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Optimization of Splitting Tensile Strength and Workability of Palmyra Fibre Reinforced Concrete Using Statistical Mixture Design Methodology

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Abstract
In this paper, optimization of splitting tensile strength and workability of palmyra fibre reinforced concrete was conducted using mixture design of experiment. Thus, twenty-one (21) concrete mixes which constitute single (main) effect, binary interaction and axial blends design points of second-order simplex design was generated from iteration of palmyra fibre content varied at 0.5-3% by weight of cement in concrete. The concrete mix proportion was designed for minimum characteristic compressive strength of 20 N/mm^2 at 28 days curing period. The workability of the concrete mixes was determined by slump test after which test specimens were produced using 100 mm diameter, 200 mm high cylindrical moulds for tensile strength and cured for 28 days. Splitting tensile strength test of the fibre reinforced concrete was conducted after the curing period. The 2nd order simplex polynomial model was fit to the experimental data. Analysis of variance (ANOVA) was used to study the influence of model parameters and their interactions using Minitab 17. Furthermore, the parameters were optimized by maximizing splitting tensile strength and slump values using desirability approach. The optimum settings of parameters are the mixture pseudo components for maximizing the tensile strength and slump test values. The slump has desirability of 0.669138 and the split tensile strength has desirability of 0.459730. The overall desirability index for the responses is 0.554638 at tensile strength of 3.2382 N/mm^2 and slump of 19.32 mm.

***Key words**: ANOVA, Desirability, Palmyra fibre, Simplex lattice design*

I. Introduction

The fresh and hardened properties of concrete viz; workability, compressive strength, flexural strength and/or tensile strength are considered as measure of concrete quality performance. Concrete is strong in compression thus its compressive strength is taken as the most important quality criteria for ascertaining its strength performance. However, concrete is brittle in character; weak in tension, hence the introduction of steel reinforcement to cater for that shortcoming. Concrete also develops internal micro cracks due to effect of compressive load and drying shrinkage. This led to the addition of randomly oriented fibres in concrete so as to enhance its mechanical performance especially the flexural and tensile strength as well as its post cracking performance. Steel and synthetic or polymeric fibres are commonly used in concrete due to their superior mechanical properties such as high tensile strength and elastic modulus. However, due to the environmental sustainability, natural fibres are considered as an alternative to man-made fibres (Kampa et al., 2021). Natural fibres which are classified into cellulose fibres (plant-based) and asbestos (mineral-based) are readily available, renewable and low-cost resource for reinforcing materials relative to synthetic fibres as well as friendlier to the environment and less energy is required in their production (Raja et al., 2017).

The palmyra also known as fan palm, is a woody palm belonging to the class of palm trees which possesses a very dense fibres of about hundred fibres per square centimeter and the usual brown colored palmyra fibres, are quite long and constitute a large surface area of about one square millimeter (Ngargueudedjim, 2015). The effect of incorporating fan palm natural fibres on the mechanical properties of concrete was carried out by Meheddene et al., (2014). The properties examined include compressive strength, splitting tensile strength and flexural strength. They concluded that fan palm fibres can be used as an additive in concrete to improve its performance and provide a new dimension to a more sustainable composite. Several studies pertaining to the improvement of mechanical strength performance of concrete using dispersed natural plant-based fibres have also been reported (Ahmad et al., 2022; Kalaivani et al., 2020; Zhang et al., 2020). It has been reported that fibres tend to decrease the workability of concrete (Ahmad et al., 2022; Bheel et al., 2021; Saandeepani and Krishna, 2013). The decrease in the workability of concrete is related to the type of fibres, geometry, volumetric ratio, and distribution in the concrete (ACI 544.1: 2009). Furthermore, since concrete is made by using different types and proportions of individual constituents, certainly the mixture proportions would influence its fresh and hardened state performance, which include workability, rheological properties, strength development as well as durability. Therefore, many research studies have been dedicated to experimental optimization of cement and concrete mixtures (Li et al., 2020).

