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Research Paper

Prediction and Optimization of Compressive Strength of Cement Concrete with Box- Behnken Model

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Abstract: In this study a Box-Behnken's Model is employed to optimize the compressive strength of concrete material, by analysing factors like Water, Cement, Sand, Reclaimed Asphalt Pavement (RAP) and Coarse Aggregates. Optimization is performed with Minitab software by target strength and maximization approaches. Analysis of experimental data demonstrates that the target strength approach provides a more realistic fundability profile and reasonable funding probabilities. The statistical analyses i.e. regression analysis and ANOVA are employed to analyse the significance of factors and their interactions on compressive strength. The regression equation from the model gives information about the numerical relationship of the factors to compressive strength. Furthermore, residual analysis and normal probability plots confirm the performance of the model and data distribution. These visualizations are the surface plot, main effects plot and interaction plots that provide more detail on the effect of each factor itself and with other factors between them on compressive strength. According to the study, it is casted that optimizing concrete mix proportions using target strength approach leads to desirable compressive strength around 30 N/mm² with optimal proportions of 24.72% for A, 9.99% for B, 25.26% for C, 33.18% for D and75 % for E and actual values then can be adjusted according to certain constraints in order more realistically find proportioned properties fulfilling this experimental result. These observations will assist in improving the reliability and application of concrete mix design processes, which would help engineers and researchers to deliver optimal properties while designing various mixes.

Keywords: *Compressive strength, Box-Behnken model, Optimization, Concrete mix design, Reclaimed asphalt pavement (RAP).*

Introduction

Growing attention on sustainable practices in the building sector in recent years has driven research into substitute materials for concrete manufacture (Xiao *et al*., 2007). Emerging as a potential candidate for increasing sustainability while preserving or improving concrete performance are reclaimed asphalt pavement aggregates (RAP) (Michael *et al*., 2021). Ensuring structural integrity and durability (Taha et al., 2002) depends on RAP concrete's compressive strength being optimized. Often time-consuming and resource-intensive, traditional approaches for mix design optimization led to the use of advanced modelling techniques such as the response surface methodology (Pradani *et al*., 2023), the Box-Behnken design. Using the Box-Behnken model, this work attempts to forecast and maximize the compressive strength of RAP concrete by methodically changing parameters including RAP substitution percentage, water-cement ratio, and curing time (Tiza *et al*., 2022).The aim of the study is to create empirical models to precisely predict compressive strength under various circumstances, so offering insightful analysis of the viability and efficiency of RAA inclusion in concrete mixes (Yryshkin, 2022).These results can guide practitioners and engineers in maximizing concrete compositions for particular performance criteria, so promoting sustainable building methods and lowering environmental impact and guaranteeing structural integrity (Tavva & Reddy, 2024).

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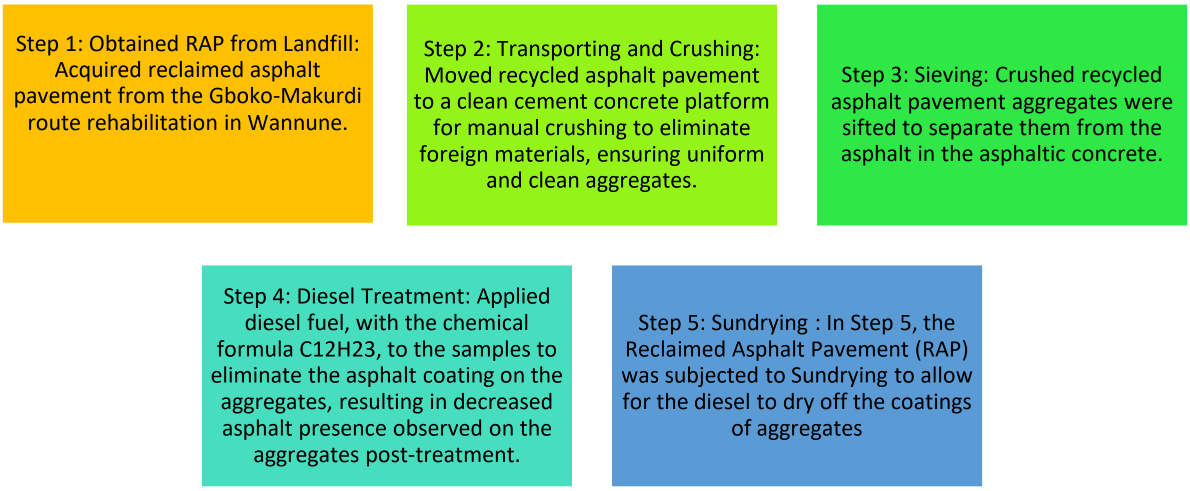
Figure 1. Crumbs of RAP in raw state

Figure 2. RAP in Manual Crushed State

Preparation of RAP

Following the acquisition of reclaimed asphalt pavement (RAP) from the Gboko-Makurdi route rehabilitation in Wannune, the material was transported to a clean cement concrete platform for hand crushing, so guaranteeing the elimination of foreign materials and uniform aggregates. The sieved crushed RAP aggregates then helped to separate them from the asphalt in asphaltic concrete (Tiza, 2022). Applied to the samples to remove the asphalt coating on the aggregates, diesel fuel-characterised by the chemical formula $C_{12}H_{23}$—then clearly reduced asphalt presence. Ultimately, the RAP was sundried to help diesel coatings from the aggregates dry off (Yaro *et al.*, 2023). This sequential process guaranteed the readiness of uniform, clean RAP aggregates for possible use in several building projects. Figures 4a and 4b show the Reclaimed Asphalt Pavement (RAP) after treatment with Diesel, aimed at eradicating asphaltic coatings; Figure 1 shows the crumbs of Reclaimed Asphalt Pavement (RAP) in their raw state; Figure 2 shows RAP after manual crushing; Figure 3. shows the stepwise process followed for obtaining and treating the recycled asphalt aggregates.



Step 1: Obtained RAP from Landfill: Acquired reclaimed asphalt pavement from the Gboko-Makurdi route rehabilitation in Wannune.

