Optimization and Predictive Models on Strengths and Durability of Reinforced Laterized Concrete

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Abstract:
The increasing demand for fine aggregates in turn has led to the astronomical increase in the cost of procuring construction materials thereby making it difficult to meet the shelter provision requirement of the teeming population of a country such as Nigeria. This study aims at optimizing and developing predictive models on the strengths and durability of reinforced laterized concrete using response surface methods with laterite being used as a partial replacement of fine aggregate in reinforced concrete. In this study, the optimized laterite content was determined at replacement level of laterite to fine aggregates at 0, 10, 20, 30 and 40% with a mix ratio of 1:2:4 and a water cement ratio of 0.65, while for the water absorption, the percentages replacement of laterite to fine aggregates was 0, 10 and 20%. The results of the strength and the durability obtained from the laboratory were subjected to statistical analysis using design expert software version 13(2021). The strength and the durability were found to be 19.044N/mm^2,27.304N/mm^2 and 3.809% for the compressive strength, flexural strength and water absorption at 10% laterite content at 28 days curing age. It was concluded that, to achieve the maximum strength (compressive and flexural) and durability requirements of laterized concrete should be produced by replacing fine aggregate with 10% laterite and cured at 28 days. The developed models could be used for the predictions of desired strengths and durability of the reinforced laterized concrete.

Keywords: Compressive strength, Design Expert Software, Flexural strength, Laterized concrete, Response Surface Methods

1. INTRODUCTION

NOWADAYS, concrete is the most often utilized building material worldwide [1, 2]. The constituent materials are in great demand due to its use in various buildings [3]. The increasing demand in turn has led to astronomical increases in the cost of procuring these materials thereby making it not easy to match the shelter provision requirement of the swarming population of a country such as Nigeria. River sand is a typical fine aggregate used in the production of concrete in Nigeria. Degradation of the ecosystem and uncontrolled depletion of natural reserves are the results of the ongoing mining of sand from our rivers [4]. It follows that there is a clear demand for the cost effective substitute for fine aggregate material. There have been various attempts to address this issue by substituting different materials for river sand in the production of concrete, either entirely or in part, one such material which is used in this research is lateritic soil. In addition, this study seeks to use the response surface method to carry out optimization as well as develop a prediction model for the strength and durability of reinforced laterized concrete. The response surface method (RSM) is a well-known statistical and mathematical prediction method. It enables the nonlinear response surface to be satisfactorily experimentally analyzed to investigate the influence of independent factors [5, 6]. In order to achieve design goals, it also determines the linear interactions and quadratic contributions of the various component, which are necessary adjustments to the proportions of the concrete mix [7]. The construction cost and failure chances of the building components are reduced since this method ensure the effective use of constituent material [7]. Effective methods that could support experimental design include optimization, statistical analysis, predictive modelling and experimental design [8]. Utilizing the collected input-output data, the predictive models equations are derived, validated and confirm to be adequate and suitable [8]. According to [9] many tropical regions, including Nigeria, have an abundance of laterite, which is a combination of clay iron, aluminum oxides and hydroxides. Concrete containing laterites is termed laterized concrete [10]. Laterized concrete is a concrete which stable laterite replaced aggregate (sand) wholly or partially [11]. [12] Conducted a laboratory investigation to evaluate the effect of steel fibre from burning of spent motor vehicle tyres on the strength characteristics of laterized concrete specimens. It was discovered that the tensile to compressive strength ratio of the specimens tested depended on the curing age, the amount of reinforcement and the mix ratio, with the ratio decreasing as the percentage of steel fibre and curing age increased. [13] discovered that the optimal compressive strength of 12.9 Nm was achieved by modified concrete with a 20 % lateritic density, set at the temperature range between 100^{0}C and 120^{0}C. [14] used laterized concrete for structural members and recommended the use of laterite content should not be more than 50 %.

This study aim at optimizing and developing predictive models on the strengths and durability of reinforced laterized concrete using response surface methods with laterite as a partial replacement of fine aggregate in the production of reinforced concrete.

