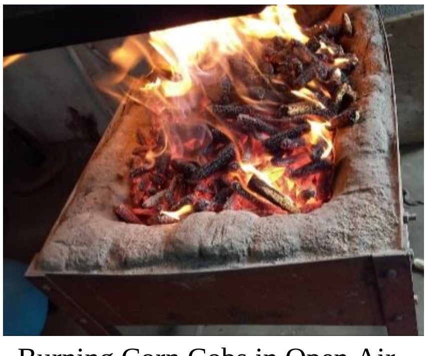
2.2.2 Corn Cob Ash

Corn cobs obtained from Siaya were sun-dried and burnt in the open air to obtain raw ash. The raw ash was further crushed using a pestle and mortar and then burnt at a controlled temperature of 800^o C for 1 hour. This ash was sieved through a 150 µm sieve size to produce fine ash. The process of corn cob ash preparation is summarized in Figure 1 below. The chemical composition of the ash was examined by the use of an X-ray fluorescence (XRF) machine at the Kenya State Department of Mining Laboratory in Nairobi and the results are captured in Table 1 above.

Raw Corn

Shelling Corn

Corn Cobs



Burning Corn Cobs in Open Air

Refined Corn Cob Ash

Burning at Controlled Temperatures

Final Product
Refined Corn Cob Ash
Figure 1. A Summary of Corn Cob Ash Preparation

2.2.3 Coarse Aggregates

Coarse aggregates were obtained locally from a hardstone quarry in Kariokor, Nairobi with a maximum aggregate size (MAS) of 12.7 mm. The coarse aggregates were washed and sieved using a sieve of the size of 3.18 mm to eliminate fine particles. The aggregates were then dried in an oven at 105° C for 24 hours to remove any moisture that may have been entrained. After cooling, the aggregates were sieved to separate them into categories of 3.18 mm - 6.35 mm and 6.35 mm - 12.7 mm.

The smaller coarse aggregates (6.35 mm - 3.18 mm) were progressively packed into the larger ones (12.7 mm – 6.35 mm) to attain the maximum dry density (MDD) after which packing curves were plotted as shown in Figures 2 and 3. Table 2 below summarizes the physical characteristics of the coarse aggregates.

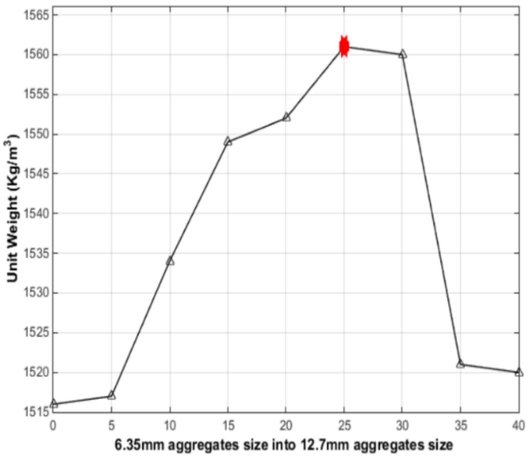


Figure 2. Packing Curve for 6.35mm CA into 12.7 mm CA (MDD at 25%)

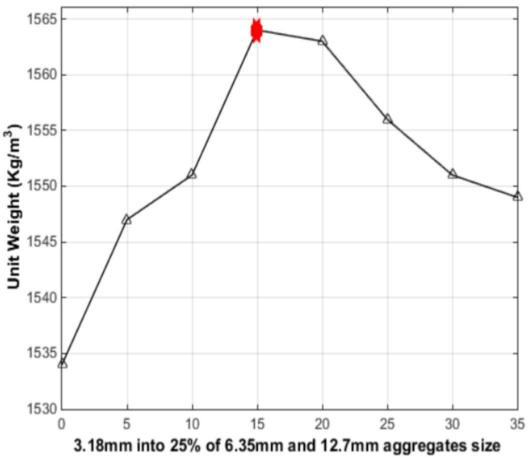


Figure 3. Packing Curve for 3.18 mm CA into 6.35+12.7 mm (MDD at 15%)

