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The effect of cement replacement with metakaolin and sugarcane bagasse ash on the properties of concrete

Aliyu Abubakar[1*], Terlumun Adagba[2], Abubakar Sabo Baba[2]
[1] Civil Engineering Department, Abubakar Tafawa Balewa University, Nigeria
[2] Civil Engineering Department, Federal University Dutsin-Ma, Nigeria

*Corresponding author E-mail: aabubakar24@atbu.edu.ng

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Abstract

The use of supplementary cementitious materials in the cement and construction industry is growing rapidly owing to the numerous benefits the application of these materials offers. In this study, the effects of metakaolin (MK) and sugarcane bagasse ash (SCBA) used to partially replace cement on concrete are investigated. The experimental plan was designed using a constant 5% MK and 0-20% SCBA contents by weight. The mix design of 1:2:3 and water-binder (w/b) ratio of 0.5 was employed. Samples prepared were tested at the ages of 7, 14, 28, and 60 days respectively. Concrete workability, water absorption, and densities all showed a decrease with an increase in the percentage of SCBA. The compressive strengths at lower percentages of SCBA (5% and 10%) recorded higher values compared to that of 5% MK and 0% SCBA. An increase in the percentage of SCBA above 10% however led to a decrease in compressive strength. The maximum compressive strength of 22.17N/mm^2 was obtained at 60 days in concrete containing 5% MK and 10% SCBA. Both the T-statistics and F-statistics values calculated were statistically significant and exceeded their critical values. This suggests that there is a good relationship between the compressive strength of SCBA and the curing period and that the variation in the curing period and SCBA also causes a variation in the concrete compressive strength. From the results obtained, it is concluded that 5% MK and 10% SCBA can be applied to replace cement for structural concrete production.

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Keywords: Metakaolin, Sugarcane bagasse ash, Compressive strength, Density, Supplementary cementitious materials; Water absorption

1. Introduction

Concrete is a widely used building material that can be molded in several geometrical configurations [1]. Its production involves the use of ingredients like cement, aggregates, water, and admixtures [2]. Among these ingredients, the binder and the costliest, environmentally unfriendly element is cement [3]. The increase in population and industrialization has increased the demand for concrete exponentially and subsequently the cost of concrete-producing materials with the attending issue of over-exploitation of our natural resources. Meeting this demand has made sustainable development a global concern which has brought about the need for alternative sources for the construction industry to mitigate primarily the issue of cost as well as resource preservation.

The partial replacement of cement in concrete has recently gained much attention and become an area of interest to researchers and professionals in the construction industry. They are usually artificial or natural materials containing silica in a reactive form [5], and its application in concrete modifies the properties of concrete through hydraulic and/or pozzolanic reactivity. Some of the benefits of applying supplementary cementitious materials in concrete are reduction in cost, elimination of waste, and reductions in the emission of dust, carbon IV oxide (CO_2), and acid gases [3]. Other benefits include reducing concrete susceptibility to cracking by reducing the high heat of hydration due to high Portland cement content and improving concrete properties such as workability, durability, and strength [6].

Sufficient reports on the replacement of saw-dust ash, cassava peel ash, fly ash, and groundnut husk ash to partially replace cement in the concrete production process have been documented. Also, studies on the suitability of replacing cement with two or more of these materials to complement their individual properties so as to further enhance the properties of the ternary blended concrete such as metakaolin and ground scoria [6], saw dust ash and eggshell powder [1] have also been carried out. A study by [7] also reported a quaternary blend containing metakaolin, slag, and rice husk ash (RHA), which in combined form increased the strength and engineering properties of the conventional concrete up by a great extent.

Sugarcane bagasse, widely used as fuel in the sugar-cane industry is also employed as a raw material in the paper-making industry. The pozzolana produced from this ash is obtained from the incineration of the waste material after squeezing out the sweet juice in sugar cane. The pozzolanic properties depend largely on the origin, burning process, and the temperature attained during its incineration. Although SCBA possesses high carbon content above 15% and excessive fineness, with proper treatment, it can provide a high pozzolanic reactivity and an increase in strength when used as a hydraulic binder [8]. The value of compressive strengths found by several researchers has shown an augmentation of concrete strength by using 10% of SCBA as a cement substitute material in concrete after 7 and 28 days respectively [4], [9].

