

Investigating the Strength Properties of Concrete containing Construction & Demolition waste using Response Surface Methodology Techniques (RSM)

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ABSTRACT

The framework through which waste from Construction and Demolition activities could be reused in concrete was developed using the Response Surface Methodology techniques. An experimental design to determine the proportions of CDW waste which include Recycled Concrete Aggregate (RCA) and Recycled Fine Aggregate (RFA) to be mixed with other concrete constituents using Central Composite Design (C.C.D) orthogonal design was performed. Four factor variables which include %RCA to replace granite, Water-cement ratio, %RFA to replace river sand and RCA aggregate size was used while the response variable is the concrete compressive and flexural strength. Thirty (30) experimental runs were generated and conducted. The result was then analyzed using the RSM regression analysis. The result showed that %RCA showed the highest influence on both compressive and flexural strength of the CDW concrete. The Contour analysis also showed the behavior of the strength properties of CDW concrete to different variations of the factor variables. The research showed that the use of CD waste in concrete production help improve the properties of concrete.

Keywords: Response surface methodology; Construction and demolition waste; Central Composite Design; Flexural Strength; Compressive Strength.

INTRODUCTION

Buildings, roads, highways, bridges, utility facilities and dams are examples of civil-engineering structures where significant volumes of construction materials are used. When new buildings and civil engineering structures are renovated or demolished, construction and demolition (CD) materials are produced. Concrete, glass, plastics, salvaged building components and other large, heavy materials are frequently contained in CD components. According to Shen et al. [8], "C & D waste is as a combination of surplus constituents generated from construction, renovation and destruction activities such as site clearance, land excavation and roadwork and demolition". The majority of CD trash generated in Nigeria is being disposed of in out-of-state landfills, with only a small percentage being recycled.

From 2015 to 2019, construction and demolition (CD) activities in Nigeria produced 1.13 billion tonnes, whereas in the United States they produced over 530 million tonnes [9]. When compared to other industrial categories, construction operations in Nigeria are the second greatest generator of garbage, second only to the plastics, food and beverage industry,

accounting for 35 percent of total waste creation [9]. According to the Environmental Protection Agency's waste characterization analysis in the Advancing Suitable Materials Management 2018 fact sheet, slightly over 455 million tonnes of CDW debris were diverted into next use (recycling) out of 600 billion tonnes of CDW waste created in the United States while the remaining were sent to landfills. The situation in underdeveloped countries in which Nigeria belongs to is the inverse. The majority of garbage created in Nigeria, including CDW, are disposed of in landfills. Unlike some other construction waste materials, which can either be reused in the construction process or sold, CDWs can only be utilized as a filler material, and the vast majority of it (more than 90 percent) ended up in landfills. However, the rapid growth in real estate construction over the last three years has resulted in a scarcity of land and had forced urban housing development near landfills, posing numerous environmental risks. As the rate of development rises, more CDWs will be generated, causing greater waste management issues. As a result, sustainable alternatives to reusing construction demolition wastes (CDWs) created in the building industry are required [10].

LITERATURE REVIEW

Concrete is the most frequently used construction material in the world; the raw ingredients required are readily available in most parts of the globe, and its manufacture does not necessitate sophisticated or expensive machinery [1]. Concrete is a high-strength, long-lasting composite material made up of cement, fine and coarse aggregate. The rapid rise of urbanization and industrialization has resulted in a substantial increase in consumption. Because natural aggregate makes up more than 70% of the volume of concrete, any increase in its use will increase the amount of natural aggregate consumed [11]. In Nigeria, around 40 billion tons of natural aggregate are consumed each year in the manufacturing of concrete to meet the various needs of the construction industry. Concrete is a non-sustainable material due to this vast use of natural resource. Thousand of years are required to create a natural aggregate source. The pace of natural aggregate formation is substantially lower than the current rate of consumption, which can only lead to its depletion. [12]. As a result, efforts to find and employ a suitable alternative construction material that is both cost-effective and viable in terms of strength and durability have intensified [1]. Because CDW is made from building debris, it has qualities that are similar to natural aggregates, such as high-water absorption that can be lowered by adding tiny granular particles. The use of CDW as a substitute aggregate for concrete reduces natural aggregate usage as well as landfill difficulties. [13].

Response Surface Methodology (RSM) is a statistical analytic technique in which each response is linked to a set of variables in order to evaluate the effect, relationship and interaction between the variables and the response. RSM analysis entails creating a series of experiments and collecting the experimental results as responses, then validating the accuracy and optimizing the variables to satisfy the intended response using response surface numerical models. [2]. RSM is a useful statistical method for designing experiments, generating models, evaluating factors and finding the best search conditions. RSM is frequently employed in circumstances where a number of variables influence one or more performance aspects, such as the response. It's used to improve one or more responses or to meet a set of requirements. [3-6]. RSM offers statistically proven predictive models that may be tweaked to discover the best process set-up. When numerous factors influence one or more performance attributes or reactions, RSM is commonly utilized. RSM, as an optimization tool, is used to improve one or more responses or to meet a set of requirements. RSM interprets experimental results using a

non-linear response surface approach and gives sufficient experimental interpretations as part of the final result [14]. The stages involved in most RSM applications include:

- A screening factor, which is run to reduce the number of factors (independent) variables to a relative few, so the procedure will be more efficient and require smaller number of runs or tests.
- Determination is made on current levels of the major effect factors resulting in a value for the response that is close to the optimum region. If the current levels of the factors are not consistent with optimum performance, then the experimenter must adjust the process variables that will lead the process toward the optimum level.
- Researchers carry out the chosen experimental design according to the selected experimental matrix.
- Mathematical/statistical models of the experimental design data are developed by fitting linear or quadratic polynomial functions. The fitness of the models then needs to be evaluated.
- The stationary points (optimum values) are obtained for the variables

MATERIAL AND METHODS

Materials Used

Grade 42.5 Portland cement, high range water reduction admixture, river sand with a specific gravity of 2.58 as fine aggregate, granite passing through sieve size 20 as coarse aggregate, and portable water for mixing were utilized in the concrete preparation. The water admixture was employed to improve the concrete's workability. The Recycled Coarse Aggregate (RCA) or simply recycle aggregate (RA) used in this study was extracted from construction demolition waste at recycling centers. The Recycled Fine Aggregate (RFA) used consisted of broken glass and ceramic tiles. These materials was extracted from construction demolition wastes and then grounded together into finer particle sizes corresponding to that obtained from the Response Surface Methodology C.C.D experimental design.