Step 2: Transporting and Crushing: Moved recycled asphalt pavement to a clean cement concrete platform for manual crushing to eliminate foreign materials, ensuring uniform and clean aggregates.

Step 3: Sieving: Crushed recycled asphalt pavement aggregates were sifted to separate them from the asphalt in the asphaltic concrete.

Step 4: Diesel Treatment: Applied diesel fuel, with the chemical formula C12H23, to the samples to eliminate the asphalt coating on the aggregates, resulting in decreased asphalt presence observed on the aggregates post-treatment.

Step 5: Sundrying : In Step 5, the Reclaimed Asphalt Pavement (RAP) was subjected to Sundrying to allow for the diesel to dry off the coatings of aggregates

Figure 3: The step-by-step process for obtaining and treating the recycled asphalt aggregates.

Figure 4 a & b: Reclaimed Asphalt Pavement After treating with Diesel to remove asphaltic coatings

Materials and Methods

This study paid close attention to choosing materials that complied with British Standards Institution (BSI) criteria so guaranteeing the quality and effectiveness of concrete manufacture. River sand satisfied BS EN 12620:2013; Dangote 3X Cement (CEMII 42.5R) was chosen in line with BS EN 197-1:2011. Following BS EN 1008:2002, borehole water was obtained in compliance; natural coarse aggregates were selected using BS EN 12620:2013 recommendations. Reclaimed asphalt pavement (RAP) from Wannune also met BS EN 12620:2013 criteria. To reduce asphalt coating before inclusion, the RAP was manually crushed and diesel treated. This rigorous respect to criteria guaranteed the fit and quality of every component for their purposes in the concrete manufacturing process (Tiza, 2023).

Figure 5a. Compression testing machine

Figure 5b. Sample Cubes used for the study

Figure 5c. Sample under compression test

Figure 5d. Sample under Failure

Figure 5a above displays the compression testing machine utilized in this study, while Figure 5b showcases the sample cubes employed for the research. Furthermore, Figure 5c exhibits a sample undergoing compression testing, and Figure 5d illustrates a sample experiencing failure during the test.

Box-Behnken Design

The experimental plan in Minitab utilized the Box-Behnken Design by setting specific low and high levels for each component of the concrete mix (Özgen & Yıldız, 2010). Water and cement were defined as percentages of the total mix weight, with water ranging from 15% to 25% and cement from 7% to 10% of the total mix weight. Sand and Reclaimed Asphalt Pavement (RAP) were designated as percentages of the total aggregate weight, varying between 25% and 45% for sand, and 10% and 50% for RAP. Coarse aggregates were structured with low, medium, and high levels, encompassing 55%, 65%, and 75% of the total aggregate weight, respectively. Minitab's design interface systematically varied these components within their specified ranges, enabling an organized exploration of how alterations in these percentages impact diverse properties of concrete mixes. This structured approach facilitated the optimization of concrete mix designs, allowing researchers to tailor compositions for desired characteristics more effectively (Asadzadeh & Khoshbayan, 2018; Kumar, 2020).

Table 1: Experimental Design for Concrete Mix Proportions Using Box-Behnken Design

Std Order	Run Order	Pt Type	Blocks (%)	Water (%)	Cement (%)	Sand (%)	RAP (%)	Coarse Aggregates (%)
37	1	2	1	20	7	35	10	65
42	2	0	1	20	8.5	35	30	65
29	3	2	1	20	8.5	25	30	55
36	4	2	1	25	8.5	35	30	75
25	5	2	1	15	8.5	35	10	65
7	6	2	1	20	8.5	25	50	65
41	7	0	1	20	8.5	35	30	65
43	8	0	1	20	8.5	35	30	65
6	9	2	1	20	8.5	45	10	65
30	10	2	1	20	8.5	45	30	55
24	11	2	1	20	10	45	30	65
5	12	2	1	20	8.5	25	10	65
20	13	2	1	20	8.5	35	50	75
4	14	2	1	25	10	35	30	65
18	15	2	1	20	8.5	35	50	55
26	16	2	1	25	8.5	35	10	65
1	17	2	1	15	7	35	30	65
17	18	2	1	20	8.5	35	10	55
12	19	2	1	20	10	35	30	75
10	20	2	1	20	10	35	30	55
15	21	2	1	15	8.5	45	30	65
33	22	2	1	15	8.5	35	30	55
8	23	2	1	20	8.5	45	50	65
3	24	2	1	15	10	35	30	65
13	25	2	1	15	8.5	25	30	65
45	26	0	1	20	8.5	35	30	65
44	27	0	1	20	8.5	35	30	65
16	28	2	1	25	8.5	45	30	65
31	29	2	1	20	8.5	25	30	75
46	30	0	1	20	8.5	35	30	65
19	31	2	1	20	8.5	35	10	75
34	32	2	1	25	8.5	35	30	55
28	33	2	1	25	8.5	35	50	65
32	34	2	1	20	8.5	45	30	75
14	35	2	1	25	8.5	25	30	65
40	36	2	1	20	10	35	50	65
22	37	2	1	20	10	25	30	65
27	38	2	1	15	8.5	35	50	65
11	39	2	1	20	7	35	30	75
9	40	2	1	20	7	35	30	55
39	41	2	1	20	7	35	50	65
38	42	2	1	20	10	35	10	65
2	43	2	1	25	7	35	30	65
21	44	2	1	20	7	25	30	65
23	45	2	1	20	7	45	30	65
35	46	2	1	15	8.5	35	30	75

Legend: *Natural Aggregates (NA); Reclaimed Asphalt Pavement (RAP), Fine Aggregates (FA)*

Although Minitab 22 produced the results as shown in Table 1 Experimental Design for Concrete Mix Proportions Using Box-Behnken Design, the outcome had to be proportioned into kilograms(kg) to facilitate the experimental process. Each value for water, cement, sand, RAP, and coarse aggregates had to be proportionally distributed to represent the equivalent of the original result the table above. This proportioning was necessary to ensure that the experimental conditions accurately reflected the intended research parameters, and the result of proportioning is as represented below in table 2.