2. Materials and Methods

2.1. Materials

Laterite samples was collected at Mil-Goma opposite Ahmadu Bello University Teaching Hospital, (ABUTH) Shika Zaria. The soil was collected at a depth of 0.5 m below the ground surface. The sample was free from tree roots, debris and inorganic materials. Portland limestone cement of grade 42.5 N was used for this research was sourced from Albabello trading company Samaru Zaria with a specific gravity of 3.16. A Crushed granite of 20 mm maximum nominal particle size was sourced from Abdukwari quarry opposite Nigeria College of Aviation Technology (NCAT), Zaria. River sand was sourced behind area G at Ahmadu Bello University Zaria with a specific gravity of 2.60. A high-yield steel reinforcement bar (12 mm diameter) was sourced from an open market in Sabon Gari, Zaria. The water used was potable, sourced from the Department of Civil Engineering Laboratory of ABU, Zaria, Kaduna State, Nigeria. Design Expert Version 13 (2021) was used for the response surface methodology employed in this study.

2.2 Methods

2.2.1 Response Surface Methodology (RSM):

Response surface methodology (RSM) is a combination of statistical and mathematical methods that is used in development of predictive models and optimization processes. The response (Y) which is a dependent variable and f_1, f_2, f_k (Independent variables) as well as the error β is expressed in equation 1.

$$Y = f(f_1, f_2 \dots\dots\dots\dots\dots\dots\dots\dots\dots . f_k) + \beta \text{ ....(1)}$$

Where Y is the response of the experiment which is the function of various independent controllable variables and β is the representation of other uncontrollable sources of variations for the outcome Y. The controllable variables, as shown in Equation 1, are in the natural form with their respective physical units that are difficult to manipulate. As a result, these variables are converted into coded variables with zero mean values and the same standard deviation as is shown in Equation 2.

$$\eta f(x_1, x_2 \dots\dots\dots\dots\dots\dots\dots\dots\dots . x_k) \text{ ....(2)}$$

The response surface is planar when the interaction term is zero or negligible. The generalized mathematical model using quadratic response surface is as given in Equation 3.

$$Y = \beta_o + \sum_i \beta_i x_i + \sum_j \beta_{ii} x_j^2 + \sum_{i,j} \sum_j \beta_{ij} x_i x_j + \epsilon \text{...(3)}$$

According to the équation above, Y represents the response, β_o is a constant, $\beta_{i,}\ \beta_{ii}$ and β_{ij} are coefficients of linear influence and double interactions, $x_i\ x_j$ are the independent factors and Є error.

3. Results and Discussions

3.1 The developed mathematical model

The influence of the independent variables (curing age and laterite content) on the responses such as compressive strength, flexural strength, and water absorption was determined. Computations of polynomial coefficients from experimental data predicted both response variables. The analysis of variance findings demonstrated that the compressive strength and flexural strength could be predicted with the cubic model while water absorption with the quadratic model. The regression equations generated for all responses using response surface methodology are illustrated in equations 5, 6, and 7.

$$F_c = 13.372 - 0.070533L_c - 0.716404C_a - 0.008913L_cC_a - 0.001516C_a^3 \text{ .... (5)}$$

$$F_f = 18.31421 + 0.074749L_c + 0.546720C_a - 0.13286L_cC_a - 0.018121L_c^2 + 0.00024C_a^3 \text{ .... (6)}$$

$$W = 2.64274 + 0.03598L_c + 0.000717L_c^2 - 0.000186C_a^2 \text{ .... (7)}$$

The regression models in the equations above F_c , F_f and W represent compressive strength flexural strength and water absorption of laterized concrete, L_c and C_a representing laterite content and curing age.

