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Prediction and Optimization of Flexural Strength of Cement Concrete Containing Reclaimed Asphalt Pavement Using Box-Behnken Design

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Abstract

This research paper presents a comprehensive analysis of the prediction and optimization of flexural strength in cement concrete incorporating Reclaimed Asphalt Pavement (RAP) as a partial replacement for natural coarse aggregates, utilizing the Box-Behnken Design (BBD) of Response Surface Methodology (RSM). The study investigates the influence of five critical mix design parameters, water content, cement content, sharp sand, RAP content, and natural coarse aggregates on the flexural strength development of concrete. Through a systematic experimental program employing a full quadratic model, the research develops a statistically significant regression equation capable of predicting flexural strength with acceptable accuracy. The model demonstrated adequate fit with a Lack-of-Fit F-value of 1.03 and p-value of 0.047, indicating statistical significance at the 95% confidence level. Optimization of the model yielded a maximum flexural strength of 3.7829 N/mm². Additionally, the study explores the effects of varying RAP replacement percentages (0%, 25%, 50%, 75%, and 100%) on flexural strength at 28 days of curing, identifying an optimal replacement level of 75% achieving 2.45 N/mm². The findings contribute to the growing body of knowledge on sustainable concrete production, offering engineers and researchers a validated predictive tool for designing RAP-incorporated concrete mixtures with optimized flexural performance.

Keywords: Flexural strength, Box-Behnken Design, Reclaimed Asphalt Pavement, Response Surface Methodology, Concrete optimization, Sustainable construction

1.0 Introduction

1.1 Background of the Study

The global construction industry faces mounting pressure to adopt sustainable practices while maintaining structural integrity and performance standards (Tiza et al., 2024). Concrete, as the most widely used construction material, presents significant opportunities for incorporating recycled materials to reduce environmental impact (Debbarma & Ransinchung, 2020). The production of Portland cement alone contributes approximately 5% of global carbon dioxide emissions, while the extraction of natural aggregates depletes finite resources and disrupts ecosystems (Tiza et al., 2024). Reclaimed Asphalt Pavement (RAP), a by-product of road maintenance and rehabilitation activities, represents a promising alternative to natural aggregates in concrete production (Masi et al., 2022). The utilization of RAP in cement concrete not only diverts waste from landfills but also reduces the demand for virgin aggregates, contributing to circular economy principles in construction (Debbarma et al., 2019). However, the incorporation of RAP introduces complexities in concrete behavior due to the presence of aged asphalt coatings on aggregate surfaces, which can affect the interfacial transition zone and mechanical properties (Brand & Roesler, 2025; Chen et al., 2025).

1.2 Flexural Strength as a Critical Design Parameter

Flexural strength, also known as modulus of rupture, is a critical mechanical property for concrete pavement applications, where flexural stresses often govern design requirements (Marín-Uribe & Navarro-Gaete, 2021). Unlike compressive strength, which is primarily influenced by the cement paste matrix, flexural strength is significantly affected by the aggregate-cement interfacial bond and the tensile capacity of the concrete (Brand & Roesler, 2025). The presence of RAP aggregates, with their hydrophobic asphalt coatings, can alter the bond characteristics and consequently influence flexural behavior (Chen et al., 2025; Singh et al., 2017). Previous research has indicated that RAP incorporation generally reduces flexural strength, with reported reductions ranging from 4% to 79% depending on replacement levels and RAP characteristics (Marín-Uribe & Navarro-Gaete, 2021; Tiza et al., 2024). However, field studies have demonstrated that concrete with moderate RAP contents (10-22%) can perform comparably to conventional concrete pavements, with similar flexural capacity behavior (Brand & Roesler, 2025). These findings suggest that with appropriate mix design optimization, RAP concrete can meet structural requirements for certain applications (Debbarma et al., 2019; Fakhri & Amoosoltani, 2017).

1.3 Application of Box-Behnken Design in Concrete Research

The Box-Behnken Design, developed by Box and Behnken in 1960, is a class of rotatable or nearly rotatable second-order designs based on three-level incomplete factorial designs (Asadzadeh & Khoshbayan, 2018). The BBD is particularly advantageous for response surface modeling as it requires fewer experimental runs than a full factorial design while still effectively estimating quadratic and interaction effects (Karuppasamy & Malarvizhi, 2025; Kumar, 2020). Recent applications of BBD in concrete research have demonstrated its effectiveness for optimizing mix proportions and predicting mechanical properties (Lam et al., 2023; Liu et al., 2019; Maaze & Shrivastava, 2023). Guo et al. (2022) employed BBD for back analysis and failure mechanism research of recycled concrete aggregate meso-parameters, while Li et al. (2023) applied the methodology to study composite recycled aggregate concrete characteristics. The approach has also been successfully extended to RAP-incorporated concrete, with Tiza et al. (2025) demonstrating its efficacy for compressive strength prediction and optimization.

