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Predicting and Optimizing the Impacts of Chipped Rubber Tire (CRT) On Concrete Using Response Surface Methodology

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Abstract
The recycling of waste tire rubber in concrete can reduce reliance on raw materials, contributing to the economic efficiency and sustainable progress of the construction sector. This study aimed to utilise Chipped Rubber Tire (CRT) as a partial substitute for coarse aggregate in the production of rubberised concrete. Various levels of chipped rubber tire replacement, ranging from 0 % to 20 % in increments of 5 %, were used to replace the volume of coarse aggregate; cubes were produced and cured for periods of 7, 14, and 28 days in fresh water. The findings revealed that the slump of the fresh concrete and water absorption increased as the percentage of CRT content increased. The compressive strength and the density of the concrete containing CRT content decreased as the proportion of CRT content rose. Nonetheless, the compressive strength of the CRT-concrete improved with longer curing periods. The generated models displayed excellent correlation, predictability, and alignment between the predicted and actual values, evidenced by high R^2 values and low P values, confirming their suitability for predictions. It was noted that the percentage error between the predicted and actual values for all responses was less than 5 %, suggesting a strong agreement between predicted and actual results under optimal mixing conditions. The optimal composition of 6.42797 % CRT and a curing age of 27.997 % yielded the highest compressive strength of 21.432 MPa, water absorption of 1.9667 % and a density of 2075.67 kg/m^3 respectively.

Keywords: Chipped Rubber Tire, Concrete, Density, Response Surface Methodology and Water Absorption

1. Introduction

The construction sector recognises its substantial role in greenhouse gas emissions, highlighting the urgent need for sustainable material production. Concerns about producing these sustainable materials have emerged over time as the industry became aware of its ecological impact. To satisfy the requirements of a growing population and urban expansion, particularly in developing countries, concrete continues to be the most widely used and favoured material in civil engineering (He *et al*., 2020). Utilising recycled scrap tires in the construction sector helps to mitigate environmental pollution and contributes to the cost-effective design of buildings and infrastructure. Rubberised concrete is particularly effective for use in Partition Walls due to its lightweight nature, making it apt for areas with minimal dead and live loads, resulting in savings on formwork and support in foundations and reinforcement. It is clear that more research is necessary to fully comprehend the behaviour of rubber within concrete under various conditions. For instance, heat poses a risk to structures and buildings in civil engineering, as it can reduce their strength. Therefore, investigating the effects of heat on rubberised concrete at different temperatures is crucial. As reported by Foraminifera Market Research (2016), Nigeria discards thousands of tons of used plastic and rubber products, including worn-out tires, each year.

The significant quantities of municipal solid waste can lead to severe environmental pollution. Using materials like crumb and chipped rubber can help foster a sustainable environment by decreasing the amount of waste disposed of improperly, which, if not managed correctly, can harm our air, water, and land, ultimately impacting our health.

Moreover, the research on the use of response surface methodology (RSM) in assessing the effects of waste tire (Chipped Tire Rubber) in concrete as coarse replacement is very scanty. Thus, this study focuses on utilising RSM to assess the effects of CRT content in the production of lightweight concrete. Bheel *et al*., (2025) utilised RSM modelling and optimisation, compared the effects of CR replacement for sand and PVA fibre by volume fraction. It was observed that the optimum compressive, tensile and flexural strengths obtained are 49 MPa, 4.31 MPa and 5.88 MPa at 10 % of sand replaced with CR and 1.5 % of PVA fibre at 28 days, respectively. Mezidi *et al*., (2025) reported that at a 5 % replacement rate, substantial reductions in compressive and tensile strength were observed at 28 days, amounting to 66.15 % and 48.72 % respectively. It was concluded that the crumb rubber can be used as a sustainable construction material. A study by Hisbani *et al*., (2025) gives a baseline for the effect of CR on normal concrete to provide a pathway for future studies on rubber concrete to reduce limitations on the use of CR in concrete. Garba *et al.,* (2024a) used response surface methodology (RSM) to predict and optimize the strengths and durability of self-compacting concrete admixed with Styrofoam. In another study conducted by Garba *et al*., (2024c), RSM was used for optimizing the cement kiln dust incorporated and developing a predictive model for the strength and durability of self-compacting concrete.

Chauhan and Sood (2017) conducted a study on rubber-modified concrete as a sustainable approach for infrastructure development to assess mechanical properties (the introduction of rubber tire particles into the concrete mix results in reduced compressive strength and split tensile strength). The rate of strength reduction intensifies with an increase in rubber tire content within the concrete mixture. The toughness and impact resistance of rubber-tire-modified concrete surpass those of conventional concrete. Kilani *et al*., (2025) reported that CR-concrete is poor in compressive, tensile and flexural strengths' enhancement; therefore, the use of CR in concrete should be limited to 0-5 %. Kantasiri *et al*., (2017) explored rubberised concrete as a lightweight option containing rubber subjected to high temperatures. They prepared four different mixtures with 3 %, 5 %, 10 %, and 15 % rubber as a coarse aggregate. After exposing the samples to temperatures of 800℃, they observed a weight loss as temperatures rose from 373℃ to 400℃, leading to reduced density. Additionally, they noted a significant drop in compressive strength (from 12 MPa to 3 MPa) for samples with higher rubber content 15 %. Research by Mohamed *et al*., (2025) indicated that the addition of crumb rubber content led to a decrease in compressive strength and ultimate load capacity, with reductions of up to 85.5 % in one-layer slabs and 50 % in two-layer slabs compared to the control samples. It was reported by Kevin *et al*., (2025) that compressive strength increased by 24.7% and 11.8% for 10 % replacement, and 27 % and 21.7 % for 20 % replacement, with CCOH and CCOHLX treatments, respectively. It was also reported that 25.9 % and 36.7 % improvement in resistance to chloride penetration and reduced abrasion mass loss by 15.5 % and 23.3 % for CCOH-M and CCOHLX-M mixes.