Experimental Mixing and Casting

The cement rate was kept constant in the concrete mix samples, while the river sand was partially replaced by recycled fine aggregate (RFA) and the granite by recycled coarse aggregate. The Central Composite Design type of the Response Surface Methodology Experimental designs determined the percentages of replacement in both circumstances. A tilting drum mixer was used to make the concrete mix. The mixer's revolution speed was 60rpm, and the total mixing time was variable. Compressive and flexural strength tests were performed on 100mm x 100mm x 100mm casted cubes and 225mm x 450mm beams respectively. The casted samples were prepared by pouring the concrete into a pre-lubricated mould and compacting it in three stages. These samples were then covered in wet sacks for 24 hours in the laboratory before being de-moulded and cured in water before testing. The compressive and flexural tests were performed after 28 days

Compressive Strength Test

The compression testing machine was used for the testing. Before putting the specimen, the bearing surface of the supporting and loading rollers were wiped clean. The specimens were positioned by applying a weight on the uppermost surface of the specimens. The specimens were positioned with the loading device with great care. The maximum load was recorded when the dial stopped moving while the load was steadily increased. The specimen's

compressive strength was calculated by dividing the highest crushing load in Newtons (N) by the effective area in millimeters(mm).

Flexural Strength Test

The beams were tested at 28 days using a flexural testing equipment in accordance with BS EN 12390-5 under four point loading till failure. A constant loading setup with a 300 mm shear span and a 3.0 shear depth ratio was used. Specimens were positioned on the supporting bearing blocks with their sides facing in the direction they would be when moulded. At one quarter distance from the end of the supports, the upper surface of the test specimen was brought into contact with the load-applying block. The beam was examined to confirm it was in uniform contact with the bearing and load-bearing blocks. Loading continued indefinitely until the specimen failed and the dial stopped moving. The maximum applied load indicated by the testing machine was recorded. The Flexural strength is calculated using equation 1.

$$R = 3Fl / 4bd^2 \quad (1)$$

R = Flexural strength (N/mm²) F = Applied load at failure l= beam span measured in millimeter
b = beam breadth measured in millimeter d= beam depth measured in millimeter

Response Surface Methodology Experimental Design

In this study, the required number of experiments was determined using RSM's Central Composite Design (C.C.D). According to [7], the central composite rotatable design allows axial points to be introduced into the experimental design. Each numerical factor in the experiment has five (5) levels of variation, which are plus Alpha (+α), minus Alpha (-α), (axial/star points) +1(high level), -1(low level) (factorial points) and the centre point (mid-level). A classic CCD design module consists of:

- Four corners of the square representing the factorial (+/- 1) design points.
- Four central points representing the axial (+/- alpha) design points.
- +/-1 to define the limits of the area of interest where the optimum is believed to exist, axial points will typically be outside this limit.
- Alphas to define the area of operability, the area of interest will be within the area of operability [15]

Table 1 gave a representation of the above explanation. The independent variables to be considered in the design are %RCA, water-cement ratio, %RFA, Aggregate size of RCA (mm), Aggregate size of PFA. They are represented as A, B and C, D and E in coded terms (independent variables) while the response variables represent the compressive strength and flexural strength (dependent variables) respectively. The coding of variable was done using equation 2.

$$\text{coded value} = \frac{r - c}{h - c} \quad (2)$$

Where r is the runs number to be coded, c is the centre point of the factor to be coded and h is the highest value of the factor being considered as given by the experimental design.

The ACI 211.1 Standard, "Recommended Practice for Selecting Proportions for Normal Weight Concrete," was used for proportioning the concrete mixtures in this study. Two water/cement ratios of 0.5 and 0.7 were selected, which corresponded to the compressive strengths at 28 days of approximately 33.0 and 24.0 MPa, respectively by ACI 211.1. Other independent variables was ranged between 50%, 80%, 20% - 50% and 9.5mm - 19mm for the percentage replacement

with recycled coarse aggregate (A), percentage replacement with recycled fine aggregate (C) and aggregate size of recycled coarse aggregate (D).

This experimental design is expected to generate range of values of the independent variables within the limit set (runs). Experiments would then be performed on those ranges of values to determine the response variables (compressive and flexural strength). The results of the conducted experiments would then be analyzed using Response Surface Regression models and ANN model. The Central Composite Design was performed using the Design Expert Software version 13.

Table 1: Independent parameters including coded levels

Parameters	Code	Unit	Coded Levels Parameters		
			-1	0	1
% RCA	A	%	50	65	80
Water-cement ratio	B	%	0.5	0.6	0.7
% RFA	C	%	20	35	50
Aggregate size of RCA	D	mm	9.5	14.25	19

Response Surface Methodology Regression Analysis

The experiment would be done after the experimental set-up design was completed, and the actual response variable values was calculated. A Regression model was developed based on the result to indicate the relationship between the individual variable and the response variable. This model could be linear, cubic or quadratic in nature. In this study, a quadratic regression model expressed in a second-order equation was used. This model was of the form:

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{j=2}^k \sum_{i=1}^{j-1} \beta_{ij} x_i x_j + \varepsilon \quad (3)$$

Where y is the response, which are flexural and compressive strength, $x_i x_j$ are the coded values for the independent variables, i is the linear co-efficient, j is the quadratic co-efficient, β represents regression co-efficient, k represents number of factors, and ε indicates random error.

To test the equation for estimating the response variables from the independent variables, an analysis of variance (ANOVA) would be performed. The ANOVA analysis's lack of fit (F-test, P-test) would be used to determine how significant the independent variables were in modelling the response variables. A P-value greater than 0.1 shows that the model is insignificant.

