Predictive Models Development to Optimize the Compressive Strength and Water Absorption of Palmyra Fibre-Reinforced Concrete

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Abstract
In this paper, predictive models were developed to optimize the compressive strength and water absorption of palmyra fibre reinforced concrete using face centered central composite design of response surface methodology. Design factors; curing period and fibre content at -1, 0, 1 coded level were adopted. The concrete mix proportion was designed to achieve minimum characteristic strength of 20 N/mm^2 at 28 days curing period. Thus, concrete test specimens were produced with fibre content varied at 0.5, 1 and 1.5 % respectively by weight of cement. The concrete test specimens were cured at 7, 14 and 28-days hydration period. Compressive strength and water absorption tests of the fibre reinforced concrete was conducted after each curing period. From the experimental results obtained, full quadratic model was chosen for estimating the performance of the reinforced fibre concrete with respect to the design factors and analysis of variance (ANOVA) was applied to determine the influence of model parameters and their interactions. The parameters were optimized by maximizing compressive strength and minimizing water absorption using desirability function approach. The optimum settings of parameters are the curing period and fibre content for maximizing compressive strength and minimizing water absorption. The water absorption has desirability of 0.56505 and the compressive strength has desirability of 1.000. The overall desirability index for the responses is 0.87659 at compressive strength of 22.12 N/mm^2 and water absorption of 2.33% for concrete with 1.5% fibre content coded at 1.0 and 28-days curing period coded at 0.72. Inconclusion, the model fitting showed that the chosen model was adequate at describing the behavior of the concrete reinforced with palmyra fibre.

1.0 Introduction
Concrete is a composite material; essentially the product of cement, fine aggregate, coarse aggregate and water. Although concrete is known for excellent ability in compression, it has some of its own limitations, such as inherent brittle character. The inherent relative weakness of concrete under tensile loading makes concrete highly susceptible to cracking when applied tensile stresses exceed the low tensile strength of concrete (Behrouz et al., 2021). Thus, short and discrete fibres randomly distributed within the concrete member are used as the reinforcing material because incorporating fibres to concrete can mitigate micro-cracks formation which leads to gradual failure (Anjali and Singh, 2022). Studies for the improvement of concrete properties using steel and/or synthetic fibres as reinforcement due to their excellent material properties have been reported (Khalel and

Khan, 2023). However, the carbon footprint and cost of synthetic fibres is higher, and the extend of waste fibres available is lower. Therefore, natural fibres become an effective replacement of synthetic fibres with lower cost and environmental impact (Hussein et al., 2023).

1.1. Palmyra

Palmyra ($Borassus\ spp$) is a genius of six species of fan- palm fruits native to tropical region of Africa and Asia (Danbature et al., 2020). It develops a smooth and grey stem, which at maturity is 15 to 20 meters tall with an appearance of a thick column at its base and bulge in the top part; it is a material that is resistant to molluscs and not rotten easily (Samah et al., 2013; Samah et al., 2015). It is a large palm tree whose wood is often used for its mechanical resistance and weathering in buildings in Africa (Ngargueudedjim et al., 2019). Palmyra fibre can be extracted from leaf-stalk and other parts of the palm. It is a hard wood fibre, composed essentially of cellulose, hemi-cellulose, lignin and extractives as main chemical composition and the cellulose content constitutes the highest composition (Pradeep and Edwin, 2015; Audu and Jimoh, 2015). In a study conducted by Meheddene et al., (2014), the effect of incorporating palmyra fibre at different volume fractions of 0, 0.5, 1, 1.5 % respectively at fibre aspect ratio of 60 and 100 on the mechanical properties and durability of concrete was evaluated. Their findings showed that the addition of Palmyra fibres increases the compressive strength, flexural and splitting tensile strength of the concrete. Plate 1 is the image of palmyra tree as captured from the location where it was sourced for the study.