Statistical mixture methodology is the response surface experiment in which the variables are the components of a mixture and the responses are a function of the proportion of the mixture. In the statistical mixture methodology, measured responses are assumed to depend on the proportion of the materials present in the mixture rather than on the quantity of mixture (Kharazi et al., 2013). Thus, the sum of components in a mixture must be equal to one. IV-optimal criterion using Scheffé canonical polynomial was applied in designing an experiment to determine the optimum proportion for a concrete mix to achieve the slump 50 - 100 mm, 3-day compressive strength of 26 - 33 MPa, 28-day compressive strength of 50 - 65 MPa, 56-day compressive strength of 62 - 70 MPa and minimum cost by (Kharazi et al., 2013). They concluded that, mathematical models established using the statistical mixture method can be used to predict the defined properties of concrete and to assess the true effect of components undetectable by the trail-and-error method.

In this study, an experiment with mixture method using simplex design was used to develop predictive models for slump and splitting tensile strength using concrete mixture components of water, cement, palmyra fibre, fine aggregate and coarse aggregate. The effect of the five components and their blending effects to obtain an optimal mix proportion was also examined. This is followed by the statistical analyses of the observed data and mixture optimization using the desirability function approach as well as subsequent validation of the results.

II. Materials and Methods

A. Materials

Cement

Portland cement (Dangote brand) of grade 42.5 N standard, specified by BS EN 197 Part 1: (2011), was used for the study.

Aggregates

Natural sand obtained from a local supplier was used as fine aggregate. The coarse aggregate used was well graded 20 mm maximum size crushed rocks of igneous origin procured from a local supplier. The fine and coarse aggregates met the requirements specified by BS EN 1097 Part 6 (2000).

Palmyra fibre

Palmyra fibre was extracted from the leaf-stalk of palmyra palm obtained at Filiya, Shongom Local Government Area in Gombe state, Nigeria. Water retting was used for the fibre extraction which required soaking the leaf-stalk in water for four (4) weeks to detach the non-cellulosic material attached to fibres in order to release individual fibres. After the retting procedure, discrete fibres were dried at ambient temperature. The dried fibres were then chopped into 40 mm maximum length at aspect ratio of 50.

Water

Portable drinking water was used for mixing of concrete constituents.

B. Methods

Mixing, Casting, Curing and Testing

The concrete was designed for medium slump and 20 N/mm^2 minimum characteristics compressive strength of concrete at a water-to-cement ratio of 0.5 using the absolute volume method of the American concrete institute, ACI 211. Five concrete constituents; water, cement, palmyra fibre, fine aggregate and coarse aggregate were mixed thoroughly on dry surface to produced different batches of concrete mixes shown in Table 2. The workability of each mix was determined using slump test in accordance with BS EN 12350 – 2: (2009) specification. Concrete specimens were cast for splitting tensile strength using 100 mm diameter, 200 mm high cylindrical molds in accordance with BS EN 12390 – 1: (2000) and BS EN 12390 – 6: (2000) specifications. The specimens were cured in water for 28 days. Three (3) concrete specimens produced for each observation were tested after each curing period and the results presented as average of the three.

Experimental Design

The measured responses in a simplex design are described by a polynomial function and this represents how the components affect the response. Simplex lattice is an ordered arrangement of a design region constituting design points. In this study, the properties of fresh (workability) and hardened (splitting tensile strength) concrete are the responses. These responses were put in a polynomial function of pseudo component of the mixture as proposed by Scheffé. The second-order Scheffé canonical polynomial is defined in equation 1.

$$Y = b_0 + \sum \beta_i x_i + \sum \beta_{ij} x_j x_j + \sum \beta_{ijk} x_i x_j x_k + \cdots + \sum \beta_{i1,i2,} \ldots x_i, x_{12}, \ldots \ldots x_{in} + e \quad --- \quad (1)$$

where, Y = the response, b_0 = arbitrary constant, x_i x_j = quadratic blending terms in the mixture experiments and the coefficients β_{ij} = quadratic or non-linear blending coefficients. $\beta_{ij} \neq 0$, means blending between components (x_i and x_j) is synergistic. e = random error. The term e, which is the random error can be neglected. The number of terms in this model is the same as the number of components in the mixture, and the number of coefficients in the model is the base for the number of mixtures to be designed.

