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PREDICTION OF MECHANICAL PROPERTIES OF WASTE COPPER WIRE FIBER REINFORCED CONCRETE USING RESPONSE SURFACE METHODOLOGY

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ABSTRACT

This study predicts mechanical properties of waste copper wire fiber reinforced concrete (WCWFRC) using response surface methodology. Plain concrete shows little resistance to tensile loads. Micro cracks due to drying shrinkage propagate easily to macro cracks under applied loads and cause brittle failure. This deficiency can be improved by addition of copper wire fibre. Copper is a durable material that functions throughout its lifetime without significant loss in performance. The experiment was designed using Face-centered central composite design of response surface method. The fibre volume was varied from 0.5 to 1.5% while the curing period was varied from 7 to 28 days. The design consists of two design factors (fiber volume and curing period) at three levels (coded as -1, 0, +1) each. The mix was designed for grade M-25 concrete and tested for mechanical properties. The results show incease in mechanical properties of the concrete with increase in fibre and curing period. The F-values for the models are greater than the critical F-value (3.59) which imply that the factors have significant effect in the models at 5% level of significance. The P-values for the models are less than P_α (0.05) which imply that the factors are significant in predicting the response. The models have R^2 values greater than 85%, adjusted R^2 values greater than 82% and predicted R^2 values greater than 73%. These indicate that the models have good predictive ability. Predicted values of the responses are very close to the experimental values which show the models are adequate.

KEYWORDS: concrete strength prediction, copper wire, flexural strength, fibre reinforced concrete, response surface methodology.

INTRODUCTION

Plain concrete is weak in tension, relatively brittle and has low resistance to cracking. Tensile strength of plain concrete is around one-tenth of its compressive strength. Micro cracks generate in the concrete due to drying shrinkage before application of load on the concrete. These cracks propagate under applied load and results in brittle fracture of the concrete. Further application of the load leads to uncontrolled growth of micro cracks to macro cracks.[1] In order to increase the performance of concrete under tensile or dynamic loading different types of the fibres are added to concrete.

In structural engineering, fibre reinforced concrete (FRC) has been in existence and used for a long time but it is not very frequently used in practice. Its application is limited to few types of structures such as graded slabs and pavements for crack control.[2] Fibres in concrete act as cracks arrester and restrict the growth of flaws into cracks under load which improves the static and dynamic properties of the concrete matrix.[1] The addition of fibres to concrete considerably improves its structural characteristics such as flexural strength, impact strength, tensile strength, ductility and flexural toughness.

Concrete containing steel fibres has excellent tensile strength, flexural strength, shock resistance, fatigue resistance, ductility and ability to arrest cracks. Mostly steel fibres are seen to be performing well as compared to other forms of fibre.[4] However, the major problem with the inclusion of macro steel fibers is the reduction in the workability of the fresh concrete due to high aspect ratio (length- diameter) and high-volume content of the fibers. This limits the use of macro steel fibers in concrete to a maximum volume content of 2%.[5] Generally, aspect ratios of steel fibres used in concrete mix are varied between 50 and 100. The most suitable volume fraction values for concrete mixes are between 0.5% and 1.5% by volume of concrete.[6] If the fibers are strong enough and sufficiently bonded to the material, they carry some stresses over a relatively great rupture strain capacity in the post-cracking stage.[7]

Copper is a highly durable material that functions throughout its lifetime without significant loss in performance. Because copper develops its own adherent protective coating, it has an excellent resistance to corrosion in all kinds of common environments including atmospheric air, potable water, soil, and even sea water and a wide variety of chemicals [8]. Copper has a density of 8960 kg/m^3 and tensile strength ranging from 200 to 250 N/mm^2 [9]. These properties encourage the use of copper wire as fibre reinforcement in this study. Also, incorporating waste copper wire as fibre reinforcement in concrete would reduce the cost of maintenance of the structure by arresting cracks propagation.

Shariful-Islam and Al-Amin.[7] investigated the behavior of low grade SFRC made with both fresh and recycled brick aggregates. They used hook ended steel fibers of length 50 mm, aspect ratio of 55.6 and volume fraction of 0, 0.5, and 1.0 %. They found about 6 to 12 % increase in compressive strengths at 28 days curing for SFRC made with both the fresh and recycled brick aggregates. On the other hand, around 5% to 10% enhancement in tensile strength was observed at 28 days when compared with that of the control mix.

MATERIALS AND METHODS

Materials

Ashaka brand of ordinary Portland cement (OPC) was used throughout the research. The cement has specific gravity of 3.14 and loose bulk density of 1550 kg/m^3. The cement paste has consistency of 28%, initial setting time of 53 minutes, final setting time of 475 minutes and soundness of 3.5 mm. The results conform with BS EN 197: Part 1[10] specifications. The fine aggregate used was obtained from a stream along Bauchi – Dass road. It has specific gravity of 2.42 and bulk density of 1611 kg/m^3. Crushed igneous rock coarse aggregate was used with maximum size of 20 mm. It has specific gravity of 2.75, moisture content of 1.1%, bulk density of 1586 kg/m^3, aggregate impact value of 14.65% and aggregate crushing value of 26.84%. The tests were conducted in accordance with BS EN 1097: Part 6.[11] BS 812: Part 2[12] and BS 812: Part 110.[13] specifications respectively. Clean water was used for preparation of the test specimens. CONPLAST SP 430 brand of superplasticizer was used throughout the study. No test was conducted on the superplasticizer. The copper wire used was factory offcuts obtained from Alind Nigeria Limited, Bauchi. Single size of one millimeter (1 mm) diameter and 60 mm long wire fibres were used according to RILEM TC 162-TDF recommendations.[14]

Methodology

Design of experiment

The experiment was designed using Face-centered central composite design method of response surface method in Design Expert software. The fibre volume was varied from 0.5 to

1.5% while the curing period was varied and 7 to 28 days. The design consists of two design factors at three levels (coded as -1, 0, +1) each. The factors are the curing period, and the fibre volume, V_f.

