
OPTIMIZATION AND PREDICTIVE MODELLING OF DOUM PALM FIBRE-REINFORCED CONCRETE INCORPORATING RICE HUSK ASH

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ABSTRACT

The growing demand for environmentally sustainable construction materials has stimulated interest in incorporating agricultural waste products into concrete production. This study investigates the mechanical performance and optimization of doum palm fibre (DF)-reinforced concrete containing rice husk ash (RHA) as a partial replacement for Portland limestone cement. A multilevel factorial experimental design based on Response Surface Methodology (RSM) was employed to evaluate the combined influence of RHA replacement (0–25%) and DF content (0–2%) on compressive strength, flexural strength, split tensile strength, and punching shear strength. Predictive regression models were developed using Design-Expert software and assessed through analysis of variance (ANOVA), coefficients of determination (R^2), and residual diagnostics. Quartic polynomial models adequately represented all responses, with predicted, adjusted and coefficients of determination ranging from 0.9529 to 0.9914. Numerical optimization identified an optimum mixture containing 2.0% DF and 10.45% RHA, producing predicted compressive, flexural, split tensile, and punching shear strengths of 18.010 MPa, 5.370 MPa, 4.420 MPa, and 1.053 MPa, respectively, at 56 days. Experimental validation showed prediction errors below 5%, confirming the reliability of the developed models. The findings demonstrate that response surface methodology provides an effective tool for optimizing sustainable fibre-reinforced concrete mixtures while reducing experimental effort. The combined use of rice husk ash and doum palm fibre offers a viable approach for producing environmentally friendly concrete with satisfactory mechanical performance.

Keywords: Response Surface Methodology; compressive strength; flexural strength; split tensile strength; punching shear strength; rice husk ash; doum palm fibre; regression models

1. INTRODUCTION

Concrete remains one of the most widely used construction materials worldwide because of its versatility, durability, structural performance, and ability to withstand diverse environmental conditions (Habert et al., 2020; Olsson et al., 2023). Rice husk ash (RHA), an agricultural by-product generated from the controlled combustion of rice husks, has emerged as a promising SCM owing to its high silica content and pozzolanic reactivity. Several recent studies have reported that the appropriate partial replacement of cement with rice husk ash can improve concrete compressive strength (Al-Alwan et al., 2024).

Although numerous studies have examined the individual effects of RHA or fibre reinforcement on concrete performance, limited information is available regarding the combined influence of RHA and doum palm fibre on both conventional strength properties and punching shear behaviour of reinforced concrete flat slabs. Furthermore, predictive models capable of optimizing these properties simultaneously remain scarce. Therefore, this study investigates the performance optimization of doum palm fibre-reinforced concrete incorporating rice husk ash as a partial cement replacement. This knowledge gap restricts the practical implementation of sustainable fibre-reinforced concrete mixtures for structural applications.

2. METHODOLOGY

2.1 Material

2.1.1 Cement

Portland Limestone Cement (PLC), conforming to BS EN 197-1, was used as the primary binder. Properties of cement were determined in accordance with BS EN 196-3:2016 to verify compliance with the relevant specifications.

2.1.2 Rice Husk Ash

Rice husk ash (RHA) was produced by controlled calcination of rice husks in a laboratory muffle furnace at temperatures between 600 and 700 °C for 4 h. The resulting ash was ground and sieved through a 75 µm sieve to obtain a fine pozzolanic material suitable for use as a supplementary cementitious material.

2.1.3 Doum Palm Fibre

Doum palm fibres (DF) were collected from naturally growing doum palm trees at Buzai Village near Zaria, Kaduna State, Nigeria. The fibres were cleaned, air-dried, and cut into lengths ranging from 20 to 25 mm, corresponding to an aspect ratio of approximately 80 to 120.

2.1.4 Aggregates

Crushed granite with a nominal maximum size of 20 mm was used as coarse aggregate. The aggregate was obtained from Abdu Kwari Quarry, Zaria, Nigeria. Natural river sand with a maximum particle size of 0.5 mm served as the fine aggregate..

2.1.5 Mixing Water

Potable water supplied by the Ahmadu Bello University, Zaria Water Works was used for concrete mixing and curing. The water satisfied the requirements of BS EN 1008:2002.

2.1.6 Statistical Software

Design-Expert Version 13 (Stat-Ease Inc., USA) was used for all the statistical analysis conducted.

2.2 Methods

2.2.1 Experimental Design

Full factorial design was adopted on Response Surface Methodology (RSM). Two independent variables were considered: Rice husk ash (RHA): 0, 5, 10, 15, 20, and 25% by mass replacement of cement. Doum palm fibre (DF): 0, 0.5, 1.0, 1.5, and 2.0% by volume of concrete. 30 different Mix ID were obtained from the design of experiment each Mix ID having 2 replica giving total of 60 runs.

