Impacts of Baobab Stem Fibre Reinforcement in Enhancing the Concrete Strength

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Abstract

Concrete has a limited ductile range, poor tensile strength, and low crack resistance. Therefore, for concrete to function at its best, reinforcing is needed to compensate for these weaknesses. The aim of the study is to assess how the inclusion of baobab stem fibre affects the mechanical characteristics of concrete. Additionally, it sought to investigate the correlation between compressive and flexural strengths when baobab stem fibre is utilised as a reinforcement material. Concrete mixed with baobab stem fibre at volumes of 0.5%, 1.0%, 1.5%, and 2.0%, each with a fibre length of 50mm, was produced using a mix ratio of 1:2:3. The concrete had a constant water/cement ratio of 0.50 and was cured for the periods of 7, 14, 28, 60, and 90 days before testing. Test are carried out to determine how the inclusion of baobab fibre as reinforcement influences workability, compressive strength, and flexural strength. The findings indicated that higher volume fraction of baobab fibre in the concrete influence negatively its workability and compressive strength, but had a positive impact on flexural strength. The flexural and compressive strength results were analysed using Analysis of Variance (ANOVA) with Minitab 19 software. The results revealed coefficients of variation, with R2 values of 97.42% and 93.41% regarding the correlation between flexural and compressive strength, respectively, considering the percentage of baobab fibre volume and curing period. indicating, the percentage baobab fibre volume and curing age are useful predictors of the generated models. The results show that adding baobab fibres to concrete can enhance its performance, especially in terms of flexural strength.

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1. Introduction

All over the world, concrete is one of the most commonly used building materials. [1]. The manufacturing process of concrete involves the utilization of components such as cement, aggregates, water, and admixtures.[2], [3]. It is, nevertheless, characterised by a basic deficiency in tensile strength and is prone to abrupt failure in the absence of reinforcing bars or fibres. [1], [4]. These fibres function majorly to improve the microstructure of concrete, thereby preventing the development and progression of micro-cracks induced by thermal and drying shrinkage as well as load distribution by its bridging effect. [5], [6].The addition of fibres to concrete makes it additionally homogenized and isotropic thus transforming it from a brittle to ductile material [4].

To explore this benefits, numerous researches have been carried out using fibers as reinforcing materials in concrete such as kenaf [7], [8] jute, [1], [9], abaca, [10], [11] palm [12], okra [13], carbon [14], glass [15], banana [16], pineapple leaf [17], [18] sisal [19] hemp [20] steel, [21] cotton [22] copper wire [23] and coir fibre [24].

Fibre reinforced concrete (FRC) is composed of a cement-based matrix incorporated with randomized discontinuous fibres [4]**.** Reinforcement with fibers can be achieved using either natural or synthetic fibers. However, natural fibers are often favoured because they overcome the drawbacks associated with artificial fibers, including higher costs, as well as health and environmental hazards. Natural fibers have qualities such as biodegradability, recyclability, cost-effectiveness, environmental friendliness, extensive availability, sustainability because of their abundant supply, renewable nature, light weight, low density, and generally favourable mechanical strength [25]. They are CO2 neutral, produced with little energy, and have a minimal abrasiveness. [26]. They are however hydrophilic hence absorb water, a property that is enhanced by the use of chemical modification, surface modification, alkalization or addition of coupling agents [27].

Natural fibres are produced from naturally available and renewable resources, such as grass, sisal, hemp, coir, ramie, sugar cane bagasse, jute, kenaf, flax, and abaca coconut, baobab, cotton, henequen, pineapple, banana etc [27], [28]. It’s advantages and desirable properties over synthetic fibers, has made natural fibres to be employed in various areas such as in the automotive industry, buildings, and constructions [29]. This has necessitated the high demand for natural fibres, thereby making the need for finding new fibre materials having the required properties, quite imperative.