Plate 1: Palmyra

1.2. Natural Fibre Composite

The interest in natural fibre composite (NFCs) has gained attention especially due their potential to replace synthetic fibre reinforced composites at reduced cost with improved sustainability (Hussein et al., 2023); however, factors such as fibre content and porosity influence the mechanical performance of NFCs while porosity which is related to water absorption in NFCs has been identified with increased fibre content as well as fibre type and orientation (Pickering et al., 2016). On the other hand, quality and strength of concrete is affected by several factors one of which is curing (Tumpu et al., 2021). Curing is the process in which the relative humidity and temperature of concrete are controlled for a certain period of time after casting or when finished to ensure proper cement hydration and adequate hardened concrete (Karim et al., 2020). Thus, curing plays a crucial role in the development of compressive strength of concrete because it is required for completing the hydration reaction in cement and concrete (Mohamed 2019). Furthermore, a well compressed or denser concrete often result in higher strength and lesser number of voids and porosity, since the smaller the voids in concrete, the lesser the permeability of water and soluble substances (Iffat 2015). In addition, water absorption would also be less while better durability is expected from the concrete. Moreover, water absorption and porosity are the two main factors which are directly related to strength and durability property of concrete (Mavoori et al., 2021). Thus, in this present study an experiment was designed for predicting optimal compressive strength and water absorption capacity of hardened concrete reinforced with palmyra (natural plant-based) fibre using response surface methodology.

1.2. Response Surface Methodology

Response surface methodology constitutes a set of planned and experimental techniques employed in the mathematical modeling of responses (independent variables). Thus, since most problems analyzed by response surface do not have a known form of relationship among the variables under study, it is necessary to find a mathematical model that describes the interaction between the systems dependent and independent variables (Lovato et al., 2011). The usual first-order and second-order, defined in equations (1) and (2) are employed in the factor space of the input or independent variables.

$$y = \alpha + \sum_{i=1}^{n} \beta_i x_i \quad (1)$$

$$y = \alpha + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{1<j}^{n} \beta_{ij} x_i x_j + \varepsilon \quad (2)$$

where y is the response variable and α, β, ε are model parameters and error respectively.

RSM such as Central Composite and Box–Behnken design applications to cement and concrete have become more increasingly used over the past few decades (Li et al., 2020). In this study, the effect of addition of palmyra fibre on compressive strength and water absorption of concrete was modeled using RSM where the experimental results were fitted to the second order model defined in equation 2.

2.0 Materials and Methods

The study is divided into three phases; procurement and characterization of the materials used, experimental design, production and testing of concrete specimens.

2.1. Materials

Portland cement (Dangote brand) of grade 42.5 N standard, specified by BS EN 197 Part 1: (2011), fine aggregate (natural sand) which constitute a bulk density, fineness modulus and specific gravity of 1506 kg/m^3, 3.2 and 2.63 respectively were used in the investigation. The graph of particle size distribution of the fine aggregate as shown in Figure 1, indicates that it falls under class C of the grading limit and suitable for reinforced concrete work. The coarse aggregate used was 20 mm maximum size crushed rocks of igneous origin which constitute a bulk density and specific gravity of 1503 kg/m^3 and 2.68 respectively. The coarse aggregate particle sizes distribution graph in Figure 2 indicates a well graded distribution of the material and thus suitable for reinforced concrete application.

