

Mechanical Properties of Eco-friendly Concrete Made with Sugarcane Bagasse Ash

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Abstract

Modern concretes lay emphasis on high strength in order to reduce structural member sizes to reduce materials used; high early strength to promote fast construction; high durability to reduce maintenance costs; and the incorporation of industrial and agricultural wastes to reduce environmental degradation. The incorporation of industrial and agricultural wastes into concrete as cement replacement materials reduces the amount of cement used in the production of concrete and the CO₂ emissions arising from cement production. Sugarcane bagasse is a waste product from the extraction of juice from sugar cane. It is estimated that 1.7 million tons of bagasse are produced worldwide every year. Much of the bagasse is used as boiler fuel and to produce electricity, and the ash is dumped in earth fills, resulting in critical environmental pollution that requires immediate attention. Available literature shows that when burned under controlled conditions, a pozzolanic ash of high silica content can be obtained, which can be used in concrete production with several advantages. This study investigates the mechanical properties of concrete designed for high strength and incorporating processed sugarcane bagasse ash in amounts of 10–40% by weight of cement in a binary combination with silica fume. Concrete workability in the fresh state and compressive, flexural, and tensile strengths in the hardened state are investigated. Water absorption of hardened concrete is also investigated as an indicator of potential durability. The results show that the mix containing 10% SCBA has the highest mechanical strength, and increasing the SCBA percentage reduces water absorption. However, the workability of concrete in the fresh state reduces substantially with an increase in ash content.

Keywords: Eco-Friendly Concrete; Sugarcane Bagasse Ash; Mechanical Strength; Water Absorption.

1. Introduction

Concrete is one of the most widely used manmade construction materials on the globe. The large-scale use of concrete is due to its readily available raw materials, flexibility in use, good hardened properties, good durability performance in aggressive environments, adaptability to a variety of dimensions and shapes, and low cost of repair during the whole life cycle [1, 2]. Cement production is rising rapidly to cope with demand. For instance, between 2005 and 2020, cement production rose from 2.3 to 3.5 Gt, an average annual increase of 2.5%. It is expected that cement production will reach 3.7 to 4.4 Gt by 2050 [1, 3]. However, cement production is ranked third in energy consumption after steel and aluminum [3]. Each ton of Portland cement requires about 110 kWh of electrical energy [4] and about 1.6 tons of raw materials [5, 6]. In addition, from the decomposition of limestone and chalk used as raw materials and

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from the fuel used to burn and grind raw materials, producing 1 ton of Portland cement generates about 1 ton of CO₂. The CO₂ increases the greenhouse effect and contributes to global warming [7–10]. Much effort has gone into research for materials which can be used as cement replacement or supplemental cementitious materials (SCMs) to reduce CO₂ emissions [2, 5, 11], and the use of nonrenewable raw materials. Commonly used SCMs are fly ash, blast furnace slag [12], palm oil fuel ash, rice husk ash, elephant grass ash, bamboo stem ash, wood waste ash, corn cob ash [13], coal bottom ash, and sugarcane bagasse ash (SCBA) [14], as well as silica fume (SF) [15]. Currently, there is no proper application of SCBA waste, resulting in it polluting the environment and causing a landfill problem [16].

Silica fume (SF) is a by-product of the production of ferrosilicon alloys, or silicon metal. It pollutes the environment and causes health hazards [17]. The SF color can be either premium white or grey [18]. Since the late 1970s, it has been extensively used to increase the density of concrete by filling the micro-voids in the cement paste [19]. Sugarcane is a widely grown crop globally, with 1.5 billion tonnes produced in over 110 nations [20]. Sugarcane bagasse is a by-product of the sugar producing factories after extracting the juice from sugarcane [21]. Annual sugarcane production is estimated to be 5.5 million tonnes. Considering sugarcane bagasse to be 0.3% of the total mass of processed sugarcane [22], annual sugarcane bagasse production worldwide is estimated to be 1.7 Mt. SCBA with good pozzolanic properties can be obtained when sugarcane bagasse is burned for 20 minutes at 800 to 1000°C [23, 24] or burned by air calcination for 3 hours at 600 °C [25]. The silica percentage in the ash varies depending on some factors, such as temperature, the soil type used to farm sugarcane, and the method of burning [3, 26]. This pozzolanic material can enhance concrete strength and durability when used as a mineral admixture for high-strength concrete [27]. The calcium hydroxide formed during Portland cement hydration reacts with the silica and alumina in the pozzolana in the presence of water to form calcium silicate hydrate (C-S-H), calcium aluminium hydrate (C-A-H), and calcium aluminium silicon hydrate (C-A-S-H) as shown in Equations 1 to 3.



These pozzolanic reactions are responsible for concrete's improved compressive strength [28–32]. Furthermore, the incorporation of SCBA delays the initial hydration, which improves the setting time, perhaps as a result of sulfur trioxide and phosphorus pentoxide content [12]. The compressive strength is influenced by various factors used in the production such as type of material, mix design, and material composition. In addition, the dosages of SCBA and curing methods have an influence on the mechanical properties of concrete [33]. The optimal content to the weight of cement varies with the characteristics of SCBA, but is generally between 10% and 20% [12].

Ahmad et al. [34] examined the effects of the temperature of calcination on the chemical and microstructure properties of SCBA. The sugar cane bagasse was collected and burned for 1 hour at 800 °C, and for 3 and 6 hours at 600 °C. The results showed that when burned for 1 hour at 800°C, the SCBA contained the highest amount of amorphous silica compared to the other ashes. On the other hand, Rajasekar et al. [35] investigated the effect of replacing cement with 5, 10, 15, and 20% SCBA by weight of cement on concrete properties and established that it is possible to produce ultra-high strength concrete by incorporating processed SCBA in concrete. Other researchers, Dineshkumar & Balamurugan [14] replaced ordinary Portland cement with 10, 20 and 30% SCBA and found that the ideal SCBA dosage is 20%, but as SCBA is increased, permeability and water absorption decreased. Similarly, Hussein et al. [8] investigated the replacement of ordinary Portland cement with 5% to 30% SCBA by weight in intervals of 5% and found that the highest compressive strength was observed with a 5% SCBA replacement level. Similar results were obtained by Mangi et al. [36] who also observed that at 5% SCBA dosage, the workability of fresh concrete did not change significantly.