Concrete mix design

The mix was designed for grade M-25 concrete using Building Research Establishment (BRE) mix design method. The minimum compressive strength is 25 N/mm^2. Moderate exposure was chosen for durability requirement. Also, moderate workability ranging from 30 – 60 mm and 30% passing 600 microns were used. Mix ratio of 1:2:3 was obtained at 0.50 water-cement ratio. The concrete specimens were cured for 7, 14 and 28 days in water respectively.

Specimens testing

Saturated density and water absorption tests were carried out on the hardened concrete specimens in accordance with BS EN 12390:7[15] and BS 1881:122.[16] specifications respectively. Compressive strength test was conducted on concrete cube specimens in accordance with BS EN 12390:3.[17] and BS EN 12390:4.[18] specifications. Also, flexural strength test was conducted on concrete beams in accordance with BS EN 12390:5[19] specifications, while split tensile strength test was conducted on concrete cylindrical specimens in accordance with BS EN 12390:6.[20] specifications.

RESULTS AND DISCUSSIONS

The results of mechanical properties of WCWFRC were summarized in Table 1 shown below. The models summary of statistic suggested Two Factor Level (2FL) model for analysis of water absorption, linear model for analysis of splitting tensile strength, and quadratic model for analysis of density, compressive strength and flexural strength.

Table 1: Summary of Mechanical Properties of WCWFRC.

Run	Block	Factors		Responses				
		CP (days)	V_f (%)	ρ (kg/m^3)	*WA* (%)	Cs (N/mm^2)	Fs (N/mm^2)	St (N/mm^2)
1	Block 1	0	0	2730	1.21	29.48	7.06	4.03
2	Block 1	0	0	2730	1.21	29.48	7.06	4.03
3	Block 1	-1	-1	2667	0.85	20.14	5.58	3.36
4	Block 1	0	1	2757	1.32	30.28	7.39	4.09
5	Block 1	0	0	2730	1.21	29,48	7.06	4.03
6	Block 1	1	1	2810	1.44	34.58	8.07	4.37
7	Block 1	1	-1	2747	1.33	31.12	7.31	4.14

8	Block 1	-1	1	2747	1.09	24.85	6.55	3.70
9	Block 1	-1	0	2707	0.97	23.52	6.09	3.59
10	Block 1	1	0	2780	1.33	33.40	7.65	4.30
11	Block 1	0	0	2730	1.21	29.48	7.06	4.03
12	Block 1	0	0	2730	1.21	29.48	7.06	4.03
13	Block 1	0	-1	2707	1.10	26.11	6.53	3.40

Contour and 3D Plots of the Responses

Figures 1A-E show the contour and surface plots of the responses against volume of fibre and curing period respectively. Figure 1A indicates that density of the concrete increases with increase in both the volume of fibre and curing period. Also, water absorption of the concrete increases with increase in both the volume of fibre and curing period as indicate in Figure 1B. Maximum water absorption (1.41%) was obtained at 28 days curing for concrete containing 1.5% waste copper wire fibre (WCWF) while the minimum water absorption (0.85%) was obtained at 7 days curing for concrete containing 0.5% WCWF. Figure 1C shows that the compressive strength increases with increase in both the volume of fibre and curing period. Maximum compressive strength of 34.58 N/mm^2 was obtained for 1.5% fibre volume at 28 days curing, while the minimum compressive strength of 20.14 N/mm^2 was obtained at 7 days curing for concrete containing 0.5% WCWF. The flexural strength increases with increase in both the volume of fibre and curing period as shown in Figure 1D. It increases from 5.58 N/mm^2 at 7 days and 0.5% WCWF contents to 8.07 at 28 days and 1.5% WCWF content. Figure 1E shows that the split tensile strength increases with increase in both the volume of fibre and curing period. It increases from 3.36 N/mm^2 at 7days and 0.5% WCWF content to 4.37 N/mm^2 at 28 days and 1.5% WCWF content. The results agreed with the finding of other researchers [21 & 22].

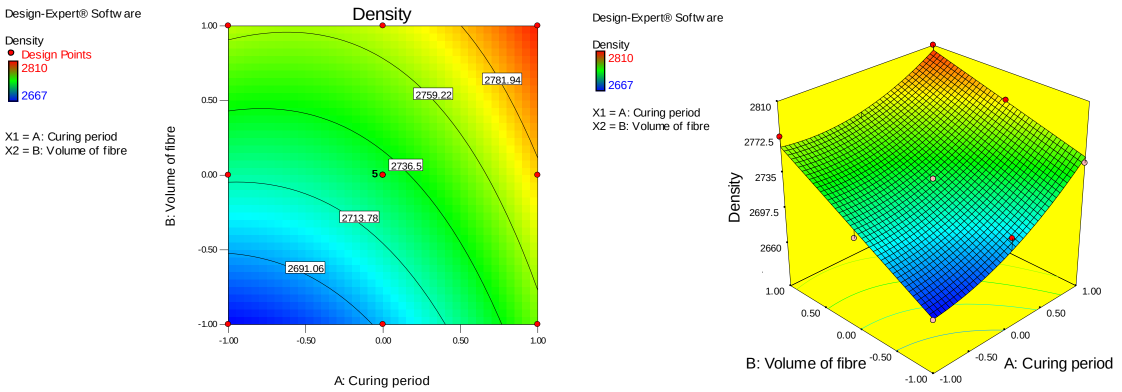


Figure 1A: Contour and Surface plots of density against volume of fibre and curing period.

