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Mechanical and Microstructural Properties of Geopolymer Concrete Containing Fly Ash and Sugarcane Bagasse Ash

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Abstract

Portland cement plays a vital role in construction and building projects. However, its manufacturing process releases detrimental pollutants and contributes to climate change. The environmental concerns linked to the manufacturing of conventional Portland cement, such as its high energy demands, raw material consumption, and significant CO_2 emissions, have prompted the need to look for alternatives such as geopolymer or green concrete. In addition, indiscriminate disposal of waste might have a detrimental effect on the environment. This paper investigates the mechanical and microstructural properties of geopolymer concrete incorporating fly ash and sugarcane bagasse ash as primary constituents. Sugarcane bagasse ash (SCBA) was employed as a partial substitute for Fly Ash (FA), with varying proportions ranging from 5% to 20% with increments of 5%. Alkaline activators utilized were NaOH (14M) and Na_2SiO_3, with a ratio of 1.5. Various tests, including the slump test, compressive strength test, splitting tensile strength test, and flexural strength test, were performed. The microstructural characteristics were assessed by scanning electron microscopy (SEM), energy dispersive analysis (EDS), and X-ray diffraction analysis (XRD). The results revealed that adding sugarcane bagasse ash influenced the workability of geopolymer concrete while enhancing its mechanical properties. The research findings have shown that the mixture comprising 5% SCBA has the greatest compressive strength of 64 MPa.

Keywords: Geopolymerization; Sugarcane Bagasse Ash; Fly Ash; Microstructure; Alkaline Activator; Building Projects.

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1. Introduction

Global warming has become a crucial concern for the long-term survival and progress of human society, requiring an approach to development that is environmentally friendly and sustainable over a long time [1, 2]. Ordinary Portland cement (OPC) is among the building materials utilized in construction most of the time. OPC manufacturing is highly energy-intensive and produces CO_2 [3-5]. From an ecological perspective, it is necessary to establish a worldwide infrastructure utilizing industrial waste materials [6]. Substantial quantities of construction and related waste are created, and the inappropriate elimination of these waste products has led to notable environmental repercussions, including flooding and the devastation of natural areas. Substituting them for cement provides a viable solution for mitigating

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ecological concerns linked to waste disposal [7]. The usage of pozzolana ingredients obtained from agricultural and industrial waste materials, such as fly ash, blast furnace slag, metakaolin, corncob ash, rice husk ash, and sugarcane bagasse ash, decreases the amount used for energy and production expenses of concrete. Moreover, it addresses the problems associated with storage and disposal, thereby facilitating the creation of environmentally friendly concrete. Thus, the development of a suitable substitute for OPC is highly significant.

Recently, inorganic polymer concrete has become a promising option for environmentally friendly building materials, offering a viable solution to the need for alternative materials in the industry [8-10]. Geopolymers, which are cementitious materials, have been recently developed as a long-term substitute for OPC to alleviate the adverse environmental effects [11]. Davidovits first presented the concept of geopolymers as a novel type of binder that falls under the classification of inorganic polymers [12-14]. Geopolymers are formed of two main components: a raw material with a high amount of SiO2 and Al2O3 and an alkaline activator solution. These materials are inorganic aluminosilicate compounds [15]. For civil engineering applications, GPC has superior chemical and mechanical characteristics over concrete based on Portland cement (PC), such as stronger mechanical strength and quick hardening [16-18], superior resilience to heat and fire [19-21], high impermeability, acid and salt resistance, and shallow chloride penetration depth [22, 23], and lower creep effects [24]. Geopolymerization is a series of steps that involve leaks and dispersals, polymerization, reorientation, and condensation [25]. The polymerization of GPC occurs due to the condensation process, resulting in heat release during the endothermic reaction [26]. An alkaline activator solution, which commonly consists of potassium hydroxide (KOH), sodium hydroxide (NaOH), potassium silicate (K_2SiO_3), or sodium silicate (Na_2SiO_3), plays a significant part in the development of Si and Al crystal structures [11]. However, a mixture of Na_2SiO_3 and NaOH is the most popular alkaline activator. At the time of geopolymerization, Si-O-Al bonds are formed through the polycondensation of aluminosilicate oxides (Si_2O_5, Al_2O_2) and alkali polysilicates (Na_2SiO_3) [27]. To produce geopolymer materials, OH ions and a collection of monomers undergo a chemical reaction that dissolves Al and Si from the waste product [26, 28]. The geopolymer can exist in various forms like -Si-O-Al-O- or –Si-O-Al-O-Si-O or –Si-O-Al-O-Si-O-Si-O-. Equations 1 and 2 can be used to depict the configuration of geopolymer material [13, 29, 30]:

$$n(si_2o_5.Al_2O_3) + 2nSio_2 + 4nH_2O + KOH\ or\ NaoH \rightarrow Na^+K^+ + n(OH)_3 - Si - O - \underset{(OH)_2}{\overset{Al^-}{|}} - O - Si - (OH)_3 \tag{1}$$

$$n(OH)_3 - Si - O - Al^- - \underset{(OH)_3}{\overset{O}{|}} - Si - (OH)_3 + NaoH\ or\ KOH \rightarrow (Na^+, K^+) - \left(-\overset{Si}{\underset{|}{\overset{|}{O}}} - O - \overset{Al^-}{\underset{|}{\overset{|}{O}}} - O - \overset{Si}{\underset{|}{\overset{|}{O}}} - O - \right) + 4nH_2O \tag{2}$$

FA remains a substance formed by coal combustion for energy generation, and it has been recognized as a detrimental agent to the environment. The annual production of FA is approximately 2.8 billion metric tons [31, 32]. The principal components of FA ash are Al_2O_3, SiO_2, CaO, and Fe_2O_3, which are found in both crystalline and amorphous oxides and a variety of minerals [33]. Minor elements, on the other hand, such as As, Pb, Cr, and Hg, may be toxic. Consequently, FA is extensively acknowledged as a detrimental by-product, and its inappropriate disposal negatively influences the environment and ecology. Additionally, the capacity of landfills will increase [34]. Recently, there have been efforts to utilize fly ash in more eco-friendly and practical applications. Instead of storing or disposing of FA, it could be used as a fundamental component in GPC to reduce waste and support sustainability. FA is categorized according to both physical and chemical characteristics. Class F is distinguished by having low silica and high calcium content and displays a lower reactivity than Class C, which contains a more significant proportion of silica [35]. The disparity in reactivity across components impacts the geopolymerization process and directly affects the geopolymer's strength [36]. On the other hand, SCBA is a globally accessible byproduct that converts bagasse into energy by combustion in boilers [37]. The yearly SCBA production is anticipated to reach 48-60 million tons based on yield [38], and if dumped recklessly will cause an environmental problem. In addition to becoming generally accessible, previous studies have shown that partially substituting cement weight with SCBA considerably enhances the mechanical characteristics and durability of the concrete mix [38-44]. High-quality SCBA can be produced by burning sugarcane bagasse at temperatures varying between 800 to 1000°C for 20 minutes [45, 46] or heating in the air at 600 °C for three hours [47]. The percentage of silica present in the ash changes depending on the temperature, the land used to cultivate sugarcane, and how it was burned [48-50].