In contrast, Chindaprasirt et al. [23] investigated pavement concrete containing 20, 40, and 60% SCBA by weight of cement and concluded that compressive strength, density, and modulus of elasticity decreased with increased volume of SCBA. In another experiment, Amin et al. [37] explored the role of finely ground bagasse ash (GBA) when used to replace 10, 20, and 30% of cement by weight. They concluded that replacement of cement by 10% of GBA produced a higher compressive strength compared to that of control. They further observed that the tensile and flexural strengths exhibited almost similar patterns to that of the compressive strength. Other research on SCBA was carried out by Rukzon & Chindaprasirt [27] investigated the compressive strength, chloride penetration depth and chloride diffusion coefficient of concrete incorporating 10, 20 and 30% SCBA. The authors concluded that the substitution of 30% SCBA is acceptable for the production of high-strength concrete (> 60 N/mm²) and also found that the incorporation of SCBA improved the resistance to chloride penetration and diffusion.

Other researches were done by Quedou et al. [38] who examined the effect of SCBA partial replacement of cement at 5, 10, 15, and 20% by weight of cement. The authors found that a 10% replacement level exhibited positive performance and can be considered a suitable cementation material in construction materials. Moreover, the water absorption increased with increasing SCBA percentage. Similarly, Jagadesh et al. [39] also investigated the mechanical

and fracture properties of mortar incorporated 5, 10, 15, 20, 25 and 30% SCBA. The authors concluded that the mechanical and fracture properties of cement mortar with 10% replacement level showed improved properties. In contrast to the aforementioned experiments.

In contrast, other researchers investigated the use of SF and the use of SF together with SCBA. Uzbas & Aydin [15] investigated the replacement of Portland cement with 5, 10, 15 and 20% SF by weight on the mechanical and microstructural properties of hardened cement paste and concrete. The authors found that SF content of up to 15% improved concrete's observed mechanical and microstructural properties. Farrant et al. [40] on the other hand, examined the effect of the mechanical and durability properties of concrete with SCBA and SF. Their results showed that with 30% SCBA and 10% SF the highest mechanical strength and the lowest permeability were realized.

In summary, the literature review clearly shows that SCBA has potential for use in concrete as a pozzolanic cement replacement material. In some of the cases, the researchers burned bagasse to produce the ash, and results varied depending on the manner in which the ash was burned. In other cases, the ash was used without any treatment, while in other cases, some method of pretreatment was used. The results obtained are, therefore, subject to many variables and do not offer a specific conclusion on what can come out of using SCBA as a partial replacement of cement in concrete production. The purpose of this research is to characterize SCBA produced by a local sugar mill, to attempt to improve it by controlled reburning, then use it to design a high strength concrete and to study its characteristics in the fresh and hardened state. The success of this research will add value to local SCBA waste, reduce the clinker associated with concrete production, and by extension, reduce the consumption of nonrenewable raw materials and CO₂ emission.

2. Materials and Methods

2.1. Material

Cement

The cement used was Portland cement *CEM I/42.5N* manufactured locally to EN 197 with a specific gravity of 3.1. The chemical composition of the cement is given in Table 1.

Table 1. Chemical Compositions of fine materials by weight

Oxides	Cement	Raw SCBA	SCBA after burning	Silica fume
Silicon dioxide (SiO ₂)	24.619	80.005	76.18	97.99
Aluminium oxide (Al ₂ O ₃)	5.454	8.923	3.62	0.00
Iron (III) oxide (Fe ₂ O ₃)	2.741	3.19	8.71	0.099
Calcium oxide (CaO)	62.741	1.482	2.88	0.664
Potassium oxide (K ₂ O)	0.607	2.705	5.495	0.123
Magnesium oxide (MgO)	0.000	2.372	0.00	0.001
Phosphorus pentoxide (P ₂ O ₅)	0.439	0.537	1.422	0.615
Titanium dioxide (TiO ₂)	0.193	0.464	0.937	0.018
Manganese oxide (MnO)	0.025	0.16	0.456	0.021
Sulfur trioxide (SO ₃)	2.964	0.00	0.00	0.394
Loss on ignition (LOI)	-	15.08	5.82	-
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	-	92.12	88.51	-

Sugarcane Bagasse Ash (SCBA)

Raw SCBA was obtained from Sukari Industries Ltd, in Western Kenya. The SCBA was oven-dried for 24 h at a temperature of 105 °C to remove the moisture, sieved through a 75 µm sieve, and tested for chemical compositions and loss on ignition (LOI). The LOI of the raw SCBA was 15.08%. The raw SCBA was re-burned in an electric furnace for 4 hours at 650 °C to reduce the LOI below 6% to meet the requirement of ASTM C618. A chemical test was repeated on the re-burned SCBA and chemical analysis of the raw and re-burned SCBA was carried out by the x-ray fluorescence (XRF) analysis. Both results are given in Table 1. The major oxide found in the SCBA after re-burning was silica (SiO₂), which was 76.18% of the total weight. The summation of SiO₂, Al₂O₃, and Fe₂O₃ was 88.51% and the LOI was 5.8 %, slightly lower than the specified limit of 6%. According to ASTM C168, the re-burned SCBA met the requirement for a Class F pozzolan. Figure 1 presents the X-ray diffraction pattern (XRD) of the raw SCBA. The raw SCBA contained the main crystallization phases of quartz, hematite, cristobalite, calcium phosphate, and potassium carbonate, as well as mulite. Figures 2-a and b show the physical appearance of raw and re-burned SCBA, and Figure 3 shows the particle size distribution of the raw SCBA, which ranged from 1.6 to 74 µm, with an average particle size distribution (D₅₀) of 16 µm. The processed SCBA had a specific gravity of 2.1.