Table 2. Proportioned values from Box-Behnken Minitab Result for Compressive Strength (Concrete Cubes)

Std Order	Run Order	Pt Type	Blocks (%)	Water (kg)	Cement (kg)	Sand(kg)	RAP (kg)	Coarse Aggregates (kg)
37	1	2	1	1.168	0.41	2.04	0.584	3.79
42	2	0	1	1.01	0.43	1.76	1.51	3.28
29	3	2	1	1.156	0.49	1.44	1.734	3.17
36	4	2	1	1.1525	0.39	1.61	1.383	3.45
25	5	2	1	0.8985	0.51	2.09	0.599	3.89
7	6	2	1	0.95	0.40	1.18	2.375	3.08
41	7	0	1	1.01	0.42	1.76	1.515	3.28
43	8	0	1	1.01	0.42	1.76	1.515	3.28
6	9	2	1	1.078	0.45	2.42	0.539	3.49
30	10	2	1	1.01	0.42	2.27	1.515	2.77
24	11	2	1	0.942	0.47	2.11	1.413	3.06
5	12	2	1	1.246	0.52	1.55	0.62	4.049
20	13	2	1	0.85	0.36	1.48	2.12	3.18
4	14	2	1	1.2125	0.48	1.69	1.45	3.15
18	15	2	1	0.95	0.40	1.66	2.37	2.61
26	16	2	1	1.3925	0.47	1.94	0.55	3.62
1	17	2	1	0.789	0.36	1.84	1.57	3.41
17	18	2	1	1.246	0.52	2.18	0.62	3.42
12	19	2	1	0.942	0.47	1.64	1.41	3.53
10	20	2	1	1.066	0.53	1.86	1.59	2.91
15	21	2	1	0.7335	0.41	2.20	1.46	3.17
33	22	2	1	0.8355	0.47	1.94	1.67	3.06
8	23	2	1	0.85	0.36	1.91	2.12	2.7625
3	24	2	1	0.774	0.51	1.80	1.54	3.35
13	25	2	1	0.83	0.47	1.39	1.67	3.62
45	26	0	1	1.01	0.42	1.76	1.51	3.28
44	27	0	1	1.01	0.42	1.76	1.51	3.28
16	28	2	1	1.1525	0.39	2.07	1.383	2.99
31	29	2	1	1.01	0.42	1.26	1.515	3.78
46	30	0	1	1.01	0.42	1.26	1.515	3.78
19	31	2	1	1.078	0.45	1.88	0.539	4.04
34	32	2	1	1.3075	0.44	1.8305	1.569	2.87
28	33	2	1	1.0875	0.36	1.52	2.175	2.82
32	34	2	1	0.898	0.38	2.02	1.34	3.36
14	35	2	1	1.3075	0.44	1.30	1.56	3.39
40	36	2	1	0.888	0.44	1.55	2.22	2.88
22	37	2	1	1.066	0.53	1.33	1.59	3.46
27	38	2	1	0.6915	0.39	1.61	2.30	2.99
11	39	2	1	0.958	0.33	1.67	1.43	3.59
9	40	2	1	1.088	0.38	1.90	1.63	2.99
39	41	2	1	0.904	0.31	1.58	2.26	2.93
38	42	2	1	1.142	0.57	1.99	0.57	3.70
2	43	2	1	1.235	0.34	1.72	1.48	3.21
21	44	2	1	1.088	0.38	1.36	1.63	3.53
23	45	2	1	0.958	0.33	2.15	1.43	3.11
35	46	2	1	0.735	0.41	1.71	1.47	3.67

Box Behnken's Regression Model for Compressive Strength

In this Box-Behnken design conducted using Minitab 22, a comprehensive investigation was undertaken to understand the effects of various continuous factors, denoted as water, cement, sand, RAP (reclaimed asphalt pavement), and coarse aggregates, on a response variable. Employing the full quadratic model allowed for a thorough exploration of these relationships, considering linear, quadratic, and potential interaction effects. The study maintained a 95% confidence level for all intervals and carefully defined the ranges and constraints for each factor, ensuring practical and meaningful experimentation. Overall, this approach enabled a robust analysis of the factors' impacts on the response variable, offering valuable insights into the underlying dynamics of the system under study (Lam et al., 2023).The details are in table 3 below.

It should be noted that the factors used in this design are in coded forms where A is water, B is Cement, C is Sharp Sand, D is RAP and E is Coarse Aggregates, and this applies throughout this study for the Box Behnken's design.