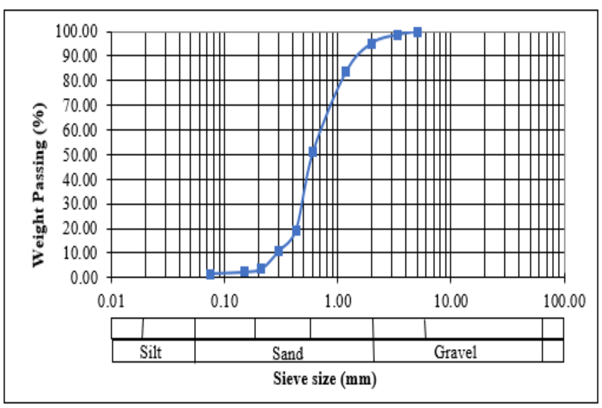


Fig. 1: Particle Size Distribution of Fine Aggregate

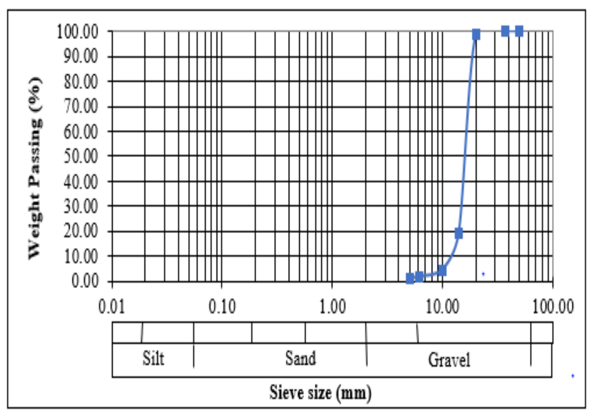


Fig. 2: Particle Size Distribution of Coarse Aggregate

The palmyra fibre was extracted from leaf-stalks (stem); harvested by cutting directly from the trees using cutlass at Filiya, Shongom Local Government Area of Gombe state, Nigeria (Plate 2). The fibres were extracted by the method of water retting (de-gumming) a technique or pre-treatment process for removing the non-cellulosic material attached to natural organic fibres in order to release individual fibres. Thus, the harvested bundles of the palmyra leaf-stalks were soaked in water at ambient temperature (Plate 3). The soaked leaf-stalks were stirred using wooden stick regularly to ensure that the fibres were segregated. The fibres were removed from water after about four weeks when the strands were fully segregated (Plate 4). The segregated fibre strands were allowed to dry at ambient temperature. The separated out dried fibre strands were further chopped to a maximum length of 40 mm to achieve an aspect ratio of 50 (Plate 5). The fibre's physical and mechanical, chemical properties are as shown in Table 1.

Plate 2: Bundles of Harvested Fibres

Plate 3: Retting of Fibres in Water

Plate 4 Air drying Fibers after Retting

Plate 5: Extracted Fibres after Retting

Table 1: Properties of Palmyra fibre

Physical and Mechanical Properties	
Parameter	**Values**
Length (mm)	40
Average diameter (mm)	0.8
Aspect ratio $(\frac{l}{d})$	50
Water absorption (%)	268.18
Elastic modulus (MPa)	188.61
Tensile stress (MPa)	19.0
Tensile strain (%)	0.2
Tensile extension (mm)	20.03
Chemical Properties	
Compositions	**Wt. conc (%)**
Cellulose	66.04
Hemicellulose	7.80
Lignin	15.51
Extractives	8.74
Ash	3.05

2.2. Experimental Design

Using the face centered central composite design (CCD) of response surface. The design consisted of two independent design factors (variables), curing period (C_p) and fibre content (F_c) at three (3) coded -1 to +1 levels respectively for low, medium and high as shown in Figure 1 and Table 2 respectively. The cement, fine aggregate, coarse aggregate and water are fixed independent factors. The experimental runs and corresponding levels proposed by Minitab Software are shown in Table 3. The fibre content was varied at 0.5, 1 and 1.5 % while the curing period was varied at 7, 14 and 28 days respectively. The response variables are compressive strength and water absorption.

Second-order response surface empirical model defined in equation (3) was used to analyze the effects of various factors on the responses:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \varepsilon \qquad (3)$$

Where β_o, β_1, β_2, β_{12}, β_{11} and β_{22} are unknown regression coefficients, ε is the experimental errors, x_1 and x_2 are predictor (input) variables while y is the response (output) variable.

Optimization was performed using the desirability method. The objective function defined in equation 4 is a geometric mean of all transformed responses:

$$D = \left(\prod_{i=1}^{n} d_i\right)^{\frac{1}{n}} = (d_1 \times d_2 \times \ldots \times d_n)^{\frac{1}{n}} \qquad (4)$$

where: d = the responses;
1, 2, …, n = the number of responses in the experiment.

Factors were set at their design goal of maximum, minimum, range or target.

Table 2: Replacement level of factors

Factor	Code	Levels of code		
		-1	**0**	**1**
Curing period, C_p (days)	A	7	14	28
Fibre content, F_c (%)	B	0.5	1	1.5

Table 3: Experimental Levels Developed by Minitab

Run Order	Blocks	Levels of coded factors	
		A	**B**
1	1	-1	1
2	1	0	-1
3	1	-1	-1
4	1	0	0
5	1	1	1
6	1	1	0
7	1	-1	0
8	1	0	0
9	1	1	-1
10	1	0	0
11	1	0	0
12	1	0	1
13	1	0	0

2.3. Concrete Production

The experimental evaluation of palmyra fibre effect on hardened concrete properties (compressive strength and water absorption) was conducted using concrete mix proportion design based on absolute volume method of the American concrete institute (ACI). The concrete specimens were produced for medium slump, water-to-cement ($\frac{w}{c}$) ratio of 0.5, minimum characteristic strength of 20 N/mm^2 at 28-day curing period. The concrete mixture constituents of water, cement, fine and coarse aggregates respectively is summarized in Table 4 while the concrete mix proportions for the 1, 0, +1 coded levels at 0.5, 1.0, and 1.5 % fibre content respectively are shown in Table 5. The concrete specimens for compressive strength were produced in accordance with BS EN 12390 – 1: (2000) and BS EN 12390 – 4: (2000) specifications respectively by casting the concrete mixes into 100 mm × 100 mm × 100 mm size molds and tested the specimens produced after curing for 7, 14 and 28 days respectively. The water absorption concrete test specimens were produced in accordance with BS 1881 Part 122: (1983) specification also using the 100 mm × 100 mm × 100 mm size moulds and tested after 7, 14- and 28-days curing period respectively. The curing water was kept at a constant temperature. Three (3) concrete specimens were produced from each batch of fibre addition and the average result taken.