The version 13 of the Design Expert software was used to develop the experimental plan for RSM. The same software was also used to analyze the data collected by following the steps as follows:

- Choose a transformation if desired. Otherwise, leave the option at "None".
- Select the appropriate model to be used. The Fit Summary button displays the sequential F-tests, lack-of-fit tests and other adequacy measures that could be used to assist in selecting the appropriate model.
- Perform the analysis of variance (ANOVA), post-ANOVA analysis of individual model coefficients and case statistics for analysis of residuals and outlier detection
- Inspect various diagnostic plots to statistically validate the model.

- If the model looks good, generate model graphs, i.e. the contour and 3D graphs, for interpretation. The analysis and inspection performed in steps (3) and (4) above will show whether the model is good or otherwise. Very briefly, a good model must be significant and the lack-of-fit must be insignificant. The various coefficient of determination, R^2 values should be close to 1. The diagnostic plots should also exhibit trends associated with a good model and these will be elaborated subsequently

Figure 1 shows the RSM methodology used in modelling the strength properties of CDW concrete.

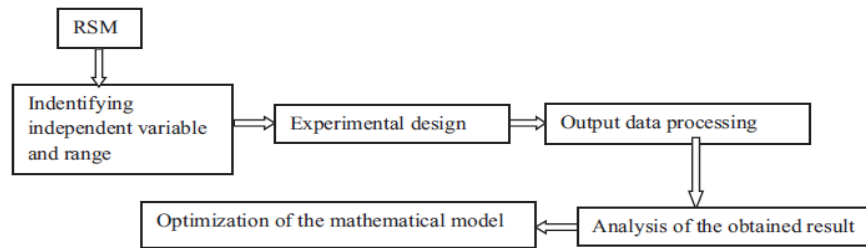


Figure 1: RSM Methodology

RESULT AND DISCUSSION

Central Composite Environmental Design Result

Table 2 showed the details of the Construction Demolition waste variables used in the experimental plan/framework for the research. The variables were inputted into the Central Composite design module of the Design Expert Software. The CDW variables were inputted into the software to determine the number of experiment (runs) and the different CDW variables mixing composition that was used in concrete production and casting on which the compressive strength and flexural strength test was carried on. The total number of experimental runs carried out was thirty. The variables which included %Recycled concrete aggregate (RCA) replacement of granite at a limit of 50% - 85%, %Recycled fine aggregate (RFA) replacement of sand at a limit of 20%-50% , water-cement ratio of between 0.5 to 0.7 and the RCA aggregate size of between 9.5 – 19. Different variations of these CDW parameters totaling thirty (30) were then produced which was used as a template for the different concrete mixes prepared for cube casting on which compressive and flexural strength test were carried out after 28 days of curing.

The concrete mix designs for all the thirty (30) experimental runs generated by the C.C.D design is presented in Table 3 It also showed the experimental concrete mixing details used for the experiment in kilogram per meter cube. A total of 30cubes and beams was casted. A mixing ratio of 1:1.5:3 was used. Table 4 showed the result of the compressive and flexural strength test carried out on the tested cubes. These data were then used in the RSM and ANN analysis to model these mechanical properties of concrete containing the Construction Demolition Waste (CDW).

Table 2: The CDW variables coded design parameters

Parameters	Code	Unit	Coded Levels Parameters				
			- α	-1	0	1	+ α
% RCA	A	%	35	50	65	80	95
Water-cement ratio	B	%	0.4	0.5	0.6	0.7	0.8
% RFA	C	%	5	20	35	50	65
Aggregate size of RCA	D	mm	4.75	9.5	14.25	19	23.75

Table 3: CDW Concrete Mix Proportion Details

Ru n	RC A	W /C	RF A	RCA size	Cement(kg /m3)	Water(kg /m3)	SP(kg/ m3)	Gran ite	RCA	Sand	RFA
1	0.6 5	0.4	0.3 5	14.25	780	312	15.6	409. 50	760. 50	760.5 0	409. 50
2	0.5	0.7	0.5	9.5	960	672	15.6	720. 00	720. 00	720.0 0	720. 00
3	0.6 5	0.6	0.3 5	14.25	780	468	15.6	409. 50	760. 5	760.5 0	409. 50
4	0.6 5	0.6	0.3 5	14.25	780	468	15.6	409. 50	760. 5	760.5 0	409. 50
5	0.5	0.5	0.5	9.5	600	300	15.6	450. 00	450	450.0 0	450. 00
6	0.6 5	0.6	0.3 5	14.25	780	468	15.6	409. 50	760. 5	760.5 0	409. 50
7	0.5	0.7	0.2	19	960	672	15.6	720. 00	720	1152. 00	288. 00
8	0.5	0.5	0.5	19	600	300	15.6	450. 00	450	450.0 0	450. 00
9	0.8	0.7	0.2	19	960	672	15.6	288. 00	115 2	1152. 00	288. 00
Ru n	RC A	W /C	RF A	RCA size	Cement(kg /m3)	Water(kg /m3)	SP(kg/ m3)	Gran ite	RCA	Sand	RFA
10	0.8	0.5	0.2	9.5	600	300	15.6	180. 00	720	720.0 0	180. 00
11	0.5	0.7	0.5	19	960	672	15.6	720. 00	720	720.0 0	720. 00
12	0.8	0.5	0.5	19	600	300	15.6	180. 00	720	450.0 0	450. 00
13	0.8	0.7	0.5	19	960	672	15.6	288. 00	115 2	720.0 0	720. 00
14	0.5	0.7	0.2	9.5	600	420	15.6	450. 00	450	720.0 0	180. 00
15	0.3 5	0.6	0.3 5	14.25	780	468	15.6	760. 50	409. 5	760.5 0	409. 50
16	0.8	0.7	0.5	9.5	600	420	15.6	180. 00	720	450.0 0	450. 00
17	0.8	0.7	0.2	9.5	600	420	15.6	180. 00	720	720.0 0	180. 00