Mohammed *et al*., (2021) found that 20 % of crumb rubber (CR) can be used to replace coarse aggregate in asphalt concrete and is suitable for wearing course, having satisfied Nigerian General Specifications for Roads and Bridges (NGSRB, 1990) for criteria of Stability and flow. Hence, the optimum percentage of crumb rubber (CR) to be used as coarse aggregate in asphalt concrete mix for wearing course is 20 %. Faraz *et al*., (2015) reported that the inclusion of rubber tire initially increased the compressive strength of concrete before resulting in a decline. The average increase in compressive strength for mix 2 was recorded as 4 %, 5.47 %, and 6.34 % after 7, 14, and 28 days, respectively. Conversely, the average decrease in compressive strength for mix 2 was observed as 6 %, 10.16 %, and 7.04 % for the same periods. Li *et al*., (2004) sought to enhance the strength and stiffness of concrete modified with used tires by utilising larger (approximately 25, 50, and 75 mm long and 5 mm thick) rubber fibres treated with NaOH. They concluded that these fibre rubbers perform better than the smaller chipped rubbers (about 25 × 25 mm squares with a thickness of 5 mm); however, the NaOH treatment was ineffective for larger chipped tires.

Khatib and Bayomy (1999) analysed the effects of adding two types of rubber: crumb (very fine to substitute sand) and chipped (ranging in size from 10 to 50 mm to replace gravel). Their findings indicated that the compressive strength of concrete diminished as the rubber content increased, and they concluded that concrete made with chipped rubber exhibited lower strength compared to that made with crumb rubber. Hernandez et al., (2021) investigated the rubber/cement interface using Scanning Electron Microscopy (SEM) and discovered that the addition of crumb rubber enhances damping capacity, bending impact strength, and toughness, making it suitable for lightweight concrete used in non-bearing walls. This study aimed to use Chipped Rubber Tire (CRT) as a partial replacement for coarse aggregate in the production of rubberised concrete.

2.0 Materials and Methods

2.1 Materials

The materials used consist of cement, fine and coarse aggregates, water, and Chipped Rubber Tire (CRT). The Portland limestone cement (PLC) utilised was Dangote cement, which has a specific gravity of 3.16. The coarse aggregate was sourced from a local quarry located in Zaria, Kaduna State. Clean river sand serves as the fine aggregate and was procured from Zaria, Kaduna State. The Chipped Tire Rubber (CRT) is a recycled product made from scrap tires from automobiles and trucks. It was acquired from Zaria, Kaduna State and then cut into small pieces ranging from 10mm to 30mm in size. The drinkable water was supplied by the Civil Engineering Laboratory at ABU.

2.2 Methods

2.2.1 Tests on Physical Properties Constituent Materials

Tests conducted on coarse aggregates and Chipped rubber tire (CRT) were Aggregate impact value (AIV) according to BS 812 PART 111, Aggregate crushing value (ACV) according to BS 812 PART 112, Aggregate specific gravity according to (ASTM, C127), and the setting times, consistency and soundness tests conducted on cement paste were in conformity with BS EN 196-3 (1995).

2.2.2 Tests on Fresh and hardened Concrete

The slump test performed on fresh concrete was carried out in accordance with BS 1881:102 (1983). The compressive strength test for the CRT-concrete was performed according to the specifications of BS 1881-116: (1983). Three cubes were analysed to calculate an average for each curing period—3, 7, and 28 days—following the casting and curing of concrete samples in potable water. Moreover, the CRT-concrete specimens were subjected to the water absorption test in compliance with BS 812, Part 2 (1995).

2.2.1 Design of Experimental (DOE) for Blend Proportions using RSM

The RSM Design of Experiment (DOE) method was used to determine the concrete mix proportions. The CRT percentage was varied from 0 to 20 %, while the curing age was varied from 7 to 28 days. The software generated thirteen (13) possible mixes by generating lower and upper bounds inside the RSM DOE matrix, as illustrated in Table 1. The central point was reproduced five times using the RSM program to improve the experiment's dependability, analysis, and error assessment.

Table 1: Design of Experiment for mixing parameters and their responses

Run	Input Factors		Responses		
	CRT	Curing Age	Compressive Strength (MPa)	Water Absorption (%)	Density (kg/m^3)
1	10	7	10.9	2	2010
2	15	28	17.2	2.24	1820
3	20	14	11.1	2.39	1680
4	0	7	14.7	1.69	2370
5	5	14	17	1.91	2080
6	20	7	7	2.34	1730
7	15	28	17.2	2.24	1820
8	0	14	18.5	1.7	2370
9	5	28	22.7	1.96	2060
10	10	28	19.1	2.02	1990
11	20	28	15.1	2.41	1770
12	5	14	17	1.91	2080
13	15	14	13.2	2.11	1890

3.0 Result and Discussions

3.1 Fine Aggregate, Coarse Aggregate and Chipped Rubber Tire (CRT)

The findings related to the physical characteristics of fine aggregate, coarse aggregate, and chipped rubber tire (CRT) tested are presented in Table 2. It was noted that all the values measured fell within the designated limits/ranges outlined by their corresponding standard codes as indicated in Table 2. This indicates that the materials are appropriate for use in concrete production.

Table 2: Physical Properties of Fine, Coarse and Chipped Rubber Tire (CRT)

Properties	Fine Aggregate	Coarse Aggregate	CRT	Range	Standard
Specific Gravity .	2.78	2.7	2.55	2.5-2.85	BS EN 196-6: 1992
Water Absorption (%)	1.01	0.5	0.66	Max 2	BS 188-122:2011
Aggregate Crushing Value (%)	-	19.05	-	Max 25	BS 812: 110 (1990
Aggregate Impact Value (%)	-	20.72	-	Max 25	BS 812: 110 (1990

In addition, the physical properties of the cement examined in Table 3 met the requirements set by BS 812:2 (1975), making it appropriate for concrete production.