Table 4: Summary of Mix Proportion

Parameter	Values	Unit
Water	186.0	kg/m^3
Cement	372	kg/m^3
Fine aggregate	868	kg/m^3
Coarse aggregate	902	kg/m^3

Table 5: Mix Proportion for Experiment

Fibre content		Water (kg/m^3)	Cement (kg/m^3)	Aggregates (kg/m^3)	
(%)	(kg/m^3)			Fine	Coarse
0.5	1.86	186	372	868	902
1.0	3.72	186	372	868	902
1.5	5.58	186	372	868	902

3.0 Results and Discussion

3.1. Experimental Observation

Compressive strength and water absorption were the performance criteria investigated in this study with respect to palmyra fibre content and 7-, 14- and 28-days curing age respectively. The experimental results are as shown in Table 6. From the results, it can be observed that the properties examined (compressive strength and water absorption) varied with the fibre content and curing age. However, the maximum compressive strength of 21.59 N/mm^2 was achieved at 28-day curing age and 1.5% fibre content while the minimum of 15.81 N/mm^2 was achieved at 14-day curing age and 0.5% fibre content whereas, the minimum water absorption of 1.55% was found at 28-day curing age and 0.5% fibre content while the maximum of 3.35% was obtained at 14-day curing and 0.5% fibre content respectively.

Table 6: Average Experimental and Predicted Results

Natural factors		Coded factors		Compressive strength (N/mm^2)		Water absorption (%)	
C_p (days)	F_c (%)	A	B	Experimental	Predicted	Experimental	Predicted
7	1.5	-1	1	17.69	19.99	3.06	2.90
14	0.5	0	-1	15.81	16.18	2.95	2.76
7	0.5	-1	-1	18.25	17.45	2.52	2.54
14	1	0	0	17.04	17.45	3.35	3.35
28	1.5	1	1	21.59	21.05	2.36	2.33
14	7	1	0	19.00	19.78	2.50	2.37
7	1	-1	0	20.22	18.72	2.93	3.07
14	1	0	0	17.04	17.45	3.35	3.35
28	0.5	1	-1	18.76	18.52	1.55	1.71
14	1	0	0	17.04	17.45	3.35	3.35
14	1	0	0	17.04	17.45	3.35	3.35
28	1.5	0	1	21.15	18.72	3.06	3.25
14	1	0	0	17.04	17.45	3.35	3.35

3.2. Mathematical modeling and Analysis of Compressive Strength and Water Absorption

The model performance is evaluated using analysis of variance (ANOVA). This involved test for significance at 95% confidence interval and 5% significance level on individual model coefficients which include the determination of the probability value (p-value) where a "$Prob. > F$" value on an F −test shows the proportion of time F −value is expected to be obtained if no factor effects are significant. Thus, the "$Prob. > F$" value obtained was compared with the desired probability or α−level at 5% (0.05) significance level. Also, to determine whether the model actually describes the experimental data, checks performed include determining the various coefficient of correlation, R −squared in which these R −squared coefficients have values between 0 and 1 and R −square closer to 1 indicates that the relationship between the response and predictor(s) is strong and thus the model perfectly described the data.

3.2.1. Compressive Strength

Based on the quadratic regression model defined in equation 3, ANOVA results for compressive strength is shown in Table 7. The proportion, R −square and R −square (adjusted) which measures the statistical significance or effect of the input variables (curing period and fibre content) predictable on the response (compressive strength) of 65% or 0.65 and 48% or 0.48 respectively were obtained using the stepwise forward selection of model parameters entered as α = 0.25.

Table 8 shows the regression coded coefficients of the model terms where the p −values, 0.34 and 0.22 (p >0.05) of the curing period (A) and two-way interaction term (A*B) of curing period and fibre content respectively are not significant. However, the p −values, 0.042 and 0.036 (p <0.05) of the fibre content (B) and quadratic term of curing period (A) respectively are statistically significant. This indicates that the full quadratic model defined in equation 5 describes the behavior of the fitted experimental result of the compressive strength. Therefore, the interaction term (A*B) can be excluded from the model.

