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Impact of Alkaline Concentration on the Mechanical Properties of Geopolymer Concrete Made Up of Fly Ash and Sugarcane Bagasse Ash

Mohammed Ali M. Rihan [1,2,*], Turki S. Alahmari [3], Richard Ocharo Onchiri [4], Naftary Gathimba [5] and Bernadette Sabuni [6]

[1] Pan African University Institute for Basic Sciences, Technology, and Innovation, Jomo Kenyatta University of Agriculture and Technology, Nairobi P.O. Box 62000-00200, Kenya
[2] Civil Engineering Department, Faculty of Engineering, University of Kordofan, El Obeid 51111, Sudan
[3] Department of Civil Engineering, Faculty of Engineering, University of Tabuk, P.O. Box 741, Tabuk 71491, Saudi Arabia; talahmari@ut.edu.sa
[4] Department of Building and Civil Engineering, Technical University of Mombasa (TUM), Mombasa P.O. Box 90420-80100, Kenya; rocharo@tum.ac.ke
[5] Department of Civil, Construction and Environmental Engineering, Jomo Kenyatta University of Agriculture and Technology, Nairobi P.O. Box 62000-00200, Kenya; n_gathimba@jkuat.ac.ke
[6] Department of Civil and Structural Engineering, Masinde Muliro University of Science and Technology, Kakamega P.O. Box 190 50100, Kenya; bsabuni@mmust.ac.ke
* Correspondence: rihan.mohammed@students.jkuat.ac.ke

Abstract: Geopolymer concrete (GPC) is a novel and environmentally friendly type of concrete that eliminates the use of cement, resulting in a significant reduction in carbon emissions and a more sustainable construction material. Alkaline activators are used in GPC to achieve rapid strength development. The most popular alkaline activators are sodium/potassium silicate and sodium/potassium hydroxide, which are known contributors to carbon emissions, hence limiting the advantages of GPC; therefore, reducing the amount of these alkaline activators that contribute to carbon emissions is necessary for developing a more sustainable geopolymer concrete. In this study, the influence of the variation in sodium hydroxide molarities on the performance of fly ash/sugarcane bagasse ash-based-geopolymer concrete was investigated. The different molarities used were 10 M, 12 M, 14 M, and 16 M sodium hydroxide solutions. In addition, the effect of sugarcane bagasse ash content (0%, 5%, 10%, 15%, and 20%) on the fresh and hardened geopolymer concrete properties were examined. The slump test, compression test, split tensile test, and flexure test were conducted on the cast samples. The results of this study showed that raising the concentration of NaOH from 10 M to 16 M while maintaining a sodium silicate to sodium hydroxide ratio of 2.5 resulted in a 3.75–10.2% improvement in compressive strength after 28 days. It is worth noting that, even at a concentration of 10 M, the concrete still achieved high strength.

Keywords: geopolymer concrete; molarity; sodium hydroxide; strength; sugarcane bagasse ash

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1. Introduction

Concrete is one of the most frequently utilized building materials, and Portland cement commonly features as one of its primary components. Because of increased urbanization and industrialization, there is increased demand for extensive infrastructural development, requiring more concrete as a construction material. In 2021, cement production reportedly reached 4.4 billion tons worldwide [1,2], and the annual concrete consumption is forecasted to pass 18 billion tons by 2050 [3]. The manufacture of Portland cement (PC) used in concrete has substantial effects on the environment in terms of high energy use, natural resource depletion, and carbon dioxide (CO_2) emissions [4–6]. The cement manufacturing industries contribute roughly 7% of global CO_2 emissions [7–11]. This environmental effect could be minimized by using less cement in concrete production or by developing a strategy for lowering CO_2 emissions. This strategy includes finding ecologically suitable materials to replace Portland cement, preferably utilizing waste by-product materials [12,13].

In the construction sector, low carbon concrete, also known as geopolymer concrete (GPC), should be preferred over Portland cement concrete due to the essential roles it can play in waste disposal, carbon dioxide emission reduction, durability, and environmental compatibility [14,15]. This inorganic alumino-silicate geopolymer has been invented and is being suggested as a PC substitute in the construction industry [16]. Alkali activation is used to make the geopolymer from geological or byproduct materials rich in silicon and aluminum, such as ground granulated blast furnace slag (GGBFs), fly ash (FA), and metakaolin [17]. In addition to having a low environmental consequence, geopolymer concrete has superior properties, including good resistance to attacks from acids and sulfates, high early age strength, low setting time, minimal shrinkage, resistance to fire, and low heat conductivity [8,10,18]. In addition to its durability and mechanical performance, GPC has good thermal resistance and can withstand temperatures as high as 1200 °C without experiencing any sudden degradation [19]. The expression "geopolymer" refers to a category of materials formed through the reaction of an alkali activator to aluminosilicate powder [20,21]. Davidovits, in 1978, was the one who first presented geopolymers to the scientific community as a novel class of binders that belonged to inorganic polymers [22,23].

Industrial byproducts, such as fly ash (FA) and sugarcane bagasse ash (SCBA), have been found to contain aluminosilicates that can be used to manufacture geopolymer concrete. About 60% of FA produced in thermal power stations is deposited in landfills [11,24]. On the other hand, SCBA is a globally available byproduct made by burning bagasse to produce energy in boilers [25,26]. The estimated annual output of SCBA is predicted to range from 48 to 60 million tonnes, depending on the yield [27], and these substances pollute the environment when dumped. One can obtain sugarcane bagasse with good pozzolanic characteristics by burning it for 20 min at 800–1000 °C [28,29] or 3 h of air calcining at 600 °C [30]. The percentage of silica in the ash varies based on temperature, the kind of soil in which the sugarcane is grown, and the burning method [31,32].