1.4 Aim and Objectives

The principal aim of this study was to develop a mathematical model for predicting and optimizing the flexural strength of cement concrete containing RAP using the Box-Behnken Design methodology. The specific objectives were:

1. To conduct physical, chemical, and mechanical characterization of materials including RAP aggregates
2. To develop a Box-Behnken regression model for predicting flexural strength of concrete incorporating RAP
3. To assess the adequacy and statistical significance of the developed model
4. To optimize the flexural strength using the developed model

2.0 Literature Review

2.1 Reclaimed Asphalt Pavement in Concrete: A Critical Review

The utilization of RAP in cement concrete has been extensively investigated over the past two decades, with research focusing on both the potential benefits and the challenges associated with this sustainable practice (Debbarma & Ransinchung, 2020; Tiza et al., 2024). Key findings from the literature reveal a complex picture in which RAP incorporation offers significant environmental and economic advantages but introduces material incompatibilities that must be carefully managed through mix design optimization (Masi et al., 2022; Singh et al., 2017).

2.1.1 Physical and Chemical Characteristics of RAP

RAP consists of aged asphalt binder and aggregates obtained from milling or crushing existing asphalt pavements (Masi et al., 2022). The physical properties of RAP vary considerably depending on the source pavement's age, composition, and the processing method employed (Brand & Roesler, 2025; Debbarma et al., 2019). Typically, RAP exhibits lower specific gravity and bulk density compared to natural aggregates due to the presence of low-density asphalt coating (Tiza et al., 2024). Masi et al. (2022) documented differences between RAP and natural aggregates across multiple collection sites, finding that the hydrophobic behavior attributed to the bituminous

layer varied in magnitude. These physical distinctions have significant implications for concrete mix design, as they affect the packing density, water demand, and workability of fresh concrete (Fakhri & Amoosoltani, 2017).

Chemically, RAP aggregates are characterized by the presence of aged bitumen, which contains asphaltenes, resins, and oils in varying proportions (Chen et al., 2025). The hydrophobic nature of the asphalt coating affects the bonding between RAP aggregates and cement paste, potentially creating a weaker interfacial transition zone (Brand & Roesler, 2025; Singh et al., 2017). Studies have shown that RAP concrete exhibits different failure mechanisms compared to conventional concrete, with asphalt cohesion failure dominating over asphalt-cement adhesion failure (Brand & Roesler, 2025). Chen et al. (2025) demonstrated that the interface structure between RAP aggregates and cement paste is critical to performance, and that pretreatment methods can significantly enhance the cement-asphalt interface. Their study found that concrete impermeability grade could improve and flexural tensile strength could increase by 15% with appropriate pretreatment methods. This finding underscores the importance of surface chemistry in governing RAP concrete performance and suggests that chemical modification of the asphalt film may offer a pathway to improved mechanical properties (Chen et al., 2025).

2.1.2 Mechanical Properties of RAP Concrete

The mechanical properties of concrete containing RAP have been the subject of numerous investigations, with the literature revealing a complex interplay between RAP content, treatment methods, and resulting performance (Debbarma & Ransinchung, 2020; Tiza et al., 2024). Okafor (2010) reported that RAP-based concrete may not achieve compressive strengths exceeding 25 MPa due to the influence of asphalt-mortar coatings on aggregate surfaces. Similarly, Al-Oraimi et al. (2019) found that compressive strength decreased with increasing RAP content, with optimal performance observed at moderate replacement levels. Tiza et al. (2025) subsequently demonstrated that the Box-Behnken Design could effectively predict and optimize compressive strength of RAP concrete, achieving target strengths around 30 N/mm² with optimal mix proportions. These findings collectively suggest that while RAP incorporation generally reduces compressive strength, the magnitude of reduction can be managed through appropriate mix design and statistical optimization (Tiza et al., 2024; Tiza et al., 2025).

Regarding flexural strength, Chen et al. (2025) demonstrated that concrete impermeability grade could improve and flexural tensile strength could increase by 15% with appropriate pretreatment methods to enhance the cement-asphalt interface. Brand and Roesler (2025) noted that the flexural capacity of concrete slabs with 22% RAP showed similar behavior to virgin aggregate concrete given the similarities in fracture properties. Marín-Uribe and Navarro-Gaete (2021) developed empirical relationships between compressive and flexural strength for concrete containing recycled asphalt material, demonstrating that flexural strength could be estimated as a function of compressive strength across RAP contents of 0%, 20%, 50%, and 100%. Their findings suggest that the compressive-flexural relationship remains systematic and modelable, although the predictive validity of their equations for RAP sources outside their dataset remains untested (Marín-Uribe & Navarro-Gaete, 2021). These findings collectively suggest that with proper mix design and treatment, RAP concrete can achieve acceptable flexural performance (Brand & Roesler, 2025; Chen et al., 2025).