Table 7: Compressive Strength Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	24.6915	6.1729	3.75	0.050
Linear	2	11.3480	5.6740	3.45	0.083
A	1	1.6960	1.6960	1.03	0.339
B	1	9.6520	9.6520	5.87	0.042
Square	1	10.4705	10.4705	6.37	0.036
A*A	1	10.4705	10.4705	6.37	0.036
2-Way Interaction	1	2.8730	2.8730	1.75	0.223
A*B	1	2.8730	2.8730	1.75	0.223
Error	8	13.1517	1.6440		
Lack-of-Fit	4	13.1517	3.2879		
Pure Error	4	0.0000	0.0000		
Total	12	37.8432			

Model Summary

S	R-square	R-square(adjusted)
1.28217	65.25%	47.87%

Table 8: Compressive Strength Regression Coded Coefficients

Term	Effect	Coefficient	SE Coefficient	T-Value	P-Value	Remark
Constant		17.451	0.485	36.01	0.000	Significant
A	1.063	0.532	0.523	1.02	0.339	Not significant
B	2.537	1.268	0.523	2.42	0.042	Significant
A*A	3.600	1.800	0.713	2.52	0.036	Significant
A*B	1.695	0.847	0.641	1.32	0.223	Not significant

Compressive Strength Equation in Terms of Coded Factors

$$Compressive\ strength = 17.45 + 0.53A + 1.27B + 1.80A^2 + 0.85AB \quad (5)$$

3.2.2. Water Absorption

The ANOVA for water absorption is as shown in Table 9. A higher value of R −square and R −square (adjusted); 95% (0.95) and 92% (0.92) respectively relative to the compressive strength were obtained (Table 9). Also, the p −values of all the model terms except the two-way interaction term (A*B) are significant (p <0.05) as shown in Table 10. This indicates that the input variables (curing period and fibre content) constitute more significant effect on the response (water absorption) and also shows that the full quadratic model defined in equation 6 adequately described the behavior of the fitted water absorption experimental result. However, the interaction term (A*B) can also be excluded from the model.

Table 9: Water Absorption Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	3.32448	0.66490	28.89	0.000
Linear	2	1.09027	0.54513	23.69	0.001
A	1	0.73500	0.73500	31.94	0.001
B	1	0.35527	0.35527	15.44	0.006
Square	2	2.21599	1.10799	48.15	0.000
A*A	1	1.10944	1.10944	48.21	0.000
B*B	1	0.32644	0.32644	14.19	0.007
2-Way Interaction	1	0.01823	0.01823	0.79	0.403
A*B	1	0.01823	0.01823	0.79	0.403
Error	7	0.16109	0.02301		
Lack-of-Fit	3	0.16109	0.05370		
Pure Error	4	0.00000	0.00000		
Total	12	3.48557			

Model Summary

S	R-square	R-square(adjusted)	R-square(predicted)
0.151699	**95.38%**	**92.08%**	**52.95%**

Table 10: Water Absorption Regression Coded Coefficients

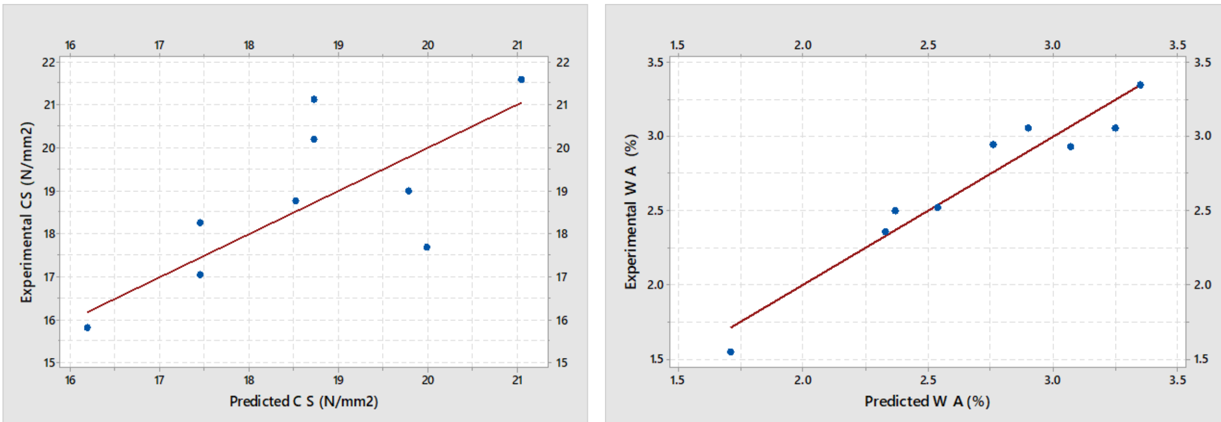
Term	Effect	Coefficient	SE Coefficient	T-Value	P-Value	Remark
Constant		3.3497	0.0630	53.18	0.000	Significant
A	-0.7000	-0.3500	0.0619	-5.65	0.001	Significant
B	0.4867	0.2433	0.0619	3.93	0.006	Significant
A*A	-1.2676	-0.6338	0.0913	-6.94	0.000	Significant
B*B	-0.6876	-0.3438	0.0913	-3.77	0.007	Significant
A*B	0.1350	0.0675	0.0758	0.89	0.403	Not significant