One of the crucial parameters for influencing GPC performance is the concentration of alkali activator (i.e., sodium hydroxide) present. As a result, several studies have been undertaken to determine the effect of alkali concentration. Verma and Dev [33] investigated how sodium hydroxide affected the mechanical characteristics of GPC made with FA and slag, with their findings indicating that, when the sodium hydroxide molarity increases, the mix design's compressive strength increases to an optimum value for the oven-cured specimens. Ghafoor et al. [34] assessed the impact of activators on the compressive strength of GPC cured at normal temperature. Their findings indicate that the strength initially increased when the sodium hydroxide molarity rose to 14 M but then subsequently declined. Investigations by Alghannam et al. [35] showed that the compressive strength decreased as the molarity was elevated from 14 M to 20 M. Pratap et al. [11] investigated the effect of sodium hydroxide molarity on the compressive strength of GPC prepared with FA and phosphogypsum. The findings indicated that the strength characteristics rose with increasing molar concentration, with a peak at 12 M, and then fell as sodium hydroxide concentration continued to rise. H.M. and Unnikrishnan [36] also studied the mechanical strength of GGBFs-SCBA-based GPC. They observed that all the mixtures' mechanical strength characteristics improved when molarity rose to 12 M from 8 M.

Research has demonstrated promising results in utilizing industrial and agricultural byproducts such as FA, GGBS, metakaolin, rice husk ash, and corncob ash for geopolymer concrete development. However, there is minimal available research on the performance of sustainable geopolymer concrete that relies only on FA and SCBA. Alkaline activators are the main cause of carbon emissions in geopolymer concrete manufacturing. As a result, lowering the amount of these components that contribute to carbon emissions is essential for the development of a more sustainable geopolymer concrete. Lowering the molarity of alkaline activator in geopolymer concrete can significantly improve sustainability by reducing the quantities consumed; however, this contradicts the common idea of increasing molarity to enhance strength. The reduction in molarity of NaOH is expected to provide further benefits, such as lower economic costs and convenience of handling. The primary objective of the present study is to investigate the influence of NaOH molarity from 10 to 14 M on the strength of geopolymer concrete containing FA and different percentages of SCBA. The slump test, compressive strength, split tensile strength, and flexural strength of the resulting geopolymer concrete mixes were evaluated.

2. Materials and Methods

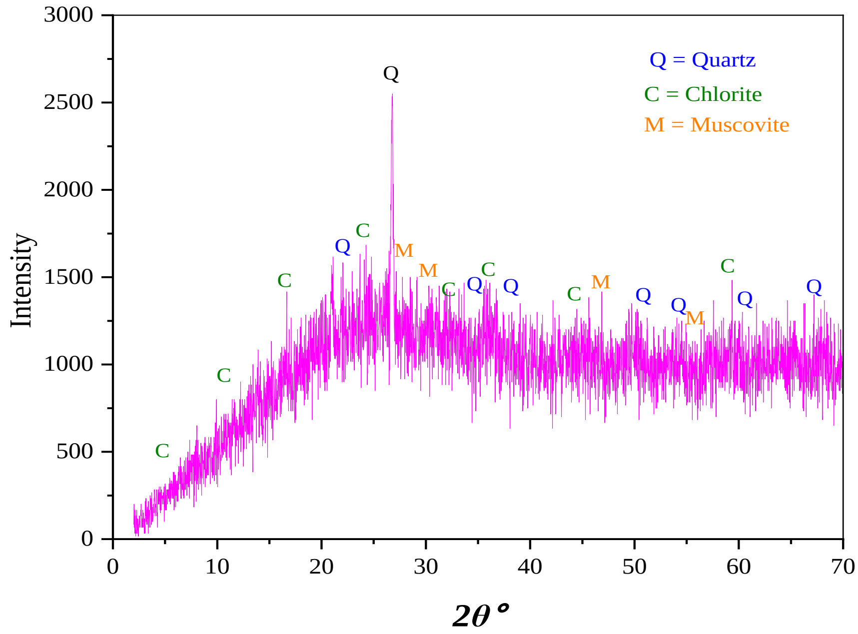
2.1. Materials Acquisition and Preparation

The materials utilized in this investigation included SCBA, FA, fine and coarse aggregate, superplasticizer, and an alkaline solution containing sodium hydroxide and sodium silicates. FA was supplied from India, while SCBA was acquired from Sukari Industries Ltd., in Western Kenya. Sugarcane ash was sieved through a 75 µm mesh screen to reach the necessary particle size and eliminate residual carbonaceous elements and large particles. After that, the loss of ignition (LOI) was assessed. The unprocessed SCBA has a LOI of 10.20%. To comply with ASTM C618, the raw SCBA was re-burned for four hours at 650 °C in a muffle furnace to lower the LOI below 6%. X-ray fluorescence (XRF) examination was used to assess the chemical compositions of FA and SCBA, with the outcomes being shown in Table 1. The specific gravity of FA and SCBA were 2.5 and 2.2, respectively.

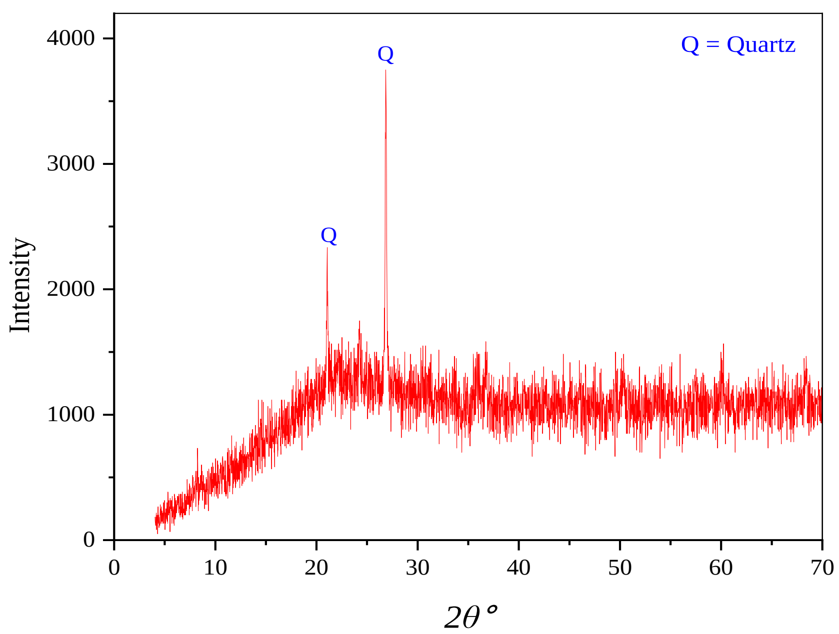
Table 1. Chemical Constituents of SCBA and FA.