Table 3: Physical Properties of Cement

Properties	Results Obtained	Range	Standard
Specific Gravity	3.16	3.1-3.16	BS 812:2 (1975)
Consistency (%)	30	26-33	BS EN 196-3: 2016
Initial Setting Time (Mins)	142	Min 45	BS EN 196-3: 2016
Final Setting Time (Mins)	214	Max 600	BS EN 196-3: 2016
Soundness (mm)	5	Max 10	BS EN 196-3: 2016

3.2 Workability

The findings from the slump test on fresh concrete with different proportions of CRT, as 0 %, 5 %, 10 %, 15 %, and 20 % are illustrated in Figure 1. It was observed that as the amount of CRT content increased, the workability of the concrete also improved. This enhancement in workability may be attributed to the inclusion of CRT and its higher surface area compared to coarse aggregates (Sulaiman *et al.*, 2022). The results also indicated that the workability of fresh CRT-concrete rose by 83.67 %, 88.24 %, 92 %, and 93.56 % for CRT contents of 5 %, 10 %, 15 %, and 20 %, respectively.

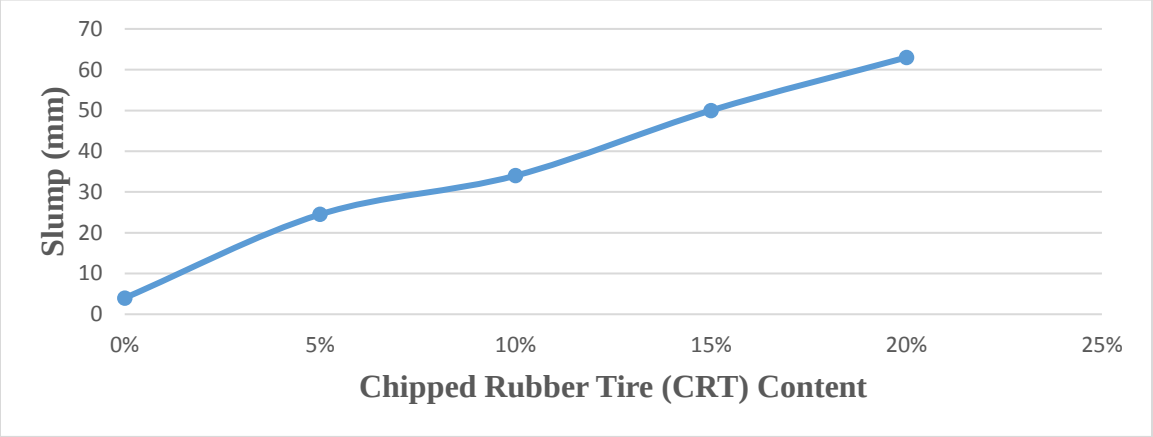


Figure 1: Relationship between Slump and Percentage Replacement of CRT Content

3.3 Compressive Strength of Concrete

The outcomes of the CRT-concrete strength evaluation are illustrated in Figure 2. It was observed that as the percentage of CRT content increases, the strength of CRT-concrete diminishes. Specifically, the strength decreased by 6.19 %, 20.66 %, 28.93 %, and 37.6 % when the CRT content was 5 %, 10 %, 15 %, and 20 %, respectively, after 28 days of curing. At 0 % CRT content and after 28 days of curing, the strength peaked at 24.2 N/mm^2, whereas the lowest value at 20 % CRT after the same curing period in fresh potable water was 15.1 N/mm^2. However, the concrete with 5 % CRT content surpassed the required design strength of 20 N/mm^2 after 28 days of curing. Looking from another perspective, CRT-concrete tends to grow stronger with prolonged curing time. Nevertheless, the reduction in concrete strength correlating with the increase in CRT percentage might be attributed to the lighter weight of CRT in comparison to conventional coarse aggregate. Additionally, the decline in strength could be linked to the macro-

porosity in concrete incorporating rubber (CRT), likely due to a rise in voids associated with the increased rubber (CRT) content (Sulaiman *et al*., 2022).

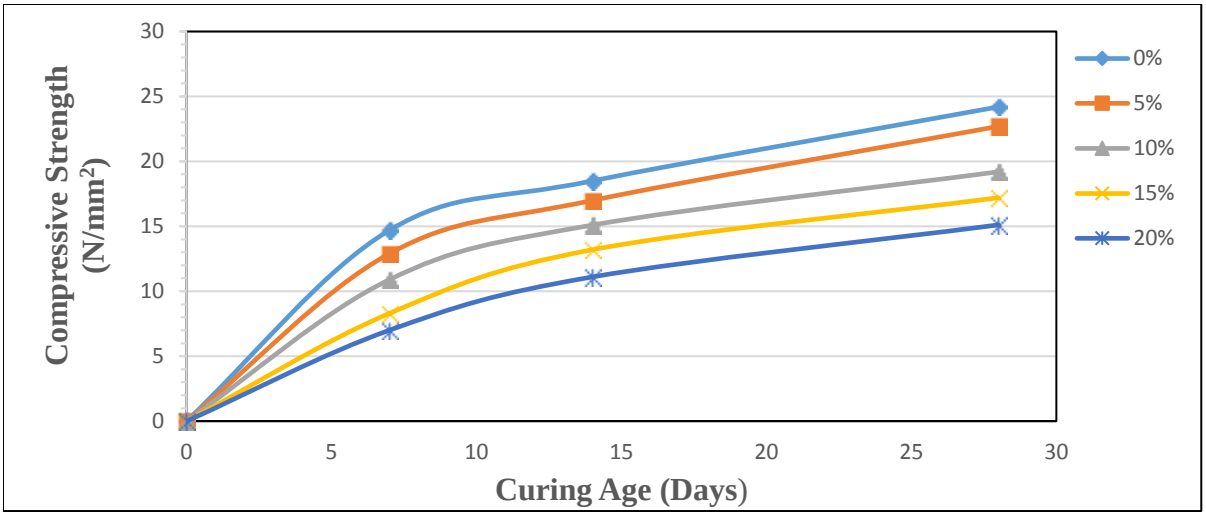


Figure 2: Compressive Strength against Curing Age (Days)

3.4 Density of Concrete

The density of concrete that incorporates CRT content is shown in Figure 3. It was noted that as the CRT content increases, the density of the concrete decreases at every curing age. This reduction in density may be attributed to the inclusion of CRT material and its lower specific gravity compared to conventional aggregates. Furthermore, the decrease in density can be linked to the flocculation of the rubber (CRT) material, which generates larger voids, resulting in increased porosity, along with the lower density of rubber (CRT) relative to coarse aggregate (Sulaiman *et al*., 2022). It indicates that concrete made with CRT contents has a lower density than standard concrete. This suggests that CRT can be utilized to create lightweight concrete. A similar pattern was observed by Sulaiman *et al*., (2020).