Water Absorption Equation in Terms of Coded Factors

$$Water\ absorption = 3.35 - 0.35A + 0.24B - 0.63A^2 - 0.34B^2 + 0.07AB \quad (6)$$

Figure 2a shows the compressive strength experimental values residual plot deviations from their predictions. It can be seen that the residuals distribution of the compressive strength data does not resemble a straight line required for a normal distribution. This may be attributed to the compressive strength variation with respect to curing period due to effects of fibres in concrete mixes.

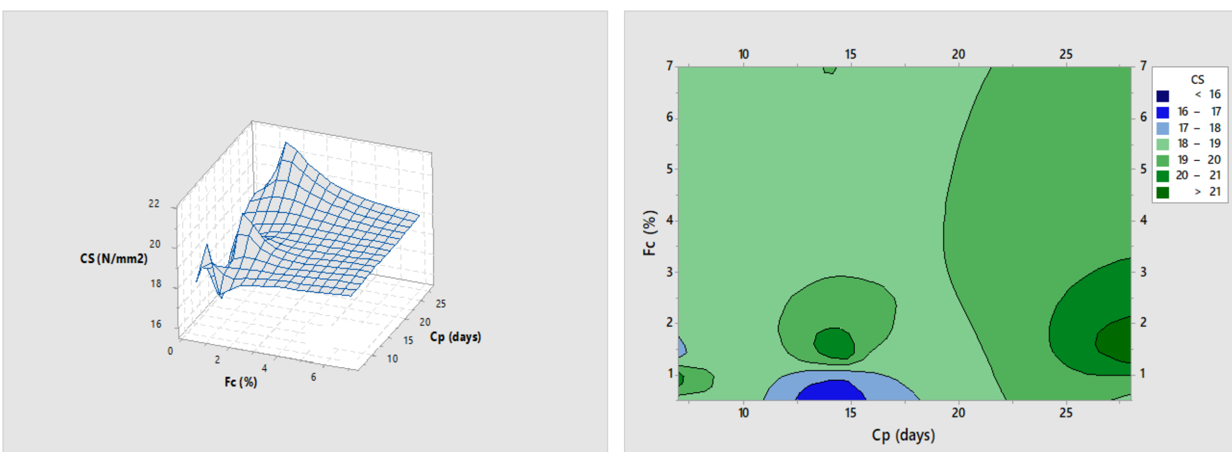
Figure 2b on the other hand, shows the residual plot deviations of the experimental water absorption values from their predictions. In this case, the distribution of the residuals for the water absorption data resembles a straight line typical of a normal distribution.



(a) (b)

Figure 2: ***Scatter Plot of Experimental and Predicted (a) Compressive strength and (b) Water absorption***