Oxides	Raw SCBA	Processed SCBA	FA
SiO_2	81.32	76	54
Al_2O_3	5.51	9	19.6
Fe_2O_3	6.95	4.2	6.9
CaO	1.71	3.1	7.9
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

Figure 1 shows the X-ray diffraction (XRD) pattern of FA and SCBA. The main FA's mineralogical phases were quartz, chlorite, and muscovite, while SCBA has more quartz phases than FA. Figure 2 illustrates the scanning electron microscopy (SEM) graphics of the FA and SCBA, which provide a more intricate depiction of the particle's structure. The SCBA particles were found to be shaped like fibrous and irregular flakes, and they feature round surface capillary pores.

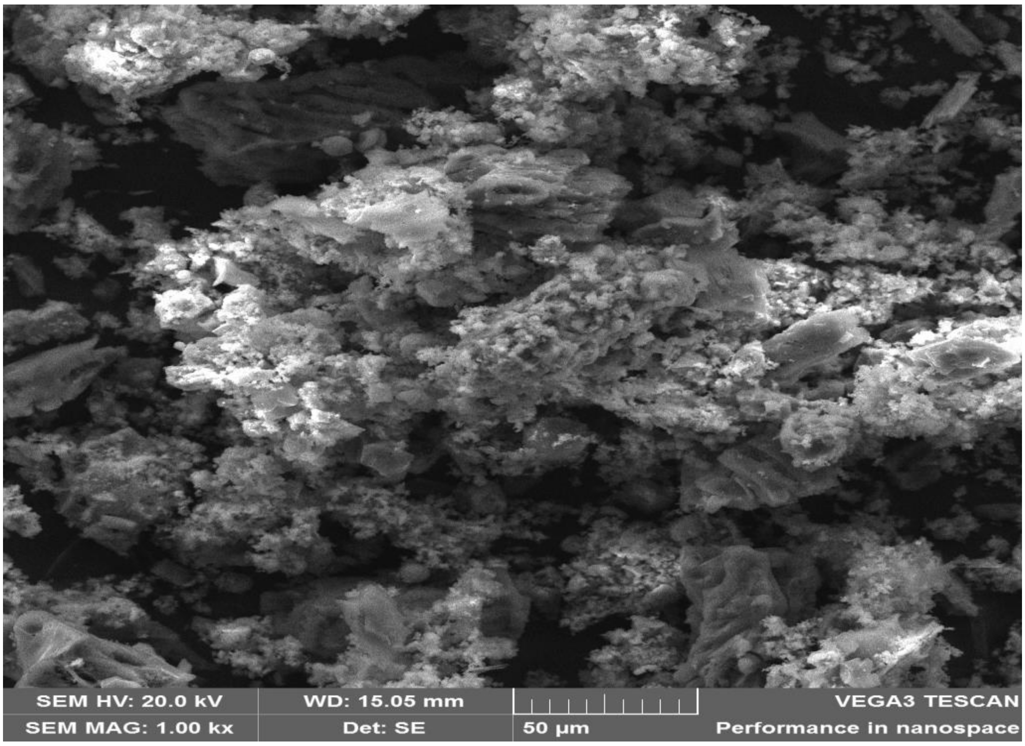


(**a**) XRD of FA

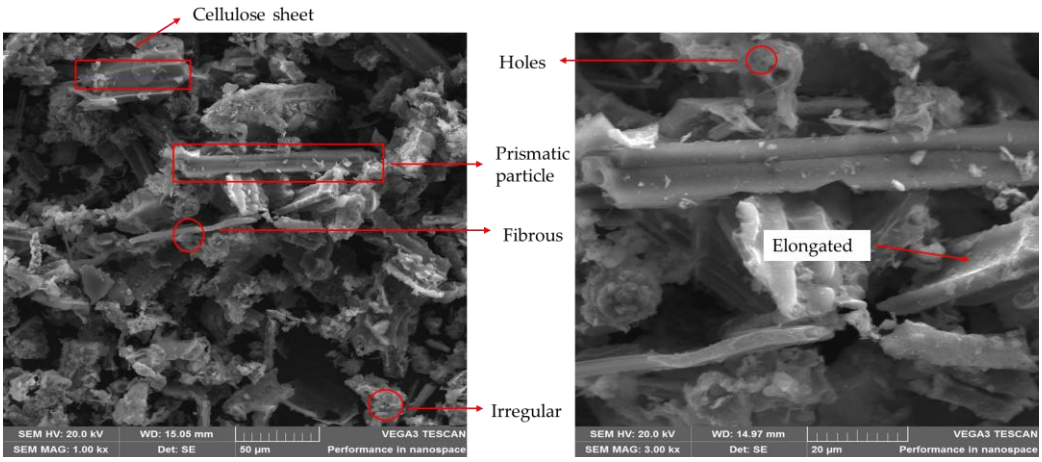


(**b**) XRD of SCBA

Figure 1. XRD of FA and SCBA.



(**a**) SEM of FA



(**b**) SEM of SCBA

Figure 2. SEM picture of (**a**) FA and (**b**) Processed SCBA.

The crushed stone used as coarse aggregate had a specific gravity of 2.66 and a maximum aggregate size of 12.5 mm. The fine aggregate was a mixture of quarry dust (30%) and river sand (70%) that had been sieved through an ASTM 0.18 mm filter, followed by oven drying for 24 h at 105 °C. The properties of the aggregates are presented in Table 2. Figure 3 depicts the distribution of particle sizes in the aggregate. A combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) was utilized as the alkaline activator in this study. Na_2SiO_3 was employed in solution form with a specific gravity of 1.530 at 20 °C and a Na_2O: SiO_2 ratio of 1:2.10 (Na_2O of 13.76% and SiO_2 of 28.9). The NaOH pearls used in the study had a purity of at least 99%.

Table 2. Aggregate physical properties.