Because natural fibres have high mechanical qualities including tensile and flexural strengths, they are used in fibre reinforced concrete composites. The factors include: fibre choice, the nature of the cement-based matrix, fibre orientation, manufacture, fibre dispersion, interface strength, and porosity [30]. In addition to these parameters, the aspects that significantly impact fibre characteristics include the specific plant part from which the fibres are extracted and the methods employed in extraction. [26].

Baobab fibre is sourced from either the pod or bark of the baobab tree and is scientifically known as Adansonia digitata L**.** In Nigeria, the baobab tree is found widely distributed in all parts of the country although more predominantly in northern Nigeria. It is an exceptionally large tree with a massive trunk, reaching up to a diameter of 10 meters, and can attain a height of up to 25m and real lifespan of up to hundreds of years. Additionally, it is prevalent in the hot and arid regions of Africa [31]. Baobab is a versatile tree that serves various purposes, offering protection and supplying food, clothing, medicine, and raw materials for numerous practical items. Researcher's have extensively explore the edibility and beneficial properties of the Fruit pulp, seeds, bark, roots, and leaves of baobabs [32].

2. Related Work

Modibbo et al., [33] investigated the impact of various treatment and solutions on the mechanical properties of indigenous plant bast fibres such as ''Roselle (Hibiscus sabdariffa)'', ''kenaf (Hibiscus cannabinus)'', ''okra (Hibiscus esculentus)'', and ''Baobab (Adansonia digitata)''. After undergoing retting, scouring, and bleaching processes, the fibers were subjected to mercerization at a temperature of about 5°C for 20 minutes, by applying as solutions of 10%, 15%, 20%, and 25% NaOH respectively. The studied parameters encompassed extension at the point of break, persistence, particular rupture work, and density. It was observed that the baobab fibres had a higher extension percentage while breaking on comparing with the other fibres. It was concluded that various treatment and solutions on has significant effect on the mechanical properties of fibers. Thus, the higher relative proportions of amorphous to crystalline regions in baobab fibres was the primary factor influencing the variability of these properties.

Shehu et al. [34] investigated the effects of two to ten weight percent (wt%) of NaOH on baobab pod fibres used as low-density polyethylene (LDPE) reinforcement. The FT-IR examination of the fibre treated by NaOH showed that the lignin band had vanished and the band linked to hemicelluloses had become less intense. In comparison to the untreated baobab fibre composite, the baobab fibre composite treated with 8 weight percent NaOH solutions showed increased tensile strength, modulus of elasticity (MOE), and elongation at break. The impact strength of composites made from fibres treated with 2 weight percent NaOH was 23 percent greater than that of composites made from unaltered fibres. In the meantime, the treated fibres' water absorption was less than 50% of that of the untreated fibres at 10 weight percent NaOH. Abdullahi et al., [35] used baobab fibre that had been retted, cleaned, dried, and finely combed; each of these steps was done independently using benzoyl peroxide and caustic soda (NaOH). Using "Methyl Ethyl Ketone Peroxide (MEKP)" as an accelerator and cobalt octanoate as a catalyst, the composites were prepared by hand lay-up process. The American Society's Tensile in Material Manufacturing (ASTM) specifications, Fourier Transform Infrared Spectroscopy (FTIR) analysis, and Scanning Electronic Microscopy (SEM) were used to determine the modification effect, tensile strength, chemical resistance, water absorption, and surface morphology. The experiments led to the conclusion that the polyester composites made of baobab fibres and benzoylated and treated with alkali had improved in every test property. Isah & Dim [31] utilised different concentrations of NaOH to look at the changes in the mechanical and physical characteristics of baobab pod fibres that had been chemically treated. According to the study, as the concentration of NaOH rose, so did the tensile strength and Young's modulus. It was shown that the removal of surface contaminants enhanced the fibres' adherence to the polymer matrix. But a high concentration of NaOH caused the fibres to break down, which in turn affected the tensile strength. The ideal fibre performance parameters, in terms of Young's modulus and tensile strength, were discovered to be fibres immersed in 6.2% NaOH at 45.63°C for 169.3 minutes.