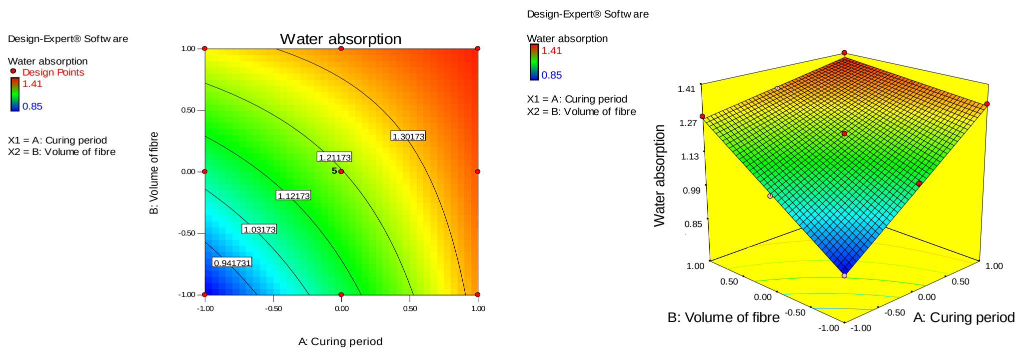


Figure 1B: Contour and Surface plots of water absorption against volume of fibre and curing period.

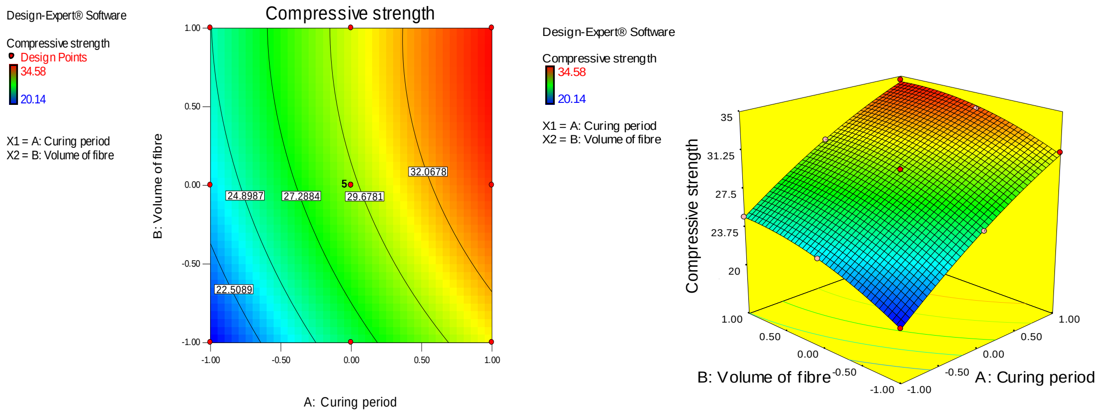


Figure 1C: Contour and Surface plots of compressive strength against volume of fibre and curing period.

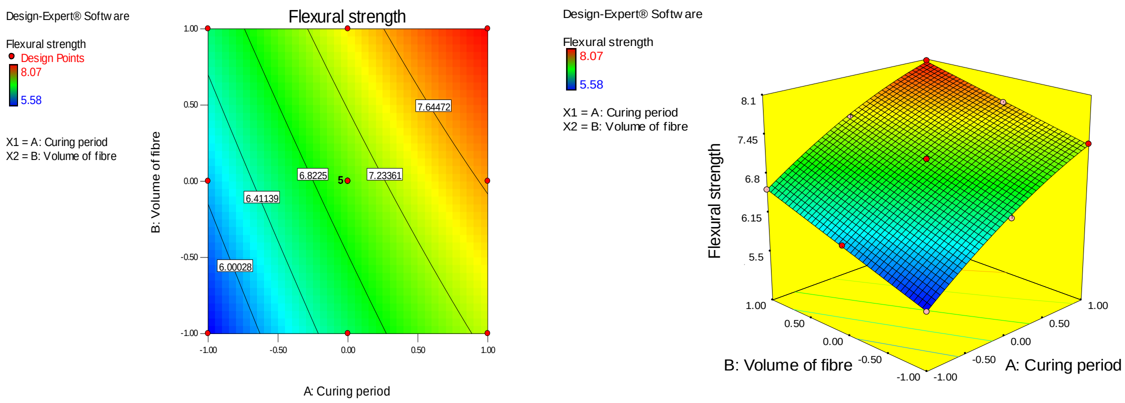
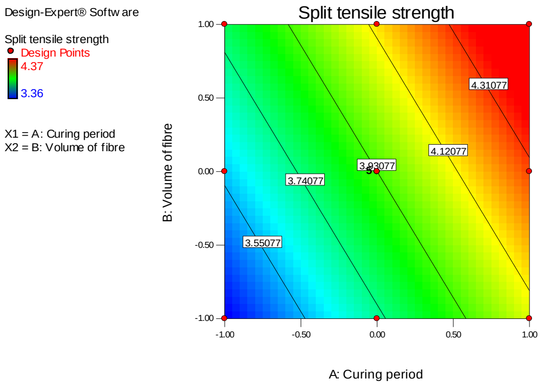


Figure 1D: Contour and Surface plots of flexural strength against volume of fibre and curing period.