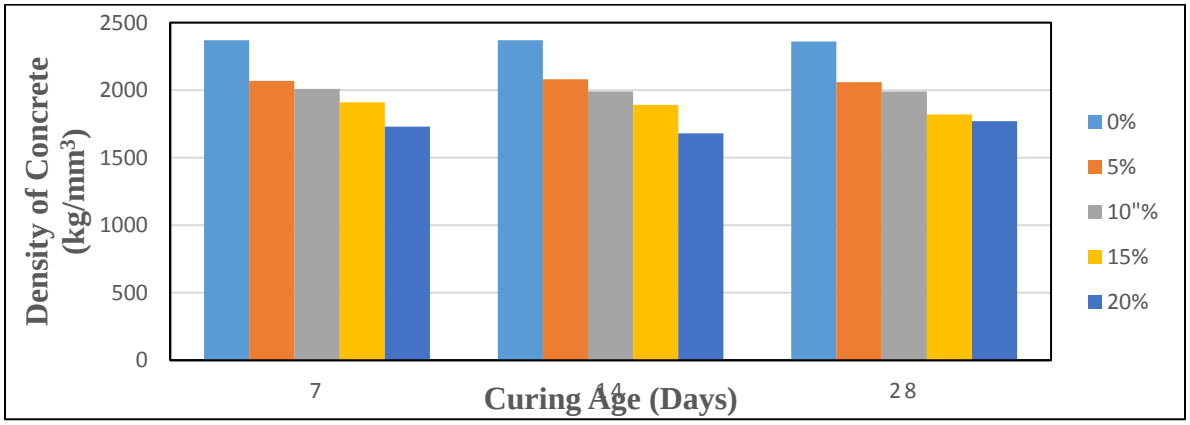


Figure 3: Density against Curing Age

3.5 Water Absorption of Concrete

Figure 4 presents the results of the water absorption test conducted on CRT-concrete. It was observed that as the level of CRT content increased, the amount of water absorbed by the concrete increased. However, after 28 days of curing, the absorption rates were observed to rise by 14.6 %, 18.13 %, 30.9 %, and 40.94 % for CRT content replacement levels of 5 %, 10 %, 15 %, and 20 %, respectively. A similar trend was noted at 14 days of curing, with increases of 12.35 %, 18.24 %, 24.12 %, and 40.56 % observed at 5 %, 10 %, 15 %, and 20 % replacement levels of CRT content, respectively. This indicates that a higher addition of CRT content leads to an increase in water absorption of the produced concrete. Ultimately, the incorporation of CRT content could be attributed to the rise in water absorption.

The increase in water absorption might result from a greater percentage of voids within the mix due to the higher rubber content and the porous characteristics of CRT (Sulaiman *et al.*, 2022). It might be due to enhanced porosity caused by the presence of CRT (Hisbani *et al.*, (2025). Therefore, as explained by Mohammed *et al*., (2018), the concrete becomes increasingly permeable to water. Similar results or patterns were reported by (Hisbani *et al.*, 2025: Kilani *et al*., 2025).

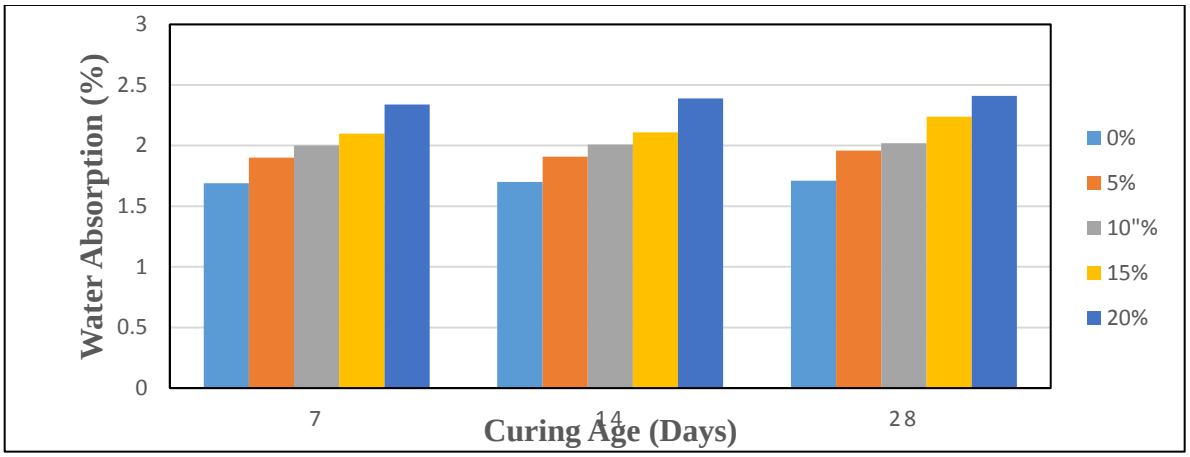


Figure 4: Water Absorption against MK content

3.6 Response Surface Methodology (RSM) for Statistical Model Analysis

Response surface methodology (RSM) was used for statistical model analysis. It was described as a mathematical and statistical method utilised in experimental design to generate interactions between various factors and predict the best available response while optimising the related parameter conditions. A quadratic and linear model were used in the regression analysis performed using RSM software. They were generated to access the compressive strength, water absorption and density of the rubberised concrete. However, the models were chosen based on the highest-order polynomial with substantial terms that were unaffected by the program's aliasing. Interestingly, the ANOVA results for the compressive strength, water absorption and density of rubberised concrete were presented in Table 4.