Isah & Dim [31] investigated the changes in the physical and mechanical properties of chemically treated baobab pod fibers using varying concentrations of NaOH. It was observed that both tensile strength and Young's modulus improved as the NaOH concentration increased; it was also observed that the fibres' adhesion to the polymer matrix improved with the elimination of surface impurities. However, a high NaOH concentration led to the degradation of the fibers, consequently affecting tensile strength. The conditions for optimal fibre performance, regarding tensile strength and Young's modulus, were found to be fibers soaked in a 6.2% NaOH concentration at 45.63°C for 169.3 minutes.

Ghabo et al., [37] reported the results of an experimental study that measured the density, water absorption rate, and moisture content of raw and treated fibers using heat treatment, alkaline treatment and thermochemical treatment. While water absorption coefficient decreased using the heat treatment, the alkaline treatment had a better effect on the apparent and absolute densities and the thermochemical treatment improved the hygroscopic properties better. He noted generally that these treatments, such as boiling, alkaline, and thermochemical, improved the properties of the fibers and made them suitable for use as reinforcement in bio-sourced composite materials. Finally concluded that baobab fibers have potentials for the manufacture of eco-friendly building materials and use in social housing.

Compressive strength is the load carrying capacity and is an important strength parameter in determining the quality of concrete. Several studies of this parameter in fibre reinforced composites have been undertaken. Studies on hemp fibre reinforcement reported up to 58% reduction in compressive strength [38] while a 6% reduction for concrete reinforced with banana fibres has also been reported [39]. Reports of increase in compressive strength up to an optimum value have also been reported by [1]. The decline in compressive strength can be ascribed to factors such as the low specific gravity of the fibres and composites, insufficient mixing, elevated porosity, and the discontinuous distribution of materials, leading to areas of low strength in the specimen [40]. Acosta-Calderon et al. [4] discovered that a fibre length exceeding 50mm can in advance affect t the strength of concrete. Yan and Chouw [41] attribute the decrease in compressive strength to the introduction of voids into the concrete due to the higher fibre content. Addition of fibres in concrete results in either enhanced or reduced concrete compressive strength Reported marginal enhancement in compressive strength up to an optimum content [5] or decreased compressive strength with increased fibres content [43].

Concrete’s flexural strength determines its deflection and cracking behavior. A study by Huang et al., [44] reported a higher average flexural strength for a constant length of 30mm at a constant sisal fibre volume of 0.13% [44]. Huang et al., [45] reported an enhanced flexural strength with increase in fibre reinforcement and a change in failure from a ductile to a brittle mode at higher reinforcement ratios. Ren et al. [46] documented that in ultra-high-performance fibre-reinforced concrete containing optimum sisal fibre content of 2.0% and a length of 18mm, there was an observed increase in flexural strength of approximately 16.7%. Klerk et al. [47] reported an 11% rise in the flexural strength of sisal fibre-reinforced concrete. Similarly, a study on jute fibers indicated a 9.63% improvement in flexural strength [1]. Consequently, natural fibers typically contribute to enhancing the flexural strength of fibre-reinforced concrete composites.

Awareness and much attention has been directed towards the environmental sustainability and innovation incorporating the use of natural fibre composites, with significant advances in the last thirty years towards understanding the short and long-term performances of fibre reinforced cementitious materials. To broaden the potentials of the applicability of baobab fibre, several literatures on the treatment of baobab to improve its properties are available, however documented literature on the experimental investigation of its application in reinforced concrete is scanty. Hence, the need for a study to characterize the properties of a cement based composite matrix containing baobab trunk fibres as reinforcement for use in social housing [37]. This research aims to examine the impact of treated baobab trunk fibres on the compressive and flexural strength of concrete. The outcomes of this study will offer insights into the characteristics of concrete reinforced with baobab fibers, contributing to the existing knowledge and highlighting the potential of integrating baobab stem fibres in the manufacture of natural fibre concrete.