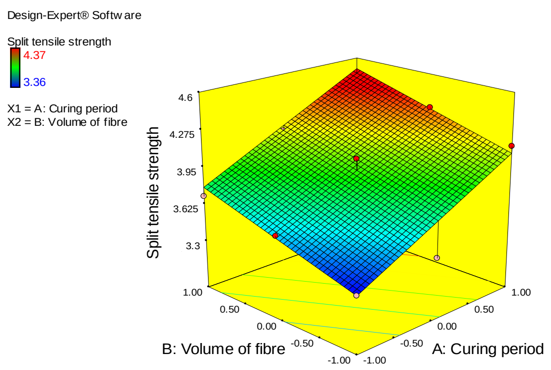


Figure 1E: Contour and surface plot of split tensilel strength against volume of fibre and curing period.

Analysis of Variance (ANOVA) and Regression Models for the Responses

The ANOVA for the responses are presented in Tables 2A-2E. From the Tables, the F-values obtained for the models are greater than the critical F-value (3.59) obtained from statistical table. This implies that the model is adequate at 5% level of significance. Also, the F-values obtained for factors A (curing period) and B (volume of fibre) are greater than the critical F-value, which indicate that A and B have significant effect in the models behavior. The P-values for the models and the factors are less than P-α (0.05) which indicates that the model is significant and the factors are significant in predicting the responses [23] and [24].

Table 2A: Analysis of variance for Density.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	15430.03	4	3857.51	57.46	< 0.0001	significant
A-Curing period	5953.50	1	5953.50	88.68	< 0.0001	
B-Volume of fibre	8066.67	1	8066.67	120.16	< 0.0001	
AB	484.00	1	484.00	7.21	0.0277	
A^2	925.86	1	925.86	13.79	0.0059	
Residual	537.05	8	67.13			
Lack of Fit	537.05	4	134.26			
Pure Error	0.000	4	0.000			
Cor Total	15967.08	12				

Table 2B: Analysis of variance for Water Absorption.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.25	3	0.084	461.68	<0.0001	significant
A-Curing period	0.13	1	0.13	727.15	<0.0001	
B-Volume of fibre	0.089	1	0.089	489.21	<0.0001	
AB	0.031	1	0.031	168.68	<0.0001	

Residual	0.0016	9	0.00018			
Lack of Fit	0.0016	5	0.00033			
Pure Error	0.000	4	0.000			
Cor Total	0.25	12				

Table 2C: Analysis of variance for Compressive Strength.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	189.23	5	37.85	1066.87	< 0.0001	significant
A-Curing period	155.96	1	155.96	4396.53	< 0.0001	
B-Volume of fibre	25.38	1	25.38	715.45	< 0.0001	
AB	0.39	1	0.39	11.01	0.0128	
A^2	1.68	1	1.68	47.35	0.0002	
B^2	3.02	1	3.02	85.00	< 0.0001	
Residual	0.25	7	0.035			
Lack of Fit	0.25	3	0.083			
Pure Error	0.000	4	0.000			
Cor Total	189.47	12				

Table 2D: Analysis of variance Flexural Strength.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	5.06	4	1.27	641.95	< 0.0001	significant
A-Curing period	3.86	1	3.86	1955.21	< 0.0001	
B-Volume of fibre	1.12	1	1.12	566.90	< 0.0001	
AB	0.011	1	0.011	5.59	0.0456	
A^2	0.079	1	0.079	40.09	0.0002	
Residual	0.016	8	0.002			
Lack of Fit	0.016	4	0.004			
Pure Error	0.000	4	0.000			
Cor Total	5.08	12				

Table 2E: Analysis of Variance for Split Tensile Strength.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Effect
Model	1.04	2	0.52	28.59	< 0.0001	significant
A-Curing period	0.78	1	0.78	42.66	< 0.0001	
B-Volume of fibre	0.26	1	0.26	14.52	0.0034	
Residual	0.18	10	0.018			
Lack of Fit	0.18	6	0.030			
Pure Error	0.000	4	0.000			
Cor Total	1.22	12				

Table 3 shows the summary of statistics for the models. The models have very small standard deviation values which indicate how the datasets are clustered to the mean. Also, the values of coefficient of variation (CV) indicate precision in the data set, and the lower the CV the more precise the dataset are. The Predicted Residual Error Sum of Squares (PRESS) value for each model is less than the sum of squares values for the model and the factors in the model which show that the models have good predictive ability (The smaller the PRESS value, the better the model's predictive ability).

The models have R^2 values greater than 0.85 (85%) and the higher the value of R^2, the better the model fits the data. Also, the adjusted R^2 values for the models are greater than 0.82 (82%). For a good model, R^2 and adjusted R^2 should be close to each other and they should be close to 100%. The Predicted R^2 values for the models are greater than 0.73 (73%). Models with larger predicted R^2 values have better predictive ability [23] and [24]. Adequate Precision measures the signal to noise ratio in a model. The models have adequate precision ratios greater than 17 which indicate adequate signals (ratio greater than 4 is desirable).