18	0.6 5	0.6	0.0 5	14.25	780	468	15.6	409. 50	760. 5	1111. 50	58.5 0
19	0.6 5	0.6	0.3 5	14.25	780	468	15.6	409. 50	760. 5	760.5 0	409. 50
20	0.5	0.5	0.2	19	960	480	15.6	720. 00	720	1152. 00	288. 00
21	0.8	0.5	0.5	9.5	960	480	15.6	288. 00	115 2	720.0 0	720. 00
22	0.9 5	0.6	0.3 5	14.25	780	468	15.6	58.5 0	111 1.5	760.5 0	409. 50
23	0.6 5	0.6	0.3 5	14.25	780	468	15.6	409. 50	760. 5	760.5 0	409. 50
24	0.5	0.5	0.2	9.5	960	480	15.6	720. 00	720	1152. 00	288. 00
Ru n	RC A	W /C	RF A	RCA size	Cement(kg /m3)	Water(kg /m3)	SP(kg/ m3)	Gran ite	RCA	Sand	RFA
25	0.6 5	0.6	0.6 5	14.25	780	468	15.6	409. 50	760. 5	409.5 0	760. 50
26	0.8	0.5	0.2	19	600	300	15.6	180. 00	720	720.0 0	180. 00
27	0.6 5	0.6	0.3 5	14.25	780	468	15.6	409. 50	760. 5	760.5 0	409. 50
28	0.6 5	0.6	0.3 5	4.75	780	468	15.6	409. 50	760. 5	760.5 0	409. 50
29	0.6 5	0.6	0.3 5	23.75	780	468	15.6	409. 50	760. 5	760.5 0	409. 50
30	0.6 5	0.8	0.3 5	14.25	780	624	15.6	409. 50	760. 5	760.5 0	409. 50

Table 4: Compression and Flexural result for the CDW Concrete

Run	Independent Variables				Response Variables	
	RCA (%)	Water-cement ratio (%)	RFA (%)	RCA aggregate size	Compressive strength (N/mm ²)	Flexural Strength (Mpa)
1	65	0.4	35	14.25	21.55	7.15
2	50	0.7	50	9.5	19.66	8.33
3	65	0.6	35	14.25	23.88	9.21
4	65	0.6	35	14.25	23.89	7.25
5	50	0.5	50	9.5	36.4	8.17
6	65	0.6	35	14.25	22.55	7.99
7	50	0.7	20	19	30.14	8.22
8	50	0.5	50	19	42	10.76
Run	Independent Variables				Response Variables	
	RCA (%)	Water-cement ratio (%)	RFA (%)	RCA aggregate size	Compressive strength (N/mm ²)	Flexural Strength (Mpa)
9	80	0.7	20	19	21	6.59
10	80	0.5	20	9.5	28.35	8.76
11	50	0.7	50	19	36.4	10.04
12	80	0.5	50	19	40	7.24
13	80	0.7	50	19	32.3	8.72
14	50	0.7	20	9.5	25.23	6.85
15	35	0.6	35	14.25	38.4	10.75
16	80	0.7	50	9.5	29.91	10.11
17	80	0.7	20	9.5	30.17	9.25
18	65	0.6	5	14.25	11.92	6.11
19	65	0.6	35	14.25	25.4	7.66
20	50	0.5	20	19	18.48	6.11
21	80	0.5	50	9.5	32.3	7.73
22	95	0.6	35	14.25	33.2	8.88
23	65	0.6	35	14.25	24.75	7.48
24	50	0.5	20	9.5	22.91	7.54
25	65	0.6	65	14.25	25.94	7.86
26	80	0.5	20	19	27.66	7.89
27	65	0.6	35	14.25	23.99	6.36
28	65	0.6	35	4.75	21.35	6.69
29	65	0.6	35	23.75	24.89	7.54
30	65	0.8	35	14.25	22.04	8.02

RSM Model Formulation Result

The model equation generated from the RSM Model for both compressive and flexural strength is given as:

Compressive Strength = $49.6259 - 1.59309 * \text{RCA} + 32.1146 * \text{Water-cement ratio} + 1.1218 * \text{RFA} - 0.935395 * \text{RFA aggregate size} - 0.27375 * \text{RCA} * \text{Water-cement ratio} - 0.00288056 * \text{RCA} * \text{RFA} - 0.0198158 * \text{RCA} * \text{RCA aggregate size} - 1.73208 * \text{Water-cement ratio} * \text{RFA} + 0.880263 * \text{Water-cement ratio} * \text{RCA aggregate size} + 0.0366754 * \text{RFA} * \text{RCA aggregate size} + 0.0164671 * \text{RCA}^2 + 20.3854 * \text{Water-cement ratio}^2 - 0.00227731 * \text{RFA}^2 + 0.0237165 * \text{RCA aggregate size}^2$

Flexural Strength = $12.6204 - 0.222579 * \% \text{RCA} - 11.7437 * \text{Water-cement ratio} + 0.0580046 * \text{RFA} + 0.519693 * \text{RCA aggregate size} + 0.09125 * \text{RCA} * \text{Water-cement ratio} - 0.00201944 * \text{RCA} * \text{RFA} - 0.00846491 * \text{RCA} * \text{RCA aggregate size} + 0.112083 * \text{Water-cement ratio} * \text{RFA} - 0.101316 * \text{Water-cement ratio} * \text{RCA aggregate size} + 0.00527193 * \text{RFA} * \text{RCA aggregate size} + 0.00268843 * \text{RCA}^2 + 4.73958 * \text{Water-cement ratio}^2 - 0.000456019 * \text{RFA}^2 - 0.00310711 * \text{RCA aggregate size}^2$

RSM Model Significance and Performance Result

Analysis of Variance (ANOVA) is used to test the significance and usability of the model. Table 5 and 6 showed the ANOVA result of the response variables which are the compressive and the flexural strength respectively.