Table 3. Box Behnken's design for Compressive Strength

Std Order	Run Order	Pt Type	Water (kg)	Cement (kg)	Sand (kg)	RAP (kg)	Coarse Aggregates (kg)	Av. of 3 Lab Response
37	1	2	1.168	0.41	2.04	0.584	3.79	30.25
42	2	0	1.01	0.43	1.76	1.51	3.28	30.5
29	3	2	1.156	0.49	1.44	1.734	3.17	30.75
36	4	2	1.1525	0.39	1.61	1.383	3.45	31
25	5	2	0.8985	0.51	2.09	0.599	3.89	31.25
7	6	2	0.95	0.4	1.18	2.375	3.08	31.75
41	7	0	1.01	0.42	1.76	1.515	3.28	32
43	8	0	1.01	0.42	1.76	1.515	3.28	32.25
6	9	2	1.078	0.45	2.42	0.539	3.49	32.25
30	10	2	1.01	0.42	2.27	1.515	2.77	32.75
24	11	2	0.942	0.47	2.11	1.413	3.06	33.25
5	12	2	1.246	0.52	1.55	0.62	4.049	33.5
20	13	2	0.85	0.36	1.48	2.12	3.18	33.75
4	14	2	1.2125	0.48	1.69	1.45	3.15	34
18	15	2	0.95	0.4	1.66	2.37	2.61	34.25
26	16	2	1.3925	0.47	1.94	0.55	3.62	34.5
1	17	2	0.789	0.36	1.84	1.57	3.41	34.75
17	18	2	1.246	0.52	2.18	0.62	3.42	35
12	19	2	0.942	0.47	1.64	1.41	3.53	35.25
10	20	2	1.066	0.53	1.86	1.59	2.91	35.5
15	21	2	0.7335	0.41	2.2	1.46	3.17	35.75
33	22	2	0.8355	0.47	1.94	1.67	3.06	36
8	23	2	0.85	0.36	1.91	2.12	2.7625	30.25
3	24	2	0.774	0.51	1.8	1.54	3.35	30.5
13	25	2	0.83	0.47	1.39	1.67	3.62	30.75
45	26	0	1.01	0.42	1.76	1.51	3.28	31
44	27	0	1.01	0.42	1.76	1.51	3.28	31.25
16	28	2	1.1525	0.39	2.07	1.383	2.99	31.5
31	29	2	1.01	0.42	1.26	1.515	3.78	31.75
46	30	0	1.01	0.42	1.26	1.515	3.78	32
19	31	2	1.078	0.45	1.88	0.539	4.04	32.25
34	32	2	1.3075	0.44	1.8305	1.569	2.87	32
28	33	2	1.0875	0.36	1.52	2.175	2.82	32.5
32	34	2	0.898	0.38	2.02	1.34	3.36	32.75
14	35	2	1.3075	0.44	1.3	1.56	3.39	33
40	36	2	0.888	0.44	1.55	2.22	2.88	33.25
22	37	2	1.066	0.53	1.33	1.59	3.46	33.5
27	38	2	0.6915	0.39	1.61	2.3	2.99	33.75
11	39	2	0.958	0.33	1.67	1.43	3.59	34
9	40	2	1.088	0.38	1.9	1.63	2.99	34.25
39	41	2	0.904	0.31	1.58	2.26	2.93	34.5
38	42	2	1.142	0.57	1.99	0.57	3.7	34.75
2	43	2	1.235	0.34	1.72	1.48	3.21	34.75
21	44	2	1.088	0.38	1.36	1.63	3.53	35.25
23	45	2	0.958	0.33	2.15	1.43	3.11	35.25
35	46	2	0.735	0.41	1.71	1.47	3.67	35.5

The coded coefficients provide in table 4 represent the coefficients of the terms in the full quadratic model used for the Box-Behnken design. Each term corresponds to a specific factor or combination of factors, with their coefficients indicating the strength and direction of their impact on the response variable. The constant term represents the baseline value of the response when all factors are at their zero levels. The coefficient values, standard errors, t-values, and p-values are crucial for assessing the significance of each term. A positive coefficient suggests a positive effect on the response variable, while a negative coefficient implies a negative effect. Additionally, the t-values and p-values help determine the statistical significance of each coefficient. Terms with p-values below a chosen significance level (e.g., 0.05) are considered statistically significant. In this analysis, several terms have statistically significant coefficients, indicating their importance in explaining the variability in the response variable. However, further interpretation and validation of these results should be conducted in the context of the specific study and its objectives (Guo et al., 2022). Additionally, consideration of multicollinearity, as indicated by the variance inflation factor (VIF), is important to ensure the reliability of the model estimates (Li et al., 2023).

Table 4. Coded Coefficients for the Box Behnken's Compressive Strength

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	104.7	49.2	2.13	0.043	
A	0.80	1.35	0.59	0.558	473.78
B	-11.52	4.75	-2.43	0.023	527.48
C	0.432	0.666	0.65	0.523	461.28
D	0.094	0.321	0.29	0.771	427.94
E	-1.260	0.735	-1.71	0.099	561.28
A*A	0.0431	0.0168	2.57	0.017	118.53
B*B	0.905	0.187	4.85	0.000	236.68
C*C	0.00432	0.00420	1.03	0.313	91.03
D*D	0.00186	0.00105	1.77	0.088	17.70
E*E	0.00995	0.00420	2.37	0.026	311.03
A*B	-0.1000	0.0828	-1.21	0.238	193.44
A*C	-0.0338	0.0124	-2.72	0.012	114.00
A*D	-0.01000	0.00621	-1.61	0.120	74.00
A*E	-0.0050	0.0124	-0.40	0.691	234.00
B*C	-0.0125	0.0414	-0.30	0.765	178.44
B*D	-0.0458	0.0207	-2.22	0.036	138.44
B*E	-0.0000	0.0414	-0.00	1.000	298.44
C*D	0.00625	0.00310	2.01	0.055	59.00
C*E	-0.00125	0.00621	-0.20	0.842	219.00
D*E	0.00281	0.00310	0.91	0.373	179.00

Table 5. Box Behnken's Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.24126	69.89%	45.81%	0.00%

The model summary in Table 5 presents key metrics evaluating the performance of the regression model. With a standard error of 1.24126, the model's R-squared value of 69.89% indicates that approximately 69.89% of the variability in the response variable is accounted for by the independent variables. However, the adjusted R-squared value of 45.81% suggests that the model's explanatory power may be slightly diminished when considering the number of predictors (Dai et al., 2019; Maaze & Shrivastava, 2023).

The analysis of variance (ANOVA) of Box Behnken's Compressive Strength design

The analysis of variance (ANOVA) provides valuable insights into the significance of the factors and their interactions in the regression model (Tiza et al., 2023). The "Model" section indicates that the overall model is statistically significant, with an F-value of 2.90 and a corresponding p-value of 0.006, suggesting that at least one of the factors has a significant effect on the response variable. The "Linear" and "Square" subsections further delve into the significance of the linear and quadratic terms, respectively. Notably, the "Square" subsection demonstrates significant effects for terms A*A and B*B, with p-values of 0.017 and 0.000, respectively, indicating the presence of nonlinear relationships between these factors and the response variable. Additionally, the "2-Way Interaction" section reveals some significant interactions between factors, such as A*C and B*D.