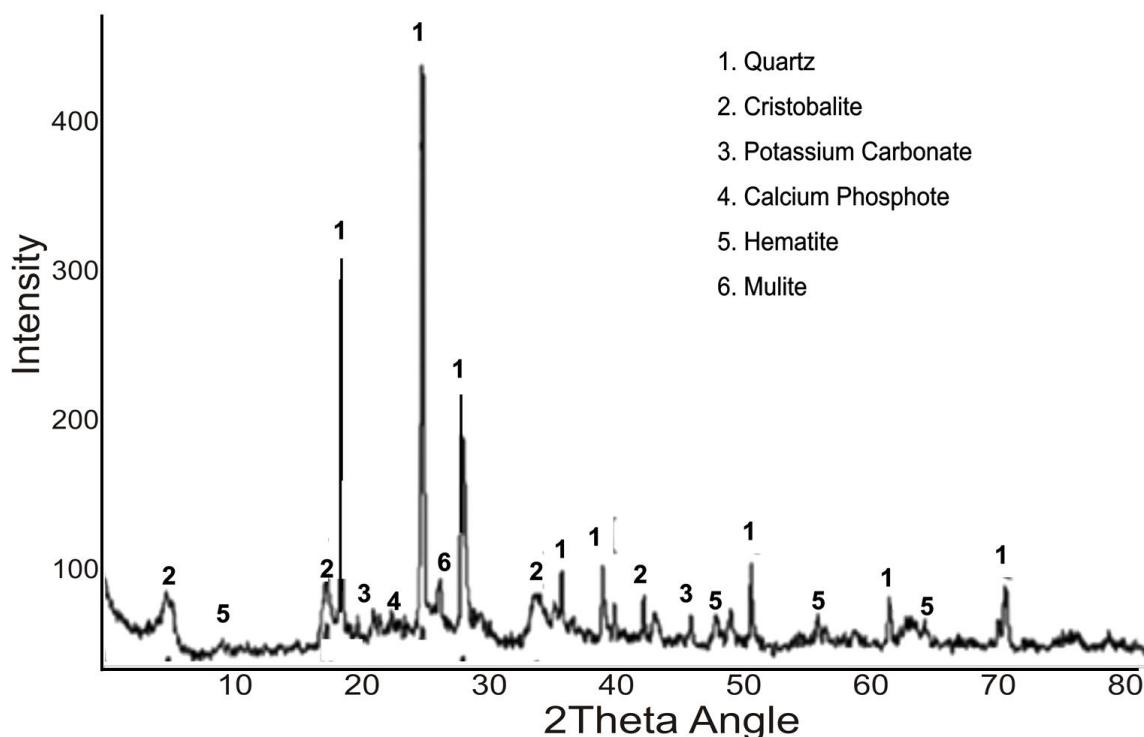


Figure 1. XRD pattern of raw sugarcane bagasse ash



Figure 2. Physical images of sugarcane bagasse ash and silica fume

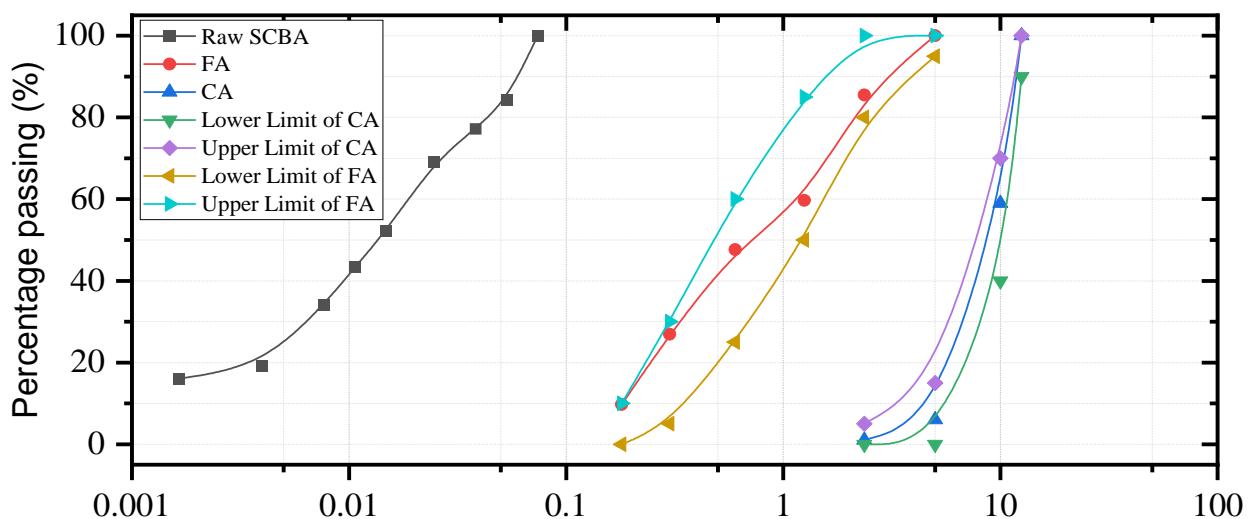


Figure 3. Particle size distribution of materials (mm)

Silica Fume

Silica fume consisted of a grey powder with a specific gravity of 2.20. The chemical compositions are shown in Table 1. SiO₂ was the major oxide present, which was 97.99%. Figure 2-c presents the physical appearance of the silica fume.