2.2.4 Fine Aggregates

River sand was utilized as fine aggregates, and it was purchased in Nairobi from a local vendor. The river sand was washed and sieved to eliminate any dust particles. To get rid of any trapped moisture, it was then oven-dried for 24 hours at 105ºC. The fine aggregates were then progressively packed into the coarse aggregates at MDD to determine the quantity of fine aggregates that was needed to obtain a new MDD. A final packing curve was plotted as shown in Figure 4 and the new MDD was used in the concrete mix design. Table 2 below lists the physical characteristics of fine aggregates.

Table 2. The Physical Properties of Aggregates
FM=Fineness modulus, AIV =Aggregate Impact Value, ACV= Aggregate Crushing Value

Types of aggregates	Bulk density (kg/m3)	Specific gravity	Water absorption (%)	FM	Silt content	AIV (%)	ACV (%)
Fine aggregates	1602	2.63	1.37	2.71	17.23	-	-
Coarse aggregates	1527	2.50	2.90	-	-	12.04	17.23

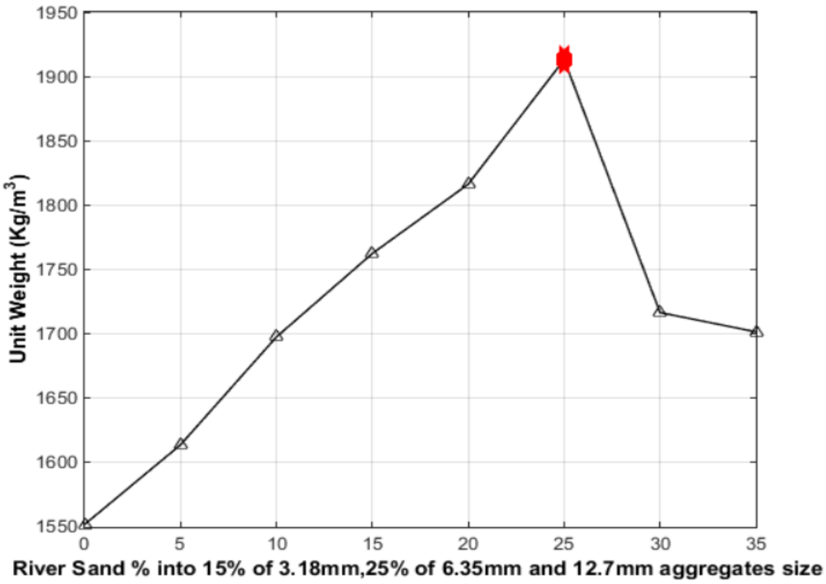


Figure 4. Packing Curve for Fine Aggregates into Coarse Aggregates (MDD at 25%)

2.2.5 Super Plasticizer

A polycarboxylate ether (PCE) superplasticizer, Sika Viscocrete 3088, produced by Sika (K) Limited in Nairobi was used. Table 3 summarizes the superplasticizer's characteristics.

Table 3. Properties of superplasticizer

Property	Colour	Form	Effect on setting	Density(kg/l)	Chemical base	Dosage
Superplasticizer	Yellowish	Liquid	Retarding according to dosage	1.05 kg/l	Aqueous solution of modified polycarboxylate	0.2-1.5 % by weight of cement

2.2.6 Silica Fume

Silica fume was obtained from Sika (K) Limited conforming to KS EAS 148. Its chemical composition was analyzed and is captured in Table 1 above.

2.2.7 Water

The Nairobi City mains provided potable tap water. The water binder ratio was kept at 0.35.