3.2 Effect of independent factors on responses.

Figure 1 and Figure 2 show the 2D and 3D plots of the compressive and flexural strength of laterized concrete respectively, it was observed from 2D plots that the strength decreases from the reddish region to the blue region of the contour as a percentage of the laterite content increases, this may be as a result of a large amount of silt, quartz and granular aggregate of kaolinite clay particles in the concrete from laterite content which tends to reduce the bond between the concrete matrix. Moreover, Figure 3 shows the 2D and 3D plots of water absorption of laterized concrete, it was observed from the 2D plot that the water absorption increases from the blue region to the reddish region of the contour plot, this is because laterite absorbed more water as the percentage of the laterite increases. Furthermore, three-dimensional (3-D) surface graphs were used to present the relationship between two independent variables and response variables. The 3-D response surface graphs of changes in compressive strengths of the laterized concrete, the flexural strengths of reinforced laterized concrete and water absorption of the laterized concrete respectively and the relationship between laterite content (L_c) and curing age (C_a). It can be seen from a 3-D plot of the compressive strength and flexural strength of laterized concrete that the strengths of laterized concrete increase with curing age and decrease with an increase in laterite content. It can be observed from plate 3, a 3-D plot that the water absorption of the laterized concrete increases with an increase in curing age and laterite content.

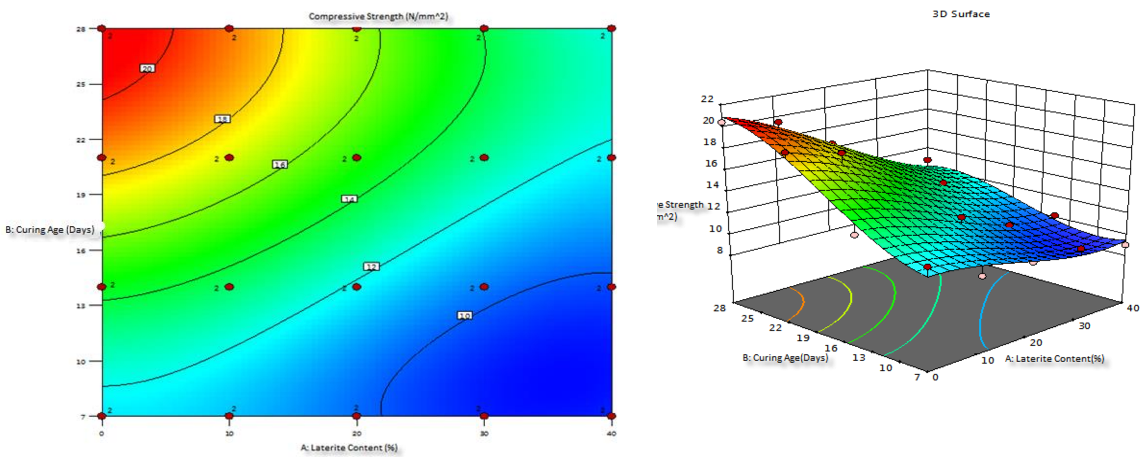

Figure 1: 2D and 3D Contour Plot for the Compressive Strength of the Laterized Concrete

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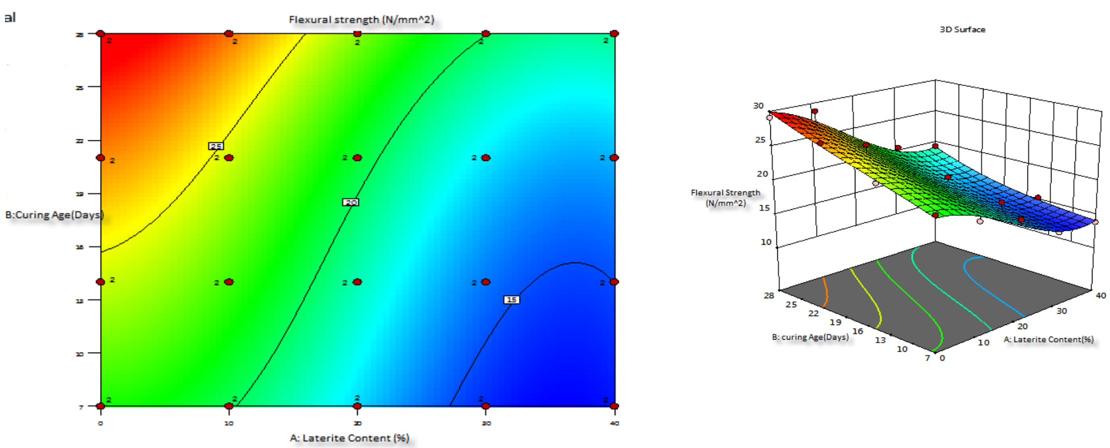