Jimenez-Quero et al. [10], partially replaced cement using 10% and 20% of SCBA. The results showed that a 10% addition of SCBA to the mortar mixtures improved the compressive strength, increased the electrical resistivity above the control, and delayed the first crack occurrence. Concrete containing 15% of SCBA unveiled good results in terms of durability, also the application of SCBA showed an ability to lower the rate of corrosion in reinforced concrete in comparison to reinforced concrete without the additive [11], [12].

Abdalla et al. [13] investigated the mechanical properties of high-strength concrete containing a binary combination SCBA of 10 – 40% by weight with silica fume. Concrete containing 10% SCBA showed high mechanical strength, while water absorption and workability reduced substantially with an increase in ash content.

The addition of SCBA as cement replacement material produced concrete with high early strength, reduced water permeability, and appreciable resistance to chlorine permeation and diffusion [14], [15]. They concluded that for a well-burnt SCBA, 20% of the pozzolana can optimally replace cement with no significant effect on the concrete properties. A study of geopolymer concrete containing bagasse ash and metakaolin, cement replacement of bagasse ash at 10% and metakaolin at 20% was the optimum percentage for compressive strength in geopolymer concrete [16].

Kumar et al. [17] investigated the durability properties of carbon dioxide-cured sugar cane bagasse ash concrete in marine environments while replacing cement with SCBA in several percentages and silica fume at 10%. Results obtained showed that 5% bagasse ash and 10% silica fume had better values compared to other levels of replacements.

Amin et al. [18] investigated the mechanical and microstructural properties of binary and ternary blends of concrete containing different percentages of cement/bagasse ash and cement/bagasse ash/silica fume.
Results obtained showed that the 20% BA binary blend and ternary blend with 33% BA and 7% SF indicated high strength as compared to others and the control, lower water absorption, and apparent porosity.

The results of a study [19] show an increased workability and decreased durability with an increase in bagasse ash percentage at a constant metakaolin percentage of 5%. An increase in the compressive, flexural, and split strength was also recorded up to 15% replacement. The study concluded that maximum compressive, flexural, and split strength was recorded at 5% metakaolin and 5% bagasse ash replacement while the optimum strength was obtained at 5% MK and 0% BA replacement.

Metakaolin is produced by the calcination of kaolinite clay at temperatures between 650℃ to 900℃ [6], [20]. The heating process spills out water from the kaolin ($Al_2O_3.2SiO_2.2H_2O$) thereby altering the material structure resulting in an amorphous aluminosilicate ($Al_2O_3.2SiO_2$) [21].

The application of MK in concrete produces concrete with improved strength and durability performance. It enhances the sustainability properties of concrete as it generates lower CO_2 and requires a lower temperature for its manufacture as compared to cement. According to [22] as reported by [23], around 175 kg of CO_2 is emitted for every ton of MK that is produced, which is significantly lower in comparison with the 1 ton of CO_2 that is released for every ton of PC that is manufactured. This low energy requirement and reduced CO_2 accounts for about a 55% reduction in greenhouse gas emissions [23].

Chen et al. [24] studied the workability, cohesiveness, strength, and sorptivity of concrete containing metakaolin (MK) content ranging from 0 to 30% and water/cementitious materials (W/CM) ratio varying from 0.30 to 0.50. The results indicated that MK up to 20% enhanced the concrete strengths at 28 and 70 days. Also, for up to 30% MK cement replacement, an increase in cohesiveness, a decrease in sorptivity, and an impairment of workability was observed.

This study seeks to investigate the suitability of varying SCBA (0 – 20%) together with metakaolin at a constant dosage of 5% as SCM in concrete. Properties such as workability, water absorption, density, and compressive strength were tested. This work contributes to the growing search for a vast number of waste materials that can replace cement in the production of concrete.

2. Materials and methods

2.1. Materials

2.1.1. Cement

The cement used in the study was obtained from the local market. The cement manufacturer claimed the cement has satisfied the requirements for concrete applications. The physical and chemical properties are as shown in Tables 1 and 2 respectively.

2.1.2. Metakaolin (MK)

The metakaolin used as a supplementary material in the study was obtained by calcining kaolin in the Kerosene Kiln at a temperature of about 650ºC to 900ºC. It was ground and sieved using a 150-micrometer sieve. X-ray fluorescence spectrometer was used in assessing the chemical composition of the metakaolin using the specified requirements at Ashaka cement factory, Gombe State, Nigeria. These properties are presented in Table 1 and Table 2.