3. Materials and Methods

3.1. Materials

3.1.1.Cement

For this study, regular Portland cement in grade 32.5 is used. The cement brand utilised is Ashaka OPC, grade 32.5. There were no lumps in the grey cement.

3.1.2. Aggregates

Crushed stones are employed as coarse aggregates and river sand as fine aggregates in this research. The source of these materials was a neighbouring quarry.

3.1.3. Water

Clean tap was used for washing aggregates, mixing and curing of concretes.

3.1.4. Baobab Fibers

The baobab trunk fibers used for this work are from a local farm at Dadur in langtang North Plateau state. The fibers were extracted and processed for use. Uniform lengths of fibers of 50mm were obtained by using Machete.

3.2. Methods

3.2.1. Tests on Aggregates

Tests conducted on the material aggregates including; specific gravity, particle size distribution, “aggregate impact value” (AIV), and “aggregate crushing value” (ACV) and were performed in adherence to the specifications as outlined in Table 1.

3.2.2. Chemical Treatment of Baobab Fibers

Baobab fibres have a propensity to absorb moisture, particularly in the initial hours following submersion in water. Fibres treated with alkali have a rougher surface, which improves mechanical bonding and decreases water absorption. To make the fibres alkali-free, they were submerged in a 5% sodium hydroxide (NaOH) solution at 96°C for three hours. After that, they were thoroughly cleaned by submersion in a clean water tank. The fibres are then dried for 24 hours at 70°C in an oven. [35].

3.2.3. Sample Preparation and Testing

In this study, a mix ratio of 1:2:3, water-to-cement ratio of 0.55 and constant fibers of 50mm in length were utilized in concrete manufacturing. Baobab, were incorporated at weight dosages of 0, 0.5, 1.0, 1.50, and 2.0%. Two distinct specimens, cubes (100 mm × 100 mm × 100 mm) and beams (100 mm × 100 mm × 500 mm), were cast to assess compressive and flexural strength, respectively. Baobab fibres were gradually and evenly added to the concrete mix after the materials had been well mixed in a concrete mixer. This ensured that the fibres were distributed uniformly throughout the concrete. After that, the moulds were filled with freshly mixed concrete. The specimens were then allowed for 24 hours to demold. Water was used to heal them for 7, 14, 28, 60, and 90 days after that. The specimens were let to dry in the open air following the curing times before their compressive and flexural strengths were evaluated. Both tests were conducted in compliance with the applicable guidelines.

4. Results and Discussions

4.1. Constituent Materials

Results of Aggregate Impact Value (AIV) and Aggregate Crushing Value (ACV) are presented in table 1. The AIV and ACV were obtained as 14.07 and 26.35 percent respectively. The values fall within the expected range of 0-30 as specified by [48], [49] specifications for AIV and ACV test. The fine aggregates were dry sand passing through a 4.75 mm sieve. The bulk density of fine aggregates 1524 kg/m^3. The bulk density of coarse aggregates was 1550 kg/m^3. Table 2 shows the properties of baobab fibres.

Table 1. Physical Properties Material Aggregates

Properties	**Coarse agg.**	**Fine agg.**
Specific gravity	2.77	2.64
Bulk density (kg/m^3)	1550	1524
Moisture content (%)	0.24	0.42
AIV (%)	14.07	-
ACV (%)	26.35	-
Void ratio (e)	0.44	-
Porosity (%)	30.55	-

Table 2. Properties of Baobab Fibres

S/No.	**Properties**	**Eltahir et al., [36]**	**Modibbo et al., [33]**
1	Guage length/mm	-	2.5
2	Tenacity (kgf)	-	0.6-1.0
3	Elongation at break (%)	-	5.3-7.6

4	Max. thermal stability (oC)	250	-
5	Crystallinity index (%)	48.01	-
6	Cellulose (%)	60.72	-
7	Lignin (%)	5.91	-
8	Hemicellulose (%)	21.98	-
9	Moisture content (%)	13	-
10	Density (g/cm3)	1.1041	1.19-1.40
11	Specific work of rupture (kgf)	-	0.05-0.21