Table 3: Summary of Statistics for the Models.

Parameter	***ρ***	***WA***	**Cs**	**Fs**	**St**
Standard Deviation	8.19	0.013	0.19	0.044	0.14
Mean	2738.38	1.21	28.57	6.96	3.93
C.V. %	0.30	1.11	0.66	0.64	3.43
PRESS	3600.05	0.0062	1.95	0.037	0.32
R-Squared	0.9664	0.9935	0.9987	0.9969	0.8511
Adjusted R-Squared	0.9495	0.9914	0.9978	0.9953	0.8214
Predicted R-Squared	0.7745	0.9756	0.9897	0.9927	0.7379
Adequate Precision	26.830	72.249	111.837	89.562	17.576

Model equations

The model equations in terms of coded factors are presented in Equations (1) – (5).

$$Density = +2730.57 + 31.50A + 36.67B - 11.00AB + 16.93A^2 \quad \dots \quad (1)$$

$$Water\ absorption = +1.21 + 0.15A + 0.12B - 0.088AB \quad \dots \quad (2)$$

$$Compressive\ strength = +29.41 + 5.10A + 2.06B - 0.31AB - 0.78A^2 - 1.04B^2 \dots (3)$$

$$Flexural\ strength = +7.03 + 0.80A + 0.43B - 0.052AB - 0.16A^2 \quad \dots \quad (4)$$

$$Split\ tensile\ strength = +3.93 + 0.36A + 0.21B \quad \dots \quad (5)$$

Diagnostic Plots

Figures {2A(a-d)} – {2E(a-d)} show dianostic plots for the responses. Figure (a) shows the normal probability plot of the residuals. The plot indicates that there is no significant deviation from the normal probability line and it can be concluded that the assumption of normality is fairly satisfied. Figure (b) shows plot of predicted values of the responses against the actual values. The points are close to the fitted line which indicates that the data fit the model. Figure (c) shows the residuals vs predicted plots. It shows that increase in predicted values of the responses does not show any significant increase or decrease in the residuals. The plots are used to check for constant error in the data. Figure (d) shows the residual vs run plot. The plot shows no significant pattern as the run order is icreased or decreased. The plots also show that the residuals are independent from one another.[25]

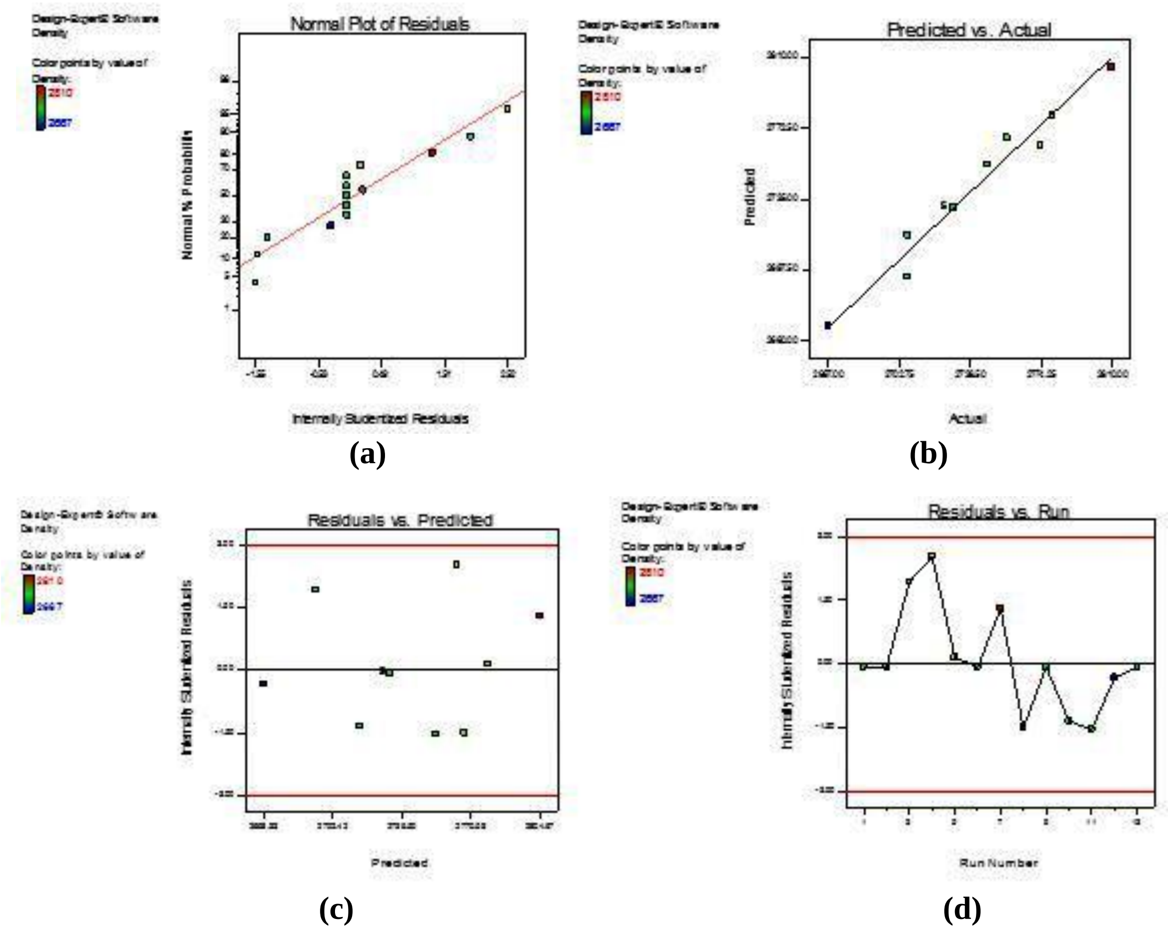
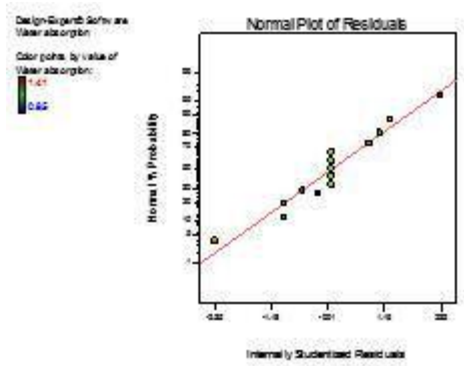
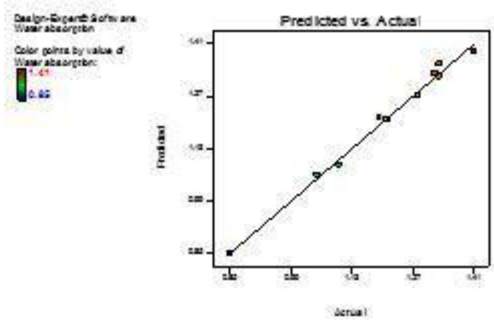
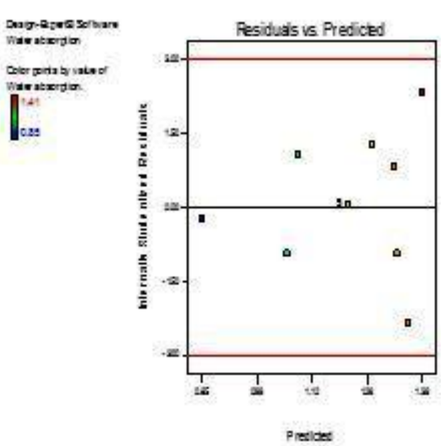