Figure 2: 2D and 3D Contour Plot for the Flexural Strength for the Laterized Concrete

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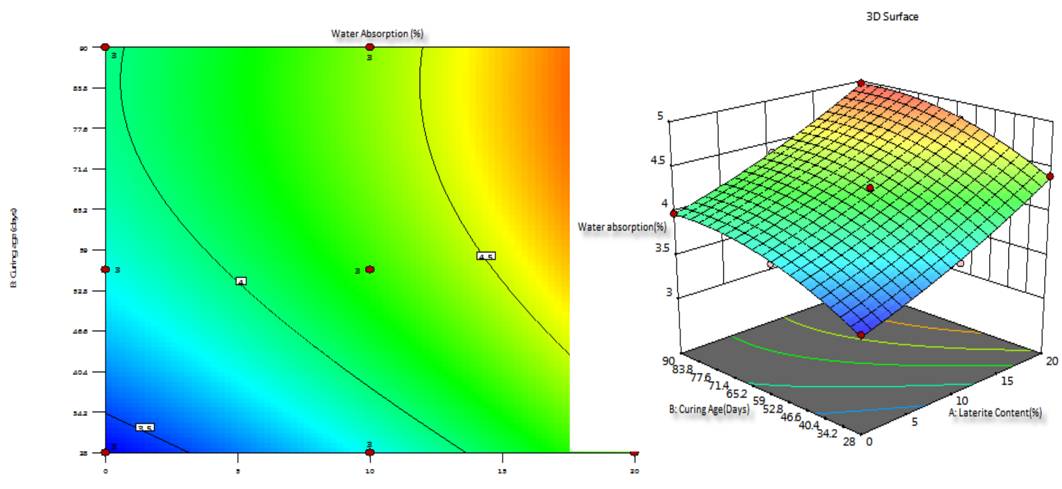

Figure 3:2D and 3D Contour Plot for the Water Absorption for the Laterized Concrete

3.3 Analysis of Variance (ANOVA)

The results of ANOVA are shown in Table 1, Table 2 and Table 3 for compressive strength, flexural strength and water absorption of laterized concrete respectively. The **F-values** of 98.02, 104.51 and 1491.81 for compressive strength, flexural strength and water absorption respectively imply the models are significant. There is only a 0.01 % chance that an F-value could occur due to noise. The significance of all models and terms was controlled using a 95% confidence interval (P<0.05). However, the terms were significant as the p-values were less than 0.05.

Table 1: ANOVA Results on Response variable (Compressive Strength of the Laterized Concrete)

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	439.53	9	48.84	98.02	< 0.0001	Significant
L_c-LateriteContent	28.30	1	28.30	56.79	< 0.0001	Significant
C_a-Curing age	37.67	1	37.67	75.60	< 0.0001	Significant
L_cC_a	29.35	1	29.35	58.92	< 0.0001	Significant
L_c^2	0.3796	1	0.3796	0.7618	0.3897	Insignificant
C_a^2	0.0336	1	0.0336	0.0675	0.7968	Insignificant
$L_c^2C_a$	0.0601	1	0.0601	0.1206	0.7308	Insignificant
$L_cC_a^2$	0.0871	1	0.0871	0.1749	0.6788	Insignificant
L_c^3	1.85	1	1.85	3.71	0.0636	Insignificant
C_a^3	4.87	1	4.87	9.77	0.0039	Significant
Residual	14.95	30	0.4982			
Lack of fit	14.95	10	1.49			
Pure error	0.0000	20	0.0000			
Cor total	454.48	39				

Table 2: ANOVA Results on Response Variable (Flexural Strength of Reinforced Laterized Concrete)