4.2. Concrete Workability

Figure 1 shows the graph of the slump test carried out on the baobab reinforced concrete. The result indicates that increase in fibre content reduced workability of concrete. This implies that concrete containing baobab fibres have reduced workability compared to those without the reinforcement. The workability of all concrete containing baobab fibre reinforcement was lower compared to the concrete with no fibre reinforcement. Adding fibres in the concrete reduces it's workability [1]. This can be attributed majorly to the hydrophilic nature of the baobab fibers, hence, the increase in the fibre volume increased the absorption of water thus reducing the available amount of water in the mixture, consequently reducing the workability. The slump values obtained for 0%, 5%, 10%, 15% and 20% baobab fibre reinforcement was 63, 45, 35, 27, and 20mm respectively. This reduction in workability can be improved upon by the use of superplasticizers.

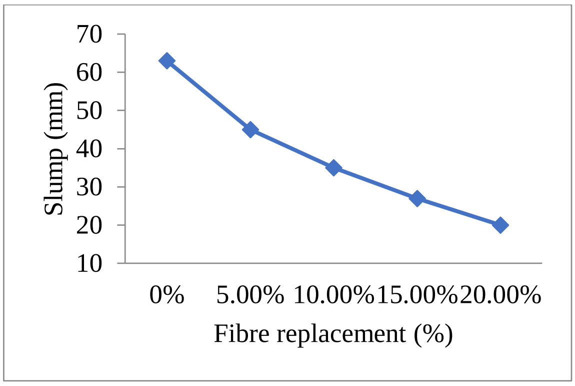

Figure 1. Concrete Slump

4.3. Compressive Strength

The comprehensive strength variation of the concrete reinforced with several volumes of baobab fibre content is shown in figure 2. The highest compressive strength recorded for the grade 20 unreinforced concrete was 19.47N/mm2 at 90 days. This agrees with the result of 19.5 N/mm2 for a grade 20 control concrete obtained in a similar research [50]. This result shows that baobab fibre inclusion in concrete generally impairs its compressive strength. This is agreed with previous studies on reinforced concrete incorporating natural fibres by [38], [39]. The results show the highest percent of 15% strength reduction of compressive strength in the fibre reinforced concrete with reference to the plain concrete was observed for the 2.0 wt% at 90 days.

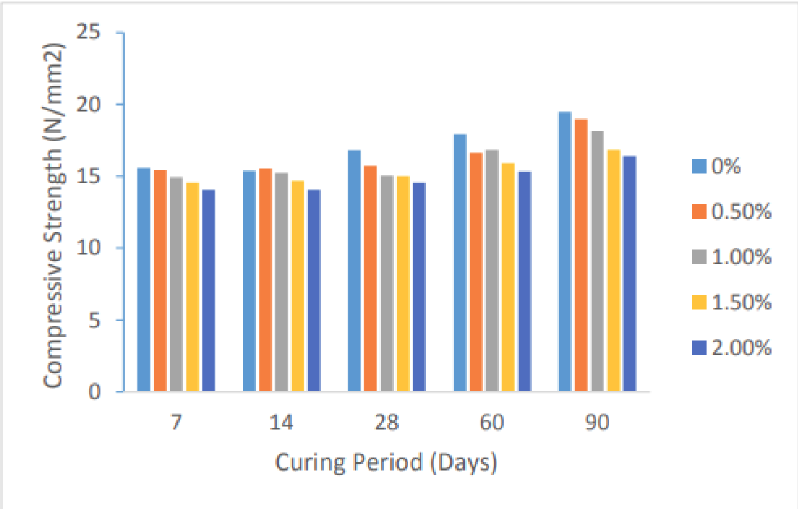

Figure 2. Compressive Strength and Curing Age with Various Fibre Content

Fibres prevent concrete from failure in tension, however, fibres do not possess such compression enhancing ability. Hence, replacing the volume of concrete with a higher volume of fibres caused the compressive ability of the concrete to reduce thereby resulting in the production of concrete with reduced compressive strength. Several other reasons such as the reduction in moisture required by the concrete for strength development due to the hydrophilic nature of the baobab fibres, an impaired fibre-matrix bond, fibre length or orientation could be responsible for the reduced compressive strength. According to [4], a fibre length of more than 50mm can impair the concrete strength, while the decrease in compressive strength can also be associated to the voids introduced into the concrete owing to the increase in fibre content [41].