2.1.3. Sugarcane bagasse ash (SCBA)

The sugarcane bagasse was obtained locally from a sugar processing company and was burned at controlled temperatures of 600°C to 800°C respectively. Sieve analysis was carried out on the ashes.
Sugarcane bagasse ash is dark greenish in color having almost the same color as ordinary Portland cement. The oxide composition and the physical properties are presented in Tables 1 and 2 respectively.

Table 1. Oxide composition of cement, metakaolin, and sugarcane bagasse ash

Oxide by Weight (%)	Ashaka Cement	Metakaolin (MK)	Sugar cane bagasse ash
S_iO_2	19.68	67.83	74.29
Al_2O_3	6.44	18.66	10.41
Fe_2O_3	3.32	1.15	3.74
CaO	60.92	1.75	1.96
MgO	0.97	0.04	1.56
SO_3	2.28	0.67	0.53
K_2O	0.85	0.13	3.66
Na_2O	0.12	0.40	0.40
LOI	-	6.12	3.20

Table 2. Physical properties of cement, metakaolin, and sugarcane bagasse ash

Physical properties	Ashaka cement	Metakaolin	Sugarcane bagasse ash
Specific gravity	3.15	2.7	1.95
Blaine Fineness(m^2/kg)	370	-	-
Soundness (mm)	8.0	-	-
Initial Setting Time (Min)	49	-	-
Final Setting Time (Min)	487	-	-
Buck Density (Kg/m^3)	1475	1525	560
pH	12.40	7.6	9.2
Loss on Ignition (%)	1.0	0.6	18-20

2.1.4. Fine aggregate

The fine aggregate used in the study was obtained from a local supplier. It has a maximum size of 4.75mm and the particle size distribution test conducted shows that it falls within zone 2. The bulk density and moisture content were conducted in accordance with the relevant specifications. The test results are presented in Table 3.

2.1.5. Coarse aggregate

The coarse aggregate used had particle sizes ranging between 4.75mm and 20mm for the study. It was obtained from a granite site in Bauchi. The physical properties of granite aggregates determined were bulk density, specific gravity, particle size distribution, moisture content, water absorption, aggregate impact value, and aggregate crushing value tests. The tests were conducted in accordance with the relevant specifications. The coarse aggregate physical properties are presented in Table 3.

Table 3. Physical properties of fine and coarse aggregates

Property	Fine Aggregates (Sand)	Coarse Aggregate (Granite)
Specific gravity	2.56	2.66
Bulk density (Kg/m^3)	1457	1518
AIV (%)	-	9.83
ACV (%)	-	14.47
Water absorption (%)	2.56	0.15

2.1.6. Water

The water used was from a municipal supply fit for drinking.

2.2. Methods

2.2.1. Workability test

The workability of the concrete was determined by a slump test. The test was conducted in accordance with the Method for Determination of Slump [25], [26].

2.2.2. Density test

The test is aimed at determining the unit weight of the concrete. The test was conducted in accordance with relevant specifications [27].

2.2.3. Preparation and testing of specimens

The mix design employed in this study was one part of the binder, two parts of sand, and three parts of crushed granites. The binder was composed of 95% cement and 5% of metakaolin as the control, while in subsequent mixes, SCBA was used to replace cement in the proportions of 5 to 20% with a constant 5% of metakaolin. The mixes were labelled as CMS0 for the control; and CMS5, CMS10, CMS15, and CMS20 (Table 4).

Cubes of dimension 100mm were prepared using a w/b ratio of 0.5 after proper mixing and vibration in the laboratory. The concrete specimens that were cured after being de-molded, were taken out of the curing tank and wiped dry in preparation for testing at the required ages. Testing was carried out using the hydraulic crushing machine of 3000kN capacity at the ages of 7, 14, 28, and 60 days respectively. This was done in accordance with relevant specifications [28], [29], [30].

Table 4. Mix proportions of the ternary blended concrete containing MK and SCBA

Specimen label	Cement %	MK %	SCBA %	Water	Cement (kg/m^3)	MK (kg/m^3)	SCBA (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)
CMS0	95	5	0	0.50	383.8	20.2	0.0	702	1054
CMS5	90	5	5	0.50	363.6	20.2	20.2	702	1054
CMS10	85	5	10	0.50	343.4	20.2	40.4	702	1054
CMS15	80	5	15	0.50	323.2	20.2	60.6	702	1054
CMS20	75	5	20	0.50	303.0	20.2	80.8	702	1054

2.2.4. Water absorption test

The water absorption test was carried out on all concrete specimens. This was done in accordance with the relevant specifications [31].

