

Empirical Modeling and Optimization of Sustainable Concrete Incorporating Blends of Digitaria Husk Ash and Ordinary Portland Cement

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ARTICLE INFORMATION	ABSTRACT
Article history: Published: October 2026 Keywords: Digitaria Husk Ash Compressive Strength Tensile Flexural Strength	This study investigates the fresh and mechanical properties of structural concrete produced by replacing Ordinary Portland Cement (OPC) with Digitaria Husk Ash (DHA). An M20 grade concrete mix was developed and cement was substituted at 5 - 20% replacement levels by mass. A Central Composite Design (CCD) of Design-Expert 13 used DHA (%) and curing age (3 to 56 days) as independent operational factors. Evaluated responses included density, compressive strength, flexural strength, and split-tensile strength. The experimental findings show that fresh concrete density systematically drops from 26.06kg/m ³ for the control mix to 25.75 kg/m ³ at 15% DHA due to the lower specific gravity of DHA relative to cement. At a 56-day curing period, the 10% DHA-blended concretes exhibit enhanced compressive strengths of 31.66 N/mm ² due to progressive pozzolanic activity. Flexural strength values peaked at 3.5N/mm ² (5% DHA), while split-tensile performance reached a maximum of 1.98 N/mm ² (10% DHA) at 56 days. Analysis of Variance (ANOVA) shows that all developed quadratic prediction models are statistically significant ($p < 0.0001$) with coefficients of determination ($R^2 > 0.98$) and Adequate Precision figures greater than 28. Numerical optimization established an optimum mix of 8% DHA at a 44-day curing, predicting a fresh density of 25.9 kg/m ³ , compressive strength of 33.7 N/mm ² , flexural strength of 4 N/mm ² , and split-tensile strength of 2N/mm ² . The study demonstrates that 5-10% DHA can serve as a sustainable, eco-friendly cement replacement option for low-cost, durable infrastructural applications.

1. Introduction

Global infrastructural development has led to a drastic surge in the usage of concrete, thereby retaining its spot as the most commonly used building material globally (Sarkin-Shanu et al., 2024). Ordinary Portland Cement (OPC), the main binder matrix in concrete, is expensive, and its production has a highly negative effect on the ecosystem. Cement manufacture is a massive source of CO₂ emission behind fossil fuels and land-usage changes due to deforestation (Adetoye et al., 2022). It is projected that the emanation of CO₂ is between 0.8 – 1.3 tons per ton of cement making and accounts for 8 – 10% of the total global CO₂ emission. Thus, the need to replace cement so as to reduce environmental footprints is immensely crucial (Agwa et al., 2020).. Over the years, researchers have suggested different industrial by-products and agricultural residues as alternative binders in the production of sustainable concrete. Replacing cement with designated percentages of pozzolana has been reported as an effective technical trajectory (Ahsan & Hossain, 2018; Akpenpuun et al., 2019 & Adetoye et al., 2023). Bheel et al. (2021), conducted a study to investigate the mechanical properties of concrete using wheat straw ash as a substitute for cement. Despite extensive research on industrial and agricultural waste materials like Rice Husk Ash (RHA) (Fapohunda et al. 2021; Ouldkaoua et al., 2020), the use of Digitaria exilis (commonly known as "Acha" or Hungry Rice) husk waste remains limited within structural concrete engineering. Digitaria is an annual cereal crop indigenous to West Africa where it is cultivated widely for its straw and edible grains. This creates massive heaps of unutilized husk residues. This study converts this agricultural byproduct into a sustainable binder option. By incorporating comprehensive experimental work and Response Surface Methodology (RSM), this research models, evaluates, and optimizes the structural behavior of concrete containing blends of Digitaria husk ash and cement.