4.4. Flexural strength

Concrete flexural strengths result with different baobab fibre content is depicted as figure 3. It be seen flexural strength increase with increase in fibre content. This agreed with previous studies by [1], [44], [46], [47]. The highest values were recorded at 2.0 wt% replacement for all curing periods. According to [5] including fibres in concrete generally presents a linear increase in flexural strength with an increase in fibre content.

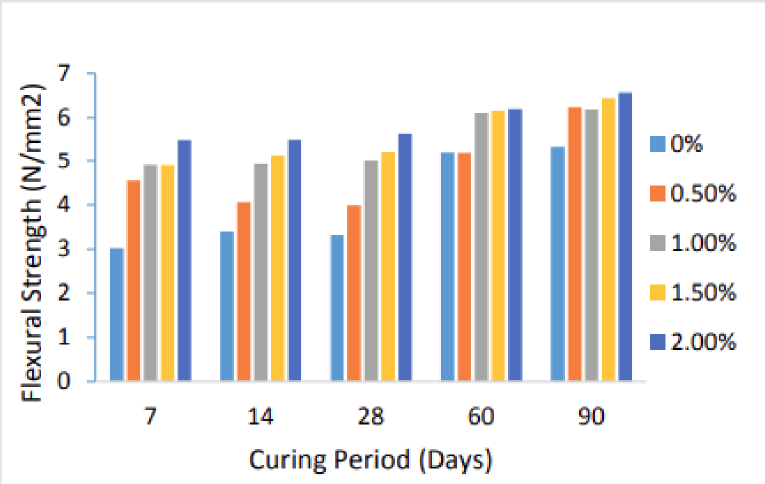

Figure 3. Flexural Strength at various Curing Ages and various Fibre Content.

A remarkable increase in flexural strength is noted for a 2.0 wt% fibre reinforcement of over 80% compared to the plain concrete at 7 days. This high flexural strength agrees with the study of a hybrid mix in which an 86% increase in flexural strength above the control was recorded with 0.3% coir and 0.4% kenaf at 7 days curing for a grade 20 concrete [51]. A hybrid of thuthi and banana fibres also recorded an increase of 115.63% [49]. A study of treated pineapple leaves fibres (T-PALF) recorded a flexural strength increase of about 113.95% [52], while an increase of about 167% and 129% was recorded in separate studies for steel fibres [53], [54].

The percentage increase for the other curing periods above the plain concrete were 60%, 70%, 19% and 23% for 14, 28, 60 and 90 days respectively. This general decrease in percentage strength gain for each curing period can be attributed to the long lasting strength development impairment due to the alkalinity of concrete [55]. This therefore confirms the ability of natural fibres in enhancing the concrete flexural strength. Consequently, the general increase in the flexural strength of baobab reinforced concrete can be as a result of the effect of the baobab fibres as the inclusion of natural fibres in concrete has shown to improve its flexural strength.

4.5. Analysis of variance (ANOVA)

Mathematical models were created to gain statistical understanding of how compressive and flexural strengths behave when reinforced with baobab fibre. The models used Baobab fibre volume percent (%BF) and curing ages (CA) as independent variables. Regression analysis was carried out using Minitab 19 statistical software in the development of the mathematical relationship.