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	787.98	9	87.55	104.95	< 0.0001	Significant
L_c-LateriteContent	110.61	1	110.61	132.58	< 0.0001	Significant
C_a-Curing age	12.97	1	12.97	15.55	0.0004	Significant
L_cC_a	6.52	1	6.52	7.82	0.0089	Significant
L_c^2	7.93	1	7.93	9.50	0.0044	Significant
C_a^2	2.93	1	2.93	3.51	0.0708	Insignificant
$L_c^2C_a$	0.1646	1	0.1646	0.1973	0.6601	Insignificant
$L_cC_a^2$	0.9245	1	0.9245	1.11	0.3009	Insignificant
L_c^3	12.70	1	12.70	15.23	0.0005	Significant
C_a^3	0.1220	1	0.1220	0.1463	0.7048	Insignificant
Residual	25.03	30	0.8343			
Lack of fit	25.03	10	2.50			
Pure error	0.0000	20	0.0000			
Cor total	813.01	39				

Table 3: ANOVA Results on Response Variable (Water Absorption of Laterized Concrete)

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	6.20	5	1.24	1491.81	< 0.0001	Significant
L_c-Laterite content	4.46	1	4.46	5368.16	< 0.0001	Significant

C_a-Curing age	1.57	1	1.57	1884.73	< 0.0001	Significant
L_cC_a	0.0001	1	0.0001	0.0959	0.7599	Insignificant
L_c^2	0.0308	1	0.0308	37.08	< 0.0001	Significant
C_a^2	0.1871	1	0.1871	225.16	< 0.0001	Significant
Residual	0.3196	27	0.0118			
Lack of fit	0.3196	3	0.1065			
Pure error	0.0000	24	0.0000			
Cor total	25.12	35				

On the other hand, all the generated models have significant R^2 values greater than 80% as shown in Table 4. Thus nearly 96.71 %, 96.92 % and 99.72 % of the experimental data of the compressive strength of the laterized concrete, the flexural strength of reinforced laterized concrete and water absorption of the laterized concrete respectively can be correlated with the models. For the R^2 values of the models to be in good agreement, the difference between the adjusted and predicted R^2 values should be less than (< 0.2). It is clear that all response variables were in good agreement.

Table 4: Coefficients of Determination for the Response Investigated

Response	R^2	Adjusted R^2	Predicted R^2	Adequacy Precision "AP"
Compressive Strength of the laterized concrete, F_C	0.9671	0.9572	0.9388	32.7084
Flexural Strength of reinforced laterized concrete F_f	0.9692	0.9600	0.9498	34.4450
Water absorption W	0.9972	0.9965	0.9956	116.7382

It was observed from Figures 4, 5 and 6 that the results obtained from the factorial design models are very close to the experimental results. The plots of the predicted versus actual values show that the values are normally distributed because almost all the values lie along the incline straight line which indicates that the prediction of the model is quite adequate

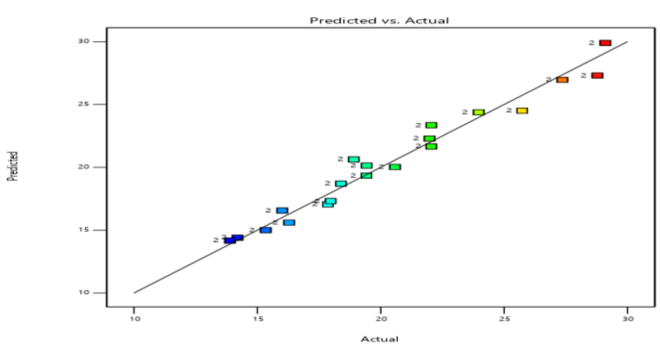

Figure 4: Predicted versus Actual plot of Compressive Strength of laterized concrete

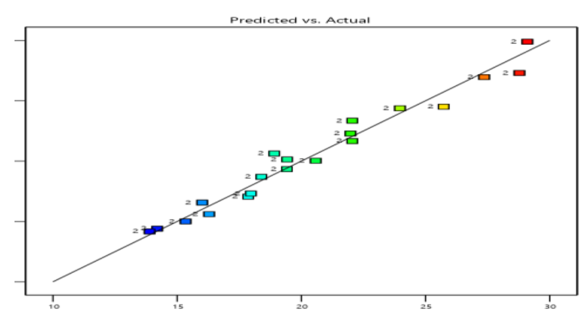

Figure 5: Predicted Versus Actual Plot of Flexural Strength of Laterized Concrete