The durability and mechanical properties of GPC utilizing GGBFs, or FA, have been researched recently. However, little research has been done on SCBA [51, 52]. Singh [53] examined the microstructure, mechanical properties, and durability of metakaolin and SCBA-based GPC. Metakaolin and SCBA were used to replace 10%, 20%, 30%, and 40% of FA in preparing FA-based GPC. Samples of geopolymer concrete Were treated in an oven at 90°C for 24 hours before being permitted to cool to room temperature. Metakaolin-contained GPC has better mechanical and durability properties than SCBA-contained. Microstructure studies showed that metakaolin containing GPC has denser intermolecular bonding than bagasse ash. H.M. and Unnikrishnan [54], in their analysis of the microstructure and mechanical strength of GPC made from GGBS-SCBA, found that as molarity rose from 8M to 12M, the strength properties of the GPC also raised. They concluded that with a Na_2SiO_3 to NaOH ratio 2.5 and an 8M NaOH solution, the geopolymer concrete composed of 80% GGBFs and 20% SCBA can achieve a desired strength of 30-35 MPa. Vanathi et al. [55] partially studied using FA to substitute SCBA in the presence of 50% GGBFs. The optimal mechanical performance is achieved when 20% of FA is replaced with SCBA. The compressive strength reaches 52.56 MPa after 28 days of curing, which is 22% higher than the control GPC. The findings showed that cylinder compressive and split tensile strengths and cube compressive and flexural strengths are all intimately related.

Researchers have demonstrated a rising interest and achieved successful results in utilizing industrial and agricultural byproducts, such as FA, GGBFs, metakaolin, rice husk ash, and corncob ash, as raw ingredients in making GPC. The efficacy of GPC derived from FA-SCBA has not been extensively studied. Therefore, synergistic use of fly ash and sugarcane bagasse ash as precursors to developing sustainable geopolymer concrete has been attempted in this study by involving partial replacement of FA with SCBA at various substitution levels ranging from 5% to 20%, with a 5% increment. Na_2SiO_3 gel and a 14M NaOH solution were the activators. Hence, in this current study, properties of newly developed sustainable geopolymer concrete have been studied in terms of workability, compressive strength, split tensile strength, and flexural strength and also in terms of microstructural characteristics based on Scanning electron microscope images, Energy dispersive X-ray analysis, and X-Ray diffraction analysis. The strength results were compared with the ordinary Portland cement concrete. The results revealed that the strength of the GPC performed better than ordinary Portland cement concrete.

2. Materials and Methods

2.1. Materials

2.1.1. SCBA and FA

Unprocessed SCBA was acquired from Western Kenya's Sukari Industries Ltd. To eliminate moisture, SCBA was dried in an oven for 24 hours at 105^{O} C. The ash from sugarcane burning was passed using a 75 µm filter to eliminate large clumps of ash substances and any remaining carbonaceous components to obtain the appropriate particle size for the SCBA. The next step involved testing the compositions of chemicals and loss of ignition (LOI). The unprocessed SCBA had a high LOI of 10.20%. As a result, it was burned again at 650 ° for four hours in a muffle furnace to decrease the LOI under 6% to conform to the ASTM C618 criteria. The LOI of re-burned SCBA was 0.97 %. A chemical analysis was performed on the raw and processed SCBA using X-ray fluorescence (XRF), and the outcomes are displayed in Table 1. The FA that was employed in this investigation was obtained from India. As indicated in Table 1, it is classified as a Class F fly ash due to its calcium oxide level being below 10%, as per ASTM C-618.

Table 1. XRF and LOI results for SCBA and FA

Oxides	Raw SCBA	SCBA after burning	FA	Specification of ASTM C 618 for class F
SiO_2	81.32	76	54	
Al_2O_3	5.51	9	19.6	
Fe_2O_3	6.95	4.2	6.9	
$SiO_2 + Al_2O_3 + Fe_2O_3$	93.78	89.2	80.5	Min (70%)
CaO	1.71	3.1	7.9	Max (10%)
K_2O	2.68	3.83	2.2	
MgO	-	2.7	6.9	
P_2O_2	0.5	0.69	0.34	
TiO_2	0.65	0.46	0.88	
MnO	0.39	0.2	0.1	
LOI	10.20	0.97	1.87	Max (6%)

2.2.2. Aggregates

The crushed stone in coarse aggregate had a specific gravity and max aggregate size of 2.66 and 12.5 mm, respectively. The coarse aggregate was washed and dried in the sun. The fine aggregate is a mixture of 30% quarry dust and 70% river sand that has been cleaned through an ASTM 0.18 mm filter, followed by oven drying for 24 hours at 105°C. Table 2 displays the aggregates' properties. All testing was performed in compliance with ASTM recommendations. Figure 1 shows the distribution of particle sizes in the aggregate.

Table 2. Aggregate physical properties

Aggregates	Fineness modulus	Specific gravity	Water absorption (%)	Density (kg/m^3)	Voids ratio (%)	Crush value (%)	Impact value (%)
Coarse aggregates	-	2.66	3.6	1468	42	17.6	6.2
Fine aggregates	2.60	2.61	3.5	1677	28	-	-

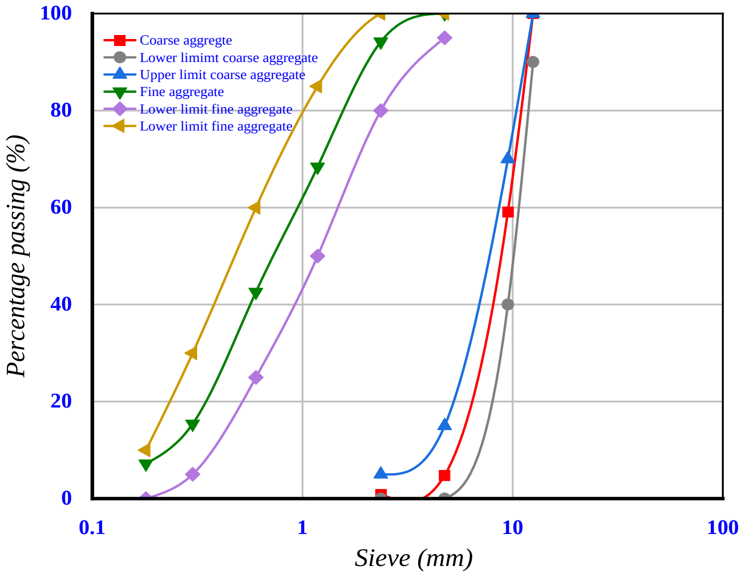


Figure 1. Aggregates' distribution of particle sizes

2.1.3. Activator Solution

Generally, three kinds of activators can be used to make GPC: Na_2SiO_3, NaOH, KOH, or a blend of both. The most commonly used activator to prepare GPC is a combination of Na_2SiO_3 and NaOH [56-58]. According to recent research and studies, using NaOH alone or in combination with Na_2SiO_3 improves the mechanics of strength and significantly accelerates geopolymer processing [59, 60]. The activators' concentration when producing geopolymer concrete or mortar influences the properties in the fresh and hardened stages [27, 61].

Alkaline activators, including Na_2SiO_3 and NaOH with a ratio of 1.5, were used to make FA-SCBA-based geopolymer concrete. They were acquired in Nairobi, Kenya, from Euro Industrial Chemicals. Sodium silicate was in solution form with a specific gravity of 1.530 at 20 ^{o} C and a Na_2O: SiO_2 ratio of 1:2.10 (Na_2O of 13.76%, and SiO_2 of 28.9). The sodium hydroxide (NaOH) pearls used in the study had a purity of at least 99%. Figure 2 shows the Na_2SiO_3 solution and NaOH pearls.