Table 4: ANOVA Model Analysis for the Responses

Parameter	Sum of Squares	Degree of Freedom	Mean Square	F-Value	P-Value	Remarks
Compressive Strength						
Model	202.55	5	40.51	261.13	<0.0001	Significant
A-CRT	83.97	1	83.97	541.27	<0.0001	
B-Curing Age	109.75	1	109.75	707.46	<0.0001	
AB	0.9946	1	0.9946	6.41	0.0391	
A^2	0.0001	1	0.0001	0.0003	0.9860	Insignificant
B^2	3.41	1	3.41	21.97	0.0022	
Residual	1.09	7	0.1551			
Lack of Fit	1.09	5	0.2172			
Pure Error	0.0000	2	0.0000			
Cor Total	203.63	12				
Final Model	Quadratic					
Water Absorption						
Model	0.6858	2	0.3429	207.55	<0.0001	Significant
A-CRT	0.6091	1	0.6091	368.66	<0.0001	
B-Curing Age	0.0095	1	0.0095	5.72	0.0378	
Residual	0.0165	10	0.0017			
Lack of Fit	0.0165	8	0.0021			
Pure Error	0.0000	2	0.0000			

Cor Total	0.7023	12				
Final Model	Linear					
Density						
Model	5.547E+05	2	2.774E+05	85.55	<0.0001	Significant
A-CRT	5.014E+05	1	5.014E+05	154.66	<0.0001	
B-Curing Age	4661.67	1	4661.67	1.44	0.2581	
Residual	32420.66	10	3242.07			
Lack of Fit	32420.66	8	4052.58			
Pure Error	0.0000	2	0.0000			
Cor Total	5.871E+05	12				
Final Model	Linear					

Additionally, the compressive strength, water absorption and density responses in the investigation showed statistical significance, with a p-value significantly below 0.0001. On the other hand, the F-values were relatively high, recorded as 261.13, 207.55 and 85.55 for the compressive strength, water absorption and density, respectively. The p-values for all the models remained below 0.05, indicating a less than 0.01 per cent possibility of such high F-values occurring by chance. To assess the model's effectiveness, a 95% confidence interval was used (Haruna *et al*., 2020:). Lastly, values of less than 0.05 were obtained for all the models' responses, indicating that all the models generated are significant at a 95 % confidence level (Garba *et al*., 2024b).

3.7 Fit Statistical Analysis

The fit statistic summaries of the compressive strength, water absorption and density models were summarised in Table 5. The coefficients of determination (R^2) are noticeably high, recorded as 0.9947, 0.9765 and 0.9448 for compressive strength, water absorption and density, respectively. These R^2 values almost match the expected R^2 values, with a difference of less than 0.2, indicating a well-balanced model. Moreover, Models' signal-to-noise ratio, suitability and adequacy were evaluated using Adequate Precision (AP). To accept the desirability of a model, the AP value should be greater than 4 (Garba *et al*., 2024b). From the responses obtained, the AP values are greater than 4; this can be used to navigate the design space. Thus, based on the results shown in Table 5, it was concluded that the developed models are not only desirable, but also capable of modelling, optimising, and predicting the compressive strength, water absorption and density of concrete produced with CRT content.

Table 5: Statistical Model Fit Analysis

Fit Statistics	Compressive Strength (MPa)	Water Absorption (%)	Density (kg/mm^3)
R^2	0.9947	0.9765	0.9448
Adjusted R^2	0.9909	0.9718	0.9337
Predicted R^2	0.9672	0.9644	0.9039
Coefficient of Variance (%)	2.55	1.96	2.88
Standard Deviation	0.3939	0.0406	56.94
Mean	15.45	2.07	1974.62
Adequate Precision	55.5591	35.8386	22.7009

Moreover, the response surface methodology models for the compressive strength, water absorption and density were indicted in equations 1, 2 and 3 respectively.

$$\boldsymbol{Fc} = 8.854 - 0.3212*\mathbf{A} + 0.8854*\mathbf{B} - 0.0056*\mathbf{AB} - 0.01165*\mathbf{B}^2 \quad (1)$$

$$\textbf{Water Absorption} = 1.67298 + 0.031578*\mathbf{A} + 0.003249*\mathbf{B} \quad (2)$$

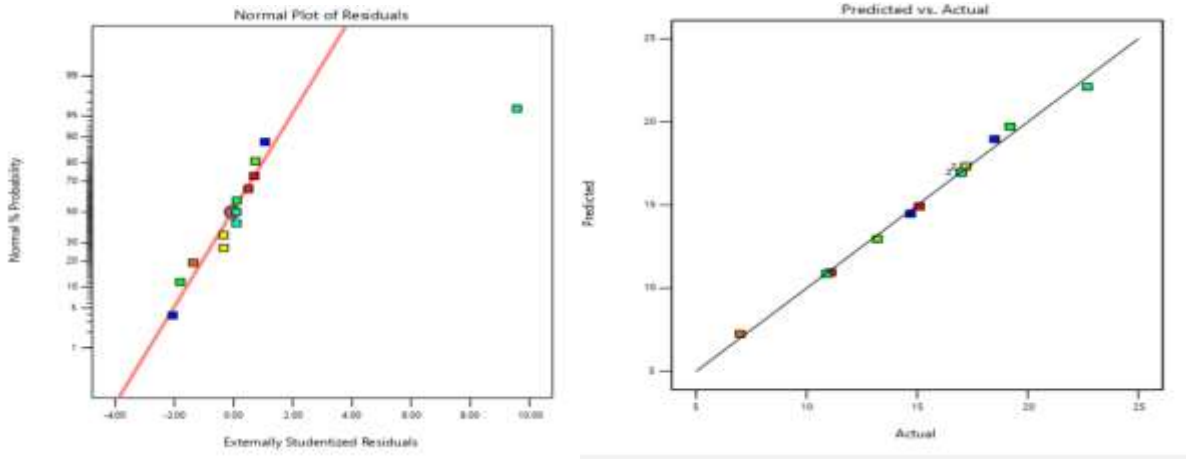
$$\textbf{Density} = 2323.7 - 28.6516*\mathbf{A} - 2.28085*\mathbf{B} \quad (3)$$

Where ***Fc***, **A** and **B** are the compressive strength, CRT content and curing age respectively.