Aggregates	Fineness Modulus	Specific Gravity	Water Absorption (%)	Density (kg/m³)	Voids Ratio (%)	Crush Value (%)	Impact Value (%)
Coarse agg	-	2.66	3.6	1468	42	17.6	6.2
Fine agg	2.60	2.61	3.5	1677	28	-	-

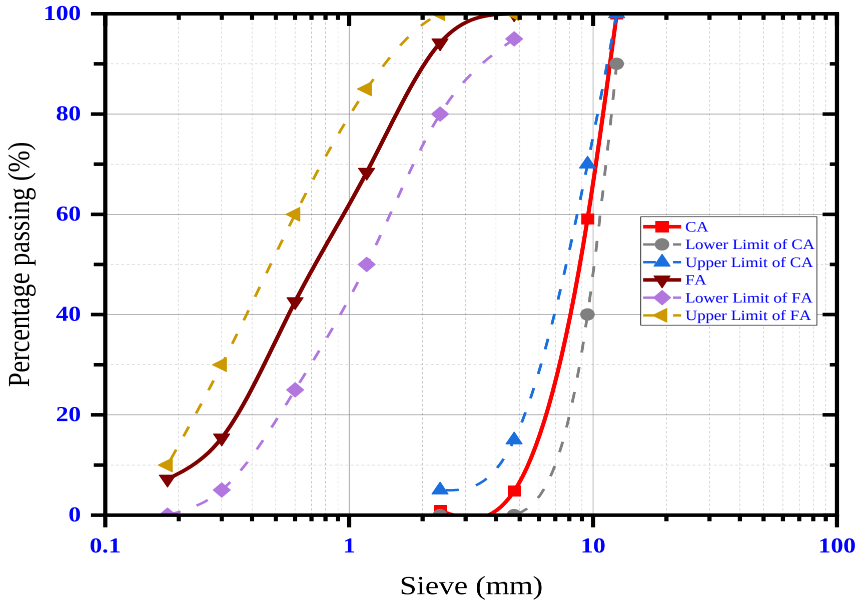


Figure 3. Aggregates' distribution of particle sizes.

2.2. Mix Proportions, Mixing, Casting and Curing

Table 3 displays the different mix proportions of geopolymer concrete used in this investigation, including SCBA and FA. The mixed variables consisted of the proportion of SCBA used as a substitute for fly ash, measured by mass. Additionally, the concentration of NaOH (ranging from 10–16 M) was also considered. The ratio of Na_2SiO_3 to NaOH has been taken to be 2.5 and 1.5, which could result in maximum compressive strengths [34,37,38]. In this investigation, the mixing technique adopted began by combining the SCBA, FA, and aggregates with the NaOH solution in order to dissolve the aluminum and silicon found in the unprocessed material. Then, Na_2SiO_3 solution was added to increase the binding strength [39], as this approach could result in greater strength in comparison to alternative production methods [40]. In detail, the dried aggregate, FA, and SCBA were combined in the mixer for three minutes. Then, the NaOH solution was progressively added and mixed for another three minutes. To guarantee perfect homogeneity, the wet mix was treated with Na_2SiO_3 solution and mixed for a further five minutes. A superplasticizer was added to enhance workability. Following the process of mixing, the GPC was poured into several molds to form cubes, cylinders, and beam specimens. Specimens were then cured at a high temperature of 80 °C in an oven for 24 h in order to accelerate the geopolymerization process while enhancing the concrete's physical and mechanical properties.

Table 3. Mix proportions details (Kg/m³).

Mix ID	FA	SCBA	Coarse Agg	Fine Agg	Alkaline Solution	S. P	NaOH M
GPC0-10	500	0	1000	700	175	12.5	10
GPC5-10	475	25	1000	700	175	12.5	10
GPC10-10	450	50	1000	700	175	12.5	10
GPC15-10	425	75	1000	700	175	12.5	10

GPC20-10	400	100	1000	700	175	12.5	10
GPC0-12	500	0	1000	700	175	12.5	12
GPC5-12	475	25	1000	700	175	12.5	12
GPC10-12	450	50	1000	700	175	12.5	12
GPC1512	425	75	1000	700	175	12.5	12
GPC20-12	400	100	1000	700	175	12.5	12
GPC0-14	500	0	1000	700	175	12.5	14
GPC5-14	475	25	1000	700	175	12.5	14
GPC10-14	450	50	1000	700	175	12.5	14
GPC15-14	425	75	1000	700	175	12.5	14
GPC20-14	400	100	1000	700	175	12.5	14
GPC0-16	500	0	1000	700	175	12.5	16
GPC5-16	475	25	1000	700	175	12.5	16
GPC10-16	450	50	1000	700	175	12.5	16
GPC15-16	425	75	1000	700	175	12.5	16
GPC20-16	400	100	1000	700	175	12.5	16

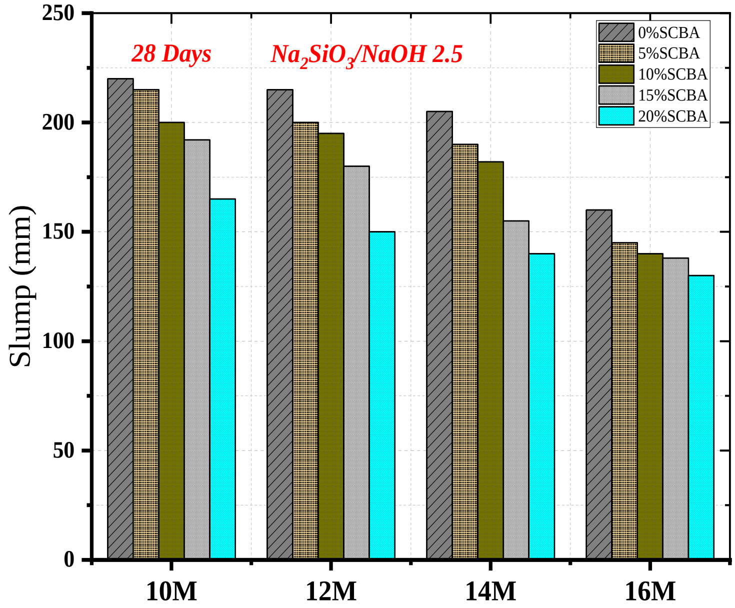
2.3. Testing Specimens

Compressive strength testing was achieved in line with the BS EN [41] BS EN 12390-03 standard. A universal compression test machine with a 1500 kN capacity was used to test the cube samples. Three cubes for each mix were tested. ASTM [42] ASTM C 496/C 496 M 04 standards were employed to measure the tensile strength of the geopolymer concrete after 28 days of the curing period. The average of three cylinder readings for each mixture was taken. In accordance with the ASTM [43] ASTM C78-02 standard, the flexural strength was evaluated after curing for a period of 28 days.