2.2.2 Concrete Mix Proportion

Concrete mixtures were proportioned in accordance with BS EN 14889-1:2006 using a constant mix proportion of 1:1.5:3 (cementitious material, fine aggregate, coarse aggregate) and a constant water-to-binder ratio of 0.50. Rice husk ash replaced Portland limestone cement at replacement levels of 0–25%, while doum palm fibre was incorporated at dosages ranging from 0 to 2.0% by concrete volume.

2.2.3 Specimen Preparation and Curing

Concrete constituents were mixed until a uniform and homogeneous consistency was achieved. 30 different mix ID were cast, 3 samples for each curing day, as 7,14,21,28 and 56 days. Total of 450 samples for each of cubes, cylinders and beams and total of 90 samples for flat slabs were cast. These implies the averages of the three (3) results for each of the sample were recorded for

analysis of the compressive, split tensile and flexural strength respectively, while the averages of the three (3) results for samples of each of the 30 Mix ID of the flat slabs for only 56 days of curing were considered for punching shear strengths analysis making 90 cast samples.

2.2.4 Mechanical Property Test

The compressive strength test was carried out in accordance with BS EN 12390-2: (2009). Three set of each concrete cubes of size 100x100x100mm were used. Split tensile strength of the fibre reinforced concrete was carried out in accordance with BS-EN 12390-6 (2009). Concrete cylinders of 100x200mm size were used. The failure load was determined and the split tensile strength was calculated using the Equation 1.

$$\text{Split tensile strength} = \frac{2P}{\pi LD} \quad (1)$$

Where P is the failure load, L is the length of the cylindrical specimen and D is the diameter of the specimen. The flexural strength test of the fibre reinforced concrete beam was carried out in accordance with BS 12390-5(2019). Beams of 100x100x450mm size were used. The flexural strength of the beam was determined using three-point bending test. The punching shear test was carried out in accordance with BS-8110-1:1997. The curing duration was 7, 14, 21, 28 and 56days for all the test, expect the punching shear, where only 56days was considered. Laboratory test results for the mechanical properties were not reported in this study only the optimized results from the software were reported.

2.3 Response Surface Modelling and Optimization

Regression models were developed to establish relationships between the independent variables (RHA replacement level and DF dosage) and the measured responses. The general polynomial model adopted is expressed as shown in Equation (2):

$$y = b_0 + \sum_{i=1}^k b_i x_i + \sum_{i=1}^k b_{ij} x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^k b_{ij} x_i x_j + \dots + \varepsilon \quad (2)$$

Where: y = predicted response variable, b_0 = intercept, b_i = model coefficients, b_{ij} = linear/interaction terms, x_i and x_j = reaction factors, ε = represents errors. The optimization objectives and constraints for the variables and responses are presented in Table 1.

Table 1: Optimization Objectives and Constraints

Variables/Responses	Goal	Lower Limit	Upper Limit
Doum Palm fibre (DF)	Maximize	0.0	2.0
Rice husk ash (RHA)	Maximize	0.0	25.0
Compressive Strength(N/mm ²)	Maximize	13.15	19.73
Flexural Strength(N/mm ²)	Maximize	4.12	5.78
Split Tensile Strength(N/mm ²)	Maximize	3.02	4.78
Punching shear strength(N/mm ²)	Maximize	0.623	1.231

3. RESULTS AND DISCUSSION

3.1 Development of predictive models

Mathematical prediction models for the strength properties of doum palm fibre reinforced concrete incorporating rice husk ash as a partial replacement of cement were developed using Design-Expert software (Version 13). The software was used to generate regression equations for all the investigated responses in both coded and actual forms. Based on model fitting and adequacy checks, quartic polynomial models were identified as the most suitable for describing the compressive, flexural, split tensile, and punching shear strengths. To improve model reliability, statistically insignificant terms were eliminated, and the final refined models were established as presented in equations (3) to (7).

$$F_c = 18.70 - 0.5183D - 2.85R - 0.0700DR - 2.09D^2 - 1.59R^2 + 0.7054DR^2 - 0.0167D^3 + 1.49D^4 \quad (3)$$

$$F_f = 5.46 - 0.0381D - 0.2500R - 0.0148DR - 0.0995D^2 - 0.0979R^2 + 0.0043D^2R - 0.1786DR^2 + 0.0389D^3 - 0.3090R^3 + 0.0871D^3R - 0.2500DR^3 - 0.1693R^4 \quad (4)$$

$$F_s = 4.46 - 0.0475D - 0.6796R - 0.0682DR - 0.1000D^2 - 0.5132R^2 - 0.1196D^2R - 0.0982DR^2 + 0.1641R^3 - 0.1020D^2R^2 - 0.2442DR^3 + 0.3011R^4 \quad (5)$$

$$F_p = 1.07 + 0.0086D - 0.2313R + 0.0057DR - 0.1021D^2 - 0.3907R^2 + 0.0178D^2R - 0.0180DR^2 - 0.0099D^3 - 0.0475R^3 + 0.0643D^4 + 0.2549R^4 \quad (6)$$

Where: D and R are coded factors for doum palm fibre and rice husk ash respectively. F_c , F_f , F_s and F_p are compressive, flexural and split tensile strength of the concrete and punching shear strength of the concrete slabs.