3. Results and discussion

3.1. Concrete workability

To establish the workability of concrete, the slump test was carried out on fresh SCBA concrete in proportions of 0%, 10 %, 15 %, and 20 %. Results obtained reveal that increased proportions of SCBA led to a decrease in slump values. This therefore implies that fresh concrete becomes less workable as the quantity of SCBA increases [32]. This is however variance from a similar research in which the study reported an improved workability with a 5% constant MK content and an increase in SCBA percentage [19].

The slump test recorded values ranging between 70mm (CMB0) and 35mm (CMB20) respectively. The slump at a cement replacement of 5% MK and 20% SCBA presents a higher slump than that obtained using 5% MK and 15% ground scoria (GS) [6]. This suggests that the replacement of cement using MK and SCBA presents a better workability than the use of MK and GS as shown in Figure 1.

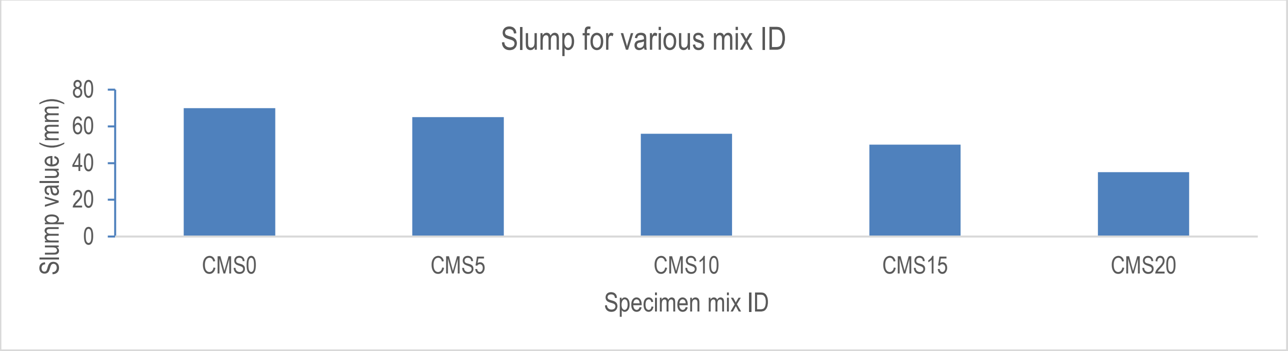

Figure 1. Slump values for different concrete mixes

3.2. Water absorption

The water absorption of concrete indicates its durability, consequently, concrete is considered durable when its absorption ability is low [33]. The variation of water absorption in reference to the percentage composition of the binder is displayed in Figure 2. This shows a decrease in water absorption at all replacement levels of SCBA and further decreases with the curing ages of the samples. The decrease in water absorption suggests a reduction in the pore connectivity and reduced porosity of the concrete due to the fineness of the SCBA and the replacement of portlandite with secondary calcium silicate hydrate (C–S–H) gel due to the pozzolanic reactivity of SCBA [34]. This could also be the reason for the low range of water absorption [33]. Table 5 shows the ANOVA. The coefficient of determination, $R^2 = 97.97\%$, and the final model is presented in Equation 1.