Table 5: ANOVA Result for Compressive Model

Source	Sum of Squares	df	Mean Square	F-value	P-value	Comment
Model	1089.57	14	77.83	3.99	0.0038	SD = 4.41
A-RCA	0.0002	1	0.0002	0.0000	0.0175	Mean = 27.22
B-Water-cement ratio	20.74	1	20.74	1.06	0.0186	R ² = 0.7885
C-RFA	360.92	1	360.92	18.52	0.0006	Adjusted R ² = 0.6876
D-RCA aggregate size	37.83	1	37.83	1.94	0.1839	AP = 8.4061
AB	2.70	1	2.70	0.1384	0.0150	
AC	6.72	1	6.72	0.3449	0.0658	
AD	31.89	1	31.89	1.64	0.0202	
BC	108.00	1	108.00	5.54	0.0326	
BD	2.80	1	2.80	0.1435	0.0710	
CD	109.25	1	109.25	5.61	0.0318	
A ²	376.53	1	376.53	19.32	0.0005	
B ²	1.14	1	1.14	0.0585	0.8122	
C ²	7.20	1	7.20	0.3695	0.0224	
D ²	7.85	1	7.85	0.4030	0.5235	
Residual	292.31	15	19.49			
Lack of Fit	287.70	10	28.77	6.71	0.0007	

Table 6:ANOVA Result for Flexibility Model

Source	Sum of Squares	df	Mean Square	F-value	P-value	Comment
Model	33.02	14	2.36	2.63	0.0365	SD = 0.9465
A-RCA	0.5017	1	0.5017	0.5600	0.0258	Mean = 8.04
B-Water-cement ratio	1.33	1	1.33	1.48	0.2419	R² = 0.8308
C-RFA	7.47	1	7.47	8.34	0.0113	Adjusted R² = 0.7408
D-RCA aggregate size	0.0117	1	0.0117	0.0131	0.2105	AP = 6.5473
AB	0.2998	1	0.2998	0.3346	0.0016	
AC	3.30	1	3.30	3.69	0.0341	
AD	5.82	1	5.82	6.50	0.0223	
BC	0.4523	1	0.4523	0.5048	0.0083	
BD	0.0371	1	0.0371	0.0414	0.8416	
CD	2.26	1	2.26	2.52	0.0433	
A²	10.04	1	10.04	11.20	0.0044	
B²	0.0616	1	0.0616	0.0688	0.0967	
C²	0.2888	1	0.2888	0.3223	0.0086	
D²	0.1348	1	0.1348	0.1505	0.0035	
Residual	13.44	15	0.8959			
Lack of Fit	9.04	10	0.9037	1.03	0.5219	Not Significant

From the ANOVA result for the compressive strength, the model is generally statistically significant from the Student's t-test ($p < 0.05$). However, for the individual coefficients that make up the model, all linear terms were statistically significant except for the coefficient (RCA aggregate size). The quadratic terms of the model are also statistically significant except for the B^2 and the D^2 . In order to improve the performance of the model and make it significant and useable, FI terms were introduced into the model. The introduction of both significant and insignificant FI terms improve the p-value of the model and the coefficient of determination (R^2). The aim was to ensure that the R^2 value is greater than 0.7, as the closer this value is to one/unity, the better the predicting ability of the model. AP means adequate precision, and it compares the range of values predicted at design point with the average prediction error. Lastly, the model had an insignificant LOF (Lack of fit) value of 6.71 which specified good fit of our developed model.

From the ANOVA result for the flexural strength, the model is generally statistically significant from the Student's t-test ($p < 0.05$). However, for the individual coefficients that make up the model, all linear terms were statistically significant except for the coefficient B(Water-cement ratio) & D (RCA aggregate size). The quadratic terms of the model are also statistically significant except for the B^2 . In order to improve the performance of the model and make it significant and useable, FI terms were introduced into the model. The introduction of both significant and insignificant FI terms improve the p-value of the model and the coefficient of

determination (R^2).. Lastly, the model had an insignificant LOF (Lack of fit) value of 1.03 which specified good fit of our developed model.

Normal Probability Distribution Plot

Data were analyzed to check the normality of residuals as well as actual versus predicted plots for the response variables (Compressive and Flexural strength). Figure 1 and figure 2 showed the normal probability distribution plot for compressive and flexural strength respectively. Both results showed that all the plotted points fell close to the fitted distribution line with the compressive strength closer to the fitted line than that of the flexural strength.

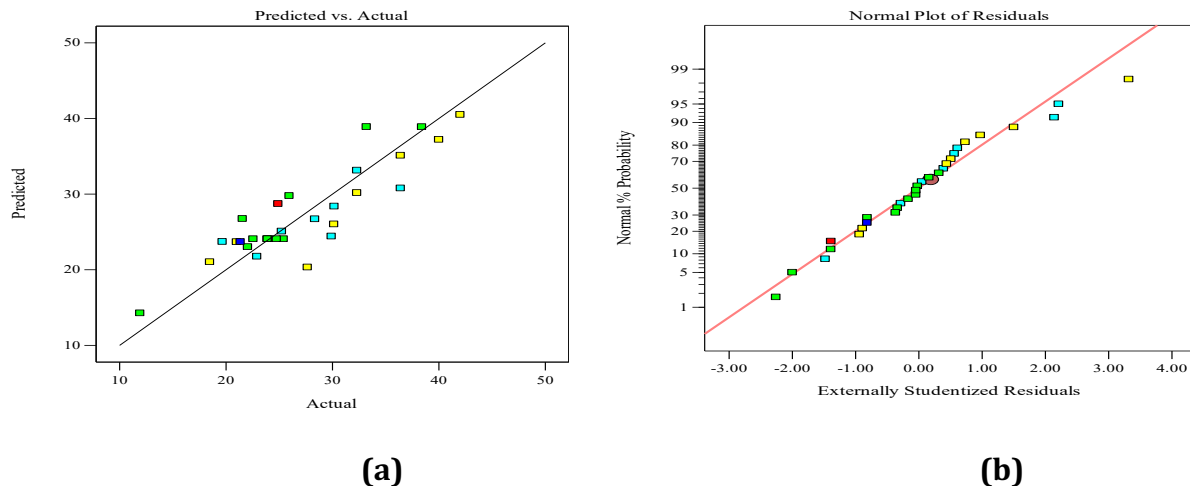


Figure 1: Normal Probability distribution plot for Compressive Strength (a)Predicted/ Actual (b) Residuals