4.5.1. Compressive strength

Table 3. shows the results of the ANOVA for the Compressive Strength. The second order polynomial was used to fit the data as it was the most suitable model for the data set and backward selection approach with alpha to remove of 0.1 was used to eliminate unimportant variables during the modelling process. The model shows statistical significance with an F-value of 188.79 for the F-value. The model terms of CA, %BF, CA x %BF and CA^2 also show statistical significance with p-values all less than 0.05 and as such have significant importance. The coefficient of determination R^2 = 97.42% of variability that 97.42% of variation in the compressive strength of Baobab fibre reinforced concrete is explained by the regression model with BF content and CP as variables respectively. The regression equation for the model generated is given by equation (1).

$$15.392 + 0.02843\,CA - 0.657\%BF - 0.01055CA \times \%BF + 0.000199\,CA^2 = CP \quad (1)$$

Table 3. ANOVA for Compressive Strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Remark
Regression	4	49.3366	12.3341	188.79	<0.001	significant
CA	1	0.8210	0.8210	12.57	0.002	Significant
%BF	1	2.0377	2.0377	31.19	<0.001	Significant
CA x %BF	1	1.3382	1.3382	20.48	<0.001	significant
CA2	1	0.4289	0.4289	6.56	0.019	Significant

Error	20	1.3066	0.0653			
Total	24	50.6432				

4.5.2. Flexural Strength

The results of the ANOVA for the flexural strength are as shown in table 4. The Second order polynomial was used to fit the data as it was the most suitable model. The model shows statistical significance with an F-value of 70.90 for the F-value. The model terms of CA, %BF, CA x %BF and CA^2 also show statistical significance with p-values all less than 0.05 and as such have significant importance. The model summary shows the coefficient of determination R^2 for the flexural strength is 93.41% indicating that 93.41% of variation in the flexural strength of Baobab fibre reinforced concrete is explained by the regression model. The regression equation for the model generated is given by equation (2).

$$2.811 + 0.03015\ CA + 2.105\%BF - 0.00850CA \times \%BF - 0.429\%BF^2 = FL \qquad (2)$$

Table 4. Analysis of Variance (ANOVA) of FS

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Remark
Regression	4	23.2860	5.8215	70.90	<0.001	significant
CA	1	7.2871	7.2871	88.74	<0.001	Significant
%BF	1	3.9355	3.9355	47.93	<0.001	Significant
CA x %BF	1	0.8690	0.8690	10.58	0.004	significant
CA2	1	0.8036	0.8035	9.79	0.009	Significant
Error	20	1.6423	0.0821			
Total	24	50.6432				

5. Conclusion

This experimental effect of baobab fibre is studied on the workability, compressive and flexural strength parameter of a concrete. Based on the experimental analysis, it can be concluded that:

- The workability of concrete reinforced with baobab fibers decreases as the percentage of Baobab fibers increases. This decrease can be attributed to the hydrophilic nature of Baobab fibers, which absorb water, consequently reducing the available water in the mixture. The use of superplasticizers may be necessary to enhance the workability of baobab fibre-reinforced concretes. The inclusion of Baobab fibres tends to impair the compressive strength parameter of concrete up to around 15% compared to the unreinforced concrete.

- Baobab fibres tend to enhance the flexural strength of concrete. An 80% enhancement when compared to the unreinforced concrete was recorded at 7 days of curing for a fibre content of 2.0 wt% of baobab fibre.

- The models for compressive and flexural strengths can explain 97.42% and 93.41% variability in the properties of the Baobab stem fibre reinforced concrete. The mathematical models obtained have R^2 values above 90%, hence the responses can be influenced by the variation in the model predictors.

- The regression equations show that the curing age has more effect on the compressive strength while the baobab fibres have a secondary effect on the flexural strength. The following is suggested for further research

- The compressive strength of Baobab reinforced fibre should be researched for content below 0.5%. Several researches have shown an enhancement of concrete compressive strength below 0.5% inclusion of natural fibre content. [1], [56].

- The flexural strength for baobab showed the highest flexural strength at 2 wt% of fibre content at all curing ages. A further varying of percentage content could establish the optimum fibre content.

- The blending of Baobab fibre with additional natural fibres to improve the characteristics of fibre-reinforced concrete.

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