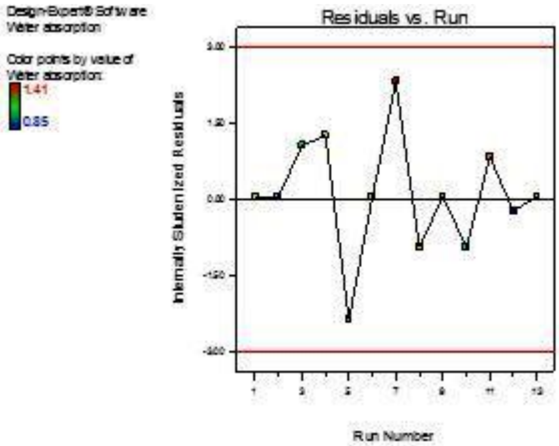
Figure 2A:Diagonestic plots for density of concrete (a) Normal probability plot of the residuals; (b) Predicted values of the responses against the actual values; (c) Residuals vs predicted values ; (d) Residual vs run plot.





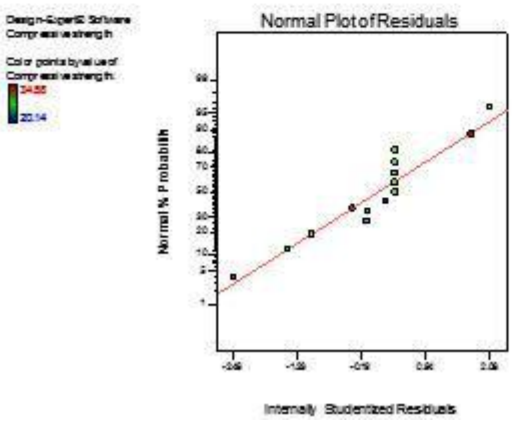
(a) **(b)**

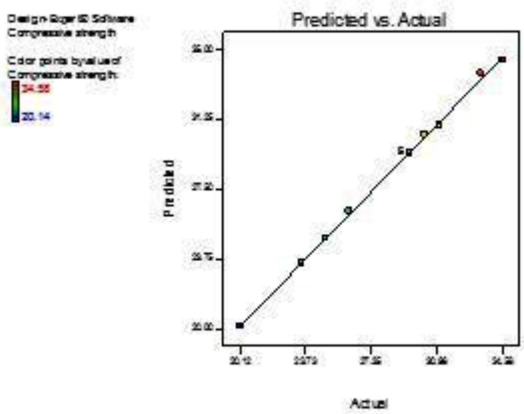




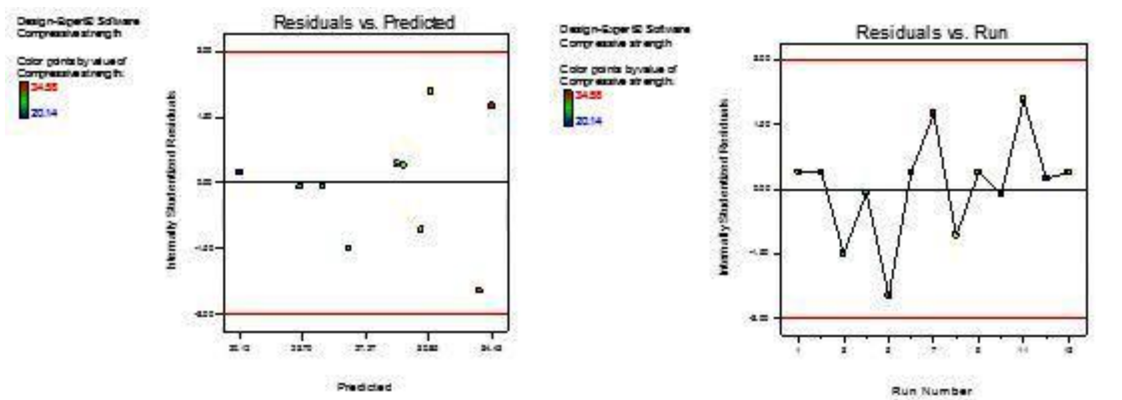
(c) **(d)**

Figure 2B: Diagonestic plots for Water absorption of concrete (a) Normal probability