Based on the constraint in mixture experiment that the proportion of components in a mixture must equal one defined by equation 2.

$$\sum_{i=1}^{q} x_1 = 1 \qquad --- (2)$$

For five component mixture, q = 5, equation (2) can now be written as:

$$\sum_{i=1}^{5} x_1 = 1 \qquad --- (3)$$

Since the total component in the mixture must be 1 or 100%, equation (3) can be written as:

$$x_1 + x_2 + x_3 + x_4 + x_5 = 1 \quad --- \quad (4)$$

For five concrete component mixtures of water, cement, palmyra fibre, fine aggregate and coarse aggregate. The Minitab software was used to generate 21 pseudo components as shown in Table 1. However, the concrete mix proportions or real (actual) constituents are transformed to agree with the simplex lattice design constrain that mixture components must be 100%. Thus, the relationship between the actual concrete mix constituent variables and the coded variables in Table 1 is established as defined in equations 5 and 6 respectively as;

$$A = [P_i] \qquad --- (5)$$
$$X = [X_i] \qquad --- (6)$$

where, $[P_i]$ = the matrix of real concrete mix constituent variables and $[X_i]$ = the matrix of coded variables. Also, based on the simplex lattice design constrain; for any run,
$X = 1 \Longrightarrow = \frac{A}{A} = \frac{1}{A} A = BA$ where, $\frac{1}{A} = B$ = matrix of inverse of $A = A^{-1}$ and $X = [P_i][X_i]B$

Thus, 21 concrete mixes of design run which constitute fifteen (15) single (main) effect and interaction blends of five concrete constituents second order simplex design, augmented with six (6) axial blends design points were generated by iteration of 0.5 to 3.0% at 0.5% interval of palmyra fibre to correspond with pseudo components proposed by Minitab 17 is shown in Table 2.

Furthermore, optimization was performed using the desirability methodology. The objective function defined in equation 7 is a geometric mean of all transformed responses:

$$D = \left(\prod_{i=1}^{n} d_i\right)^{\frac{1}{n}} = (d_1 \times d_2 \times \ldots \times d_n)^{\frac{1}{n}} \quad --- (7)$$

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 1: Simplex Design Runs for the Five Components Mixture

Standard Order	**Run Order**	**Pseudo components**				
		X_1	**X_2**	**X_3**	**X_4**	**X_5**
12	1	0.0	0.0	0.5	0.0	0.5
19	2	0.1	0.1	0.6	0.1	0.1
21	3	0.1	0.1	0.1	0.1	0.6
11	4	0.0	0.0	0.5	0.5	0.0
5	5	0.5	0.0	0.0	0.0	0.5
15	6	0.0	0.0	0.0	0.0	1.0
9	7	0.0	0.5	0.0	0.0	0.5
16	8	0.2	0.2	0.2	0.2	0.2
1	9	1.0	0.0	0.0	0.0	0.0
2	10	0.5	0.5	0.0	0.0	0.0
13	11	0.0	0.0	0.0	1.0	0.0
4	12	0.5	0.0	0.0	0.5	0.0
20	13	0.1	0.1	0.1	0.6	0.1
14	14	0.0	0.0	0.0	0.5	0.5
17	15	0.6	0.1	0.1	0.1	0.1
18	16	0.1	0.6	0.1	0.1	0.1
10	17	0.0	0.0	1.0	0.0	0.0
8	18	0.0	0.5	0.0	0.5	0.0
7	19	0.0	0.5	0.5	0.0	0.0
3	20	0.5	0.0	0.5	0.0	0.0
6	21	0.0	1.0	0.0	0.0	0.0

Table 2: Designed Mixture Proportions

Run Order	Fibre (%)	Water kg/m^3	Cement kg/m^3	Fibre (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)
1	2.30	186	372	8.56	868	902
2	0.70	186	372	2.60	868	902
3	1.90	186	372	7.07	868	902
4	1.70	186	372	6.32	868	902
5	2.50	186	372	9.30	868	902
6	3.00	186	372	11.16	868	902
7	2.50	186	372	9.30	868	902
8	1.92	186	372	5.95	868	902
9	0.50	186	372	1.86	868	902
10	0.75	186	372	2.79	868	902
11	2.00	186	372	7.44	868	902
12	1.25	186	372	4.65	868	902
13	1.90	186	372	7.07	868	902
14	2.50	186	372	9.30	868	902
15	2.00	186	372	7.44	868	902
16	2.20	186	372	8.18	868	902
17	1.50	186	372	5.58	868	902
18	1.50	186	372	5.58	868	902
19	1.25	186	372	4.65	868	902
20	1.00	186	372	3.72	868	902
21	1.00	186	372	3.72	868	902