3.8 Model Diagnostic Plots

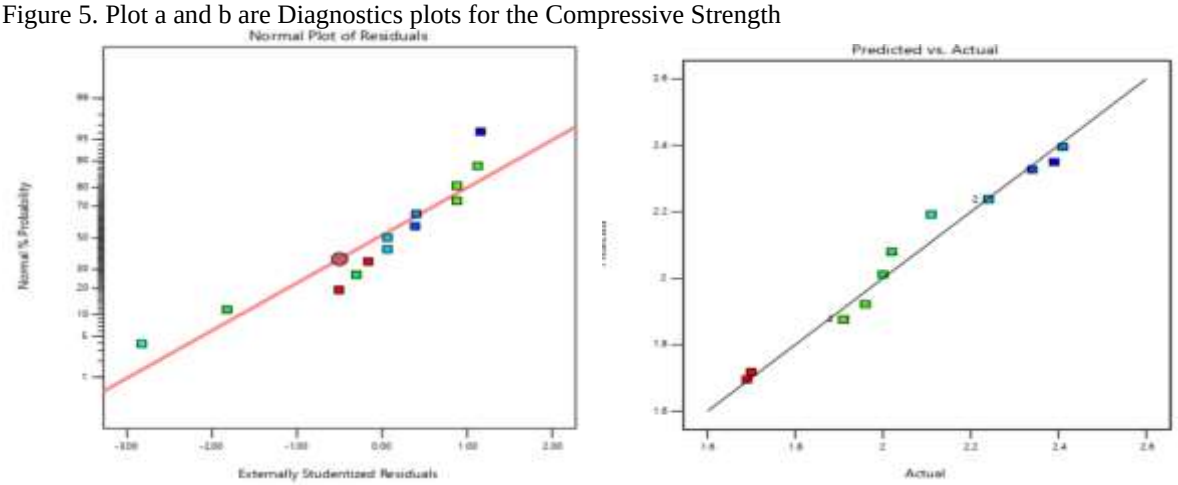
Figure 5 displayed the residue's probability and normal plot for the compressive strength, water absorption and density models. The symmetry of the residual points with a straight line in this figure highlights the accuracy of the regression models (Yaro *et al*., 2021; Muhammad *et al*., 2024). The data points closely follow the equality line, illustrating the models' dependability. Figure 5 also compares the projected values to the actual test findings for compressive strength,

water absorption and density models. The data points were evenly spread along the line, resulting in a uniform design that indicates that the model correctly predicted the responses. This symmetrical alignment emphasises the model's fitness and precision, as it closely matches the actual laboratory data (Jae *et al*., 2024).



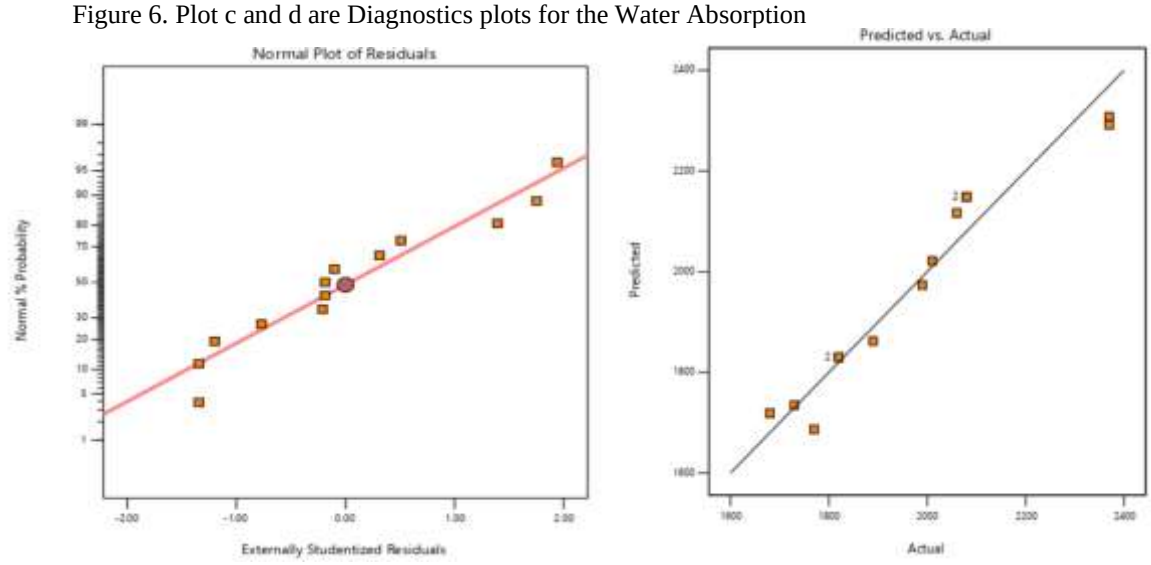
(a) (b)

Figure 5. Plot a and b are Diagnostics plots for the Compressive Strength



(c) (d)

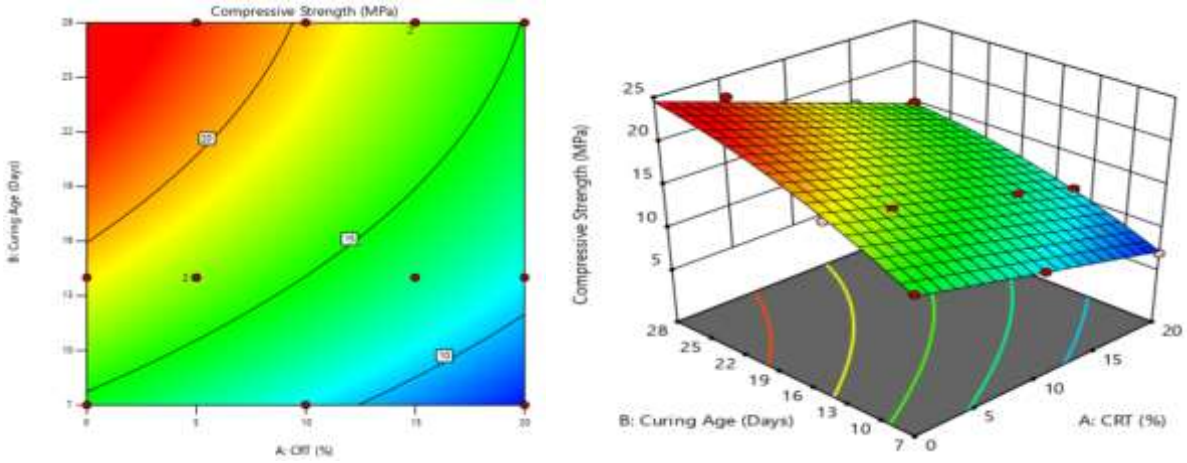
Figure 6. Plot c and d are Diagnostics plots for the Water Absorption