Superplasticizer

The superplasticizer (SP) used was a locally produced polycarboxylate based superplasticizer. The properties are presented in Table 2.

Table 2. The properties of superplasticizer

Colour	Yellowish
Specific gravity	1.08
Solid content (%)	34

Aggregates

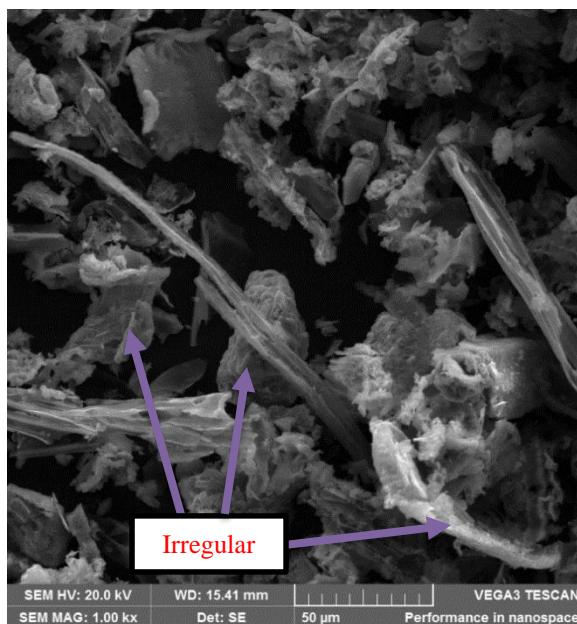
Coarse aggregate (CA) consisted of crushed stone of maximum aggregate size (MAS) 12.5 mm. The CA was washed through ASTM sieve No. 2.36 mm and sun-dried before use. Fine aggregate (FA) consisted of river sand and quarry dust, both of which were washed on ASTM 0.18 mm sieve and oven-dried at 105°C for 24 hours, then mixed in the ratio of 70% sand to 30% quarry dust. Table 3 shows the properties of the aggregates. All tests were conducted in accordance with ASTM standards. The aggregate particle size distribution is shown in Figure 3.

Table 3. The physical properties of the aggregates

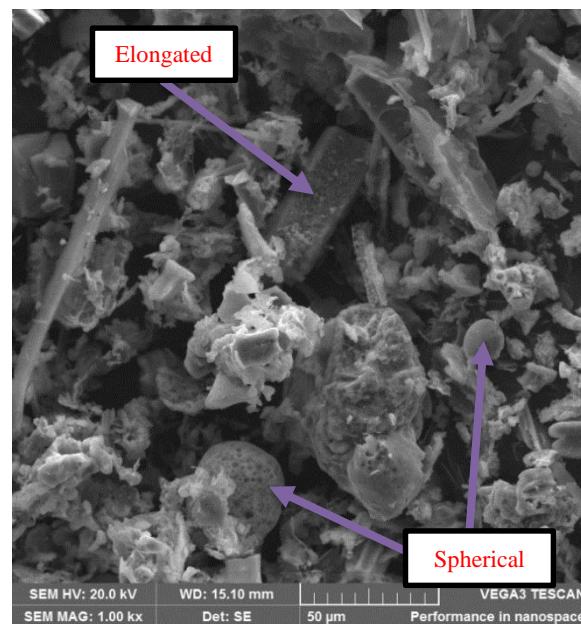
Type of aggregates	Fineness modulus	Specific gravity	Water absorption (%)	Density (kg/m ³)	Voids ratio (%)	Aggregate crushing value (ACV) (%)	Aggregate impact value (AIW) (%)
Coarse aggregates	-	2.66	3.5	1,468	42	17.6	6.2
Fine aggregates	2.70	2.61	7.61	1,677	28	-	-

Scanning Electron Microscope (SEM) Imaging of the Powders

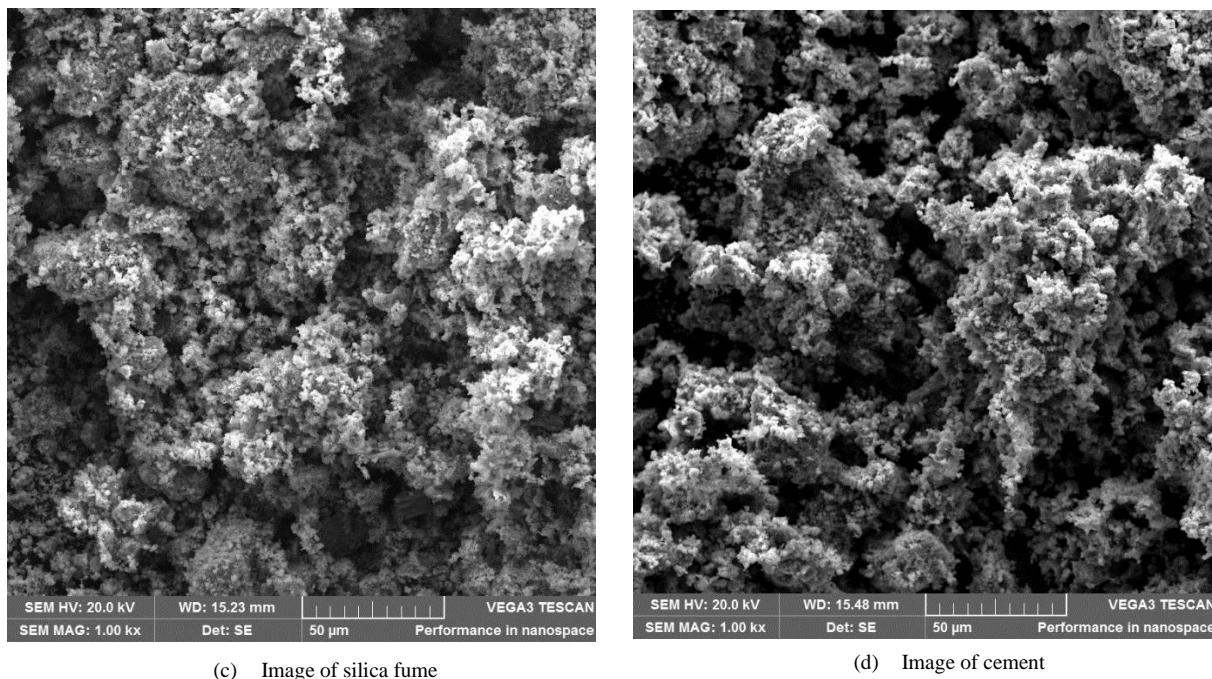
Figure 4 shows the microscopic images of the SCBA, silica fume, and, cement which were taken using scanning electron microscopy (SEM) to reflect the details of the particle's morphology. The SEM images of the SCBA show that most of the SCBA particles are irregular in shape with a non-smooth surface, and porous. As a result, when the SCBA was blended into the cement matrix, the water demand increased. Silica fume was observed as fine particles that increased the physical packing of paste, thus improving durability and the ultimate strength by enhancing the bond between hardened cement paste and aggregates.