III. Results and Discussion

A. Experimental Observations

Table 3 shows the observed (experimental) and predicted results of slump and 28-day splitting tensile strength. From the results, it can be seen that the maximum slump value of 22 mm was obtained at 0.5% fibre content while the minimum of 3.0 mm was obtained at 3% content of fibre. On the other hand, the optimum splitting tensile strength of 3.9 N/mm^2 was recorded at 3% fibre content addition while a minimum of 2.72 N/mm^2 was recorded at 1.5% fibre addition. These results also agree with the findings reported by other researchers in which the decrease in workability has been associated with increased specific surface area, resulting to increase in the area cement mortar is required to cover and increase in split tensile strength is related to strength of fibre (Bheel et al., 2021; Islam and Ahmed 2018).

Table 3: Experimental and Predicted Results of Slump and 28-day Splitting Tensile Strength

Fibre content (%)	Slump (mm)		Split tensile strength (N/mm^2)	
	Observed	Predicted	Observed	Predicted
2.30	4.0	4.93	2.94	3.32
0.70	12.0	8.03	3.56	3.21
1.90	3.5	3.09	3.34	3.53
1.70	6.0	5.74	3.24	3.26
2.50	3.5	1.79	3.83	3.59
3.00	3.0	1.75	3.90	3.93
2.50	3.5	6.18	3.78	3.56
1.92	7.0	7.24	3.42	3.32
0.50	22.0	19.37	2.93	3.24
0.75	20.0	14.99	3.11	3.22
2.00	5.0	3.36	3.78	3.83
1.25	10.0	11.37	3.71	3.53
1.90	3.5	5.65	3.19	3.33
2.50	3.5	2.55	3.35	3.32
2.00	5.0	11.90	3.41	3.29
2.20	4.5	9.28	3.67	3.32
1.50	8.0	8.11	2.72	2.70
1.50	8.0	6.99	2.72	2.80
1.25	10.0	9.36	3.71	3.88
1.00	12.0	13.74	3.02	2.97
1.00	12.0	10.61	3.02	3.19

B. Modelling

The mixture (blending) response surface was analyzed by fitting the experimental data to second-order polynomial model using Minitab 17. Prediction models of the responses (slump and splitting tensile strength) were obtained as a function of coded mixture components. The analysis of variance (ANOVA) for each model gives the sum of squares (SS), mean squares (MS), F-values, and p-values of slump and splitting tensile strength respectively.

Based on the Scheffé second-order polynomial model defined in equation 1, ANOVA results for slump and splitting tensile results are as shown in Tables 4 and 5 respectively. Figures 1 and 2 respectively show the contour plot and 3D surface plot of the slump and splitting tensile strength response surface results respectively.

The predictive estimates coefficients of the slump and splitting tensile strength for the second-order polynomial fit of the data are shown in Tables 6 and 7 respectively. The coefficient of determination, R^2 of the second-order model fit defined in equation (5) for the slump predictive model was obtained as 74.27% (Table 6) while R^2 for the splitting tensile strength predictive model of the second-order model fit defined in equation (6) was found to be 71.67% (Table 7).

Figures 3 and 4 respectively show the residuals and fitted plots for the slump and splitting tensile strength observed values. The residual plots explained the percentage of response variable variation or the coefficient of determination (R^2) by its relationship with the predictor variables. The more variance that is accounted for by the model the closer the data points will fall to the fitted regression line and the higher the R^2, the better the model fits the data. Thus, the predictive models are considered adequate in view of the acceptable p-values and reasonably high R^2 values of the responses (slump and splitting tensile).