The ANOVA results presented in Tables 2 to 5 summarize the relevant statistical parameters evaluated at a 95% confidence level for 60 runs signifying 2 replicate of the 30 Mix ID.

Table 2: ANOVA Results for Compressive Strength of doum palm fibre reinforced concrete with rice husk ash as partial replacement of cement

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	257.98	8	32.25	179.08	< 0.0001	Significant
D	0.7754	1	0.7754	4.31	0.0430	
R	227.11	1	227.11	1261.17	< 0.0001	
DR	0.0686	1	0.0686	0.3809	0.5398	
D^2	1.34	1	1.34	7.42	0.0088	
R^2	24.26	1	24.26	134.69	< 0.0001	
DR^2	2.38	1	2.38	13.20	0.0006	
D^3	0.0007	1	0.0007	0.0042	0.9488	
R^4	0.8538	1	0.8538	4.74	0.0341	
Residual	9.18	51	0.1801			
Cor Total	267.16	59				

Table 3: ANOVA Results for Flexural Strength of doum palm fibre reinforced concrete with rice husk ash as partial replacement of cement

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	8.83	12	0.7360	274.52	< 0.0001	Significant
<i>D</i>	0.0042	1	0.0042	1.56	0.2180	
<i>R</i>	0.1879	1	0.1879	70.08	< 0.0001	
<i>DR</i>	0.0002	1	0.0002	0.0717	0.7900	
<i>D</i> ²	0.1040	1	0.1040	38.79	< 0.0001	
<i>R</i> ²	0.0042	1	0.0042	1.56	0.2177	
<i>D</i> ² <i>R</i>	0.0001	1	0.0001	0.0336	0.8554	
<i>DR</i> ²	0.1524	1	0.1524	56.84	< 0.0001	
<i>D</i> ³	0.0041	1	0.0041	1.52	0.2233	
<i>R</i> ³	0.2535	1	0.2535	94.54	< 0.0001	
<i>D</i> ³ <i>R</i>	0.0096	1	0.0096	3.57	0.0650	
<i>DR</i> ³	0.0829	1	0.0829	30.94	< 0.0001	
<i>R</i> ⁴	0.0155	1	0.0155	5.76	0.0204	
Residual	0.1260	47	0.0027			
Cor Total	8.956	59				

Table 4: ANOVA Results for Split tensile Strength of doum palm fibre reinforced concrete with rice husk ash as partial replacement of cement.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	11.91	11	1.08	263.21	< 0.0001	Significant
<i>D</i>	0.0286	1	0.0286	6.95	0.0112	
<i>R</i>	1.39	1	1.39	337.59	< 0.0001	
<i>DR</i>	0.0083	1	0.0083	2.01	0.1631	
<i>D</i> ²	0.0444	1	0.0444	10.79	0.0019	
<i>R</i> ²	0.1079	1	0.1079	26.25	< 0.0001	
<i>D</i> ² <i>R</i>	0.0701	1	0.0701	17.04	0.0001	
<i>DR</i> ²	0.0461	1	0.0461	11.21	0.0016	
<i>R</i> ³	0.0714	1	0.0714	17.37	0.0001	
<i>D</i> ² <i>R</i> ²	0.0174	1	0.0174	4.23	0.0451	
<i>DR</i> ³	0.0791	1	0.0791	19.25	< 0.0001	
<i>R</i> ⁴	0.0489	1	0.0489	11.89	0.0012	
Residual	0.1974	48	0.0041			
Cor Total	12.1074	59				

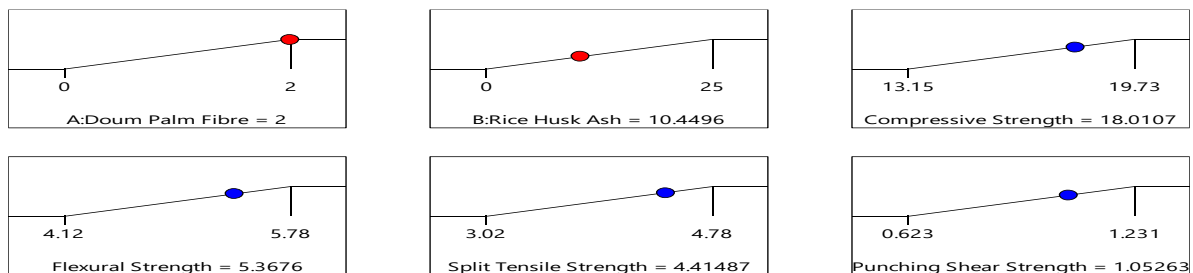
Table 5: ANOVA Results for Punching shear Strength of doum palm fibre reinforced concrete with rice husk ash as partial replacement of cement