(a) Image of raw SCBA



(b) Image of processed SCBA

**Figure 4. SEM imaging of SCBA, silica fume and cement**

Mix Proportions

A total of five (5) mixes of concrete were prepared according to the procedure given in ACI 211.4R-2008. The control mix 1 had 0% SCBA. The remaining four mixes were prepared by partial replacement of cement with SCBA at 10, 20, 30, and 40%, respectively. All mix details are given in Table 4. The amount of superplasticizer used varied according to the weight of the powders. In addition, the water-binder (w/b) ratio was increased for the mixes with 30% and 40% SCBA.

Table 4. Mix proportional of concrete (kg/m³)

Mix	SCBA (%)	Cement	SCBA	Silica fume	Water	Superplasticizer	Fine aggregate	Coarse aggregate
1	0	475	0	25	175	3.0	700	1000
2	10	428	48	25	175	6.0	700	1000
3	20	380	95	25	175	9.0	700	1000
4	30	333	143	25	225	6.0	700	1000
5	40	285	190	25	225	7.5	700	1000

2.2. Methodology

Execution of the Study

The study was carried out to the flow chart given in Figure 5. The materials were collected, prepared, characterized, and then used to prepare the test samples. The samples were tested as described in the following sections.

Concrete Mixing

A rotating drum mixer was used for mixing the concrete. Water was added to the mixer followed by cement, SCBA and SF and these were mixed to form a uniform paste. Fine aggregate was then added to the paste and mixing continued to produce uniform mortar. Lastly, coarse aggregates were added to the mortar and mixed to produce concrete of uniform consistency. SP was added to the mix at all stages to maintain a workable mix.

Workability

The workability of freshly mixed concrete for all mixes was determined by the slump test in accordance with ASTM C143/C143M – 10.

Preparation and Curing of Test Samples

Rate until the cube was crushed. The maximum load attained was recorded and used to calculate the crushing load intensity. Concrete into the cube in two equal layers and compacting each layer by 25 tamps of a standard tamping rod.

The top of the cast cube was levelled smooth using a trowel. For the split tensile and water absorption tests, a total of 30 cylinders of 100 mm diameter and 200 mm height were cast by placing the concrete into the mould in three equal layers and compacting each layer by 25 tamps of the standard tamping rod, then levelling off the surface smooth with a trowel. Lastly, 15 prisms of size 150×150×500 mm were cast for the flexural strength test. All cast specimens were covered by moist cloth and left to stand overnight. The samples were then demoulded and cured in water until the time of test.

Compressive Strength

A universal compression testing machine with a load capacity of 150 Mt. was used to test the cube samples. At the specified age, the concrete samples were removed from the curing tank, wiped dry using a soft cloth, and then left to stand for 1 h to air dry. Each sample was then placed centrally between the battens of the compression testing machine. The top batten was brought into contact with the top surface of the sample, and load was then applied at a constant rate until the cube was crushed. The maximum load attained was recorded. Tests were carried out at 3, 7, 14, 28, and 56 days and 3 cubes were tested to obtain an average value for each record. The tests were carried out to BS EN 12390- 03.

Split Tensile Strength

Split tensile strength test was carried out at 28 days to ASTM C 496/C 496M – 04. 3 cylinders were tested for each mix and the average value was recorded.

Flexural Strength

Flexural strength test was carried at 28 days to ASTM C78 – 02. 3 prisms were tested for each mix and the average value was recorded.

Water Absorption

Water absorption test was carried out at 28 days to BS 1881-122 (2011). 3 cylinders were tested for each mix and the average value was recorded.