2.2.8 Mix Design Calculation using DMDA

The concrete mix design was carried out by the DMDA method based on the assumption that; 'Concrete is made up of aggregates of varying sizes bound together by a cementitious paste. The composition of the aggregates is determined from the relative amounts of the different sizes making up the MDD. The paste consists of cementitious powder, mixing water and superplasticizer, and a unit volume of consolidated fresh concrete is composed of both coarse and fine aggregates, paste, and a small volume of air [9][10][11].

The mass of quantities required for one cubic meter of concrete mix were computed and captured in Table 4 below.

Table 4. Quantities of Materials in $1m^3$ of Fresh Concrete

Mix	CCA-SF (%)	Cement	CCA	SF	Water	SP	FA	Coarse aggregates		
								9.52-12.7	6.35-9.52	6.35-3.18
1	0	396	0	0	140	0	480	916	306	216
2	5	376.2	9.9	9.9	140	7.92	480	916	306	216
3	10	356.4	19.8	19.8	140	7.92	480	916	306	216
4	15	336.6	39.6	19.8	140	7.92	480	916	306	216
5	20	316.4	59.6	19.8	140	7.92	480	916	306	216

2.3 Concrete Mixing

Paste volumes of 0, 5, 10, 15, and 20% were prepared for concrete mix proportions and an appropriate addition of SP to give free-flowing concrete without bleeding. A $0.02m^3$ paddle mixer Katerina model B200A made in China captured in Figure 5 was used for concrete mixing. Water was added followed by cement, CCA and SF to achieve a uniform binder paste. Onto the binder paster, fine aggregates were slowly but progressively added from the finest to ensure consistency in concrete. Similarly, coarse aggregates were added while ensuring uniform consistency.

Figure 5. Paddle Mixer

2.3.1 Preparation and Curing of Test Samples

Once a uniform workable concrete mix was achieved, it was poured into the moulds. Cube moulds of 100 mm x 100 mm x 100 mm conforming to BS EN 12390-1:2021 were used and the specimen cast to BS EN 12390-2:2019. Cement was replaced partially with CCA-SF blend by weight in percentages of 0, 5, 10, 15 and 20% with 0% replacement as the control sample which served as the reference for all replacement performances.

According to Abram's law, which states that the strength of concrete is inversely related to the water-cement ratio, a constant water binder ratio of 0.35 was used for all the mixes to give a fair balance of workability and strength. In a water tank filled with saturated lime, the samples were cast and allowed to cure.

2.3.2 Compressive Strength Test

Universal compression-testing equipment was used to conduct the compressive strength test with a 150 kN load. Compressive tests conforming to BS EN 12390-4 (2019) were undertaken at 3, 7, 14,28 and 56 days.

2.3.3 Flexural Strength Test

Flexural test strength was carried out after 28 days by four-point load flexural test until failure in accordance with BS EN 12390-5:2019. Figure 6 shows a beam on the testing machine before the flexural test.

Figure 6. A Beam on the Flexural Testing Machine

2.3.4 Water Absorption Test

At 28 days, the water absorption test was conducted in accordance with BS 1881-122 (2011).

2.3.5 Electrical Resistivity Test

An electrical resistivity test was carried out at 28 days in accordance with AASHTO-TP-95. The electrical resistivity test in progress is depicted in Figure 7.

Figure 7. Electrical Resistivity Test in Progress

3. Result and Discussion

3.1 Compressive Strength

Figure 8 shows the results of the compressive strength of CCA-SF blend concrete. The results reveal that the compressive strength increased gradually with the increase in curing age except for the 10 and 15% CCA-SF blend. Also, the compressive strengths increased steadily with the increasing percentage of CCA-SF blend up to 10% replacement then dropped. The control sample containing 0% CCA-SF blend, exhibited a high early strength of 29.5MPa by day 3 and steadily rose to 42.5MPa by day 28 and maintained its strength even at day 56. The sample with 5% CCA-SF blend at day 3 also exhibited a very high early strength of 37.5 MPa, which rose steadily to 56.5 MPa at day 56.