plot of the residuals; (b) Predicted values of the responses against the actual values; (c) Residuals vs predicted values ; (d) Residual vs run plot.



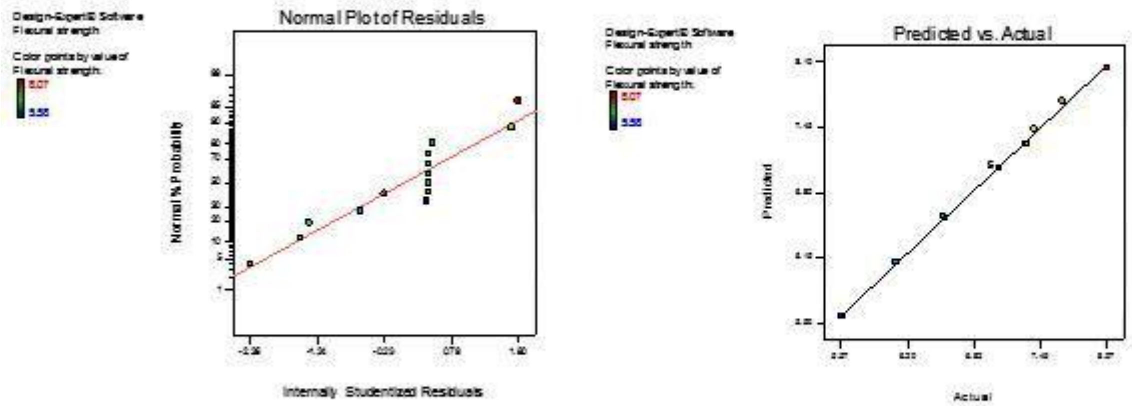


(a) **(b)**

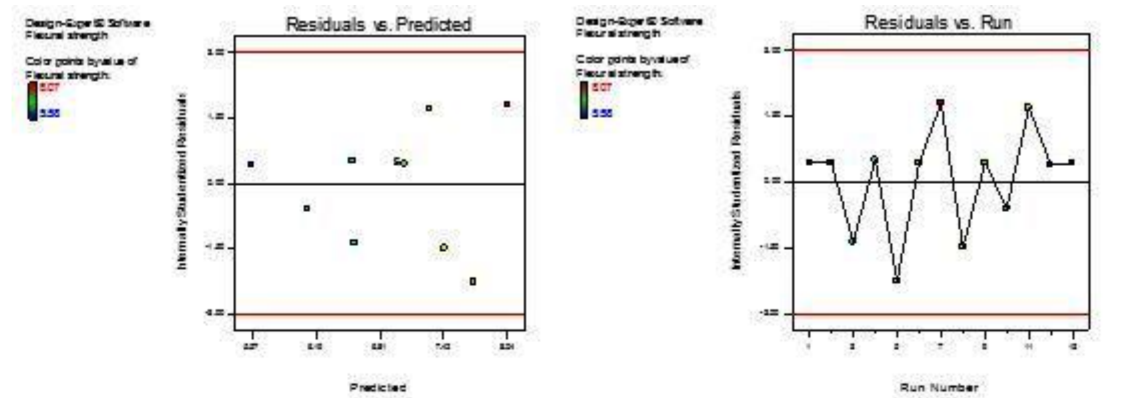


(c) (d)

Figure 2C: Diagonestic plots for compressive strength of concrete (a) Normal probability plot of the residuals; (b) Predicted values of the responses against the actual values; (c) Residuals vs predicted values ; (d) Residual vs run plot.