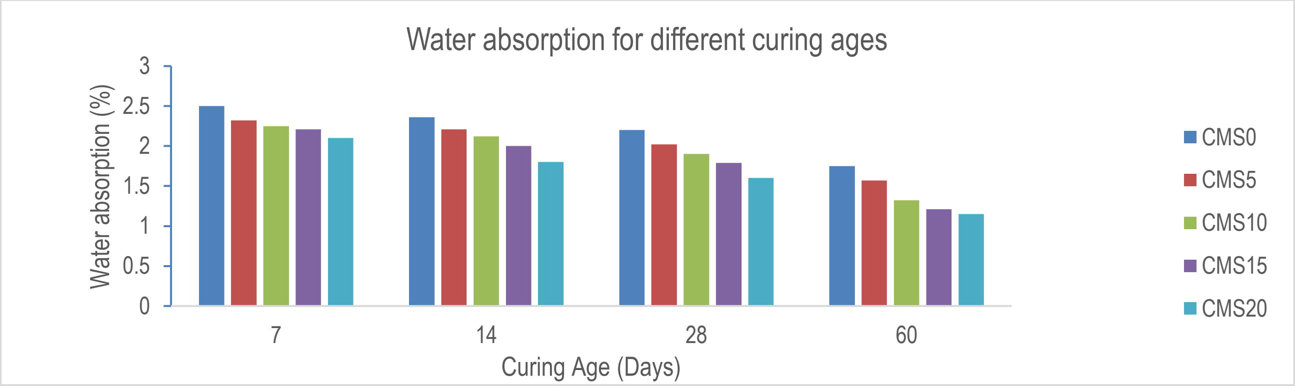

Figure 2. Water absorption for the concrete mixes at different ages

Table 5. ANOVA for water absorption

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Effect
Regression	2	2.8184	1.4092	21.37	0.000	Significant
CP	1	2.1346	2.1435	9.91	0.000	Significant
SCBA	1	0.6838	0.6838	5.18	0.000	Significant
Error	17	0.0584	0.0034			
Total	19	4.8768				

$$\text{Water absorption (\%)} = 2.6177 - 0.016043*CP - 0.02615*SCBA \qquad (1)$$

3.3. Concrete density

The graph showing the density of the samples with various SCBA content displayed in Figure 3 indicates a decrease in density with an increase in SCBA percentage and an increase in density with an increase in the curing period. The decrease in density can be attributed to the low specific gravity of sugarcane bagasse ash. The samples containing 0% SCBA had densities ranging from 2767 to 2873 kg/m^3 and of concrete samples containing 5 - 20% SCBA had densities ranging from 2367 to 2840 kg/m^3 which is slightly lower than that containing 0% SCBA. Table 6 represents the ANOVA. The coefficient of determination, $R^2 = 92.08\%$, and the final model is presented as Equation 2.

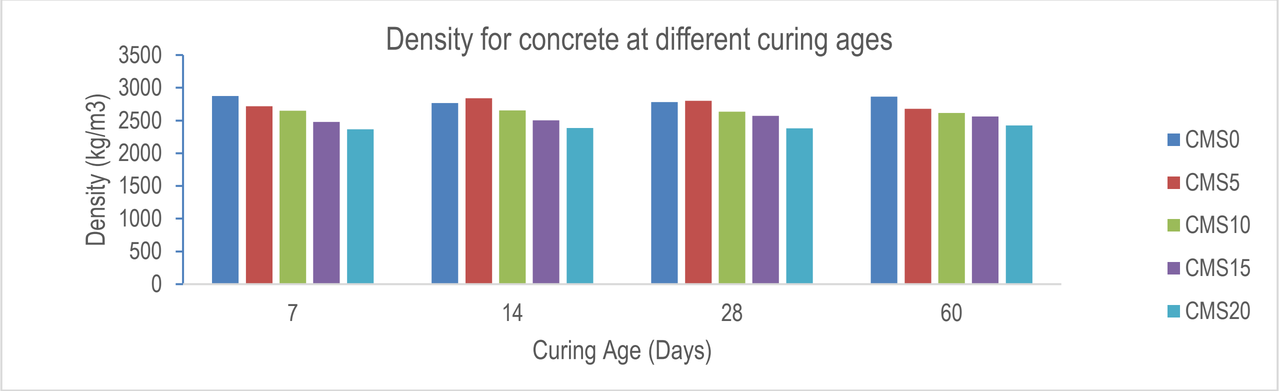

Figure 3. Concrete density for the concrete mixes at different ages

Table 6. ANOVA for concrete density

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Remark
Regression	2	477305	238652	98.85	0.000	Significant
CP	1	101	101	0.04	0.000	Significant
SCBA	1	477204	477204	197.66	0.000	Significant
Error	18	41044	2414			
Total	20	518348				

$$\text{Density (kg/m}^3\text{)} = 2842.70 + 0.1100*CP - 21.85*SCBA \qquad (2)$$

3.4. Compressive strength of concrete

Concrete strength behavior observed in this study was a general increase in strength with an increase in curing age. This was observed for all mixes at all curing ages (Figure 4). However, the strength development of MK/SCBA concrete showed low strength values as compared to the control concrete at 7 days. This may be attributed to the dilution effect of cement in the concrete mixes and little effect of pozzolanic activity state [34], [35].

From the results, the highest strength value was 22.17 N/mm^2 at 10 % SCBA (CMS10), and 60 days curing age which was above the design strength of 20 N/mm^2, with the lowest value of 13.01 N/mm^2 at 20 % SCBA (CMS20) and 7 days curing. Also, concrete with 10% SCBA (CMS10) showed better compressive strength than 0% SCBA (CMS0) at 14, 28, and 60 days of curing respectively (Figure 4). This therefore suggests that the optimal replacement of cement at a 5% MK is 10% SCBA (CMS10) since it performed better than the 0% SCBA (CMS0).