The sample containing 10% CCA-SF blend proved to be optimum, by attaining the highest early strength of 41 MPa at day 3 and ultimately 61 MPa by day 56 which is within the HPC range of 60 – 125 MPa. At 15% CCA-SF blend, day 3 results attained 35.5 MPa and rose steadily to 48 MPa by day 56. At 20% CCA-SF blend replacement, day 3 results dropped by 7% from 29.5 to 27.5 MPa. The cube strength rose steadily to 39.5MPa by day 56.

Within the first three days of curing, there is a notable increase in strength that can be attributed to the Portland cement's calcium silicates hydrating to form C-S-H gel and release Ca $(OH)_2$. According to a study [12], the initial three days of mixing concrete result in a quick and exothermic reaction.

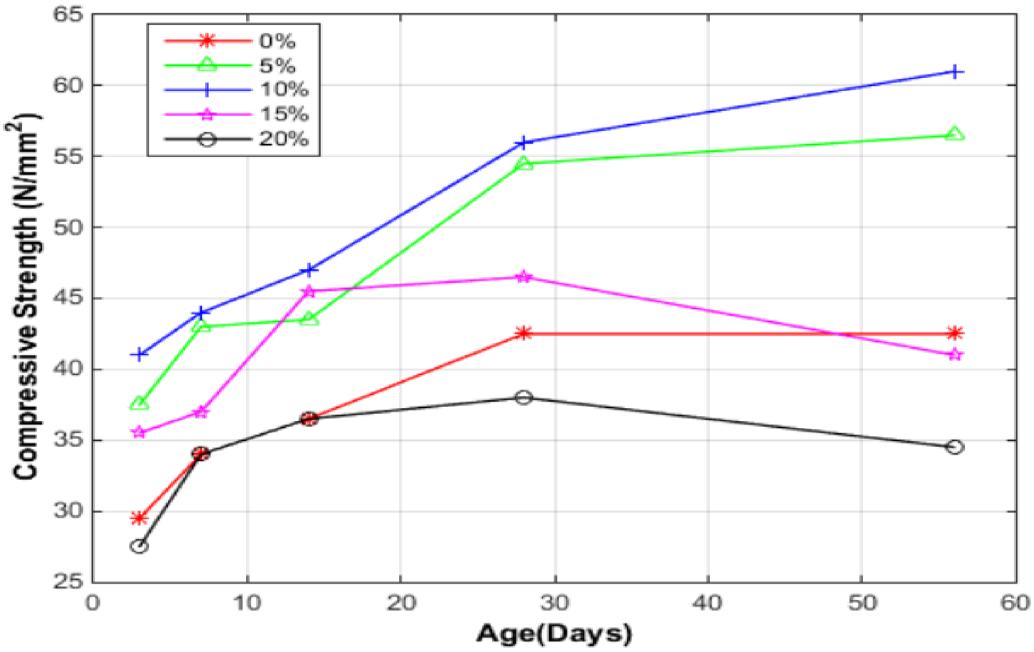


Figure 8. Compressive Strength Development with Age

Also, previous study [13] discovered that adding more cement than is necessary to a mix tends to reduce the effectiveness of mineral admixtures, which lowers strength. They contend that the pozzolanic reaction begins to be regulated by lime rather than pozzolana. To put it another way, it depends on how much Ca (OH)2 is released during cement hydration. In this instance, the addition of SF raises the pozzolana concentration above the recommended amount. Thus, rather than SF's reactivity, the rate of Ca (OH)2 release governs the rate of the pozzolanic reaction. The control mix curve levels off at day 28 as expected because the reaction is complete. Beyond 28 days for 5,10,15 and 20 % replacement, there is consistent strength gain due to the pozzolanic reaction continuing over time as well as additional C-S-H gel being formed.

The use of SP, which successfully dispersed cement particles and aided in the homogenous development of C-S-H gel throughout the concrete, may also be responsible for the increase in strength.