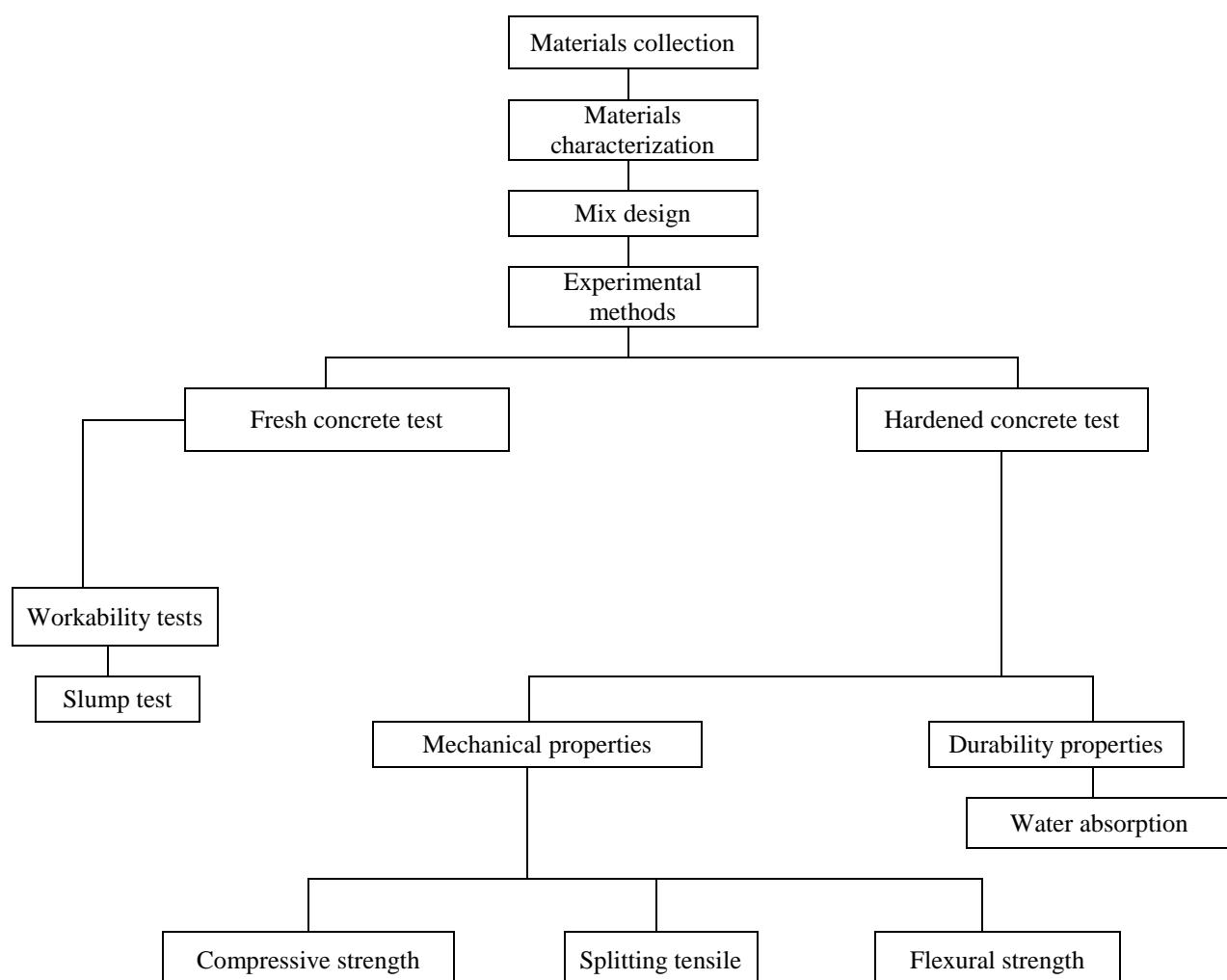


Figure 5. Flow chart for the study

3. Results and Discussion

3.1. Workability

In previous studies, it has been observed that the water demand increases with increasing SCBA replacement ratio in concrete, which decreases workability as reported by Jha et al. [24] and Landa-Ruiz et al. [17]. However, other studies have also observed that improvement in workability can be attributed to the low value of LOI as reported by Wu et al. [41] and Hussein et al. [8], which indicates that the SCBA is low in carbon content. In this study, Figure 6 shows the slump value for all concrete mixes at different SCBA contents. It is observed that the slump decreases with an increase in SCBA content. This can be attributed to the flaky shape, rough texture, and porosity of SCBA grains, as can be observed from SEM images.

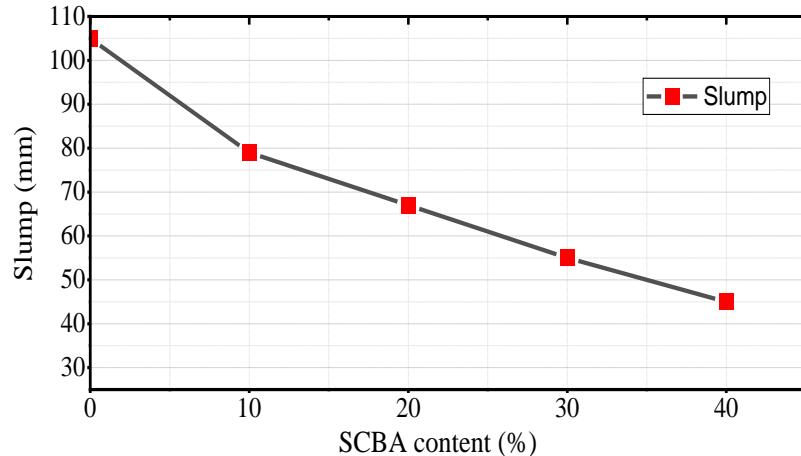


Figure 6. Effect of the SCBA on the workability of concrete

3.2. Compressive Strength

Figure 7 shows the compressive strength results for the five mixes over the 56-day test period. A significant increase in strength over the control is observed in mix 2 with an increase of 6% at 28 days and 11% at 56 days which is attributed to the conversion of dormant $\text{Ca}(\text{OH})_2$ in the control mix to cementitious C-S-H, C-A-H, and C-A-S-H. However, at higher SCBA dosages, the strength reduces with respect to the control. Strength gain can only take place when there is enough $\text{Ca}(\text{OH})_2$ to react with all the SCBA. When the amount of SCBA exceeds the amount of available $\text{Ca}(\text{OH})_2$, the SCBA exerts a diluting effect on the paste resulting in a reduction in strength. It is also observed that, whereas 10% SCBA inclusion produced concrete in the high strength category with compressive strength at 28 days in excess of 60 MPa, all the other mixes with SCBA inclusion up to 40% produced structural grade concrete with 28-day strength in excess of 25 MPa.