Regression Equation in coded Units

$$\text{Compressive Strength} = 200.0 + 0.238\,A - 14.18\,B + 0.0606\,C + 0.0174\,D - 0.1370\,E + 0.001725\,A^2 + 0.4023\,B^2 + 0.000043\,C^2 + 0.000005\,D^2 + 0.000099\,E^2 - 0.0133\,A{*}B - 0.000675\,A{*}C - 0.000100\,A{*}D - 0.000100\,A{*}E - 0.00083\,B{*}C - 0.001528\,B{*}D - 0.00000\,B{*}E + 0.000031\,C{*}D - 0.000013\,C{*}E + 0.000014\,D{*}E \qquad (1)$$

In this equation, *A, B, C, D, and E represent the actual values of the factors (A is Water,B is Cement, C is Sand, D is RAP, and E is Coarse Aggregates), while* A^2*,* B^2*,* C^2*,* D^2*, and* E^2 *represent the squared values of these factors. Each coefficient represents the change in compressive strength associated with a one-unit change in the respective factor, holding all other factors constant.*

Table 6. Analysis of Box Behnken's Compressive Strength Residuals

Run Order	Water (kg)	Cement (kg)	Sand (kg)	RAP (kg)	Coarse Aggregates (kg)	Av. of 3 Lab Response Value (N/mm²)	Predicted Value (N/mm²)	Residual (N/mm²)
1	1.16	0.41	2.04	0.584	3.79	30.25	32.135	-1.88
2	1.01	0.43	1.76	1.51	3.28	30.5	31.167	-0.667
3	1.15	0.49	1.44	1.734	3.17	30.75	32.141	-1.391
4	1.15	0.39	1.61	1.383	3.45	31	32.083	-1.083
5	0.89	0.51	2.09	0.599	3.89	31.25	32.271	-1.021
6	0.95	0.4	1.18	2.375	3.08	31.05	30.859	0.641
7	1.01	0.42	1.76	1.515	3.28	31.75	31.167	0.583
8	1.01	0.42	1.76	1.515	3.28	32	31.167	0.833
9	1.07	0.45	2.42	0.539	3.49	32.25	31.328	0.922
10	1.01	0.42	2.27	1.515	2.77	32.05	33.578	-1.078
11	0.94	0.47	2.11	1.413	3.06	32.75	34.12	-1.37
12	1.24	0.52	1.55	0.62	4.049	33	32.641	0.359
13	0.85	0.36	1.48	2.12	3.18	33.25	33.563	-0.313
14	1.21	0.48	1.69	1.45	3.15	33.05	32.969	0.531
15	0.95	0.4	1.66	2.37	2.61	33.75	32.969	0.781
16	1.39	0.47	1.94	0.55	3.62	34	32.99	1.01
17	0.78	0.36	1.84	1.57	3.41	34.75	34.094	0.156
18	1.24	0.52	2.18	0.62	3.42	35	33.375	1.125
19	0.94	0.47	1.64	1.41	3.53	35.25	34.01	0.74
20	1.06	0.53	1.86	1.59	2.91	35	34.542	0.458
21	0.73	0.41	2.2	1.46	3.17	35.25	35.599	-0.349
22	0.83	0.47	1.94	1.67	3.06	35.5	33.896	1.604
23	0.85	0.36	1.91	2.12	2.7625	35.75	34.547	1.203
24	0.77	0.51	1.8	1.54	3.35	36	35.75	0.25
25	0.83	0.47	1.39	1.67	3.62	30.25	31.036	-0.786
26	1.01	0.42	1.76	1.51	3.28	30.05	31.167	-0.667
27	1.01	0.42	1.76	1.51	3.28	30.75	31.167	-0.417
28	1.15	0.39	2.07	1.383	2.99	31	30.943	0.057
29	1.01	0.42	1.26	1.515	3.78	31.25	31.859	-0.609
30	1.01	0.42	1.26	1.515	3.78	31.05	31.167	0.333
31	1.078	0.45	1.88	0.539	4.04	31.75	31.719	0.031
32	1.3075	0.44	1.8305	1.569	2.87	32	33.115	-1.115
33	1.0875	0.36	1.52	2.175	2.82	32.25	31.708	0.542
34	0.898	0.38	2.02	1.34	3.36	32.05	32.797	-0.297
35	1.3075	0.44	1.3	1.56	3.39	32.75	33.13	-0.38
36	0.888	0.44	1.55	2.22	2.88	33		
37	1.066	0.53	1.33	1.59	3.46	33.25	33.307	-0.057
38	0.6915	0.39	1.61	2.3	2.99	33.05	34.99	-1.49
39	0.958	0.33	1.67	1.43	3.59	33.75	33.854	-0.104
40	1.088	0.38	1.9	1.63	2.99	34	34.385	-0.385
41	0.904	0.31	1.58	2.26	2.93	34.25	35.604	-1.354
42	1.142	0.57	1.99	0.57	3.7	34.05	35.042	-0.542
43	1.235	0.34	1.72	1.48	3.21	34.75	34.312	0.438
44	1.088	0.38	1.36	1.63	3.53	35	32.776	2.224
45	0.958	0.33	2.15	1.43	3.11	35.25	34.339	0.911
46	0.735	0.41	1.71	1.47	3.67	35.5	33.86	1.635

The table 6 above presents a comparison between the average of three lab response values and their corresponding predicted values, along with residuals and percentage errors. Overall, the model appears to perform reasonably well, with most percentage errors being relatively low, indicating accurate predictions.