2. Methodology

The primary cement binder employed in this research was Portland Limestone Cement (PLC CEM II 32.5N) sourced locally in Bauchi and conforming to BS EN 197-1. River sand was collected from Gwol stream and sieved through a 4.75 mm screen to serve as fine aggregate, exhibiting a specific gravity of 2.65 and a fineness modulus of 2.897. Crushed granite stones with a maximum nominal size of 20 mm were utilized as coarse aggregates, showing a specific gravity of 2.68, an aggregate crushing value (ACV) of 22.0%, and an aggregate impact value (AIV) of 24.5%. Pure tap water matching BS EN 1008 specifications was deployed for batching. The raw Digitaria husk was obtained from Ta-Hoss in Riyom L.G.A., Plateau State. The hulls were calcined in an industrial furnace at a controlled temperature of 600°C for 2 hours to produce highly reactive amorphous ash. The ash was ground and sieved

under a 425 μm sieve. Central Composite Design (CCD) response surface methodology was executed via Design-Expert 13 for an M20 grade concrete mix (1:2:4 ratio). The factor parameters were Factor A (DHA % from 5% to 15%) and Factor B (Curing age from 3 to 56 days), which established 13 structural test runs. Concrete consistency, slump indices (ASTM C143), fresh concrete density, compressive strength (BS EN 12390-3), flexural strength (BS EN 12390-5), and split-tensile stress values (ASTM C496) were evaluated.

3. Results and Discussions

3.1 Oxide Composition of *Digitaria Husk Ash*

Chemical characterization via X-Ray Fluorescence (XRF) demonstrated that the processed DHA constitutes a high-quality pozzolanic matrix. Table 1 outlines the precise mass percentages of elemental oxide components within the material.

Table 1: Oxide Composition Analysis of DHA

Oxide Compound	Mass Percentage (%)
Silicon Dioxide (SiO_2)	76.60
Aluminum Oxide (Al_2O_3)	8.70
Iron Oxide (Fe_2O_3)	4.90
Calcium Oxide (CaO)	4.70
Magnesium Oxide (MgO)	1.20
Sulfur Trioxide (SO_3)	1.50
Potassium Oxide (K_2O)	1.05
Loss on Ignition (LOI)	3.00

The cumulative sum of acidic structural oxides ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 = 90.20\%$) significantly exceeds the prescriptive 70% threshold required for ASTM C618 Class N pozzolans, confirming outstanding capacity for secondary pozzolanic reactions.

3.2 Paste Consistency and Retardation Effects.

The result of consistency test and setting time of paste are shown in Figures 1 and 2 respectively.