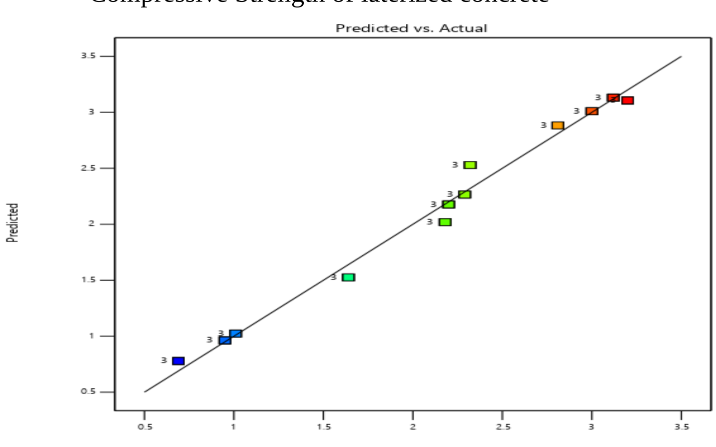

Figure 6: Predicted Versus Actual Plot of Water Absorption of Laterized Concrete

3.4 Optimization Results

The optimization goal, constraint and optimized results of compressive strength and flexural strength and water absorption of laterized concrete are shown in Table 5, Table 6, Table 7 and Table 8 respectively. The optimized solution with a desirability value of 0.918 is selected for the strength (compressive and flexural) respectively since they were close to 1 by considering the other desirability values. The results show that the compressive strength and flexural strength were approximately 19.044N/mm^2 and 27.304N/mm^2 respectively when concrete is produced by partially replacing fine aggregate with 10 % laterite content at 28 days of curing.

Table 5: Optimization Goal and Constraint for Compressive and Flexural Strength of Laterized Concrete

Name	Goal	Lower Limit	Upper Limit
L_c:Laterite content (%)	Target = 10	0	40
C_a: Curing age (Days)	in range	7	28
Compressive Strength(N/mm^2)	Maximize	9.03	20.43
Flexural strength(N/mm^2)	Maximize	13.89	29.1

Table 6: Optimized Result for Compressive and Flexural Strength of Laterized Concrete

S/No.	Laterite content	Curing age	Compressive. Strength	flexural strength	Desirability	
1	10.000	28.000	19.044	27.304	0.918	Selected
2	9.726	28.000	19.108	27.403	0.914	

Moreover, the optimized solution with a desirability values of 0.860 was selected for the water absorption since it was close to 1 by considering the other desirability values. The results show that the water absorption of 3.809% is obtained when concrete is produced by partially replacing fine aggregate with laterite at 10% and cured at 28 days

Table 7: Optimization Goals and Constraint for Water Absorption

Name	Goal	Lower Limit	Upper Limit
L_c:Laterite content (%)	Target = 10	0	20
C_a: Curing age(days)	is in range	28	90
W: Water absorption(%)	Minimize	3.4	4.97

Table 8: Optimized Result for Water Absorption of Laterized Concrete

S/No.	Laterite content	Curing age	Durability	Desirability	
1	10.000	28.000	3.809	0.860	Selected
2	10.000	28.254	3.814	0.858	
3	10.000	90.000	4.399	0.603	

CONCLUSIONS

The following conclusions can be withdrawn based on the above findings;

i. The optimized results are 10 % laterite content and 28 days curing age with strength and durability values of 19.04 N/mm^2, 27.3 4N/mm^2 and 3.81 % for the compressive, strength, flexural strength and water absorption respectively.

ii. The developed mathematical predictive models that were obtained had R^2 values of 96.71, 96.92 and 99.72 % for compressive strength, flexural strength and water absorption at 10 % laterite content at 28 days of curing age.

iii. It was concluded that the predictive models developed could be used to predict the compressive strength, flexural strength and water absorption of reinforced laterized concrete.

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