This enhanced concrete's compaction, cohesiveness, and strength as a result. The use of SP made it possible to lower the water-binder ratio, which boosted the concrete's strength.

But between days 28 and 56, the strength for 15 and 20% replacement decreased, indicating that the bond in the concrete's structure had broken. A similar observation [14] demonstrated that concrete's compressive strength was reduced when silica fume was added more than the recommended amount to Portland cement. This is explained by self-desiccation-induced autogenous shrinkage in cemented concrete. A study [15] confirms that autogenous shrinkage is more pronounced in high-performance concrete containing additional cementitious ingredients such as silica fumes that raise the water requirement and have water binder ratios lower than 0.4. Therefore, it is clear that although the test specimen was cured in water, low relative humidity was present as a result of the water's inability to fully penetrate the densified pore structure and reach the inner core of the concrete.

This is in line with earlier studies that found that pozzolanic concrete has a strength activity index that lasts longer than 28 days and came to the conclusion that the compressive strength of concrete decreases as the CCA-SF blend replacement percentage increases by up to 10%. The overall compressive strength of concrete diminishes after 10% replacement.

These outcomes matched those of [16]. According to previous research [17][4], the later age strength was due to the secondary reaction over time between the free lime ($Ca(OH)_2$) from the hydration of cement and the SiO_2 present in the CCA to produce compounds that provide strength such as calcium silicate hydrate (C-S-H). CCA was used as an inert filler of voids and did not contribute to the strength gain, the early strength was attributable to the cement's hydration.

3.2 Flexural Strength

The breakdown of a beam under four-point load flexural test is depicted in Figure 9. The failure on the beam was seen to occur as anticipated in the middle of the loaded length. The results of the flexural strength test performed on beams at 28 days are displayed in Table 5.

Table 5. Flexural Strength Results

Mix	0% CCA-SF Blend	10 % CCA-SF Blend
Cube Strength (MPa)	42.5	56.0
Experimental Flexural Strength	5.0	7.9
Calculated Flexural Strength	6.2	7.4

Figure 9. Beam Failure under Flexural Load

The flexural strength of the control mix determined from the experiment is 12% of the cube strength and is lower than the calculated flexural strength from EN 2 whereas the experimental flexural strength of 10 % CCA-SF blend is 14% of the cube strength and is higher than the calculated flexural strength.

3.2.1 Water Absorption

Figure 10 plots the samples' water absorption overtime on day 28. As water permeates through the loose outer surface of the concrete, it can be seen that during the first 10 minutes, the water absorption for the two mixes steadily increases. However, over time, the 10% CCA-SF blend absorbs a lesser amount of water compared to the control mix (0%) because of its dense pore structure. Since both silica fume and corn cob ash have very fine particles, the spaces between the aggregates and cement will be filled thus ensuring a dense structure.

A study [18], on the experimental and analytical analysis of the concrete's water absorption behaviour. Their research showed that curing age, water-to-binder ratio, and mineral additive all significantly affected the concrete's drying and absorption curves. Concrete that contained fly ash or slag exhibited a more obvious abnormal absorption behaviour. This describes how the 10% CCA-SF blend, which also contains silica fume and corn cob ash, behaves. The volume, morphology, and structure of C-S-H are all impacted by CCA and SF, which also has an impact on how much C-S-H can swell.