Table 4: Analysis of Variance for Slump (Pseudo components)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	425.775	425.775	85.1551	8.66	0.001
Linear	4	365.650	384.063	96.0156	9.76	0.000
Quadratic	1	60.125	60.125	60.1253	6.11	0.026
$x_1 * x_5$	1	60.125	60.125	60.1253	6.11	0.026
Residual Error	15	147.534	147.534	9.8356		
Total	20	573.310				

Table 5: Analysis of Variance for Splitting tensile strength (component proportions)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	7		1.98409	0.283441	4.70	0.008
Linear	4	0.67198	1.43670	0.359174	5.95	0.006
Quadratic	3	1.31210	1.31210	0.437367	7.25	0.004
$x_2 * x_3$	1	0.72769	0.67797	0.677969	11.24	0.005
$x_2 * x_4$	1	0.34047	0.39270	0.392701	6.51	0.024
$x_4 * x_5$	1	0.24395	0.24395	0.243949	4.04	0.066
Residual Error	13	0.78431	0.78431	0.060332		
Total	20	2.76840				

Table 6: Estimated Regression Coefficients for Slump (Pseudo components)

Term	Coefficient	SE Coef	T	P	Remark
x_1	19.37	2.297	*	0.00	Significant
x_2	10.61	2.102	*	0.00	Significant
x_3	8.11	2.102	*	0.00	Significant
x_4	3.36	2.102	*	0.00	Significant
x_5	174	2.297	*	0.00	Significant
$x_1 * x_5$	-35.07	14.185	-2.47	0.026	Significant
S = 3.13618					
PRESS = 491.517					
R-Square = 72.27%					
R-Square(adjusted) = 65.69%					

Slump Polynomial model with Respect to Coded Factors

$$Slump = 3.238x_1 + 3.194x_2 + 2.699x_3 + 3.829x_4 + 3.932x_5 + 3.752x_2x_3 - 2.861x_2x_4 - 2.251x_4x_5 \quad \text{--- (5)}$$

Table 7: Estimated Regression Coefficients for Splitting Tensile Strength

Term	Coefficient	SE Coeff	T	P	Remark
x_1	3.238	0.1653	*	0.00	Significant
x_2	3.194	0.1975	*	0.00	Significant
x_3	2.699	0.1807	*	0.00	Significant
x_4	3.829	0.1975	*	0.00	Significant
x_5	3.932	0.1807	*	0.00	Significant
$x_2 * x_3$	3.752	1.1193	3.35	0.05	Significant
$x_2 * x_4$	-2.861	1.1213	-2.25	0.024	Significant
$x_4 * x_5$	-2.251	1.1193	-2.01	0.066	Significant
S = 0.245625					
PRESS = 4.84307					
R-Square = 71.67%					
R-Square(adjusted) = 56.41%					

Splitting Tensile Strength Polynomial Model with Respect to Coded Factors

$$Split\ tensile\ strength = 19.37x_1 + 10.61x_2 + 8.11x_3 + 3.36x_4 + 1.74x_5 - 35.07x_1x_5 \quad \text{--- (6)}$$