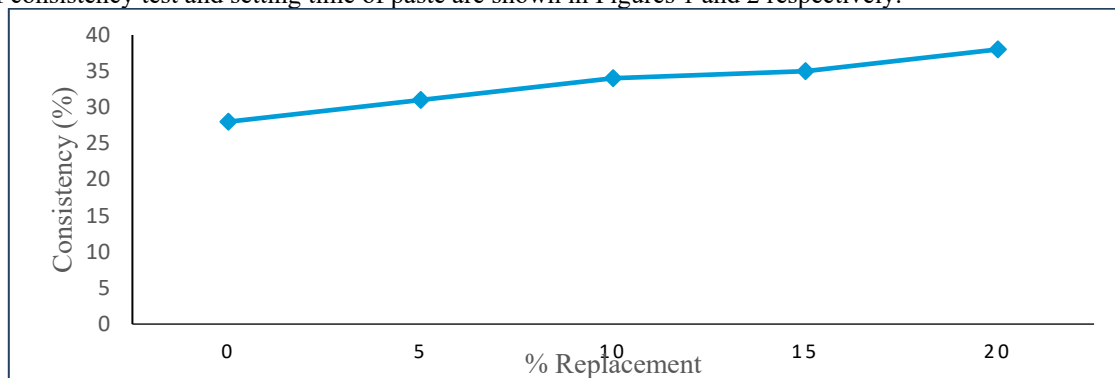


Figure 1: Consistency Result of Admixed Concrete

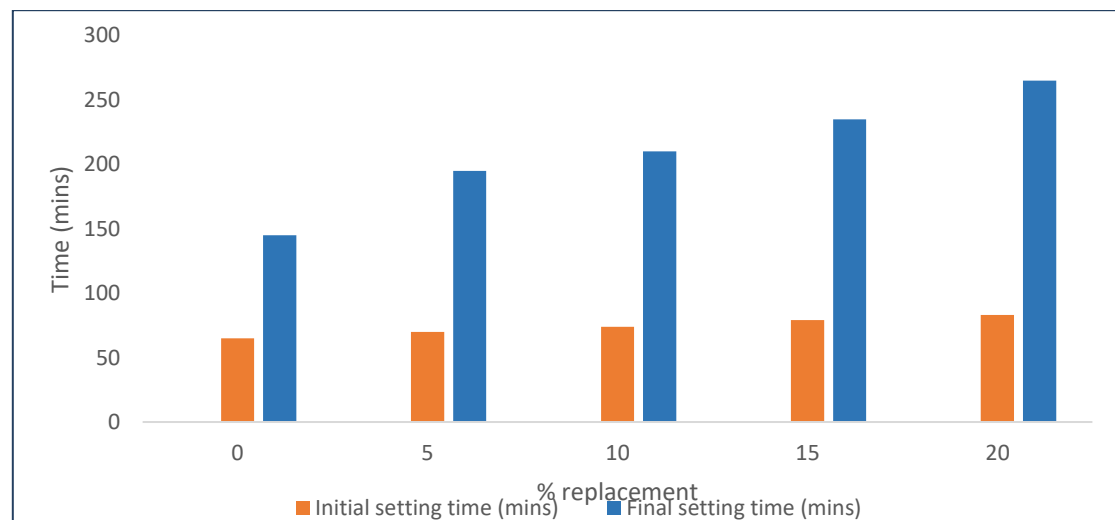


Figure 2: Setting-Times of Paste

The water consistency of pure cement paste was 29%. Incorporating DHA linearly increased consistency requirements to 31%, 34%, 35%, and 38% at 5%, 10%, 15%, and 20% cement replacement, respectively. This increase is attributed to the porous texture and higher surface area of the ash particles. Concurrently, the setting times elongated with increasing DHA content. Initial setting times expanded from 65 to 83 minutes, while final setting times lengthened from 145 to 265 minutes, revealing a distinct structural setting retardation effect. Olu et al. (2020) examined the setting times of mortar blended with Locust Bean Pod Ash and Egg Shell Ash and reported a series of accelerations and retardations as the cement replacement levels increased.

3.3 Performance Evaluation of DHA in Concrete

The performance of the admixed concrete by digitaria husk ash was conducted by series of tests such as density, compressive, flexural and tensile strength tests as presented in Table 2. The properties were analysed using Central Composite Design of Design Expert 13 Software.

Table 2: Performance Evaluation of DHA in Concrete

Run	Factor 1 A: DHA %	Factor 2 B: Curing Age days	Response 1 Density kg/m ³	Response 2 Compressive Strength N/mm ²	Response 3 Flexural Strength N/mm ²	Response 4 Split-Tensile Strength N/mm ²
1	10	28	25.96	30.34	3.7	1.88
2	15	3	26.3	9.64	1.47	0.54
3	10	3	26.39	12.19	3.23	1.12
4	5	3	26.5	11.9	3.04	1.08
5	15	56	25.75	26.47	3.54	1.64
6	10	28	25.96	30.34	3.7	1.88
7	5	56	25.97	31.54	3.6	1.93
8	10	28	25.96	30.34	3.7	1.88
9	15	28	25.81	24.21	3.52	1.6
10	10	56	25.87	31.66	4.0	1.98
11	10	28	25.96	30.34	3.7	1.88
12	10	28	25.96	30.34	3.7	1.88
13	5	28	26.2	29.79	3.58	1.84

3.4 Analysis of Variance (ANOVA) and Predictive Modeling

Statistical evaluations using ANOVA confirmed that all developed quadratic empirical equations are highly valid. Tables 3 to 6 document the detailed ANOVA metrics for concrete density and structural compressive strength.