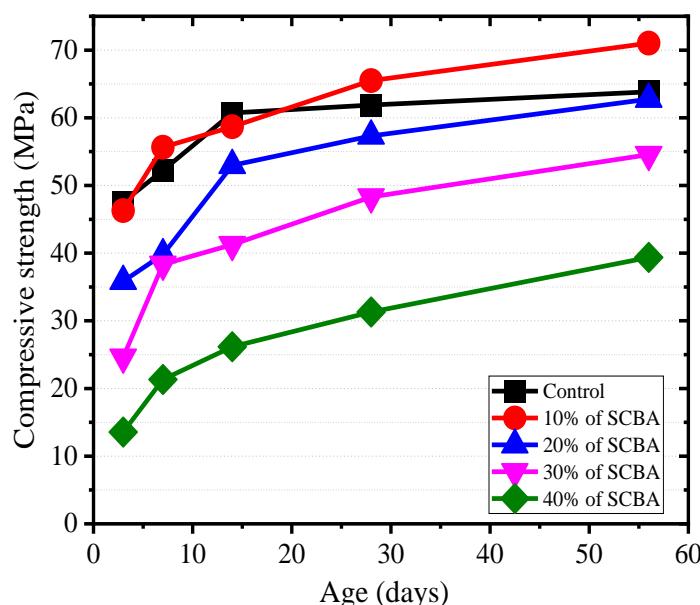


Figure 7. Effect of the SCBA on compressive strength of the concrete

Another significant observation is that mixes 2, 3, and 4 produced concrete with high early strength of 25 MPa and above at 3-days. This can allow early removal of formwork and accelerate the rate of construction with significant savings in costs and time. The increase in strength may be attributed to the fine particle size of SCBA, which is distributed all over the mix of concrete and increases the packing density. Also, the fine reactive silica content reacts with calcium hydroxide and forms calcium silicate hydrate (C-S-H), which is responsible for the strength of concrete, as reported by Akram et al. [42], Jagadish et al. [5], and Shah et al. [33]. Moreover, also previous studies have found a similar trend of decreasing strength at an early age and then increasing strength with increasing curing ages, as observed by Amin et al. (2022) [43], Chindaprasirt et al. [4], and Amin et al. (2020) [37], which can be attributed to the late pozzolanic activities of the SCBA.

In Figure 8, the compressive strengths per unit weight of concrete are compared. The lower unit weight of SCBA compared to cement results in the reduction of the weight of concrete. It is observed that when this consideration is made, mix 3 with SCBA content of 20% compares well with the control mix. The weight advantage of mix 2 over the control is also observed to increase.

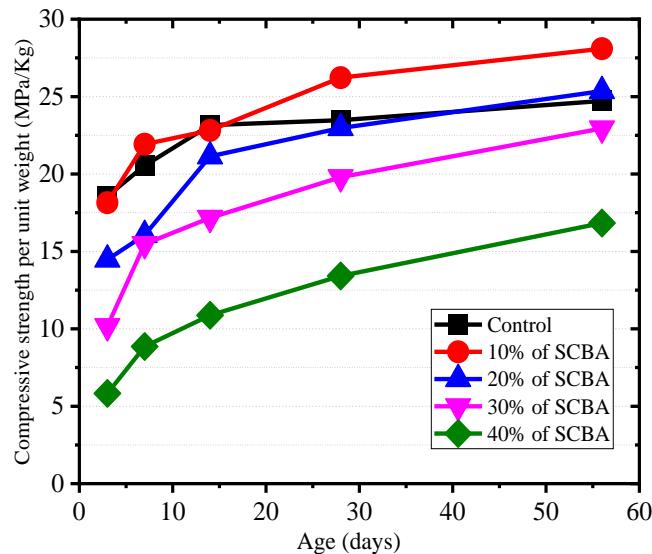


Figure 8. Effect of the SCBA on compressive strength per unit weight of the concrete

3.3. Split Tensile Strength

Figure 9 presents the split tensile strength results at 28 days, which followed a similar trend as observed in the compressive strength. A mix incorporating 10% SCBA showed the highest tensile strength value, which was 10% higher than the control mix, whereas mixes containing 20%, 30%, and 40% SCBA showed 3.9 %, 11 %, and 35 %, respectively, lower than the control mix. A similar decrease in splitting tensile strength was observed as SCBA percentage increased, as reported by Shafiq et al. [44] and Gupta et al. [19], which followed the same trend as for compressive strength.

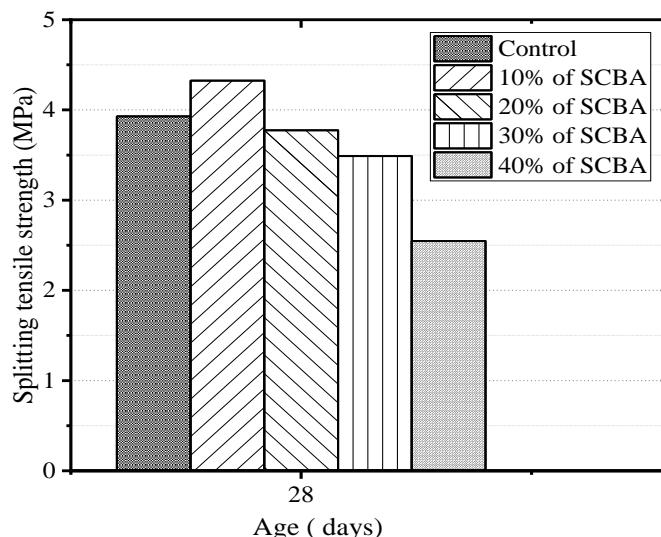


Figure 9. Effect of SCBA on the 28-day split tensile strength of concrete

3.4. Flexural Strength

The test results for 28-day flexural strength are shown in Figure 10. The results followed the same trend as for compressive strength. The mix containing 10% SCBA had the highest flexural strength, which was 8 % greater than the control mix. A mix containing 20% SCBA showed slightly lower flexural strength, whereas mixes containing 30 % and 40 % SCBA replacement showed much lower strengths of 23% and 28%, respectively.