(a) (b)

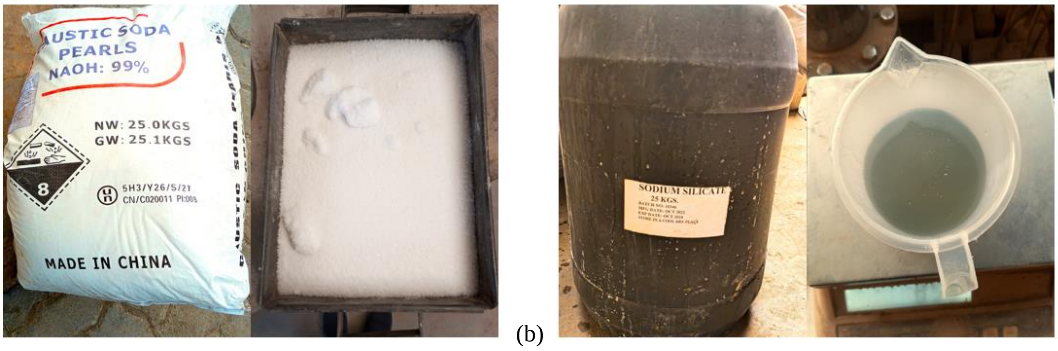


Figure 2. (a) Sodium hydroxide pearls and (b) sodium silicate solution

2.1.4. Water

Laboratory potable tap water was employed to prepare an alkaline solution.

2.1.5. Superplasticizer

A commercially available superplasticizer (SP) (ViscoCrete-20 HE KE) was utilized to increase the workability and flowability of fresh concrete. It satisfied the standards for SP as stated by ASTM-C-494 Type G and EN 934-2 with a specific gravity of 1.09 and clear color.

2.2. Mix proportions

This research employed different SCBA and fly ash variations in geopolymer concrete mixtures. The composition of the blended FA-SCBA geopolymer concrete is detailed in Table 3, in which SCBA took the place of FA at 5%, 10%, 15%, and 20% of the total binder.

Table 3. FA-SCBA-based geopolymer concrete proportions in kg/m^3

Mix ID	Cement	FA	SCBA	Coarse agg	Fine agg	Na_2SiO_3	NaOH	water	S. P
Control	500	-	-	1000	700	-	-	175	12.5
0% SCBA	-	500	0	1000	700	105	70	-	12.5
5% SCBA	-	475	25	1000	700	105	70	-	12.5
10% SCBA	-	450	50	1000	700	105	70	-	12.5
15% SCBA	-	425	75	1000	700	105	70	-	12.5
20% SCBA		400	100	1000	700	105	70	-	12.5

2.3. Methodology

2.3.1. Execution of the Study

The study was carried out according to the flow chart shown in Figure 3. The materials were collected, prepared, characterized, and then used to prepare the test samples. The samples were tested as described in the following sections.

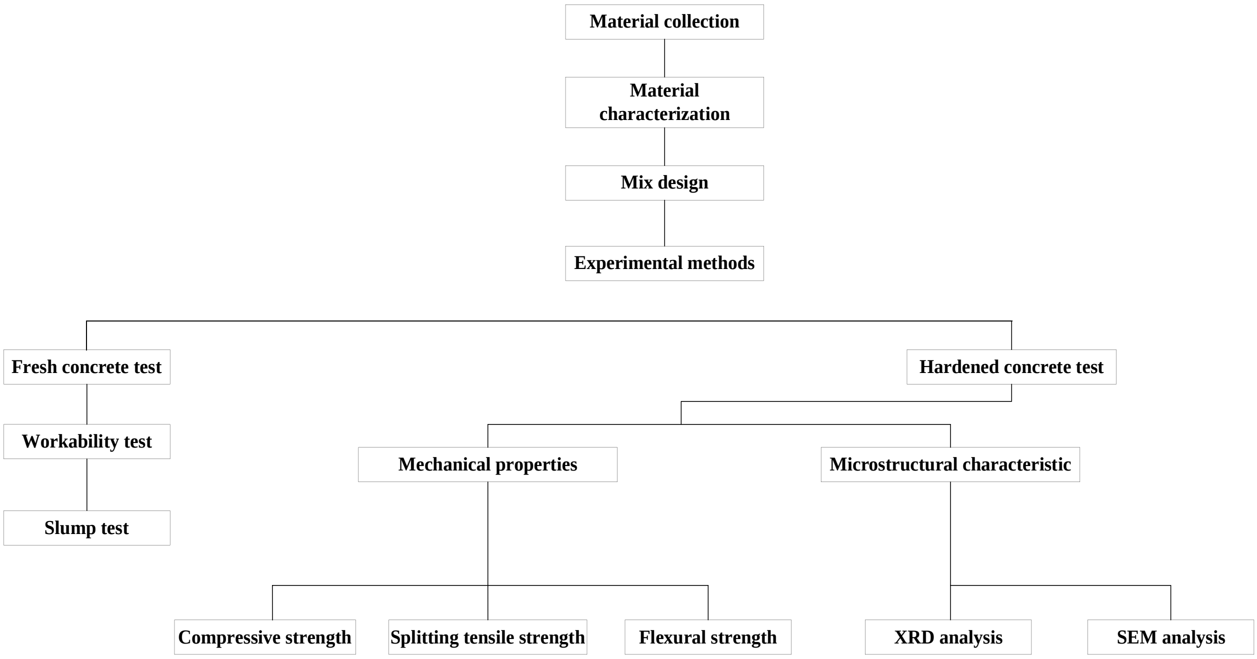


Figure 3. Flowchart of the study

2.3.2. Mixing Procedure

To make the NaOH solution, a suitable dose of NaOH pearls was dissolved in one liter of water to achieve the preferred NaOH concentration (14 M) 24 hours before casting. The mixing technique adopted in this study began by combining aggregates, FA, and SCBA with the Solution containing NaOH to break down the aluminum and silicon found in the unprocessed material. Then Na_2SiO_3 solution was added to increase the binding strength [32]. This mixing approach resulted in greater strength than alternative production methods [61]. A superplasticizer was added to compensate for the workability losses that occurred in the fresh condition. The superplasticizer was introduced progressively at a rate of 2.5%. The GPC mixture was blended for five minutes before being used. This was done to produce the needed flowability and workability of fresh concrete. Finally, the finished product was poured into several standard testing molds and cured at an oven temperature of 80°C for 24 hours.

2.3.3. Methods of Testing

2.3.3.1. Compressive Strength

After 7, 14, and 28 days, a total of 45 cubes, each measuring 100 100 100 mm, were evaluated. Following the British Standard EN 12390-03, a compressive strength test was performed. The cube samples were assessed using universal compression testing equipment with a capability of 1500 kN. Three cubes were utilized to determine the average compressive strength.

2.3.3.2. Splitting Tensile Strength

Fifteen cylinders were cast, each measuring 100 mm in diameter and 200 mm in height. ASTM C 496/C 496M 04 standards were employed to measure the split tensile strength at 28 days. The average of three-cylinder readings for each mixture was given.

2.3.3.3. Flexural Strength

In agreement with the ASTM C78 - 02 standard flexural strength, fifteen beams of 100x100x350 mm were evaluated after 28 days. Each mixture was examined with three prisms, and the average of the results was recorded after each examination.

3. Results and Discussions

3.1. Microstructure of Source Material

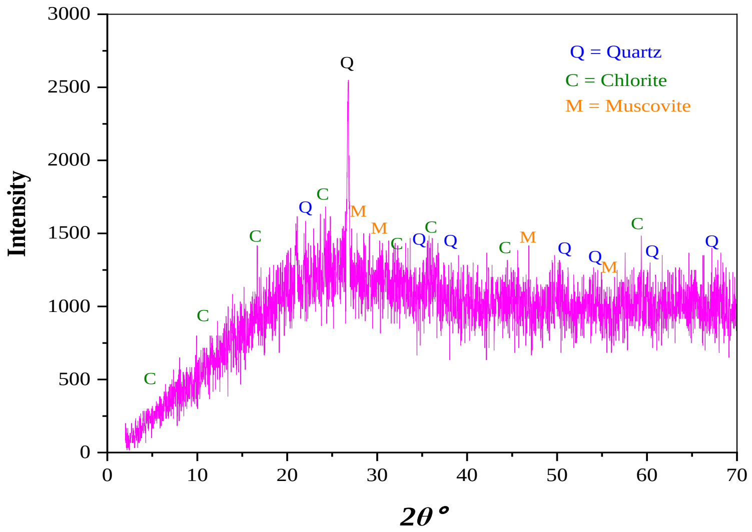
3.1.1. XRD Analysis

As illustrated in Figure 4-a, the primary FA's mineralogical phases were quartz, chlorite, and muscovite. The mineralogy properties of these cementitious materials were determined using XRD analysis on processed SCBA, as shown in Figure 4-b. Quartz was found to be present in the SCBA, as demonstrated by the results, which were also reported by Rukzon & Chindaprasirt [62], Andrade Neto et al. [63], and Abdalla et al. [64].