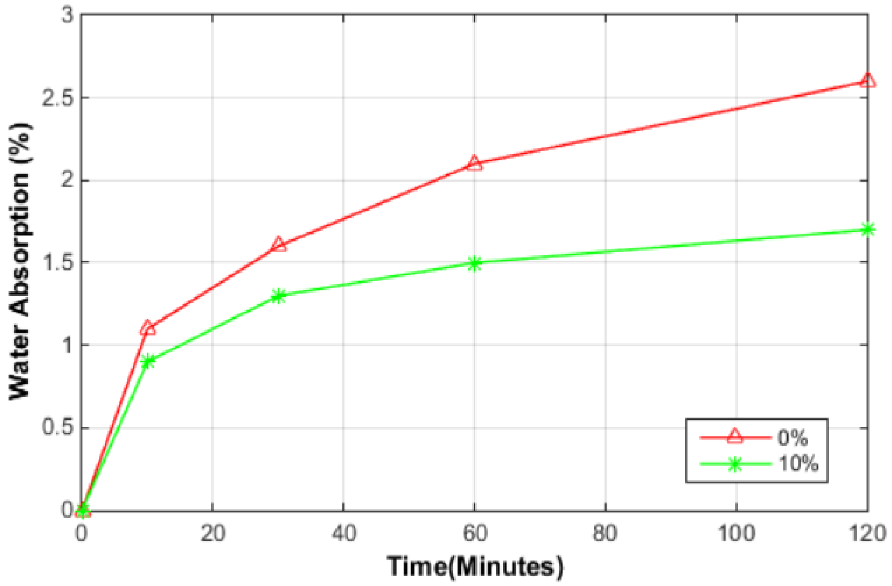


Figure 10. Changes in Water Absorption With Time

A study [19] on the factors influencing the capillary absorption characteristics of concrete and their relationship to pore structure. Water binder ratio was one of the factors that were explored and it was found that an increase in w/b increased the porosity of the concrete as a result there was a rapid acceleration of the rate of water uptake. This explains why both the control and 10% CCA-SF blend concrete rate of water absorption was steady. This was due to the use of a low water binder ratio of 0.35 in both mixes, which led to either little or a gradual increase in water absorption.

3.3 Electrical Resistivity

The samples' electrical resistivity (ER), with a 10% CCA-SF blend is shown in Table 6 showing a higher ER compared to the control mix.

Table 6. Electrical Resistivity

Mix	0% CCA-SF blend	10% CCA-SF blend
Electrical Resistivity (Ω)	11.0	29.5

According to AASHTO TP 95, an electrical resistivity range of between 9.5 to 16.5 kΩ-cm depicts moderate penetrability whereas a range of between 29 to 199 kΩ-cm depicts very low Cl penetrability which is an indication of a good level of pore density and enhanced durability. This level of durability enhances the long-term performance of the concrete. Mix 2 which is a partial replacement of cement with CCA-SF blend has a higher percentage ER increase of 168 compared to the control which is 0% CCA-SF blend. The reduced electrical resistivity of the 10% CCASF blend can be attributed to the finer particles of CCA and SF which possibly filled the pores with C-S-H and calcium aluminium silicate hydrate (C-A-S-H). Since the matrix is dense, the pore interconnectivity decreases and so is the porosity. These results coincided with previous studies [20] [21].

4. Conclusion

The following inferences can be made based on the outcomes of the numerous tests that were conducted that compressive strength results at 10% CCA-SF blend replacement produced a strength of 61 MPa at day 56 compared to 42.5 MPa which represented an increase of 44%. Flexural strength results exhibited an increase of 58% from the control mix of 5.0 to 7.9 for 10% CCA-SF blend concrete. Water absorption results showed that there was a decrease of 1.6% for the 10% CCA-SF blend compared to 2.6% for the control mix. Electrical resistivity results decreased from 29.5 kΩ-cm at 10% CCA-SF blend which depicted very low chloride penetrability compared to 11 kΩ-cm which depicted moderate penetrability. Further research should be carried out to figure out ways of reducing the content of potassium in the ash to make it a better SCM. Additionally, further studies should be carried out on the properties of fresh concrete of CCA-SF blend.

Acknowledgement

The authors are grateful to the Director Civil Engineering Department at the Technical University of Kenya for allowing the use of the Concrete Laboratory to carry out the tests and to Sika (K) Limited for the supply of silica fume and superplasticizer used in the study.

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