Table 3: ANOVA Results for Concrete Density ($R^2 = 0.9803$)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	0.6173	5	0.1235	69.78	< 0.0001
A-DHA (%)	0.1094	1	0.1094	61.82	0.0001
B-Curing Age	0.4267	1	0.4267	241.13	< 0.0001
B2	0.0736	1	0.0736	41.60	0.0004
Residual	0.0124	7	0.0018	-	-
Cor Total	0.6297	12	-	-	-

Table 4: ANOVA Results for Compressive Strength ($R^2 = 0.9941$)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	820.90	4	205.23	336.79	< 0.0001
A-DHA (%)	27.78	1	27.78	45.59	0.0001
B-Curing Age	521.55	1	521.55	855.90	< 0.0001
A2	20.30	1	20.30	33.32	0.0004
B2	190.63	1	190.63	312.83	< 0.0001
Residual	4.87	8	0.6094	-	-
Cor Total	825.78	12	-	-	-

Table 5: ANOVA Results for Flexural Strength ($R^2 = 0.9925$)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	1.64	5	0.3277	186.36	< 0.0001
A-DHA	1.30	1	1.30	741.24	< 0.0001
B-Curing Age	0.1350	1	0.1350	76.78	< 0.0001
A ²	0.1262	1	0.1262	71.79	< 0.0001
B ²	0.0144	1	0.0144	8.19	0.0242
Residual	0.0123	7	0.0018	-	-
Lack of Fit	0.0123	3	0.0041	-	-
Pure Error	0.0000	4	0.0000	-	-
Cor Total	1.65	12	-	-	-

Table 6: ANOVA for Split-Tensile Strength ($R^2 = 0.9844$)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	2.28	4	0.5711	126.41	< 0.0001
A-DHA	0.1908	1	0.1908	42.24	0.0002
B-Curing Age	1.32	1	1.32	291.29	< 0.0001

A ²	0.1157	1	0.1157	25.61	0.0010
B ²	0.4438	1	0.4438	98.24	< 0.0001
Residual	0.0361	8	0.0045		
Lack of Fit	0.0361	4	0.0090		
Pure Error	0.0000	4	0.0000		
Cor Total	2.32	12			

The model equations derived for all responses are detailed in Equations 1 – 4:

$$\text{Density} = 26.8 - 0.0449A - 0.024B - 2.489e - 05 * AB + 0.0009A^2 + 0.00023B^2 \quad \dots (1)$$

$$\text{Compressive str} = 3.45 + 1.74A + 1.053B - 0.108A^2 - 0.012B^2 \quad \dots (ii)$$

$$\text{Flexural str.} = 3.073 + 0.07A + 0.01B + 0.00018AB - 0.009A^2 - 0.0001B^2 \quad \dots (iii)$$

$$\text{Tensile strength} = 0.572 + 0.12A + 0.05B - 0.008A^2 - 0.001B^2 \quad \dots (iv)$$

where, A is DHA and B is Curing Age

3.3 3D Response Surface Graph Analyses

The 3D response surface plot correlates the dependent variables against independent response indices as shown in Figures 3 to 6..