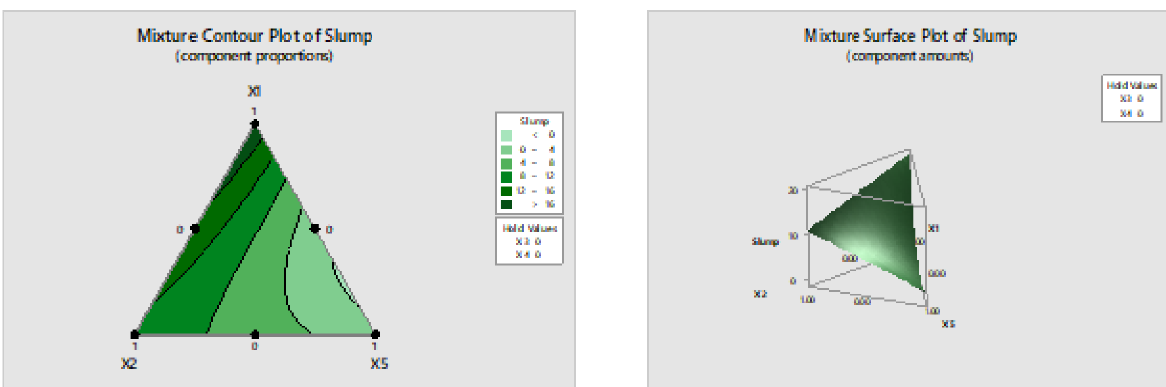

Figure 1: Contour Plot and 3D Surface Plot of Slump Results

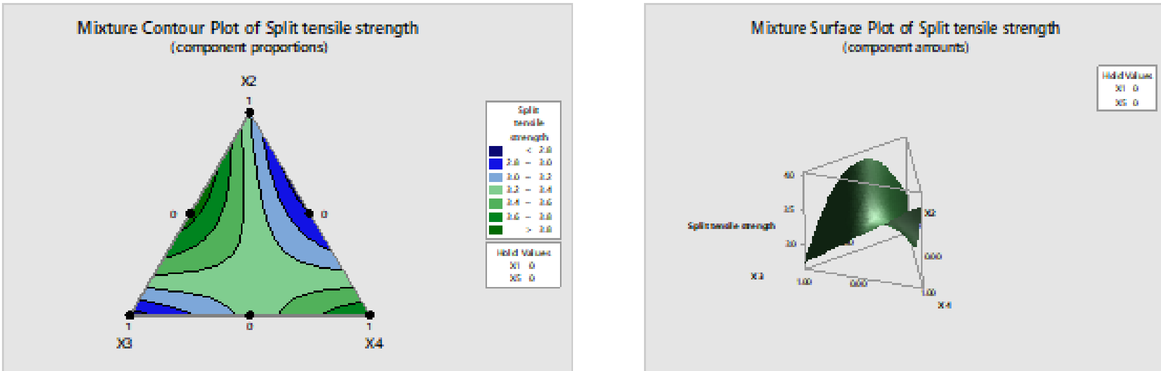

Figure 2: Contour Plot and 3D Surface Plot of Tensile Strength Results

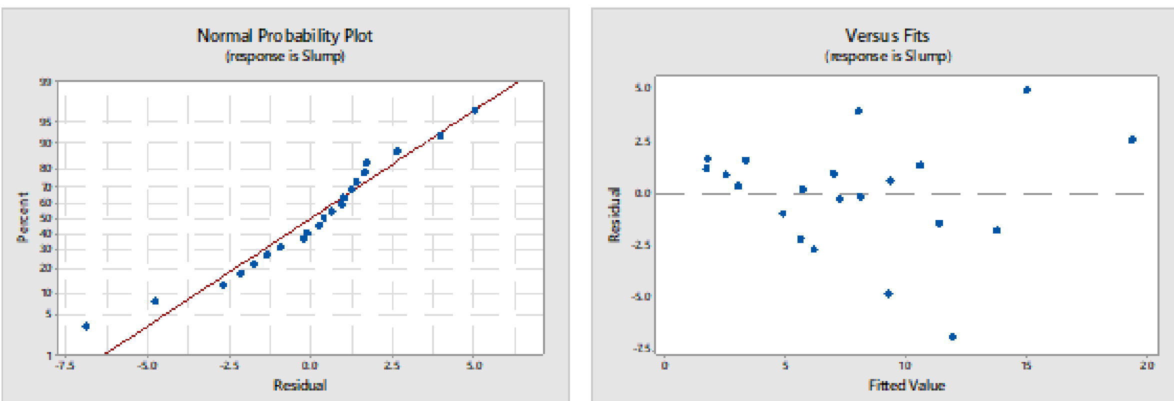

Figure 3: Plot of slump residuals and fitted values

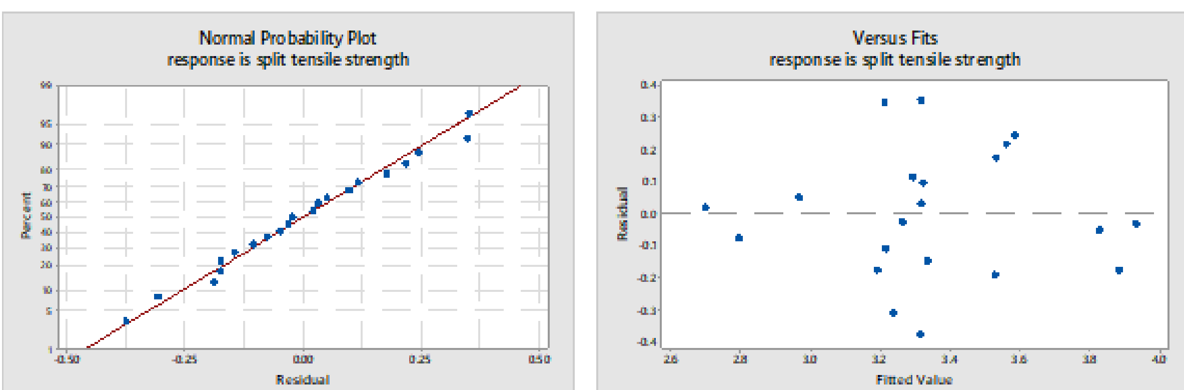

Figure 4: Plot of split tensile strength residuals and fitted values

C. Response Optimization

The response optimization was analyzed using the constrained parameters shown in Table 8. The objective is to maximize the responses; slump and splitting tensile strength respectively. The optimization solution based on desirability approach set the starting point mixture components for slump as ($x_1 = 1, x_2 = 0, x_3 = 0, x_4 = 0, x_5 = 0$) and the local solution mixture components for tensile strength as ($x_1 = 0, x_2 = 0, x_3 = 0, x_4 = 0, x_5 = 1$).

Figure 5 shows the optimization plot of slump and splitting tensile strength respectively. The optimization solution analyzed by Minitab then reveals predicted response for the splitting tensile strength as 3.2382 N/mm^2 with desirability index of 0.459730 and slump of 19.3678 mm with desirability index of 0.669138 while the composite desirability was obtained as 0.554638.