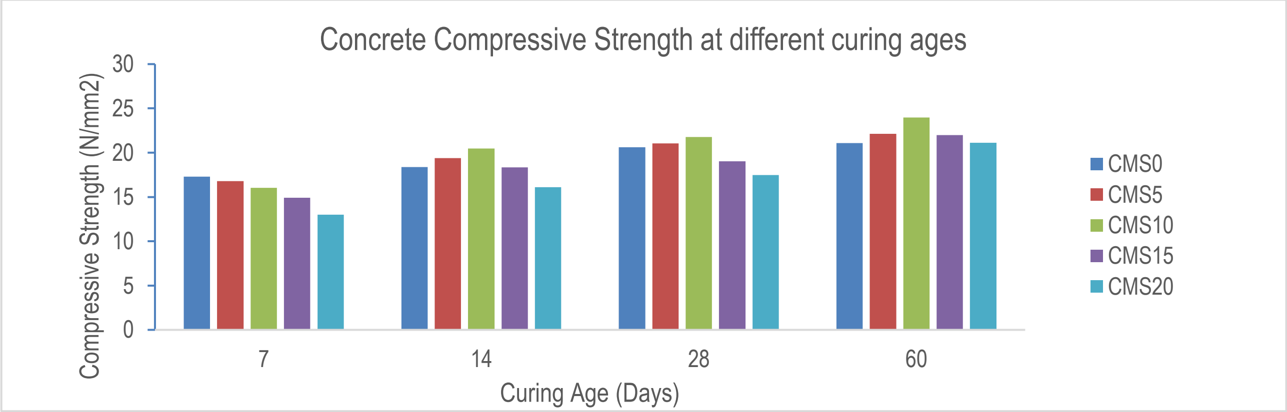

Figure 4. Concrete compressive strength and ages for the various mixes

Pozzolans contain silica, which reacts with the free lime released during cement hydration to form additional calcium silicate hydrate (CSH) as new hydration products, which improves the compressive strength of concrete. Therefore, when the optimum amount required to combine with the liberated lime during the process of hydration is exceeded, the excess silica seeps out, hence the reduction in strength as it replaces part of the cementitious material but does not contribute to strength [19]. This explains the observed increase in strength gain up to 10% SCBA (CMS10) and then a decline in strength for any further increase in % SCBA. Table 7 shows the ANOVA for the compressive strength while the regression equation is presented in Equation 3.

Table 7. ANOVA for the concrete compressive strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Remark
Regression	2	107.85	53.93	22.09	0.000	Significant
CP	1	92.89	92.90	38.06	0.000	Significant
SCBA	1	14.96	14.96	6.13	0.024	Significant
Error	17	44.50	2.44			
Total	19	152.35				

$$\text{Compressive strength} = 17.386 + 0.1058*\text{CP} - 0.1223*\text{SCBA} \qquad (3)$$

The coefficient of determination, R^2 is 72.22%. At a 5% significance level, the T-statistics values obtained are greater than the T-critical ($T_{24,\ 0.05} = 2.797$), with the t-statistics probability values of $P < 0.05$. This indicates a strong relationship between the compressive strength SCBA and the curing period.

Table 7 presents the ANOVA results for the concrete compressive strength. The results show that the F-statistics values were 22.09, 38.06, and 6.13 for the regression, CP, and SCBA respectively, which are greater than the F-critical ($F_{2,\ 17,\ 0.05} = 3.59$). The F-statistic obtained has probability values of $P < 0.05$, hence, the variation of CP and SCBA affects the concrete compressive strength.

4. Conclusions

In this study, an investigation of concrete containing metakaolin and sugarcane bagasse ash as partial replacement of cement using several percentages of SCBA (0%, 5%, 10%, 15%, and 20%) and a constant 5% metakaolin dosage was conducted. Concrete properties examined were workability, water absorption, density, and compressive strength. Results obtained indicate that the incorporation of metakaolin and sugarcane bagasse ash to partially replace cement in concrete resulted in reduced workability, improved compressive strengths and durability properties and as such can be used in producing concrete. From the results obtained, it is concluded that 5% MK and 10% SCBA can be applied to replace cement for structural concrete production. This provides a potential for the development of economical and environmentally sustainable concrete.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in the paper.

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