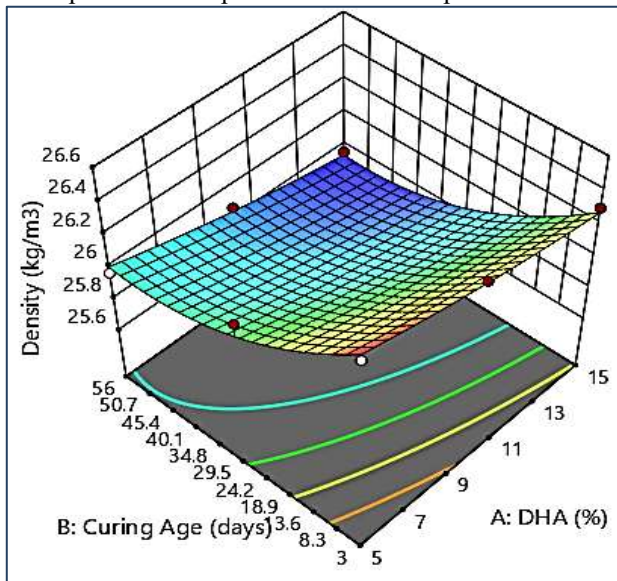


Figure 3: DHA and C.A on Density of Concrete

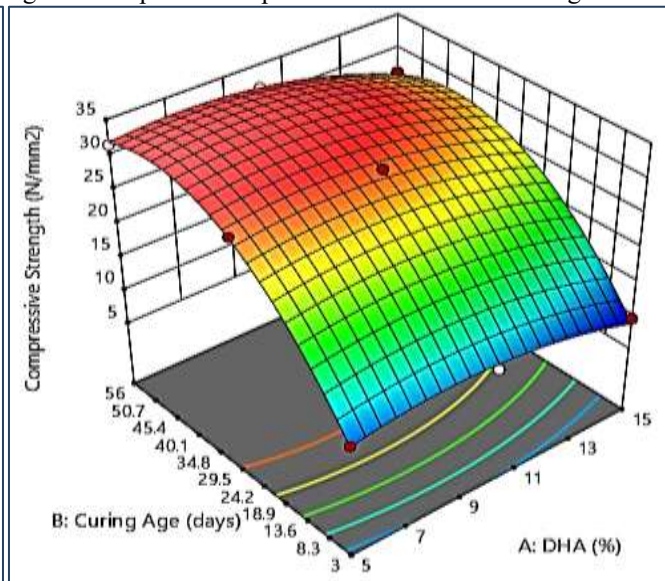


Figure 4: DHA and C.A on Compressive Strength

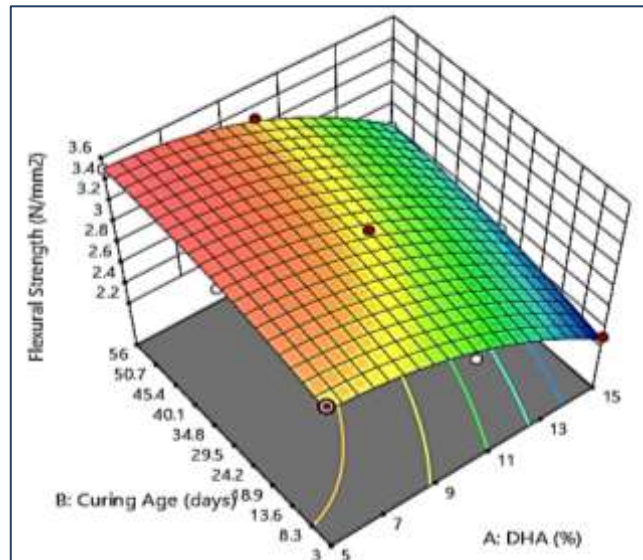


Figure 5: DHA and C.A on Flexural Strength

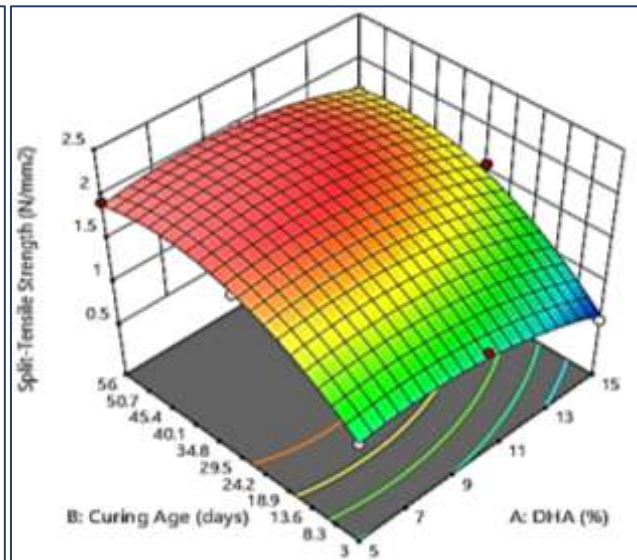


Figure 6: DHA and C.A on Split-Tensile Strength

The graphical evaluation establishes that a systematic increase in the replacement dosage of DHA drives a downward profile shift in the fresh concrete density across all curing ages. Conversely, lengthening the curing age shifts the density upwards as the matrix hydrates. The 3D response surface loop for compressive strength and tensile strength exhibits a highly defined parabolic curvature profile. At early curing timelines (3 to 14 days), the surface declines as the DHA content increased from 5% up to 15%, showing that dilution controls the early matrix phase. However, as curing age parameters advance toward the 56-day boundary, a prominent peak forms across the surface topology. This hump establishes a peak zone situated structurally between the 5% and 10% DHA replacement boundaries, yielding up to 31.66 N/mm² strength.