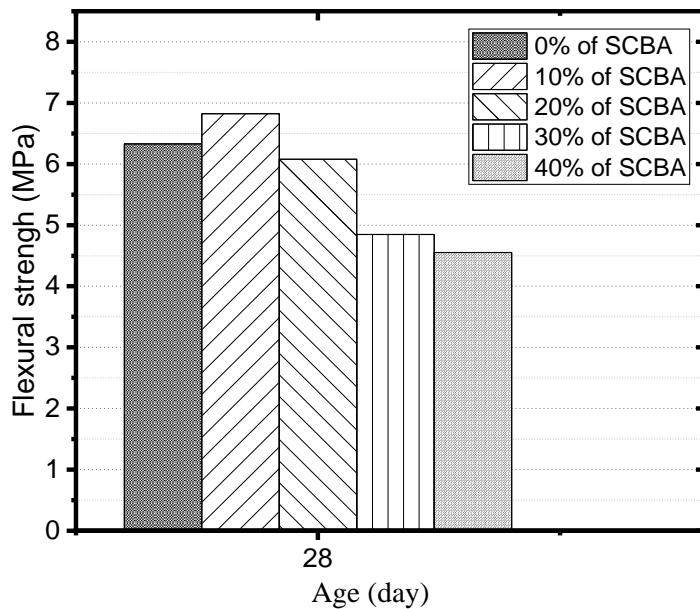


Figure 10. Effect of SCBA on the 28-day flexural strength of concrete

3.5. Water Absorption

Table 5 shows the water absorption results of the five mixes. As the percentage of SCBA is increased, the water absorption decreases. The water absorption rate for mixes containing 10%, 20%, 30%, and 40% of SCBA gradually decreased by 9%, 8%, 14%, and 15%, respectively, compared to the control mix. The decrease in water absorption percentages at all SCBA replacement levels indicates that SCBA has a filling effect in the concrete mixes. A similar study by Dineshkumar & Balamurugan [14] stated that due to the use of fine bagasse ash, the pores between the concrete particles were filled, resulting in a lower percentage of water absorption. On the other hand, another study by Amin et al. [43] concluded that the decrease in water absorption could be attributed to the pozzolanic reaction of the concrete becoming slower with a high percentage of bagasse ash cement replacement. The percentage of water absorption was calculated using Equation 4.

$$\text{Percentage of absorption} = \frac{W_w - W_d}{W_d} \times 100 \quad (4)$$

where, W_w is wet weight of the specimen, and W_d is dry weight of the specimen.

Table 5. Water absorption percentage

SCBA (%)	Dry weight (g)	Wet weight (g)	Percentage of absorption (%)
0	3721	3766	1.21
10	3742	3783	1.10
20	3641	3682	1.12
30	3541	3578	1.04
40	3425	3460	1.03

4. Conclusion and Recommendation

In this study, researchers have investigated the possibility of using SCBA up to 40% and its blend with SF as a partial replacement of cement to produce sustainable and high-strength concrete. The influence of cement replacement with SCBA and silica fume on the fresh properties of concrete (slump), the hardened mechanical properties of concrete (compressive strength, splitting tensile strengths, and flexural strength) and water absorption was assessed and compared to that of the control mix.

The results demonstrated that slump content decreases with an increase in SCBA content. On the other hand, a high early strength of 25 MPa and above is obtained at 3-days with SCBA addition of up to 30%, with potential for the early striking of formwork and fast construction. In addition, concrete of a high 28-day strength in excess of 60 MPa can be produced by replacing cement with 10% SCBA, and concrete of a normal 28-day strength above 25 MPa can be obtained by substituting cement with SCBA up to 40%. At 28 days of age, the compressive strength, split tensile strength, and flexural strength followed the same trend. Furthermore, the addition of SCBA reduces the water absorption of concrete, which increases with the amount of SCBA added up to 40%. This has the potential to enhance the durability of concrete.

The authors recommend that SCBA can be used as a cement replacement material at various dosages of up to 40% to impart advantages to concrete in the form of increased strength, reduced weight, and reduced water absorption. The incorporation of SCBA in concrete adds value to the material and offers an avenue for the disposal of SCBA waste, thereby creating a cleaner environment. Partial replacement of Portland cement with SCBA reduces the amount of cement used in construction. Hence, clinker is required to produce cement. The result is reduced CO₂ emitted during clinker production, environmental pollution and global warming. A new industry can be developed around the processing of raw SCBA for use in concrete, resulting in increased jobs and enhanced economic activity.

5. Declarations

5.1. Author Contributions

Conceptualization, T.A.A, D.O.K, S.M.S, and M.M.; methodology, T.A.A.; validation, D.O.K, S.M.S, and M.M.; investigation, T.A.A.; data curation, T.A.A, and D.O.K.; writing—original draft preparation, T.A.A.; writing—review and editing, D.O.K, S.M.S, and M.M.; supervision, D.O.K, S.M.S, and M.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding and Acknowledgements

The authors appreciate and acknowledge the African Union for financial support for this work. Also, the authors appreciate Pan African University, Institute for Basic Science, Technology, and Innovation, and Jomo Kenyatta University of Agricultural and Technology for technical support and for the use of the Structural Engineering Laboratory.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

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