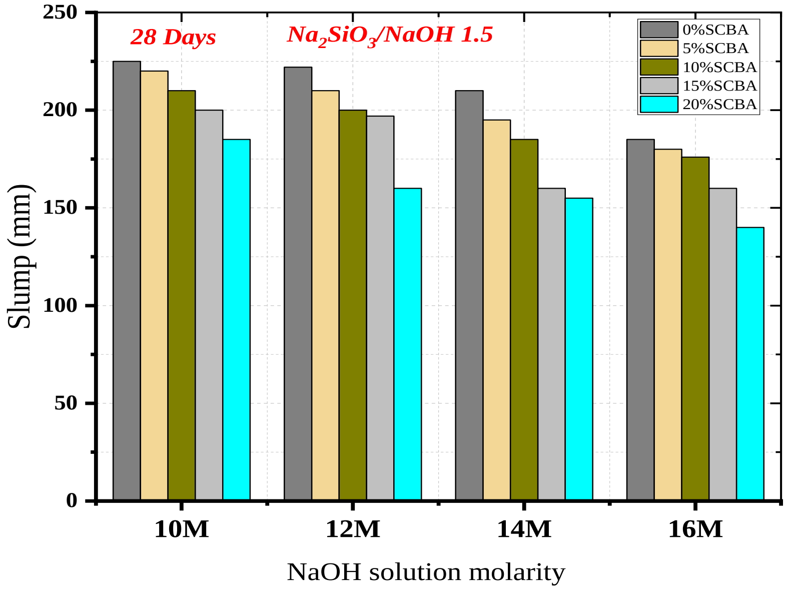
3. Results and Discussion

3.1. Workability

The effect of the molarity of the NaOH solution on the workability of fly ash−sugarcane bagasse ash-based GPC is illustrated in Figure 4. These graphs show that the slump is lowered when the sodium hydroxide solution's molarity is increased. This is the same trend as reported by Naenudon et al. [44]. Utilization of a higher concentration of NaOH solution resulted in increased alumina and silica leaching from FA and SCBA, and hence caused the mixture's viscosity to rise [45,46]. Furthermore, the decrease in water contents in an alkaline solution with the increase in NaOH molarity resulted in a decline of GPC workability [47,48]. It is worth mentioning that the slump values that were recorded for each of the combinations exhibited satisfactory workability.



(**a**) $Na_2SiO_3/NaOH$ 2.5



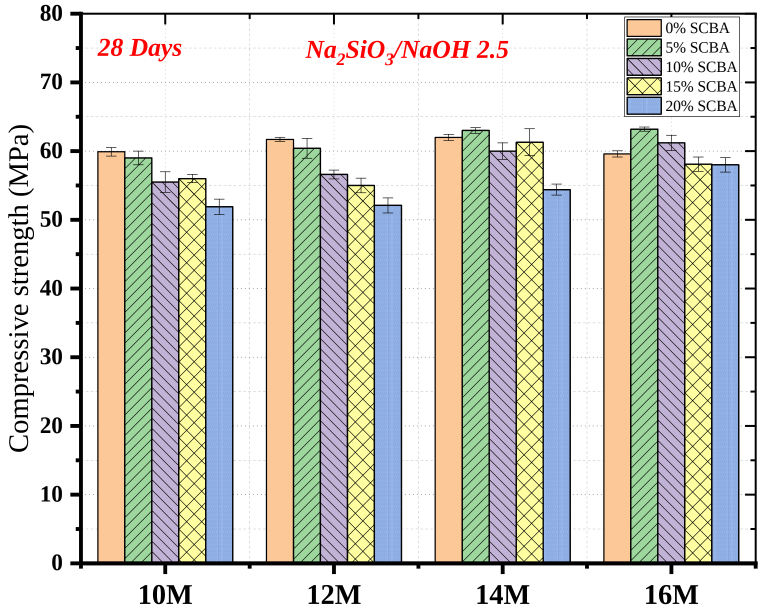
(**b**) $Na_2SiO_3/NaOH$ 1.5

Figure 4. Effect of NaOH molarity on FA-SCBA based GPC slump.