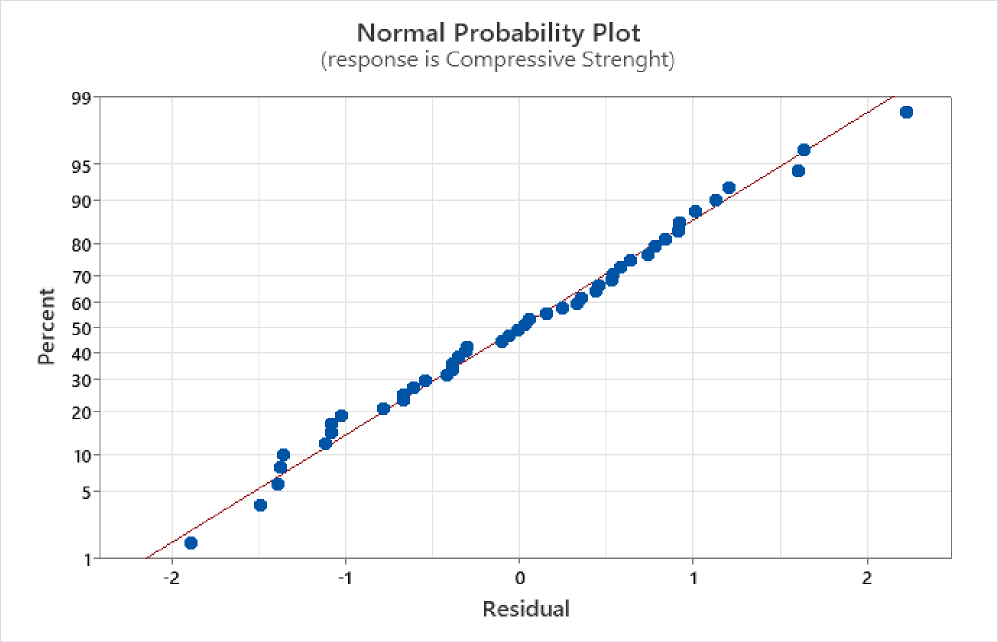


Figure 6. Normal Probability Plot

The Normal Probability Plot in figure 6 above visually assesses whether the data points align with a normal distribution by comparing them to the expected alignment represented by the red line. In this plot, the blue dots represent individual data points of compressive strength, and their proximity to the red line indicates the degree of conformity to a normal distribution. The closely packed arrangement of the dots suggests a good level of adherence to normality, indicating that the compressive strength data follows a relatively normal distribution. However, slight deviations from the red line may still be observed, suggesting minor departures from perfect normality. Overall, the pattern observed in the plot suggests that the compressive strength data is reasonably well-distributed and conforms reasonably well to a normal distribution (Liu et al., 2019).

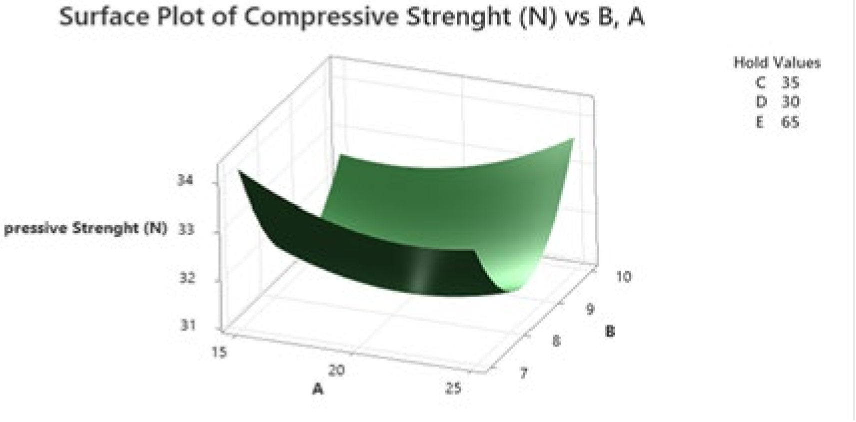


Figure 7. Surface Plot of Compressive Strength

The Figure 7 above shows the 3D surface plot depicts the relationship between two variables, A and B, and their influence on compressive strength in cement concrete. The x-axis represents variable A, ranging from 15 to 25, while the y-axis represents variable B, ranging from 7 to 10. The vertical z-axis illustrates compressive strength in Newtons (N), ranging from 31 to 34. The surface shape of the graph showcases a curved structure, indicative of how compressive strength varies with different combinations of A and B. An intriguing observation is that as variable B decreases and variable A increases, there is a discernible trend of increased compressive strength. This trend is visually evident from the upward curvature of the surface plot. It implies that adjustments in these variables can significantly impact the compressive strength of the material.

Furthermore, the "Hold Values" table in the top right corner provides specific numerical values for variables C, D, and E, namely 35, 30, and 65, respectively. These values likely represent constants or fixed parameters within the experimental setup, influencing the behavior of A and B in relation to compressive strength. In summary, the surface plot highlights the interplay between variables A and B and their effect on compressive strength. The visualization suggests that higher values of A and lower values of B contribute to stronger compressive strength in the cement concrete mixture, providing valuable insights for optimizing concrete formulations to achieve desired strength characteristics.

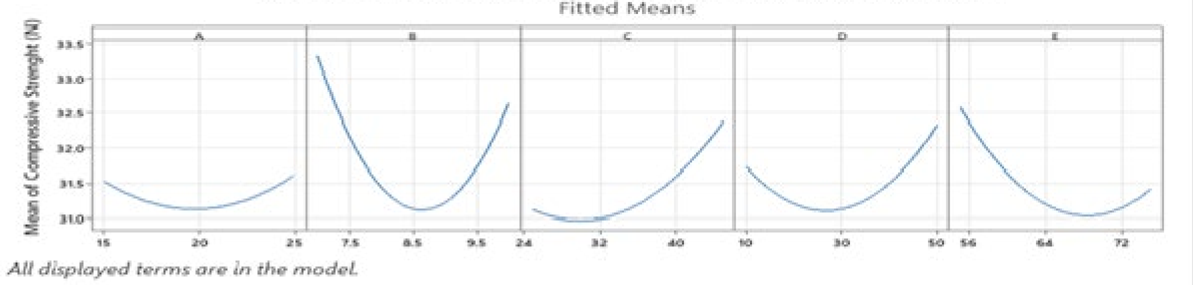


Figure 8: The Main Effects Plot for Compressive Strength

The Main Effects Plot for Compressive Strength in figure 8 with Fitted Means provides insights into the impact of different scenarios labeled A to E on the compressive strength of the material. Although the variable represented on the x-axis is unspecified in the image, it is evident that each scenario corresponds to a specific value of this variable, with the y-axis representing the mean compressive strength in N/mm^2.

Each scenario exhibits a U-shaped curve, starting from a low point, rising to a peak, and then decreasing. This characteristic curve shape indicates that there are optimal values of the variable where compressive strength is maximized.

Scenario A: The curve peaks around a certain value of the variable, suggesting an optimal point where compressive strength reaches its highest level.

Scenario B: Similar to scenario A, but with a different peak, indicating another optimal value of the variable that maximizes compressive strength.

Scenario C: In contrast to scenarios A and B, the curve for scenario C is relatively flat, implying less sensitivity to changes in the variable and a more consistent compressive strength across different values.