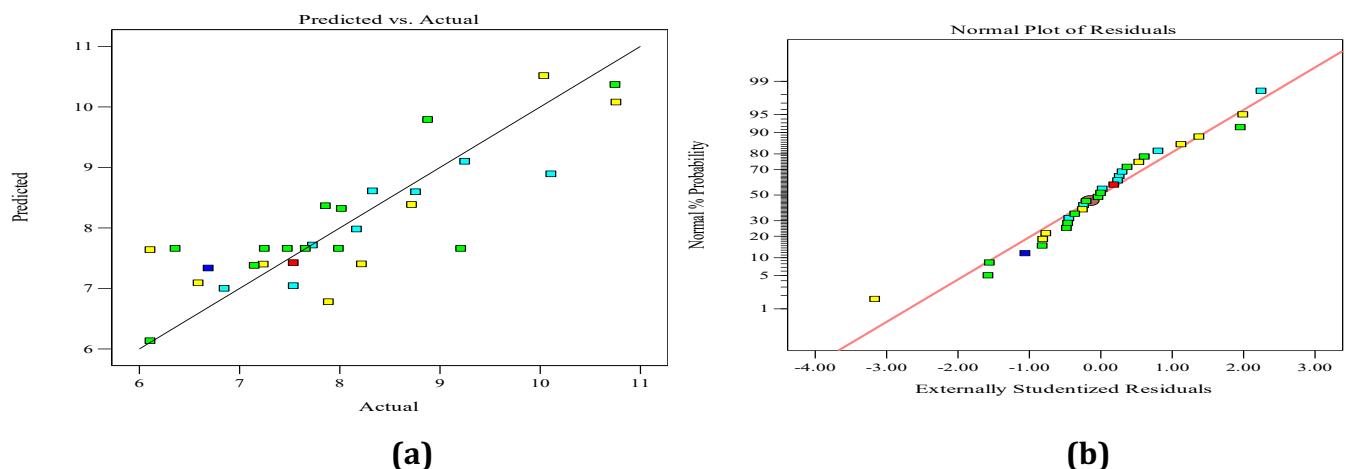


Figure 2: Normal Probability distribution plot for Flexural Strength (a)Predicted/ Actual (b) Residuals

Perturbation Plots of the derived model

Perturbation plots in RSM design revealed significant parameters by displaying changes in response of each factor as each factor moves from the reference point, which is the zero coded level of each factor, with all other factors held constant at the reference value.

From the perturbation plot for compressive strength in figure 3, all the factors displayed a slight influence on the compressive strength. Factor A(%RCA) and factor C (%RFA) showed the most significant influence on the compressive strength of CDW concrete with A(%RCA) showing the highest of the two factors. However, the behavior of changes in %RCA which is the replacement of granite with RCA on the compressive strength is quadratic in nature while that of the % RFA which is the replacement of fine sand with tiles is linear in nature. This means that as the % of the RFA increases, the compressive strength also increases while as the % RFA increases, the compressive strength decreases until a minimal point is reached, then further increase continuously increases the compressive strength of the CDW concrete.

From the perturbation plot for flexural strength, all the factors displayed a slight influence on the flexural strength. Factor A(%RCA) showed the most significant influence on the flexural strength of CDW concrete. The changes in %RCA which is the replacement of granite with RCA is quadratic in nature. This means that as the % of the RFA decreases, the flexural strength decreases gradually until a minimal point is reached, then further increase continuously increases the flexural strength of the CDW concrete.

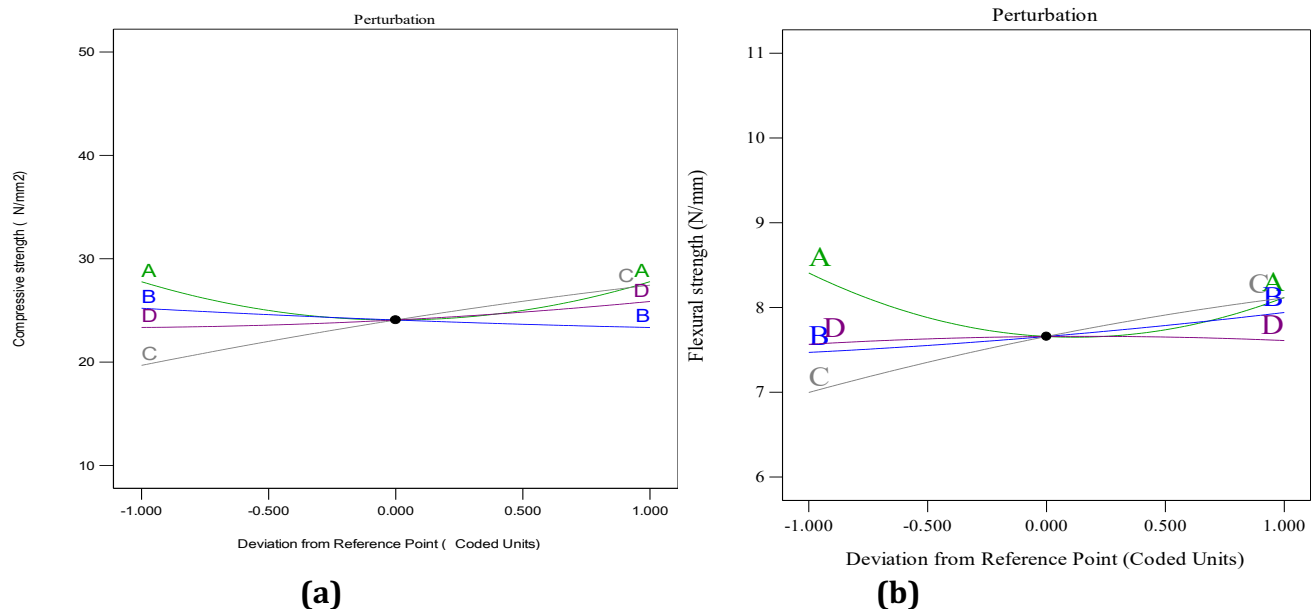


Figure 3: Perturbation graph of effects of individual factors on response (a) Compressive (b) Flexural

Contour Plot of the Response Variables (Compressive Strength)

An assessment of the interactive relationship between the factors variables and the compressive strength was done using contour and 3D plots of RSM. These plots are presented in Figure 4a to f. It displayed the contour plots of the factors/independent variables as function of two factors/independent variables while the third and fourth factors/independent variables is held constant.