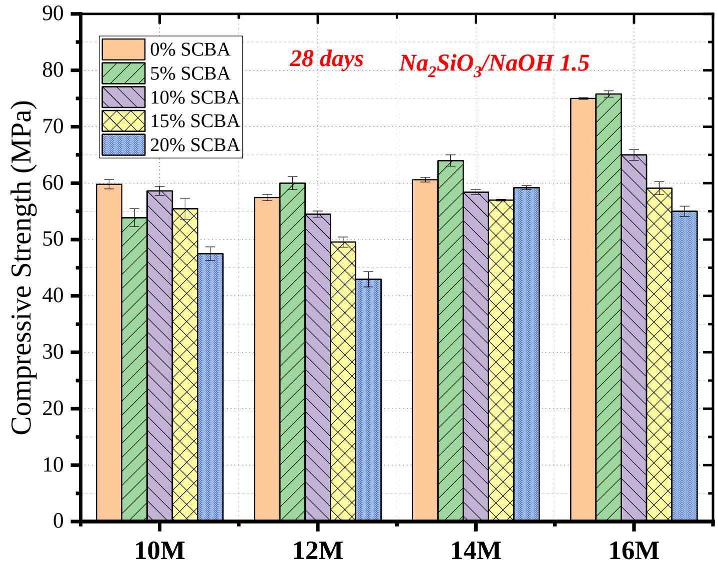
3.2. Compressive Strength

The compressive strength of geopolymer concrete mixes containing 10 M, 12 M, 14 M, and 16 M after 28 days of curing are displayed in Figure 5a,b, respectively. According to the test results, the compressive strength of the GPC mixes increased when the molarity of the NaOH solution was increased from 10 to 16 M for a $Na_2SiO_3/NaOH$ ratio of 2.5. However, for mixtures containing 0% and 15% of SCBA, the strength decreased after 14 M, although the decrease was not substantial, which is similar to what several researchers have reported [33,35]. Alghannam et al. [35] found that the compressive strength declined as the molarity of NaOH increased from 14 to 20 M, indicating that the correlation between molarity and compressive strength aligns with prior research [49,50]. Meanwhile, as the molarity of NaOH rose from 10 to 16 M, with a $Na_2SiO_3/NaOH$ ratio of 1.5, it resulted in an overall improvement in compressive strength, even though a slight drop was observed at 12 M. The observed variation in compressive strength clearly demonstrates the influence of NaOH molarity on GPC. The reason behind this is that sodium hydroxide creates the alkaline environment that geopolymer gels need to bind together [51–53]. Raising the concentration of NaOH can speed up the breakdown of aluminosilicates, encouraging the quick creation of geopolymer gels and the attainment of superior compressive strength [33,54–56]. The reduction in strength can be ascribed to the delay of geopolymerization induced by an overabundance of soluble silicates, specifically when the molar concentration surpasses 12 M or 14 M [33], resulting in the extraction of the Al^{3+} and $Si4^{+}$ ions by leaching [57]. This may have potentially compromised the synthesis of C-A-S-H and N-A-S-H gel structures, consequently resulting in a fall in the material's strength [58].

Finally, the compressive strength of GPC composites is enhanced as the molarity of NaOH is increased. This effect is due to the breakdown of aluminum and silicon particles throughout the polymerization process [59], consequently contributing to the enhancement of the compressive strength of geopolymer concrete mixtures [47].



(**a**) $Na_2SiO_3/NaOH$ 2.5

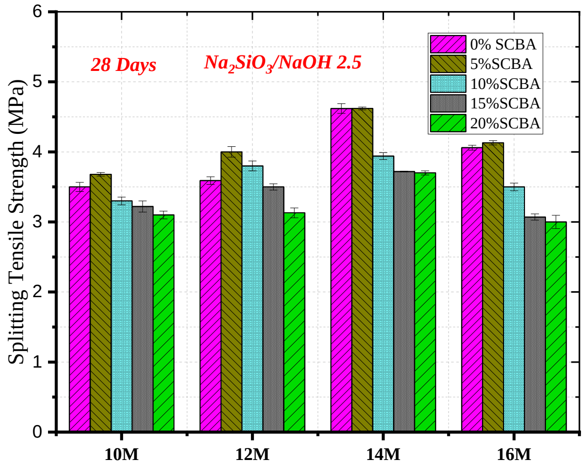


(**b**) $Na_2SiO_3/NaOH$ 1.5

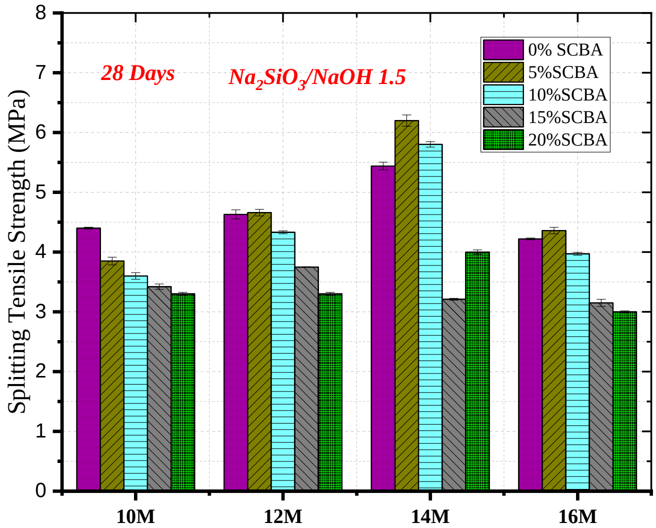
Figure 5. Effect of NaOH concentration in the compressive strength of FA-SCBA based GPC.

3.3. Tensile Strength

Figure 6 depicts the tensile strength of GPC investigated after 28 days of curing. The tensile strength of GPC obtained using 10 M, 12 M, 14 M, and 16 M mixes showed a comparable tendency to that of compressive strength at all replacement levels. The tensile strength rises from 15.5% to 61% when the molarity is raised from 10 to 14 M. Molar concentrations are essential for increasing strength during polymerization. The increase in molarity raises the matrix's pH, which promotes the development of the amorphous phase. Lower dissolution of Si^{4+} and Al^{3+} ions causes a decrease in matrix strength growth when the molarity ratio is smaller [60]. The higher splitting tensile strength is a result of increased silica and alumina dissolution. Beyond a certain point, additional increases in molarity result in a decline in GPC strength [61,62].