Scenario D: This scenario exhibits another peak, albeit at a different value of the variable, signifying a different optimal point for maximizing compressive strength.

Scenario E: In this scenario, the curve shows a gradual decline, indicating that increasing or decreasing the variable leads to a decrease in compressive strength.

The text at the bottom of the plot states that "All displayed terms are in the model," suggesting that the graph represents the effects of specific terms within a statistical model. This implies that the observed variations in compressive strength across different scenarios are accounted for by the terms included in the model, providing a comprehensive understanding of the factors influencing compressive strength in the material.

The main plot in Figure 9 titled “Interaction Plot for Compressive Strength (N)” with a subtitle “Fitted Means.” Within the main plot, there were nine smaller plots, each representing interactions between two variables (e.g., AB, AC, BC, AD, BD, CD, AE, BE, and C*E). The Y-axis represented the mean compressive strength in Newtons, ranging from approximately 30 to 35. The X-axis corresponded to the values of variables A to E, each with specific numeric scales. Legends on the right side indicated values associated with line styles and colors. A note at the bottom stated: “All displayed terms are in the model.” This suggested that the graph represented the effects of specific terms within a statistical model, providing insights into the interactions between different variables and their impact on compressive strength.

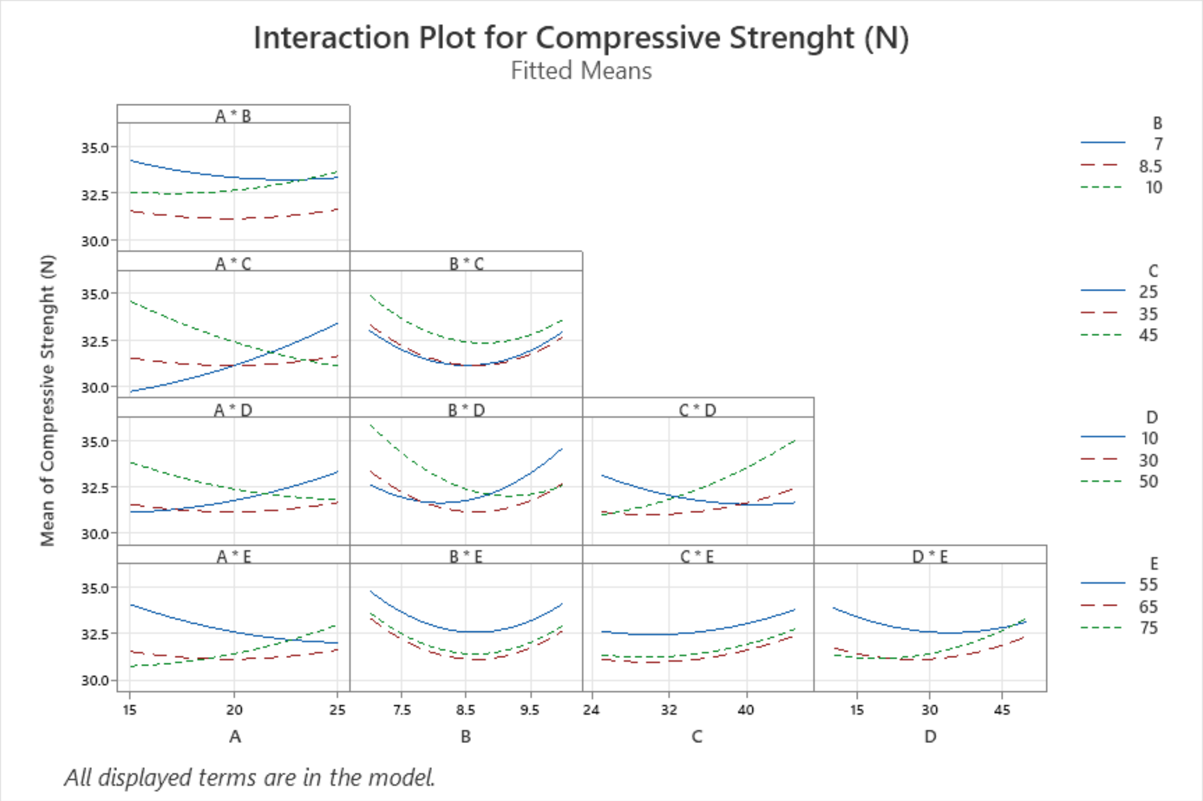


Figure 9. Interaction Plot for Compressive Strength

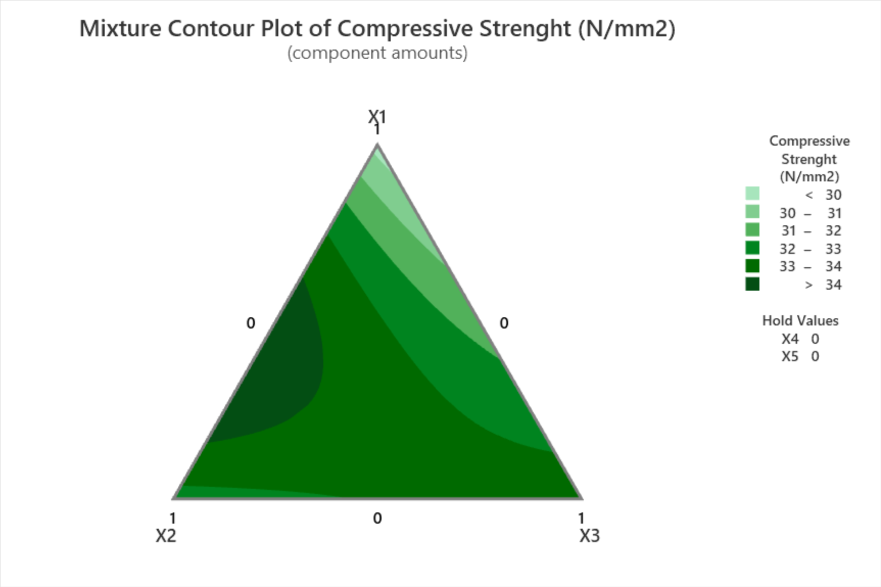


Figure 10. Mixture Contour Plot of Compressive Strength (N/mm^2)