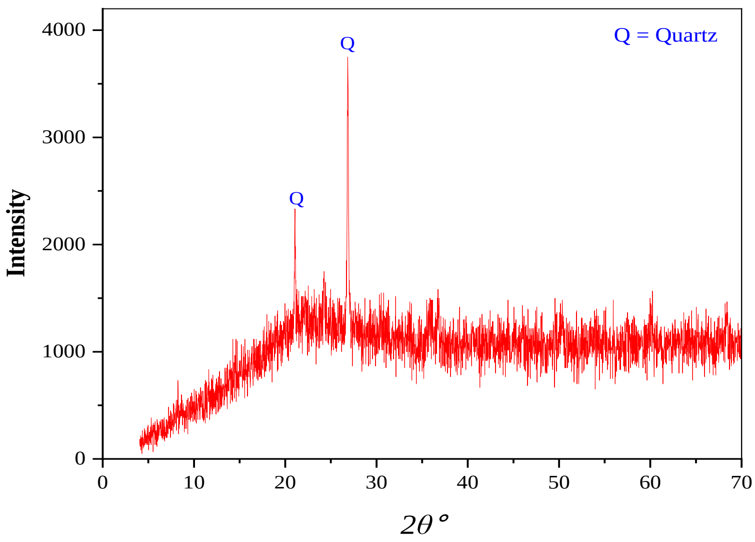
3.1.2. SEM and EDS Analysis

SEM pictures can aid in understanding the behavior of pozzolans and admixtures in geopolymer concrete. Pozzolans and admixtures were morphologically examined using SEM to assess the elements' shape, size, and surface structure. SEM was used in this investigation to capture images of the SCBA in microscopy, as Figure 5-a illustrates. The SCBA particles were found to be shaped like fibrous and irregular flakes and have round surface capillary pores. The particles are elongated, oval-shaped, and have several pores. SCBA requires more water than cement in concrete due to pores on the surface and the fibrous morphology of the particles, resulting in poorer workability. The porosity (sponginess) of these materials influences other concrete qualities. According to Yadav et al. [65], the consistency test revealed that SCBA needed 17-24% more water than cement. Additionally, it was noted that the configuration of SCBA resembles a cellulose sheet, suggesting that SCBA is organized into sub-microcrystalline aggregates, resulting in its inherent porosity. Combining SCBA into sub-microcrystalline clusters results from the imperfect crystallization of SCBA.

This permeable particle indicates that the SCBA particle combustion temperature has not yet reached the critical temperature in the boiler to convert it into a non-permeable state and enhance its ability to absorb water. Additionally, prismatic tetrahedral crystals were found in SCBA, which are just metastable cristobalite forms. SEM analysis of bagasse ash by Chusilp et al. [66] revealed that large surface areas, high porosity, and rough surfaces characterized the raw SCBA particles. The SCBA particles were small after grinding, but their surfaces were rough and porous. Jha et al. [45] used SEM to examine the SCBA, and it was discovered that the surface of the SCBA has a fibrous character, a tetrahedral shape (prismatic), and a crystalline character similar to that of the quartz mineral of silica. Abdalla et al. [64] observe that SCBA particles exhibit a fibrous structure characterized by elongated, irregular flakes with irregular shapes and circular capillary pores on the surface. The particles transform into a more spherical shape following the treatment. The SEM pictures in Figure 5-b reveal that the FA particles have a spherical morphology, characterized by spherical-shaped balls with fragmented Ceno spheres.

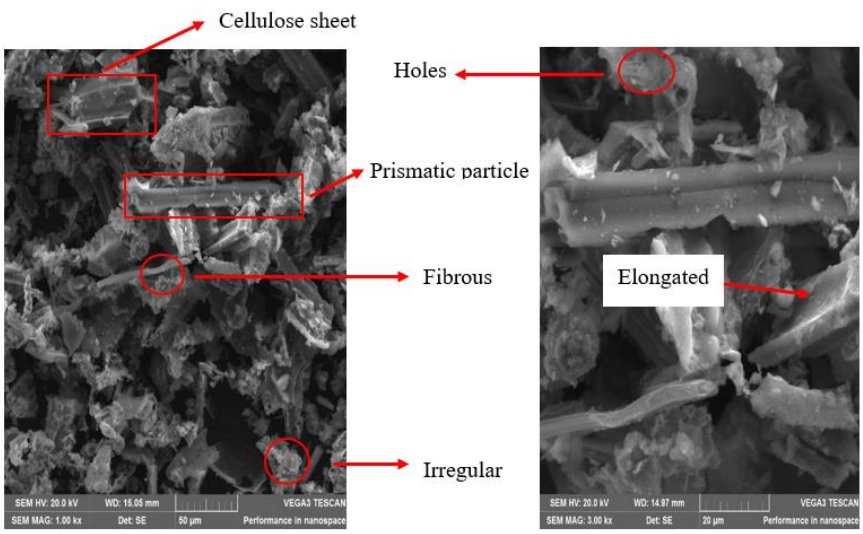


(a)



(b)

Figure 4. XRD of (a) FA and (b) processed SCBA



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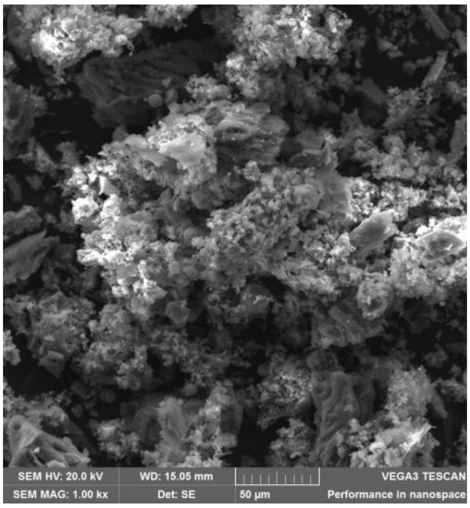
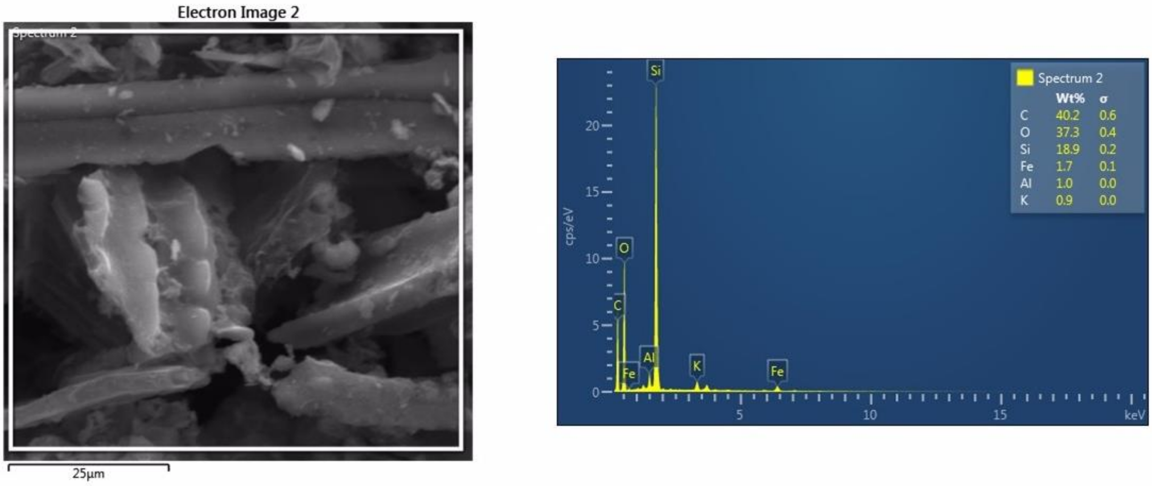