Table 8: Optimization constraints

Parameters	Goal	Lower	Target	Upper	Weight	Import
Slump (mm)	Maximum	1	3.9	3.9	3	3
Split tensile (N/mm^2)	Maximum	1	22.0	22.0	3	3

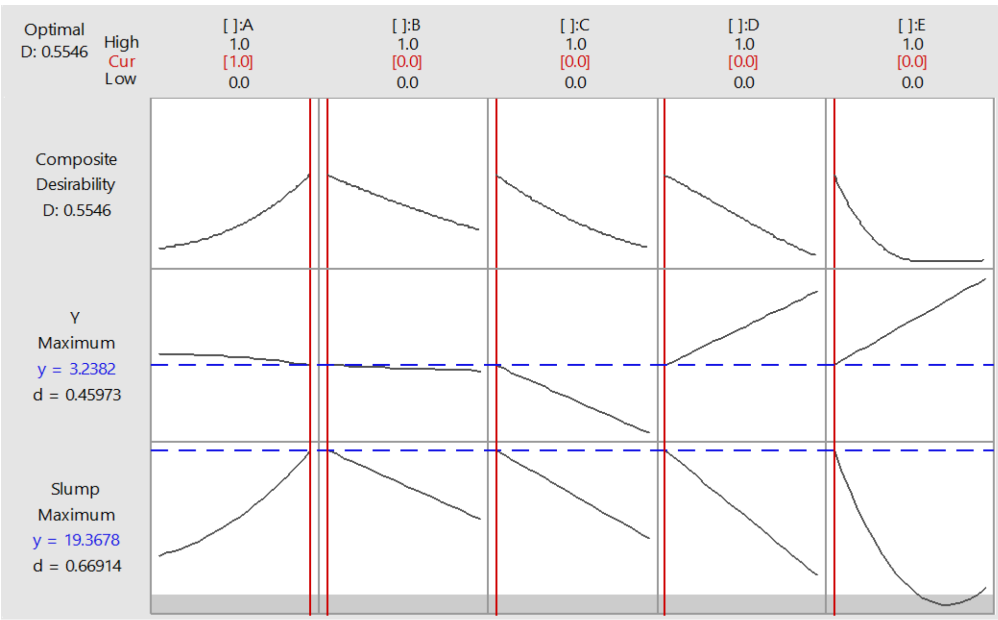

Figure 5: Optimization plot

VI. Conclusion

Experimental results of slump and splitting tensile strength of palmyra reinforced fibre concrete was fit to the second order simplex polynomial model and the following conclusions can be drawn from the study.

i. The slump of the palmyra reinforced fibre reinforced concrete decreased with increasing fibre content while the splitting tensile strength increased with increase in fibre addition.

ii. The predictive models are considered adequate in view of the acceptable p-values and reasonably high R^2 values.

iii. The optimization solution reveals predicted response for the splitting tensile strength as 3.2382 N/mm^2 with desirability index of 0.459730 and slump of 19 mm with desirability index of 0.669138. The composite desirability is obtained as 0.554638.

iv. Based on the optimization solution, 0.5% is the fibre content that produced the balance between slump and splitting tensile strength of the fibre reinforced concrete.

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