3.5 Numerical Optimization and Validation

Multi-objective numerical optimization targeted maximum mechanical strengths within acceptable density guidelines. Experimental verification runs validated these model predictions with absolute variations remaining securely below the 5% error limit, confirming excellent model robustness.

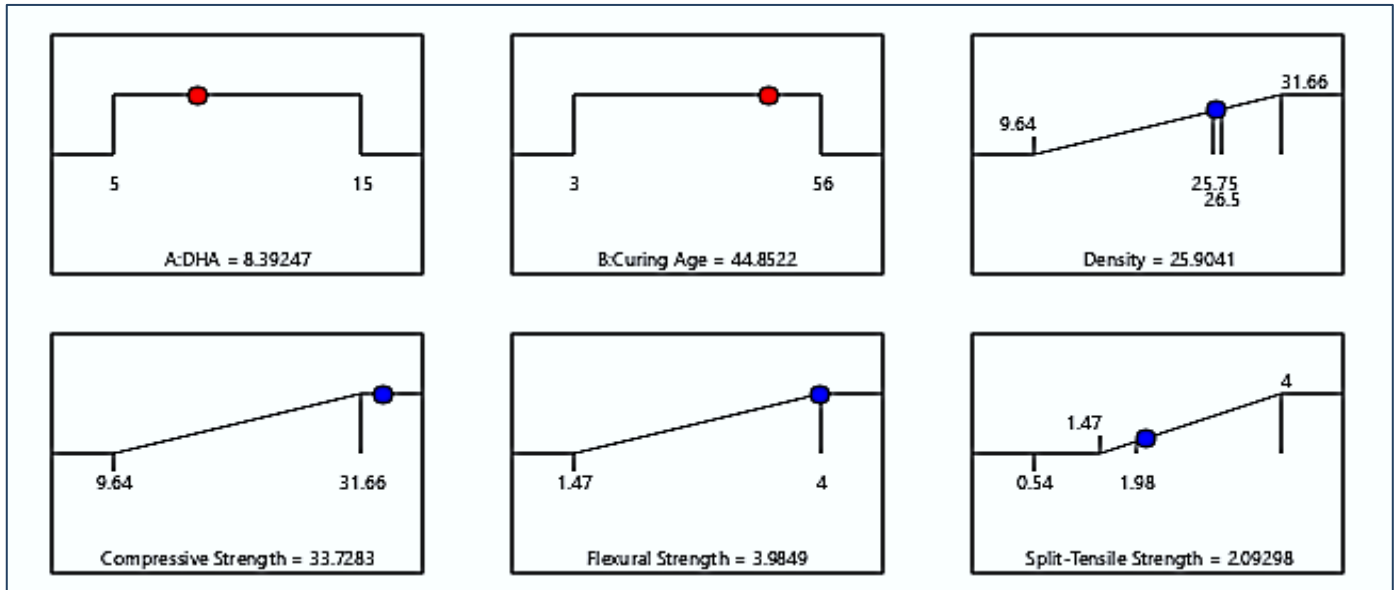


Figure 7: Ramp Plot Showing the Optimal Values for Responses

The optimal result showed 8% DHA at 44 days gave the density of 25.9 kg/m³, compressive strength of 33.7 N/mm², tensile strength of 2 N/mm² and flexural strength of 4 N/mm².

4. Conclusions and Recommendations

Based on the experimental investigation, the following conclusions are drawn:

- Processed Digitaria Husk Ash satisfies all chemical compliance criteria for Class N pozzolans, with active silica-alumina content reaching 90.20%.
- DHA increases the water demand of blended cement pastes and acts as a setting retarder due to physical water absorption.
- Cement replacement at 5% and 10% levels improves compressive and split-tensile parameters at late curing ages through pozzolanic C-S-H creation.
- Long-term mechanical performance balances out dilution effects. Mixes with 5% and 10% DHA achieved 56-day compressive strengths of 31.54 N/mm² and 31.66 N/mm², outperforming the control mix due to progressive pozzolanic reactions.
- The optimized target matrix configuration of 8% DHA at 44 days provides an excellent balance of structural performance and resource sustainability, showing minimal variance (< 5%) from validated model targets.
- It is highly recommended to use 5 - 10% DHA blends for sustainable, eco-friendly concrete structural works to improve structural economics and waste valorization.

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