(b)

Figure 5. SEM picture of (a) Processed SCBA and (b) FA

The elemental composition can be ascertained using the analytical technique known as EDS. The system assumes that every voltage pulse's magnitude is directly proportional to the X-ray photons' energy being detected [67]. EDS was utilized to ascertain the elemental composition of each powder after samples were taken randomly from each powder. Figure 6 displays variations in the composition of elements between unprocessed SCBA and treated SCBA, as determined by SEM/EDS studies. The analysis reveals that every SCBA sample consists of oxygen, carbon, silica, aluminum, potassium, iron, and calcium as primary constituents, with variable proportions.



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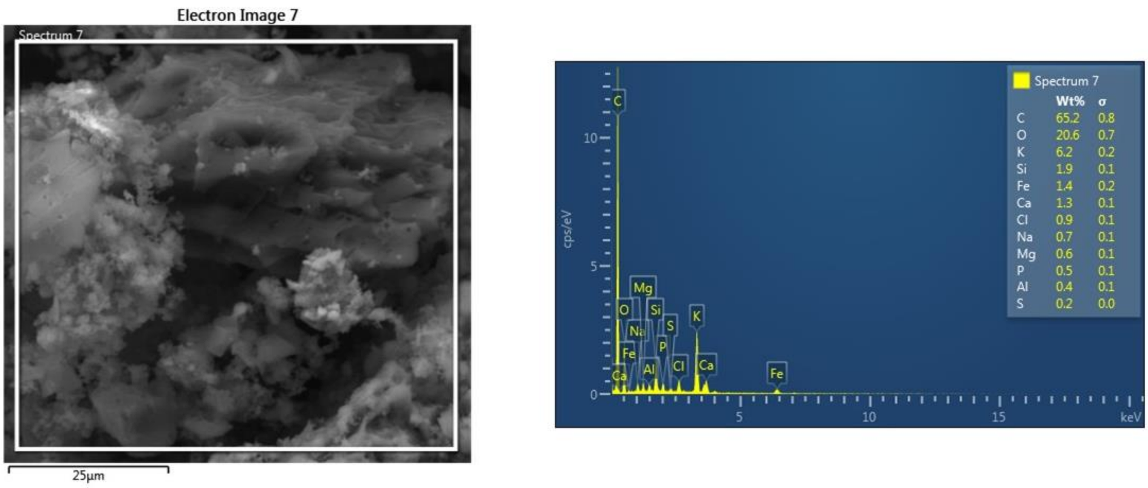


(b)

Figure 6. SEM/EDS analysis of (a) SCBA and (b) FA

3.2. Fresh Properties of FA-SCBA-based Geopolymer Concrete

3.2.1. Workability

Figure 7 displays the slump values for all geopolymer concrete mixes with various levels of SCBA replacement. The workability of the geopolymer mixes was discovered to diminish with an increase in the amount of SCBA. The slump values of mixes were 150, 210, 195, 185, 160, and 155 mm for cement concrete, 0%, 5%, 10%, 15% and 20% SCBA respectively. Prior research has demonstrated that the rise in the amount of SCBA causes a reduction in the workability of GPC [54, 68]. The values agree with the outcomes of Landa-Ruiz et al. [69] and Abdalla et al. [64], who discovered a decrease in workability with increasing SCBA volume. The decline in workability is explained by the lowered specific gravity of SCBA, which is 2.2, compared to FA, which is 2.5. Additionally, the presence of fibrous and uneven flakes on the surface of SCBA with spherical capillary holes, as observed in SEM images, increases water demand. There is a severe issue with activated alkali materials. Due to the materials' high viscosity and resulting inadequate workability parameters, it may be essential to employ superplasticizers to resolve the problem [70]. Furthermore, GPC is more workable than cement concrete. This is because the fine materials have smooth surfaces and hollow spherical shapes.

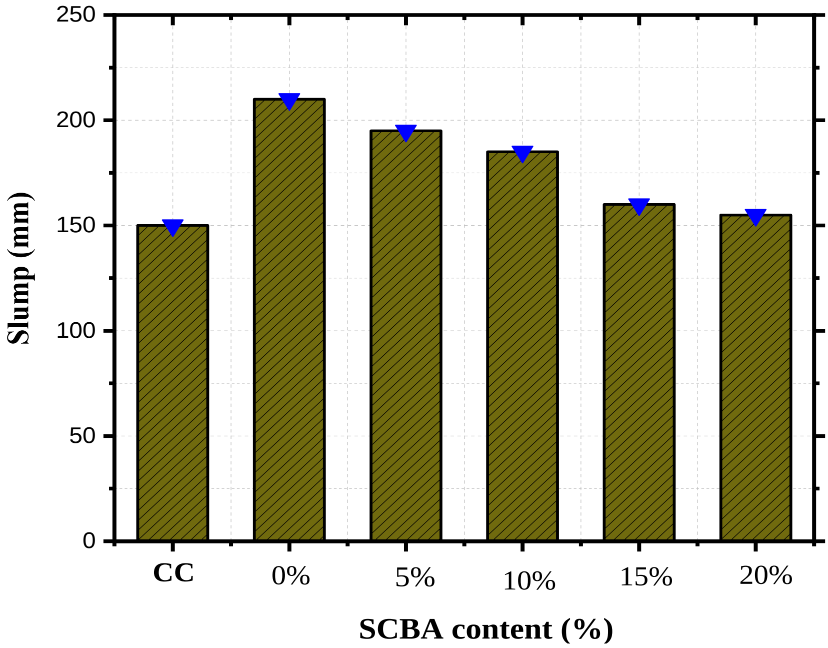


Figure 7. The impact of SCBA content on the GPC workability

3.3. Mechanical Properties

3.3.1. Compressive Strength

Figure 8 shows compressive strength outcomes for the five mixes of FA-SCBA-based geopolymer concrete (14M, SS/SH = 1.5) at different percentages of SCBA from 0 to 20%. The average compressive strength of mixes 0%, 5%, 10%,15, and 20 of SCBA at 7 days were 55.3, 62.5, 53.8, 55.4, and 49.5 MPa respectively. And at 14 days was 57, 63.1, 57.7, 56.7, and 58.5 MPa, respectively. The average compressive strength of 28 days was 60.6, 64, 58.4, 57 and 59.2 respectively. A significant increase in strength over the cement concrete and 0% SCBA is observed in a mix containing 5% SCBA, with an increase of 28% and 6%, respectively. A comparison was made between the compressive strength of cement concrete mix and geopolymer concrete mixes. The compressive strength of the GPC demonstrated a higher level of performance than conventional Portland cement concrete. The enhanced strength can be ascribed to the small particle size of FA and SCBA, which is uniformly dispersed throughout the geopolymer concrete mixture and improves the density. There was a progressive increase in strength as the SCBA content increased up to 5%, after which there was a little decline. However, in all situations, the strength exceeded that of normal concrete. The 5% level of SCBA replacement exhibited maximal strength compared to the other mixtures. The drop in compressive strength that occurred with an increasing amount of SCBA can be assigned to the higher permeability of the materials (Figure 5). A comparable conclusion was reached by Chindaprasirt et al. [46].