(e) (f)

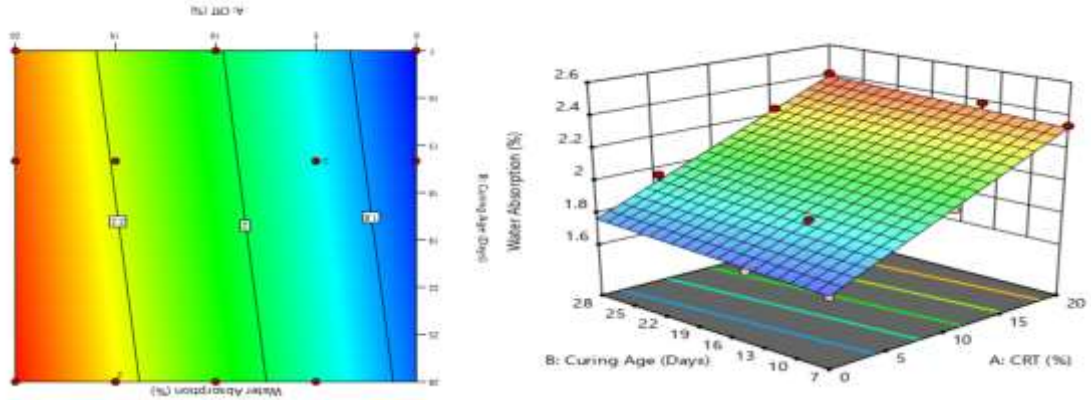
Figure 7: Plot e and f are Diagnostics plots for the Density

In another development, Synergistic Variables' Influences of CRT and curing age on the responses were shown in Figure 8, Figure 9 and Figure 10 for the compressive strength, water absorption and density, respectively. The diagnostic plots of 2D and 3D shown in Figure 8 indicated that the compressive strength of concrete decreased as the addition of CRT content increased, and increased with an increase in the curing age. The water absorption of concrete increased as the addition of CRT and curing age increased, as depicted in Figure 9 of the diagnostic plots of 2D and 3D. Finally, the diagnostic plots of 2D and 3D of density shown in Figure 10 revealed that the density of concrete produced with CRT content decreased as CRT content increased, indicating that CRT can be used to produce a lightweight concrete.



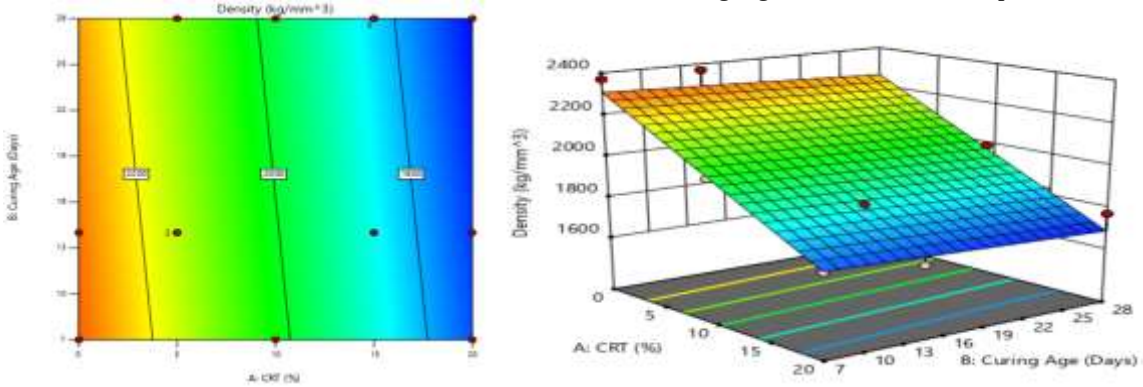
(g) (h)

Figure 8: 2D and 3D Synergetic Influence of CRT and Curing Age on the Compressive Strength



(i) (j)

Figure 9: 2D and 3D Synergetic Influence of CRT and Curing Age on the Water Absorption



(k) (l)

Figure 10: 2D and 3D Synergetic Influence of CRT and Curing Age on the Density

3.9 Models Numerical Optimization

A numerical optimisation approach was used to test models' precision and achieve certain goals. The main purpose is to maximise compressive strength, water absorption and density of concrete while maintaining the required CRT content and curing age levels. The optimisation results indicated the best parameters for optimising and predicting the compressive strength, water absorption and density of concrete. Based on the outcomes, the best input factors to achieve the desired performance were 6.428 % CRT and 28 days of curing. Moreover, the maximum compressive strengths, water absorption and density obtained using these values are 21.43 MPa, 1.967 % and 2075.67 kg/m^3, respectively.