The main plot is titled “Mixture Contour Plot of Compressive Strength (N/mm^2)” with a subtitle “(component amounts).” Within the plot, a triangular representation is observed, with each corner corresponding to a component labeled as X1, X2, and X3. The varying shades of green filling the triangle indicate different levels of compressive strength, with darker greens representing higher strengths. The Y-axis denotes the mean compressive strength in N/mm^2, ranging from approximately 30 to 34. A legend on the right side explains that lighter greens signify lower compressive strengths (around 30 N/mm^2), while darker greens indicate higher strengths (around 34 N/mm^2). Hold values are listed for X4 and X5, both set to 0. This plot visually depicts the relationship between these components and their effect on compressive strength. Practical Application: Engineers or researchers can utilize this information to optimize the mixture of components for achieving the desired compressive strength in materials. By adjusting the proportions of X1, X2, and X3, they can enhance the material's performance.

Optimization of Compressive Strength Using Box Behnken's Model

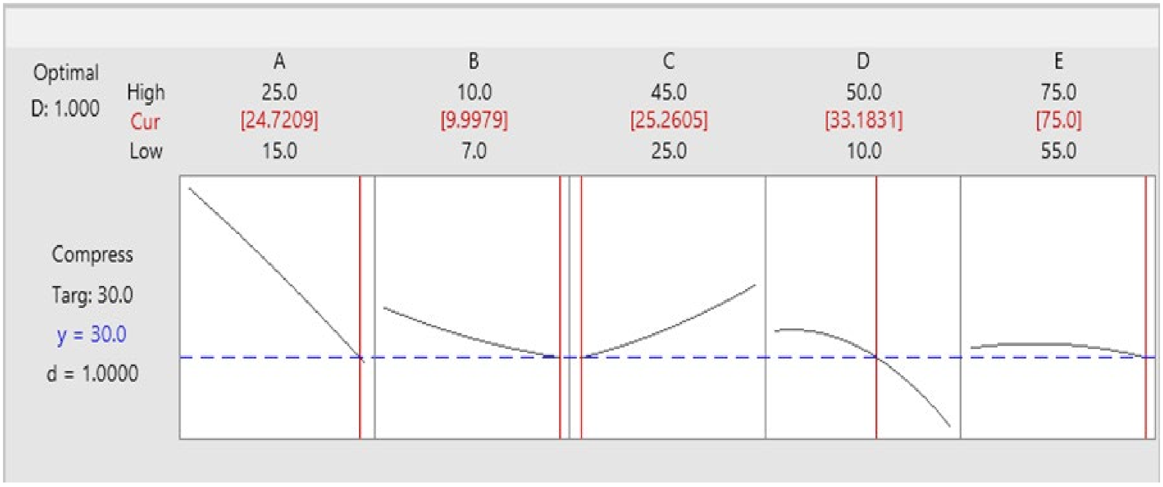


Figure 11. Optimization Results of Compressive Strength Using Box Behnken's Model

The graph presented in Figure 11 illustrates the ideal blend proportions for maximizing compressive strength in concrete, with distinct sections representing Water, Cement, Sand, RAP (Reclaimed Asphalt Pavement), and Coarse Aggregates, expressed in percentages. Each material level—High, Optimal, and Low—represents the required quantities for achieving varying compressive strength outcomes. The blue dashed line signifies the optimal mix, resulting in approximately 30.00 N/mm² of compressive strength. The decision to employ the target strength approach in optimization using Minitab for the Box-Behnken model is founded on a practical assessment of experimental data and the quest for a feasible solution (Hari & Mini, 2023). Given that most experimental values cluster around 30 N/mm², opting for a maximization approach often yields excessively high values, potentially straying from practical feasibility. By setting a target strength, the optimization process seeks to align with observed experimental trends, ensuring that the optimized solution remains within realistic and attainable parameters. This approach mitigates the risk of overestimation or underestimation of the desired outcome, thereby enhancing the reliability and applicability of the optimization process for concrete mix design. Specifically, at 30 N/mm², the optimal proportions were found to be 24.72% for A, 9.99% for B, 25.26% for C, 33.18% for D, and 75% for E. To obtain the actual values, this result will be adjusted to 100% constraint and then proportioned accordingly to match experimental realities, in this context, the results yields 14.68% for A, 5.94% for B, 15.00% for C, 19.69% for D, and 44.69% for E.

Conclusion

In conclusion, this study has investigated the potential of reclaimed asphalt pavement aggregates (RAP) in enhancing the sustainability of concrete production while optimizing its compressive strength. Through the utilization of advanced modeling techniques such as the Box-Behnken design, we systematically varied parameters including RAP substitution percentage, water-cement ratio, and curing time to predict and optimize compressive strength. Our findings suggest that RAP incorporation can indeed improve the sustainability of concrete mixes without compromising structural integrity or durability. The developed empirical models accurately forecast compressive strength under diverse conditions, providing valuable insights into the feasibility and effectiveness of RAP incorporation in concrete mixes. These results hold significant implications for engineers and practitioners seeking to optimize concrete compositions for specific performance requirements while advancing sustainable construction practices and reducing environmental impact. Ultimately, this research contributes to the growing body of knowledge on sustainable construction materials and practices, paving the way for more environmentally friendly and resilient infrastructure in the future.

Recommendations

To advance research and practical applications in sustainable concrete production using reclaimed asphalt pavement aggregates (RAP), several recommendations are proposed. Continued research efforts should focus on long-term performance and durability assessments of RAP concrete, alongside exploration of optimization techniques to refine mix design processes. Comprehensive material characterization is essential to understand RAP aggregate properties fully. Standardization efforts are necessary to establish clear guidelines for RAP concrete usage, while industry collaboration can facilitate technology transfer and knowledge dissemination. Education and training programs should be developed to raise awareness among construction professionals, while supportive policies and incentives are crucial to incentivize the adoption of RAP concrete in construction projects. Through concerted efforts across research, industry, and policy spheres, the widespread adoption of RAP aggregates in concrete production can be promoted, fostering sustainability and resilience in infrastructure development.

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