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2.09	11	0.1897	503.84	< 0.0001	Significant
<i>D</i>	0.0002	1	0.0002	0.5610	0.4575	
<i>R</i>	0.1608	1	0.1608	427.12	< 0.0001	
<i>DR</i>	0.0005	1	0.0005	1.20	0.2784	
<i>D</i> ²	0.0032	1	0.0032	8.46	0.0055	
<i>R</i> ²	0.0666	1	0.0666	176.99	< 0.0001	
<i>D</i> ² <i>R</i>	0.0015	1	0.0015	4.10	0.0484	
<i>DR</i> ²	0.0016	1	0.0016	4.13	0.0477	
<i>D</i> ³	0.0003	1	0.0003	0.7012	0.4065	
<i>R</i> ³	0.0060	1	0.0060	15.87	0.0002	
<i>D</i> ⁴	0.0016	1	0.0016	4.24	0.0449	
<i>R</i> ⁴	0.0350	1	0.0350	93.04	< 0.0001	
Residual	0.0181	48	0.0004			
Cor Total	2.1081	59				

The ANOVA results indicate that rice husk ash replacement was the dominant factor governing the strength properties, contributing approximately 88% of the model sum of squares for compressive strength.

3.2 Optimization

The essence of optimization was to obtain optimal values of factors that yielded optimum responses. Figure 1 illustrates the optimized outcomes corresponding to the most suitable solutions for the selected response variables. From the optimization search, the software identified four (4) possible solutions, of which the most desirable was achieved at a doum palm fibre content of 2.00% and a rice husk ash replacement level of 10.45% at 56 days curing age.



Desirability = 0.712
Solution 1 out of 4

Figure 1: Optimization ramp combination for independent variables and results outcomes for responses

The optimized strengths values of 18.011 N/mm² for compressive strength, 5.368 N/mm² for flexural strength, 4.415 N/mm² for split tensile strength, and 1.053 N/mm² for the punching shear strength of the flat slab were obtained from the optimisation analysis of the Design-Expert software at this mix combination. The overall desirability index for this solution was 0.712, which indicates a satisfactory level of optimization.

Table 6: Optimization Result of doum palm fibre reinforced concrete with rice husk ash as partial replacement of cement

S/N	Doum Palm Fibre(%)	Rice Husk Ash(%)	Compressive Strength (N/mm ²)	Flexural Strength (N/mm ²)	Split Tensile Strength (N/mm ²)	Punching Shear Strength(N/mm ²)	Desirability
1	2.000	10.450	18.011	5.368	4.415	1.053	0.712
2	2.000	10.207	18.061	5.370	4.425	1.054	0.712
3	2.000	10.000	18.104	5.372	4.432	1.055	0.711
4	1.467	10.511	18.492	5.444	4.510	1.078	0.708

3.3 Model Validation

The validation of the developed models were carried out experimentally and the percentage error differences were indicated in Table 7.

Table 7: Experimental Model Validation

Responses	Doum palm fibre(%)	Rice husk ash (%)	Curing Age(days)	Predicted Values	Experimental Values	Error (%)
Compressive strength(N/mm ²)	2.00	10.45	56	18.011	18.51	2.70
Flexural strength(N/mm ²)	2.00	10.45	56	5.368	5.25	-2.25
Split Tensile Strength(N/mm ²)	2.00	10.45	56	4.415	4.30	-2.67
Punching shear strength(N/mm ²)	2.00	10.45	56	1.053	1.10	4.27

The percentage errors were found to be below 5%, this suggested that the predicted values from the developed models are in close agreement with the experimental result.

4. CONCLUSION

This study developed response surface models for predicting the mechanical properties of doum palm fibre-reinforced concrete incorporating rice husk ash as a partial cement replacement. The developed quartic models demonstrated excellent predictive capability, with the predicted, adjusted and coefficients of determination exceeding 95% for all investigated responses and experimental validation errors below 5%. Multi-response optimization identified an optimum mixture containing 2.0% doum palm fibre and 10.45% rice husk ash, providing a balanced improvement in compressive, flexural, split tensile, and punching shear strengths. And row experimental strengths properties were not reported in this study only the responses from software were reported for modelling and optimization.

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