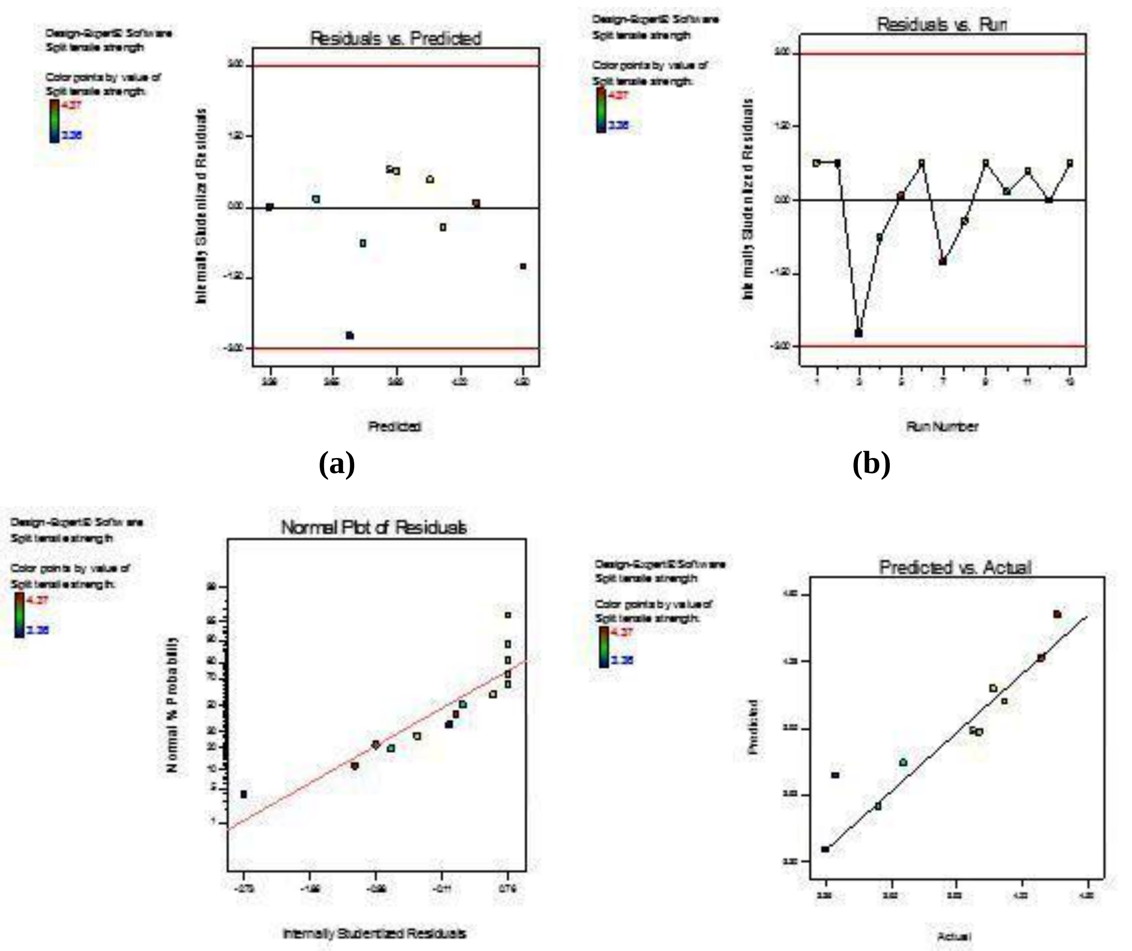


(a) (b)



(c) (d)

Figure 2D: Diagonestic plots for flexural strength of concrete (a) Normal probability plot of the residuals; (b) Predicted values of the responses against the actual values; (c) Residuals vs predicted values ; (d) Residual vs run plot.



(a) (b)

(c) (d)

Figure 2E: Diagonestic plots for split tensile strength of concrete (a) Normal probability plot of the residuals; (b) Predicted values of the responses against the actual values; (c) Residuals vs predicted values ; (d) Residual vs run plot.

Actual and Predicted Values of the Responses

Table 4 presented actual values of the responses obtained from the experiments and the values predicted by their respective models. All the predicted values of the responses agree with their respective experimental values.

Table 4: Actual and predicted values of the responses.

Density		**Water absorption**		**Compressive strength**		**Flexural strength**		**Split tensile strength**	
Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
2667.00	2668.33	0.85	0.85	20.14	20.12	5.58	5.59	3.36	3.36
2747.00	2753.33	1.33	1.32	31.12	30.94	7.31	7.30	4.14	4.08
2774.00	2763.67	1.28	1.27	24.85	24.86	6.55	6.56	3.70	3.78
2810.00	2804.67	1.41	1.39	34.58	34.43	8.07	8.06	4.37	4.50
2707.00	2716.00	1.05	1.06	23.52	23.53	6.09	6.07	3.59	3.57

2780.00	2779.00	1.33	1.36	33.40	33.73	7.65	7.68	4.30	4.29
2707.00	2693.90	1.10	1.09	26.11	26.31	6.53	6.60	3.40	3.72
2757.00	2767.24	1.32	1.33	30.28	30.42	7.39	7.46	4.09	4.14
2730.00	2730.57	1.21	1.21	29.48	29.41	7.06	7.03	4.03	3.93
2730.00	2730.57	1.21	1.21	29.48	29.41	7.06	7.03	4.03	3.93
2730.00	2730.57	1.21	1.21	29.48	29.41	7.06	7.03	4.03	3.93
2730.00	2730.57	1.21	1.21	29.48	29.41	7.06	7.03	4.03	3.93
2730.00	2730.57	1.21	1.21	29.48	29.41	7.06	7.03	4.03	3.93

CONCLUSIONS

The following conclusions were drawn from the results of this research work:

1. There is general incease in mechanical properties of the concrete with increase in WCWF and curing period.
2. The F-values for the models are greater than the critical F-value (3.59) which imply that the factors have significant effect in the model behavior and the models are adequate at 5% level of significance.
3. The P-values for the models are less than P_α (0.05) which imply that the factors are significant in predicting the response.
4. The models have R^2 values greater than 85%, adjusted R^2 values greater than 82% and predicted R^2 values greater than 73%. These indicate that the models have good predictive ability.
5. The Adequate Precision value for the models are greater than the minimum value of 4 which imply adequate signal to noise ratio in the models and the models can be used to navigate the design space.
6. The predicted values of the responses are very close to the experimental values which show the models are adequate.

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