(**a**) $Na_2SiO_3/NaOH$ 2.5

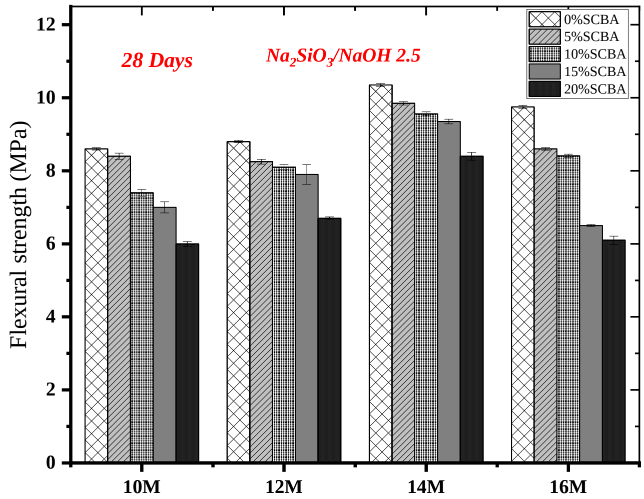


(**b**) $Na_2SiO_3/NaOH$ 1.5

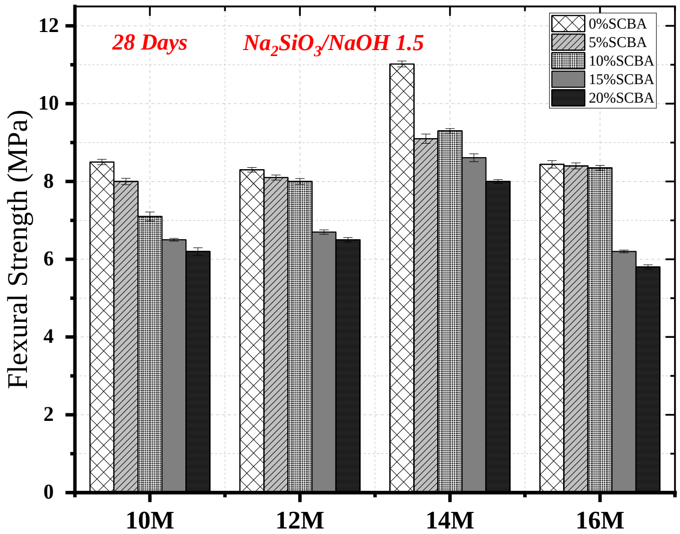
Figure 6. Effect of NaOH concentration in splitting strength of FA-SCBA based GPC.

3.4. Flexural Strength

The 28-day flexural strength of fly ash–sugarcane bagasse ash-based GPC is shown in Figure 7. The findings indicate that, in all cases, flexural strength tends to decrease as SCBA content substitution increases. As the molarity of NaOH rises, the flexural strength value increases up to 14 M and then declines at 16 M. With the molarity rising to 14 M, the flexural strength increases from 17.3 to 40%. This is because a higher concentration of sodium hydroxide promotes better alumina and silica leaching, which improves geopolymerization and increases strength.



(**a**) Na_2SiO_3/NaOH 2.5



(**b**) Na_2SiO_3/NaOH 1.5

Figure 7. Effect of NaOH concentration in flexural strength of FA-SCBA based GPC.

3.5. Correlation between the Mechanical Properties

In this section, a regression analysis was conducted with the aid of the Origin Pro program in order to determine the correlation between the splitting tensile strength and compressive strength, as well as flexural strength with compressive strength.

3.5.1. Splitting Tensile Strength vs. Compressive Strength

Table 4 shows the models that have been proposed to explain the relation between the splitting tensile strength and the compressive strength of geopolymer concrete composed of fly ash and sugarcane bagasse ash. The equations for the proposed model have been constructed for a mean compressive strength ranging from 47 to 75 MPa. The equations that are proposed for the model are represented as Equations (1)–(8).

Table 4. Proposed model for the relationship between the splitting tensile strength and the compressive strength.

$Na_2SiO_3/NaOH$ 2.5		
NaOH molarity	**Equations**	
10 M	Y = 0.04932x + 0.5269	(1)
12 M	Y = 0.10596x − 2.3292	(2)
14 M	Y= 0.1109x − 2.41803	(3)
16 M	Y = 0.2013x − 8.67818	(4)
$Na_2SiO_3/NaOH$ 1.5		
NaOH molarity	**Equations**	
10 M	Y = 0.08939x − 0.95248	(5)
12 M	Y = 0.08633x − 0.43122	(6)
14 M	Y = 0.48777x − 0.79358	(7)
16 M	Y = 0.06926x − 0.79358	(8)

When Y stands for the splitting tensile strength and x denotes the compressive strength.

Figure 8 illustrates the correlation between the splitting tensile strength and compressive strength of geopolymer concrete. It shows that the coefficient of determination (R^2) for all models of 10, 12, and 16 M was 94% fit to forecast the connection of 94% confidence bound of compressive strength. The correlation established in this experiment is comparable to Alomayri et al. [63] and Zareei et al. [64], where the R^2 for the relation between tensile strength and compressive strength were 92 and 94%, respectively. As a result, the derived model equations can be utilized to forecast the compressive strength of FA-SCBA-based GPC between 47 and 75 MPa.

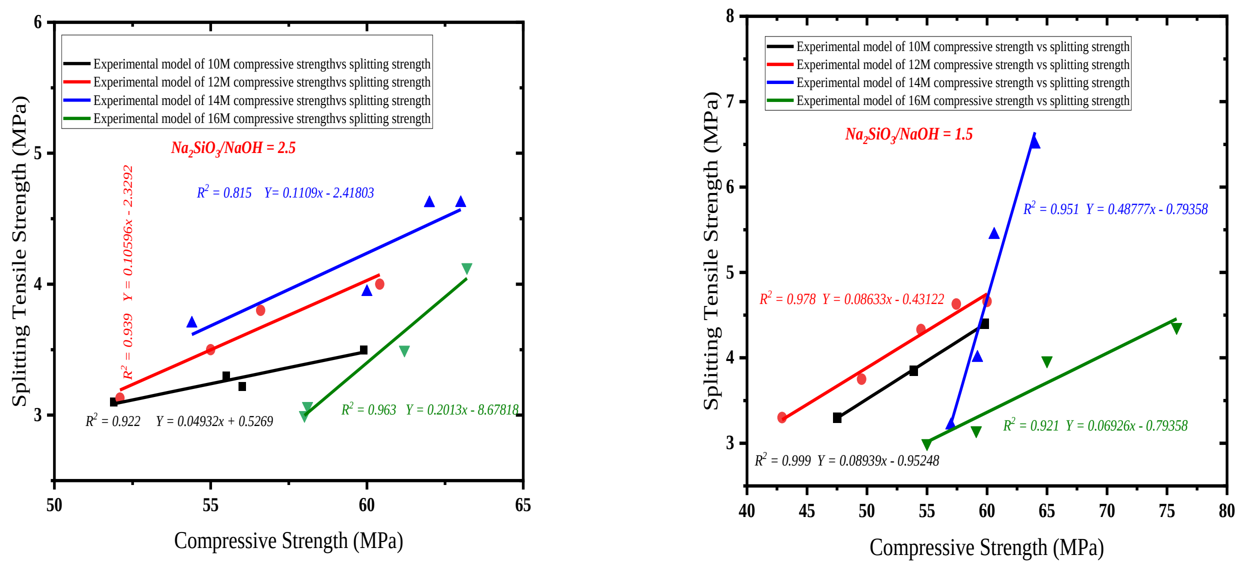


Figure 8. Correlation between splitting tensile strength and compressive strength of 10 M, 12 M, 14 M, and 16 M of NaOH in GPC.