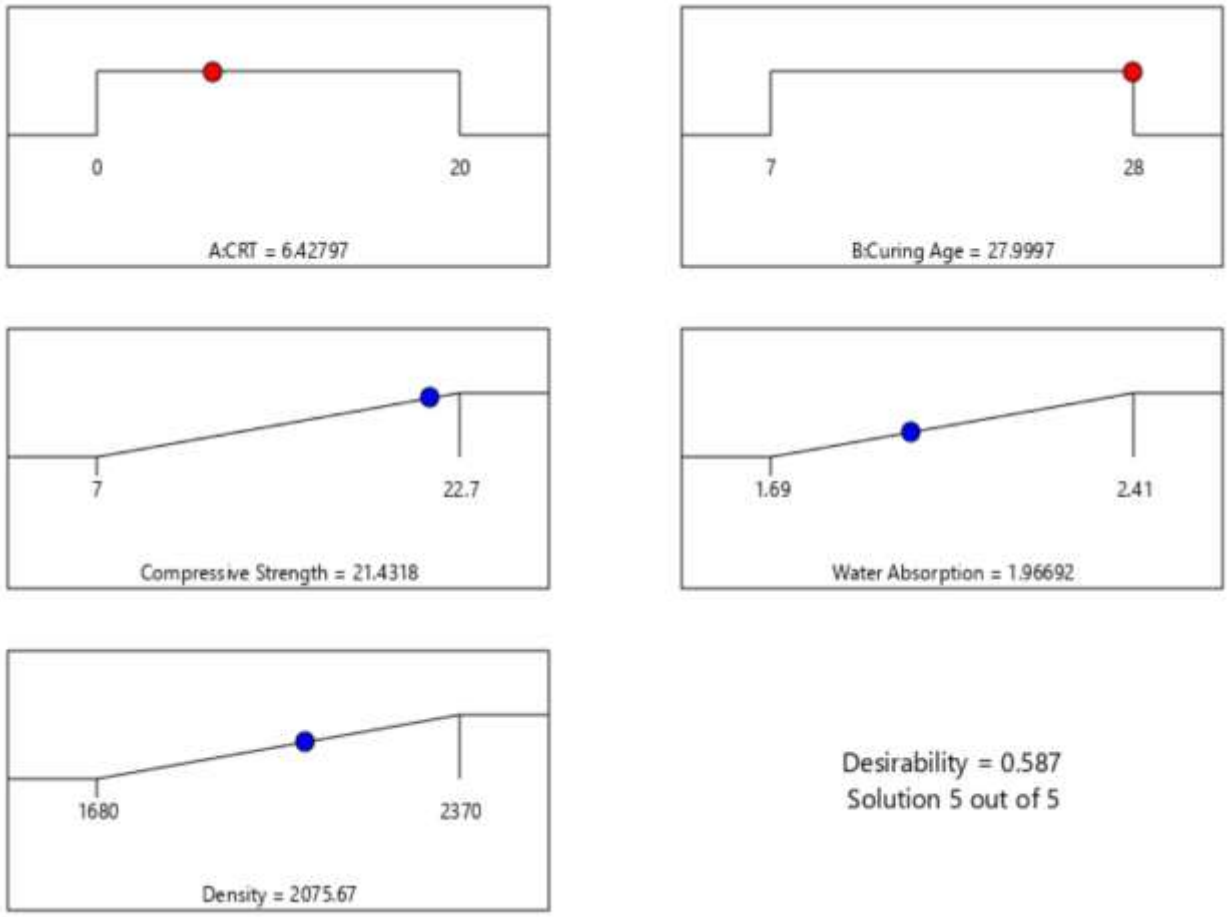


Figure 11: Ramps for RSM Numerical Optimization

3.1 Model Optimization and Verification

Table 6 presents the optimised range of variables and responses. A numerical method was used to establish the multi-objective optimisation in order to obtain the desired values of CRT and curing age for achieving the maximum compressive strength, water absorption and density of concrete within the range. The optimisation was aimed at finding a suitable combination of CRT and curing age and maximising the performance of the concrete. Moreover, the numerical optimisation results for the established models are shown in Table 6. Additionally, five different solutions were obtained from the responses, and the best desired mix combination was selected based on the highest desirability. Thus, 6.428 % and 28 curing age were chosen to give maximum compressive strength, water absorption and density within the range with combined desirability of 0.587 as presented in Figure 11 by ramps for numerical optimisation. An additional set of experiments was conducted to verify the appropriateness of the optimisation results and the response models using the enhanced mix proportion to validate the optimised mix proportion within the design mix. Equation 1 was used to calculate the percentage error between the experimental and predicted values.

$$Error(\%) = \frac{Experimental - Predicted}{Experimental}\ x\ 100 \quad (1)$$

The variation in the percentage error shown in Table 7 was found to be less than 5 % in almost all the responses assessed, which shows that the predicted values for the established models are in agreement with experimental values.

Table 6: Optimization Bench Mark

Variables and Reponses	Purposes	Lower Limits	Upper Limits
CRT	In Range	0	20
Curing Age	In Range	7	28
Compressive Strength	Maximize	7	22.7
Water Absorption	Maximize	1.69	2.41
Density	Maximize	1680	2370

Table 7: Model Verification

Responses	Solution	CRT	Curing Age	Predicted	Experimental	Error
Compressive	1	0	7	14.48	14.7	0.015
Strength	2	15	14	13.80	13.2	-0.045
(MPa)	3	20	28	14.92	15.1	0.012
Water	1	0	7	1.696	1.69	-0.004
Absorption	2	15	14	2.192	2.11	-0.038
(%)	3	20	28	2.396	2.41	0.006
Density	1	0	7	2307.73	2370	0.026
(kg/m^3)	2	15	14	1861.99	1890	0.015
	3	20	28	1686.80	1770	0.047

3.1 Conclusions

Based on the findings presented, the following conclusions were made:

i. The constituent materials used satisfied the standard requirements and are appropriate for use in concrete production.
ii. The addition of CRT content increased the workability (slump) of fresh concrete and water absorption of hardened concrete.
iii. The compressive strength and density of concrete decreased with an increase in the percentage of CRT content.
iv. The generated models displayed excellent correlation, predictability, and alignment between the predicted and actual values, evidenced by R^2 values and low P values, confirming their suitability for predictions.
v. It was noted that the percentage error between the predicted and actual values for all responses was less than 5 %, suggesting a strong agreement between predicted and actual results under optimal mixing conditions.
vi. The optimal composition of 6.42797 % CRT and a curing age of 27.997 days yielded the highest compressive strength of 21.432 MPa, water absorption of 1.9667 % and a density of 2075.6 kg/m^3 respectively.
vii. The use of CRT content for the production of lightweight concrete should not be greater than 5 % for better performance.

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