The observations made from the contours and 3D plots in figure 4a, decrease in the B (water-cement ratio) and increase in the A(%RCA) will decrease the compressive strength of CDW concrete. Figure 4b showed that increase in B (Water-cement ratio) and C(%RFA) increases the compressive strength of CDW concrete. Figure 4c showed that increase in A(%RFA) and

C(%RCA) increased the compressive strength of CDW concrete. Figure 4d showed that increase in D (RCA aggregate size) and increase in A(RCA) will increase the compressive strength of CDW concrete. Figure 4e showed that increase in D (RCA aggregate size) and decrease in B (Water-cement ratio) will increase the compressive strength of CDW concrete. Figure 4f showed that decrease in D (RCA aggregate size) and (%RFA) will decrease the compressive strength of CDW concrete.

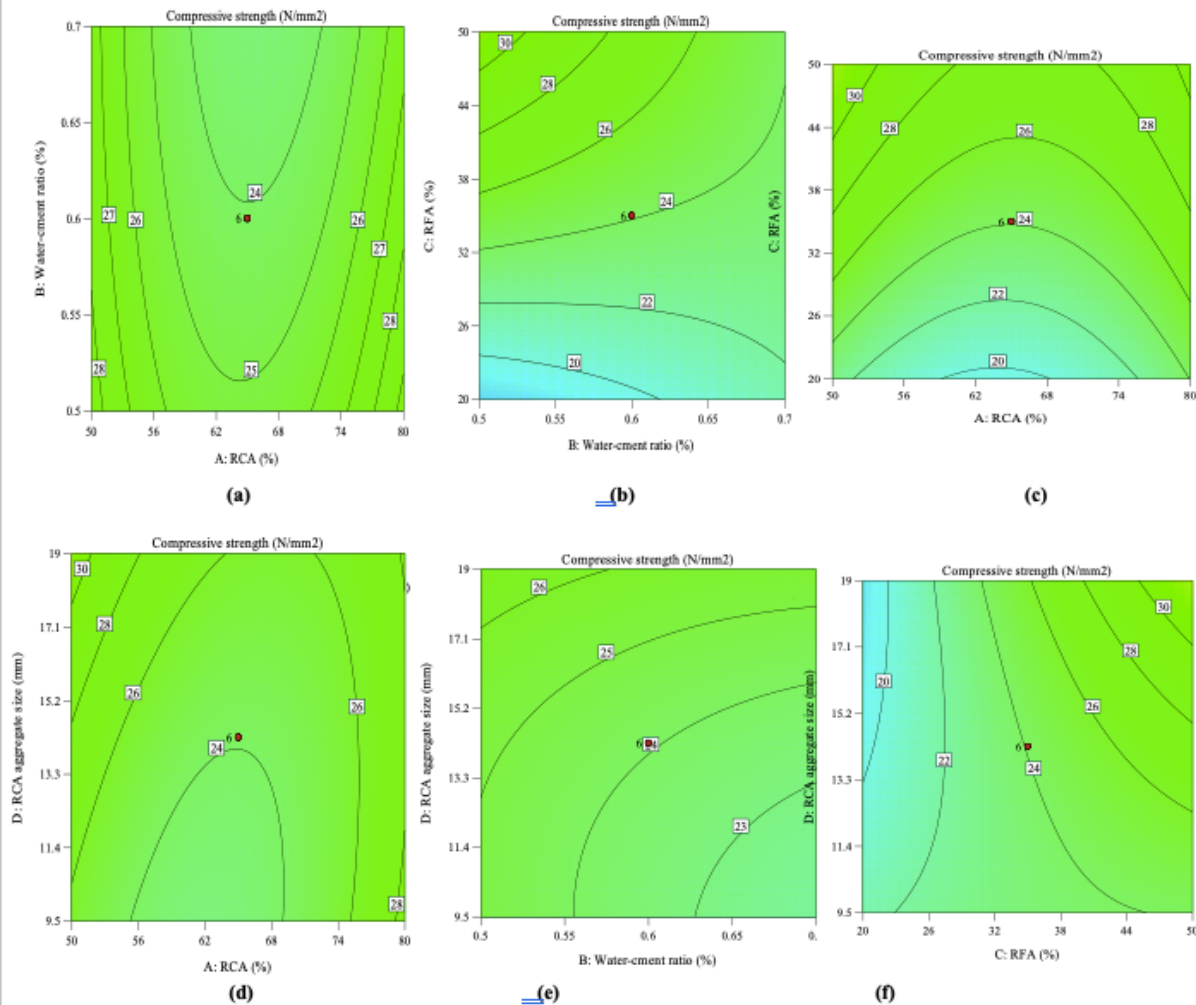


Figure 4: Contour Plots for compressive strength (a) AB- RCA & Water-cement ratio (b) BC- Water-cement ratio & RFA (c) CA- RFA & RCA (d) AD- RCA & RCA aggregate size (e) BD- RCA aggregate size & Water-cement ratio (f) CD- RFA & RCA aggregate size

Contour Plot of the Response Variables (Flexural Strength)

An assessment of the interactive relationship between the factors variables and the flexural strength was done using contour and 3D plots of RSM. These plots are presented in Figure 5. It displayed the contour plots of the factors/independent variables as function of two factors/independent variables while the third and fourth factors/independent variables is held constant.

The observations made from the contours and 3D plots in figure 5a, increase in the B (water-cement ratio) and increase in the A(%RCA) will increase the flexural strength of CDW concrete.