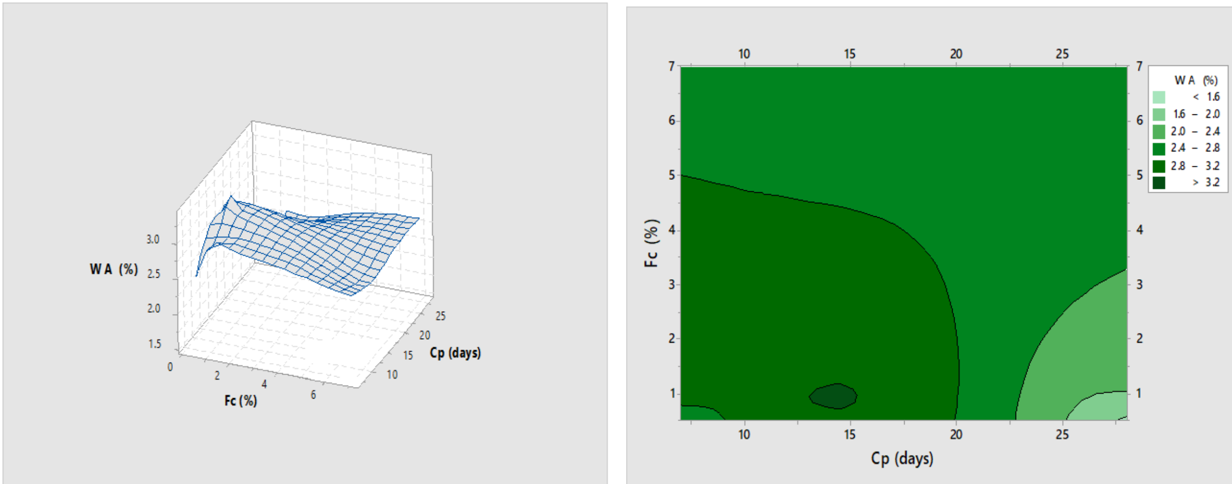
Figure 3 shows the graphical representation of the compressive strength model. Figure 3a is the plot of the plane of response variable (compressive strength) generated by the various combination of the factor (input) variables (curing period and fibre content) while Figure 3b is the contour lines of the response compressive strength in the plane of the curing period and fibre content respectively. It can be observed that because the response surface is not plane, the contour lines are curved.



(a) (b)

Figure 3: ***3D surface plot (b) Contour lines of Compressive strength***

Figure 4 on the other hand shows the graphical representation of the water absorption model. Figure 4a is the plot of the plane of response variable (water absorption) generated by the various combination of the factor variables (curing period and fibre content) while Figure 4b is the contour lines of the response water absorption in the plane of the curing period and fibre content respectively. It can also be observed that since the response surface has curvature, the contour lines appeared are not straight lines.



(a) (b)

Figure 4: ***3D surface plot (b) Contour lines of Water absorption***

3.3. Response Optimization

Table 11 shows the constraints for the response optimization. The objective was to optimize the compressive strength and minimize the water absorption of the reinforced fibre concrete. Thus, the three components of optimization identified as; objective functions, variables and constraints for the data were the compressive strength and water absorption as well as the variables, curing period (C_p) and fibre content (F_c), constrained at 7days $\leq C_p \leq$ 28 days and 0.5% $\leq F_c$ 1.5% respectively.

Table 11: Constraints for optimization

Parameters	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: C_p	Constrained	-1	1	1	1	3
B: F_c	Constrained	-1	1	1	1	3
Water absorption (%)	minimize	1.55	3.35	1	1	1
Compressive strength (N/mm^2)	maximize	15.81	21.59	1	1	3

The response optimization analyzed using the constrained parameters shown in Table 11 revealed the response optimization result shown in Table 12. Based on the optimization solution, the water absorption has desirability of 0.56505 at a minimum water absorption of 2.33 % while the compressive strength whose targeted goal was ‘maximum’ have desirability of 1.000.

Table 12: Response Optimization

		Starting Values		
Variable Setting				
A 0.72				
B 1				
Solution				
Solution A B	**Compressive Strength Fit**	**Water absorption Fit**	**Composite Desirability**	
1 1 1	22.1223	2.33290	0.867007	
Multiple Response Prediction				
Variable Setting				
A 1				
B 1				
Response	**Fit**	**SE Fit**	**95% CI**	**95% PI**
Compressive Strength	22.12	*	(19.17, 25.28)	(17.76, 26.96)
Water Absorption	2.333	0.135	(2.014, 2.652)	(1.853, 2.813)

Figure 5 shows the optimization plot of compressive strength and water absorption respectively. The overall desirability for the responses is 0.867 at optimum compressive strength of 22.12 N/mm^2 for concrete with 1.5% fibre content coded at 1.0 and 28-days curing coded at 0.72.