3.5.2. Flexural Strength vs. Compressive Strength

Table 5 shows the models that have been proposed to explain the relationship between the flexural strength and compressive strength of GPC that is based on FA-SCBA. The equations for the proposed model have been constructed for a mean compressive strength ranging from 47 to 75 MPa. The equations that are proposed for the model are represented as Equations (9)– (16).

Table 5. Proposed model for the relation between the splitting tensile strength and the compressive strength.

$Na_2SiO_3/NaOH$ 2.5		
NaOH molarity	**Equations**	
10 M	Y = 0.34008x − 11.69282	(9)
12 M	Y = 0.18108x − 2.40095	(10)
14 M	Y = 0.18962x − 1.90198	(11)
16 M	Y = 0.48684x − 21.86886	(12)
$Na_2SiO_3/NaOH$ 1.5		
NaOH molarity	**Equations**	
10 M	Y = 0.18817x − 2.54255	(13)
12 M	Y = 0.11587x − 1.39236	(14)
14 M	Y = 0.67945x − 30.21794	(15)
16 M	Y = 0.1140x − 0.47941	(16)

When Y stands for the flexural strength and x denotes the compressive strength.

As can be seen in Figure 9, the relationship between the compressive strength and the flexural strength of GPC demonstrates that the coefficient of determination (R^2) of the models was 93 percent. This indicates that the models were able to accurately predict the connection with 93% confidence. Therefore, the model equations generated can be used to forecast the 47–75 MPa compressive strength of FA-SCBA-based geopolymer concrete, given the flexural strength.

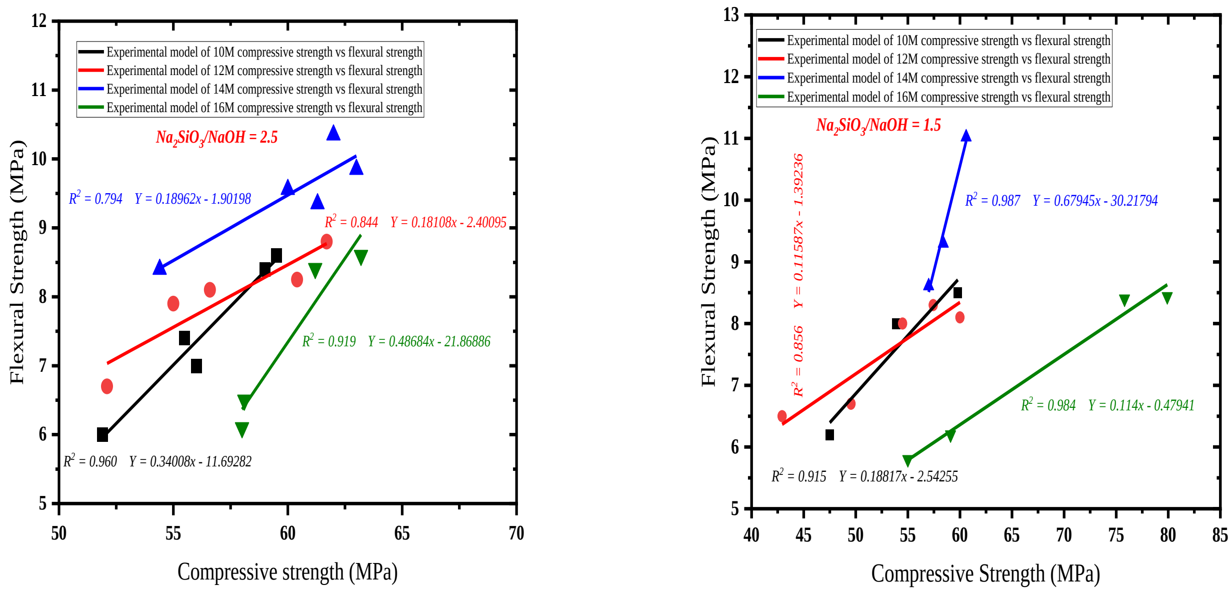


Figure 9. Correlation between flexural strength and compressive strength of 10 M, 12 M, 14 M, and 16 M of NaOH in GPC.

4. Conclusions

In this study, the impact of sodium hydroxide molarity on fly ash–sugarcane bagasse ash-based geopolymer concrete was explored. Based on the investigation carried out, the sodium hydroxide molarity plays a vital role in the compressive strength, splitting strength, and flexural strength of geopolymer concrete samples. From the investigations, the following can be concluded:

1- An increase in the molarity of the sodium hydroxide solution decreases the slump because the higher concentration of the sodium hydroxide solution enhanced the leaching of silica and alumina from GPC, which raised the mixture's viscosity and lowered its water content. Remarkably, the reported slump values for all combinations demonstrated acceptable workability.
2- Increasing the molarity of NaOH in the mix increases the compressive strength; however, the compressive strength decreases after a certain point. This is because sodium hydroxide produces the alkaline environment that geopolymer gels require to bind together.
3- Increasing the NaOH concentration can accelerate the aluminosilicates' breakdown, promoting the rapid formation of geopolymer gels and achieving excellent compressive strength.
4- The splitting tensile strength of fly ash–sugarcane bagasse ash-based GPC produced with 10, 12, 14, and 16 M mixes has demonstrated a comparable pattern to compressive strength at all the replacement levels in most cases.
5- The flexural strength decreased as the substitution of SCBA concentration increased. As the concentration of NaOH increased, the flexural strength value initially increased to 14 M and subsequently decreased at 16 M.
6- The findings of the regression analysis demonstrated that there was a substantial correlation between the suggested model equations and the experimental data.

The results will be valuable as the utilization of sugarcane bagasse ash appears to positively impact the strength properties of GPC, supporting its potential as a sustainable construction material. However, future studies should investigate the impact of low molarity on the mechanical properties and long-term durability of geopolymer concrete made from fly ash and sugarcane bagasse ash.

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