Figure 5b showed that increase in B (Water-cement ratio) and decrease in C(%RFA) decreases the flexural strength of CDW concrete. Figure 5c showed that increase in A(%RFA) and C(%RCA) increased the flexural strength of CDW concrete. Figure 5d showed no clear interaction between D (RCA aggregate size) and A(RCA) on the flexural strength of CDW concrete. Figure 5e showed that increase in D (RCA aggregate size) and decrease in B (Water-cement ratio) will increase the flexural strength of CDW concrete. Figure 6f showed no clear interaction between D (RCA aggregate size) and A(%RFA) on the flexural strength of CDW concrete.

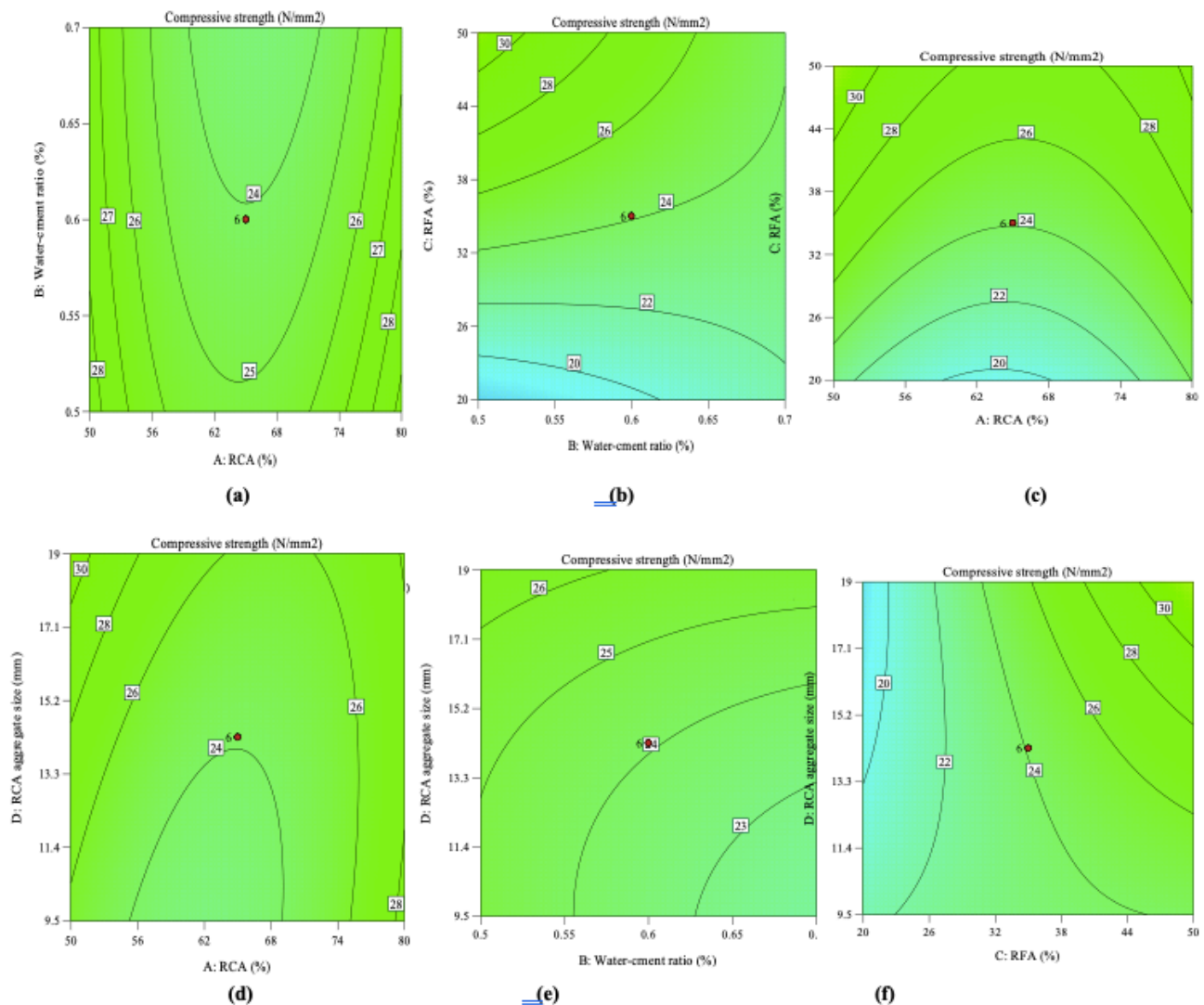


Figure 5: Contour Plots for compressive strength (a) AB- RCA & Water-cement ratio (b) BC- Water-cement ratio & RFA (c) CA- RFA & RCA (d) DB- RCA aggregate size & Water cement ratio (e) DA- RCA aggregate size & RCA (f) DA- RFA aggregate size & Water cement ratio

CONCLUSIONS

- From the perturbation plot, all the factors displayed a slight influence on the compressive strength. But Factor A(%RCA) and factor C (%RFA) showed the most

significant influence on the compressive strength of CDW concrete with A(%RCA) showing the highest of the two factors.

- From the perturbation plot for flexural strength, Factor A(%RCA) showed the most significant influence on the flexural strength of CDW concrete.
- Decrease in the B (water-cement ratio) and increase in the A(%RCA) will decrease the compressive strength of CDW concrete if the other two factors remain constant
- Increase in B (Water-cement ratio) and C(%RFA) increases the compressive strength of CDW concrete if the other two factors remain constant
- Increase in A(%RFA) and C(%RCA) increased the compressive strength of CDW concrete if the other two factors remain constant
- Increase in the B (water-cement ratio) and increase in the A(%RCA) will increase the flexural strength of CDW concrete if the other two factors remain constant
- Increase in B (Water-cement ratio) and decrease in C(%RFA) decreases the flexural strength of CDW concrete if the other two factors remain constant
- Increase in A(%RFA) and C(%RCA) increased the flexural strength of CDW concrete if the other two factors remain constant

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