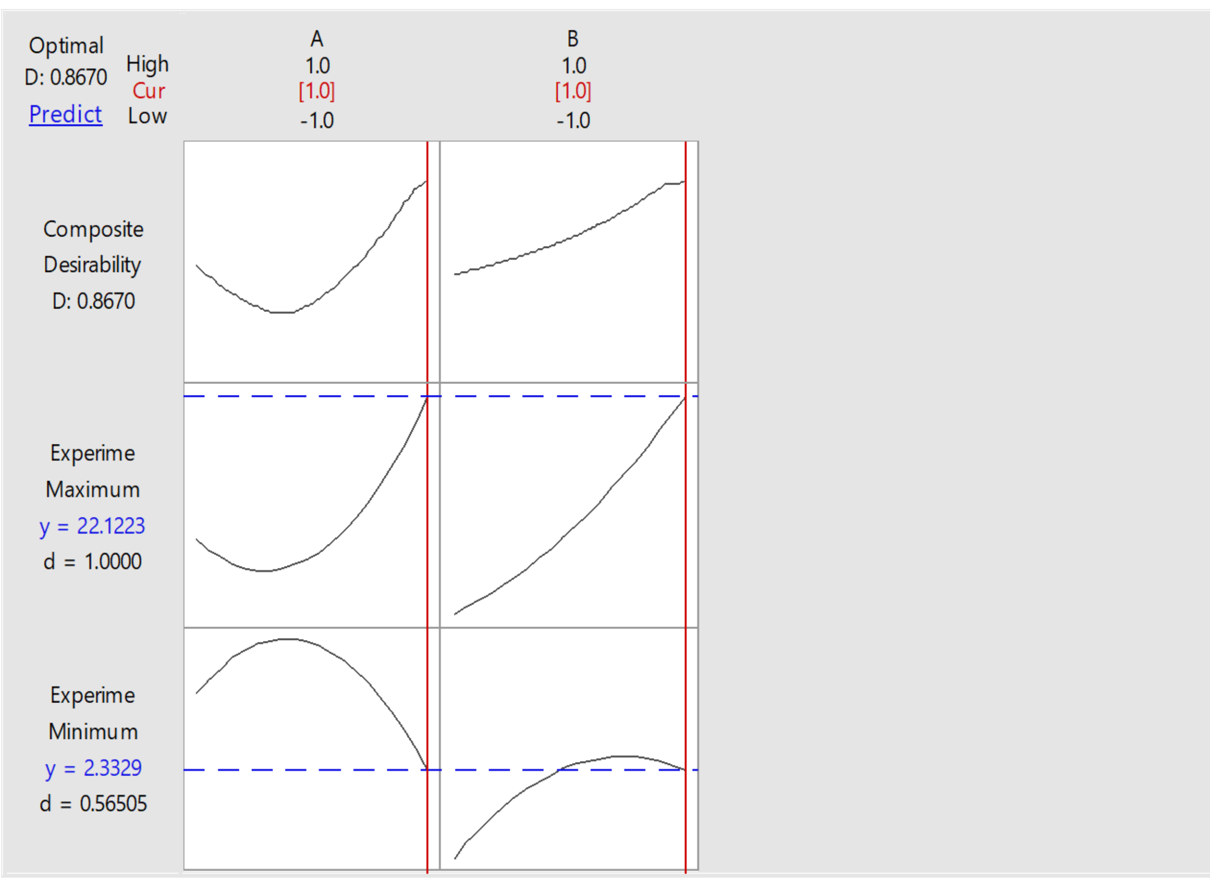


Figure 5: ***Optimization plot***

4.0. Conclusion

An experiment was designed using the response surface methodology in which full quadratic model regression equations were developed for predicting compressive strength and water absorption of palmyra reinforced fibre concrete. The following conclusions can be drawn from the study.

i. The performance of the fitted regression models evaluated using analysis of variance at 95% confidence level showed that the factor variables (curing period and fibre content) are useful predictors of the response variables (compressive strength and water absorption).
ii. Three components of optimization (objective functions, variables and constraints) were used to minimized the water absorption and maximized compressive strength of the reinforced fibre concrete experimental observations using the variables; curing period (C_p) and fibre content (F_c), constrained at 7days $\leq C_p \leq$ 28 days and 0.5% $\leq F_c$ 1.5% respectively.
iii. The water absorption has desirability of 0.56505 while the compressive strength whose targeted goal was 'maximum' has desirability of 1.000.
iv. The overall desirability for the responses is 0.87659 at compressive strength of 22.12 N/mm^2, and water absorption of 2.33% for concrete with 1.5% (1.0 coded) at 28 days curing (0.72 coded).

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