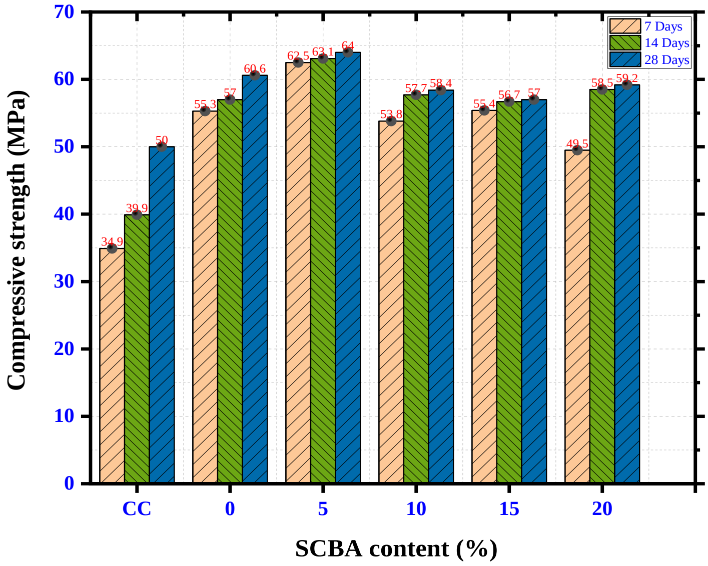


Figure 8. Compressive strength at different ratios of SCBA of FA-SCBA geopolymer concrete

3.3.2. Splitting Tensile Strength

The indirect tensile strength of the design mix for the GPC is ascertained using the splitting tensile strength test. Figure 9 displays the splitting tensile strength of geopolymer concrete after testing for 28 days. The splitting tensile strength of geopolymer concrete mixes has a comparable pattern to that of compressive strength. The mixtures of geopolymer concrete that contain 0%, 5%, 10%, 15%, and 20% have achieved split tensile strengths of 5.44, 6.2, 5.8, 3.21, and 4 MPa correspondingly after 28 days. Compared to a mixture consisting only of FA, the SCBA mixture containing 5% SCBA exhibited the highest tensile strength values, similar to the observation from the compressive strength results. Shafiq et al. [71] stated that a rise in the percentage of SCBA resulted in a corresponding decrease in splitting tensile strength, which exhibited a comparable trend to the decline in compressive strength.

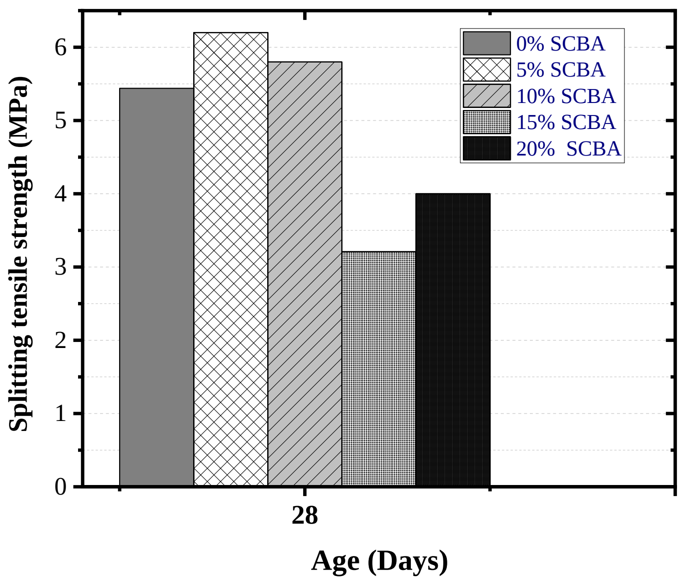


Figure 9. SCBA's Effect on the 28-day split tensile strength of GPC

3.3.3. Flexural Strength

The flexural strength of blends of geopolymers based on FA-SCBA is displayed in Figure 10 after 28 days, with varying amounts of SCBA. The specimens with fly ash only exhibited superior flexural strength compared to the others. The mean flexural strength values at 28 days for SCBA samples with 0%, 5%, 10%, 15%, and 20% content were 11.02, 9.1, 9.3, 8.61, and 8 MPa, respectively. The flexural strength of cement concrete was 7.7 Mpa. The GPC specimen exhibited superior flexural strengths compared to the PCC specimen. The reason for this could be the higher strength of Si-O-Al bonds (GPC) compared to C-H-S bonds (OPC) [72, 73], resulting in GPC having a stronger bond than PCC.

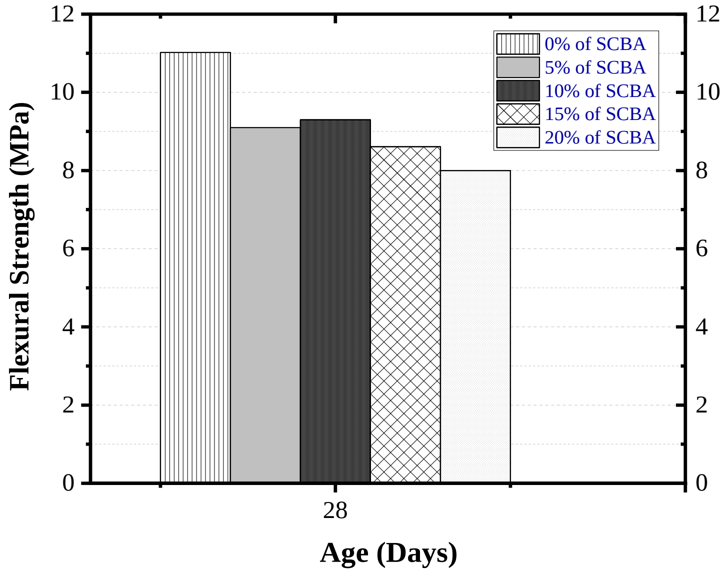
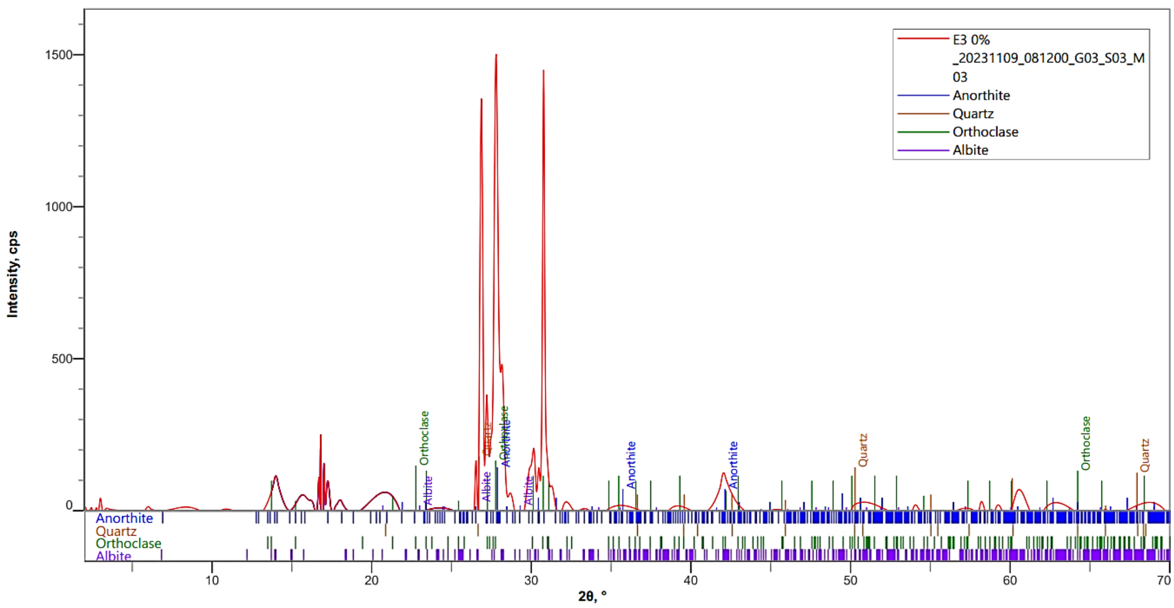


Figure 10. The Impact of SCBA on the 28-day flexural strength of GPC

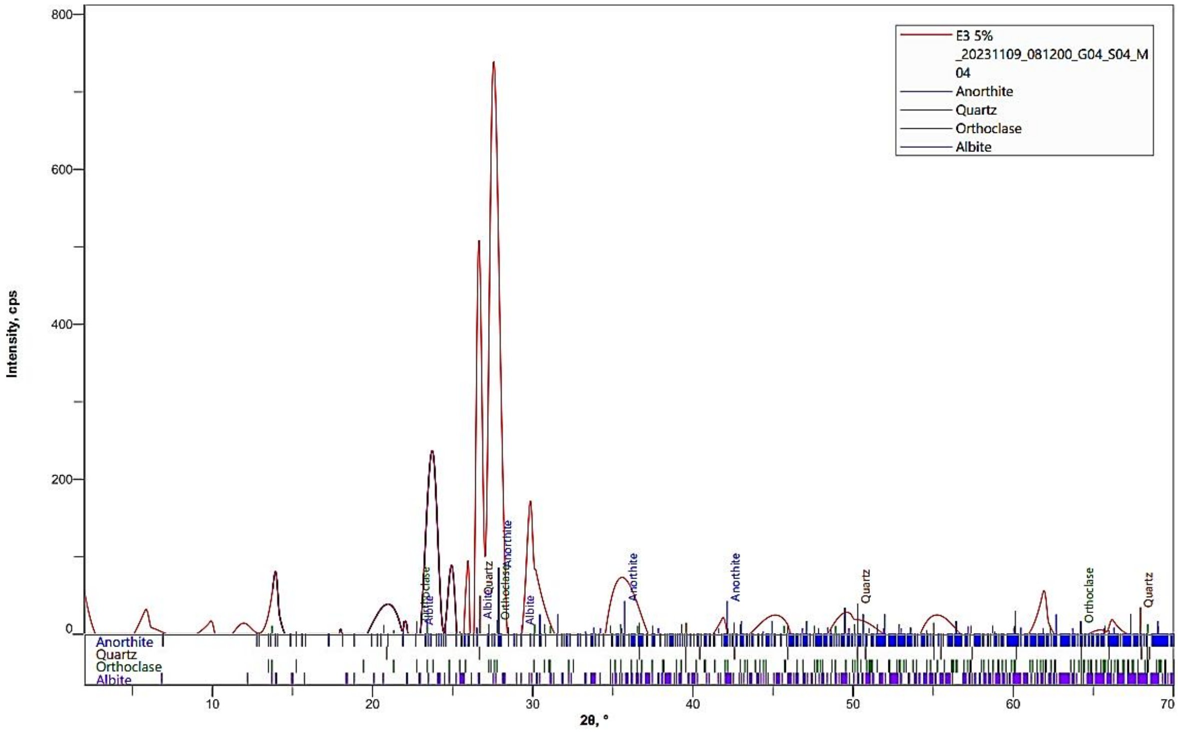
3.4. Microstructure Characteristics of FA-SCBA Geopolymer Concrete

3.4.1. XRD Analysis

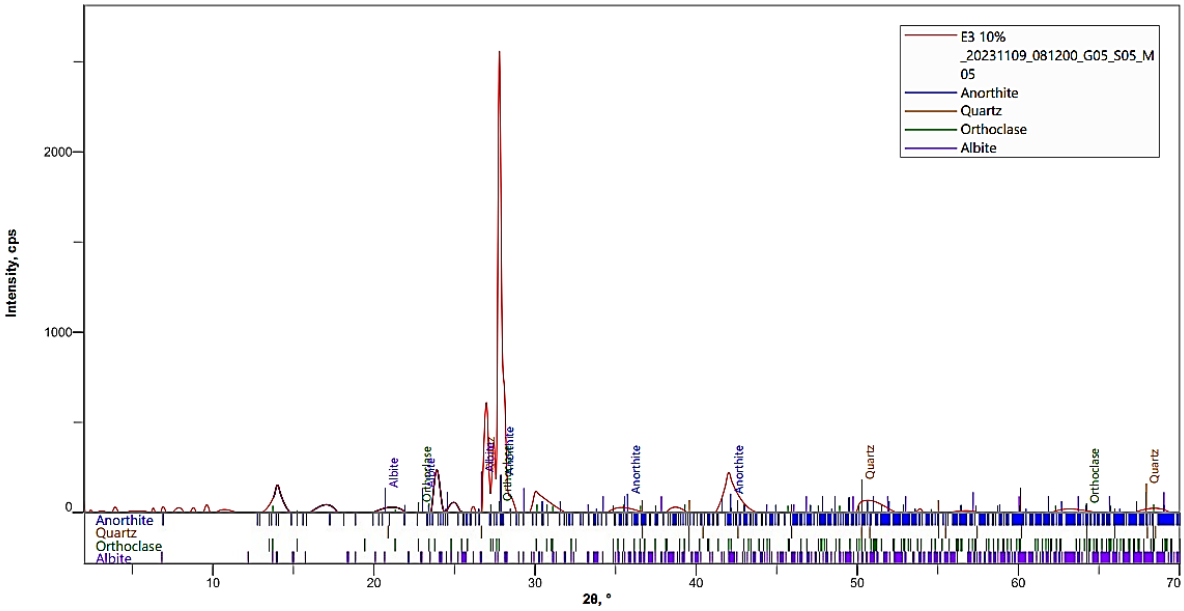
The X-ray diffraction (XRD) results of GPC at 28 days with 0, 5, and 10% SCBA are displayed in Figure 11. These mixes were selected based on their higher percentages of strength improvement. The broad peaks identified between 26.8º and 67.9º on the 2θ scale suggest a reaction of geopolymerisation, which results in the creation of the geopolymer product. Furthermore, prominent peaks in the geopolymer concrete signify a dominant crystal phase accompanied by a smaller amorphous phase. In addition, the mixtures indicated the existence of Partially crystallization phases that were previously described in the ash XRD investigation (Figure 4), as well as a new stage consisting of albite, orthoclase, and anorthite emerged as a result of the geopolymerization reaction. Mineral phases of quartz detected on the FA and SCBA diffractograms are still present following the geopolymerization reaction. This indicates that these minerals remained unaltered or did not undergo geopolymerization, allowing them to operate as aggregates and strengthen the geopolymer. Furthermore, quartz consists primarily of silica-based oxides, which significantly enhance GPC's strength and mechanical performance. Albite, which occurs in a partially crystalline form, belongs to the N-A-S-H gel family and is a polymeric material made of sodium-polysialate, as demonstrated by earlier studies [74, 75]. The anorthite phase that forms is categorized as a C-A-S-H gel and serves as a nucleation site, facilitating further geopolymer connections. This results in a more compact and tightly connected microstructure. The formation of CASH gels occurs through the reaction between alkalis in GPC and calcium, which assists in the hydration and strengthening of GPC [76].



(a) 0% SCBA



(b) 5% SCBA

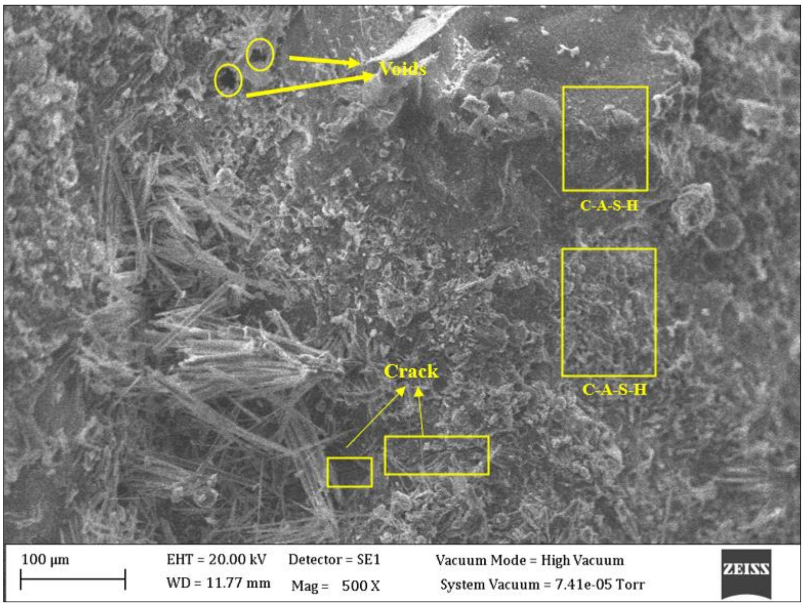


(c) 10% SCBA

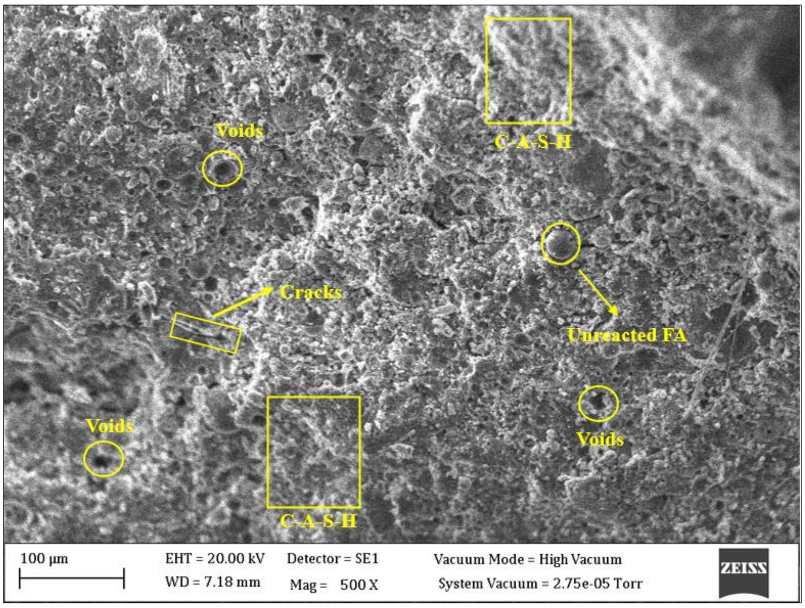
Figure 11. FA-SCBA based geopolymer concrete 28-day XRD patterns

3.4.2. SEM Analysis

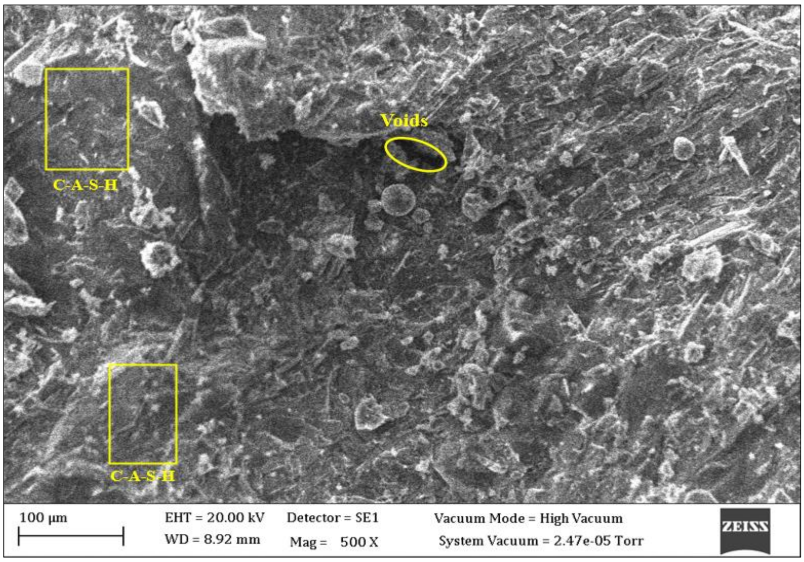
To test the rate of polymerization and the efficacy of the geopolymer gel within the matrix, specimens that had been aged for 28 days and tested for compressive strength were used to obtain samples of geopolymer concrete. Figure 12 shows SEM pictures of GPC mixes made with FA and SCBA. The sample findings showed that the geopolymer concrete had less density and void spaces Because of large spheres of unreacted FA. The voids were formed due to the incomplete dissolving of FA during the initial mixing of GPC. Moreover, the presence of unreacted particles of FA and the free water evaporating throughout the aging-curing mechanisms likely contributed to the formation and spread of microcracks [74]. The inclusion of SCBA in the overall composition of the binder led to notable enhancements in the microstructure of geopolymer concrete. After 28 days, the microstructure of the 5 percent SCBA mixture showed a significant advancement in the density and consistency of the gel composition, outperforming that of the other mixtures. The geopolymerization process encompasses a chemical interaction between aluminosilicate minerals and an alkaline solution, which leads to the dissolving of FA and SCBA. This process creates geopolymeric gels that efficiently occupy the empty spaces and gaps in the geopolymer concrete [14].



(a) 0% SCBA



(b) 5% SCBA



(c) 10% SCBA

Figure 12. SEM micrograph of FA-SCBA-based geopolymer concrete

4. Conclusions

An investigation based on experiments was carried out to examine the effects of binary binders composed of FA and SCBA on the mechanical characteristics and microstructure of geopolymer concrete. Compressive strength, split tensile strength, flexural strength, X-ray diffraction, and scanning electron microscope were conducted. The results of the investigation allow for the drawing of the following conclusions:

- SEM pictures demonstrate that SCBA is made up of elongated, irregular forms with spaces between them, which negatively affected the workability of the paste while also increasing the need for water due to increased porosity.
- XRD analysis of the mineralogical phases confirmed the presence of albite, quartz, orthoclase, and anorthite phases in all geopolymer concrete mixtures.
- The combination containing 5% SCBA increased the density of the geopolymer matrix in the SEM image. This was confirmed by the presence of less unreacted or partially reacted FA particles compared to other mixtures.
- Concrete made of geopolymer has superior workability in comparison to ordinary Portland cement concrete.
- The compressive strength of the FA-SCBA-based GPC was discovered to be greater than that of ordinary Portland cement concrete. The combination with 5% SCBA provided the highest compressive strength, which is 64 MPa.
- The 5% mixture exhibited superior split tensile strength performance at 28 days, similar to compressive strength. Its split tensile strength was 6.2 MPa. However, the flexural strength reached the maximum at 100% of FA.

This study highlights the potential for producing geopolymer concrete using waste materials like fly ash and sugarcane bagasse ash, supporting resource conservation and green building techniques. Future studies should look at alternate waste resources, and geopolymer concrete's thermal performance and long-term durability should be investigated. Geopolymer concrete has the potential to be a viable substitute for conventional Portland cement-based concrete with more study and innovation, making the built environment more durable and environmentally friendly.

5. Declarations

5.1. Author Contributions

Conceptualization, M.A.M.R.; methodology, M.A.M.R.; validation, M.A.M.R.; formal analysis, M.A.M.R.; investigation, M.A.M.R.; resources, M.A.M.R.; writing—original draft preparation, M.A.M.R.; writing—review and editing, R.O.O., N.G., and B.S.; visualization, R.O.O.; supervision, R.O.O., N.G., and B.S. 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 on request from the corresponding author.

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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