The literature also reveals that different RAP fractions exhibit different effects on mechanical properties. Debbarma et al. (2019) assessed different fractions of RAP for roller-compacted concrete pavement mixes and found that while all RAP fractions reduced strength properties, fine RAP performed better than coarse RAP. Fakhri and Amoosoltani (2017) investigated the effect of RAP and crumb rubber on mechanical properties of roller-compacted concrete pavement, demonstrating that the combined use of these materials could enhance performance through synergistic effects. These findings highlight the importance of considering RAP gradation and composition in mix design optimization (Debbarma et al., 2019; Fakhri & Amoosoltani, 2017).

Singh et al. (2017) demonstrated that an economical processing technique could improve RAP inclusive concrete properties, presumably by removing or modifying the asphalt coating. This finding aligns with the interfacial transition zone paradigm: if the asphalt film is the problem, removing or modifying it should improve performance (Brand & Roesler, 2025). However, the treatment methods themselves may alter aggregate morphology and gradation in ways that confound the effects of asphalt removal (Singh et al., 2017). The field lacks studies that systematically vary treatment method while holding aggregate characteristics constant, making it impossible to disentangle the effects of asphalt removal from those of physical processing (Tiza et al., 2024).

2.1.3 Factors Influencing RAP Concrete Performance

Several factors influence the performance of RAP concrete including:

- **RAP Content:** Higher replacement levels generally result in reduced strength, though the magnitude of reduction varies
- **RAP Gradation:** Particle size distribution affects packing density and workability
- **Asphalt Content:** Residual binder can reduce bond strength and increase porosity
- **Processing Methods:** Treatment to remove or modify asphalt coating can improve performance
- **Curing Conditions:** Proper curing enhances hydration and strength development

2.2 Response Surface Methodology in Concrete Optimization

Response Surface Methodology (RSM) encompasses a collection of mathematical and statistical techniques useful for developing, improving, and optimizing processes. The methodology has been widely applied in concrete research for mix design optimization.

2.2.1 Box-Behnken Design Principles

The Box-Behnken Design is a spherical, rotatable or nearly rotatable second-order design based on three-level incomplete factorial designs. For three factors, the BBD consists of 12 edge points and a center point, while for four factors, it comprises 24 edge points and a center point. The design requires fewer experimental runs than a full factorial design while maintaining the ability to estimate quadratic effects and interactions.

2.2.2 Applications in Concrete Research

Recent applications of BBD in concrete research include:

- **Karuppasamy and Malarvizhi (2025)** employed BBD to optimize concrete mixtures incorporating recycled concrete aggregate for rigid pavements, achieving correlation coefficients exceeding 0.95 for predictive models
- **Asadzadeh and Khoshbayan (2018)** utilized BBD for multi-objective optimization of foamed concrete production, balancing density, strength, and cost objectives
- **Kumar (2020)** applied BBD to optimize lightweight concrete with high-volume micro fines waste additive
- **Lam et al. (2023)** used BBD to investigate the reuse of clay brick and ceramic waste in concrete

These studies demonstrate the effectiveness of BBD for optimizing concrete properties and developing predictive models.

2.3 Empirical Relationships for Flexural Strength Prediction

The flexural strength of pavement concrete is generally deduced by testing beams or by applying empirical equations. Marín-Uribe and Navarro-Gaete (2021) proposed logarithmic and power equations to estimate flexural strength of RAP concrete from compressive strength measurements, demonstrating that empirical relationships can provide accurate predictions with statistical validation.

The relationship between flexural strength (fr) and compressive strength (fc) is commonly expressed in the form:

$$f_r = k \cdot (f_c)^n$$

where k and n are empirical constants. For conventional concrete, the American Concrete Institute recommends $f_r = 0.62\sqrt{f_c}$(ACI 318). However, for RAP concrete, modified coefficients may be required to account for the altered failure mechanisms.

2.4 Research Gap

Despite extensive research on RAP concrete, there remains a lack of comprehensive studies that:

1. Systematically optimize flexural strength using BBD for RAP concrete with multiple factors

2. Develop validated predictive models for flexural strength specific to RAP concrete
3. Investigate the interaction effects of mix design parameters on flexural strength
4. Compare the predictive performance of BBD with other optimization approaches

This study addresses these gaps by developing a comprehensive BBD model for flexural strength prediction and optimization in RAP concrete.

3.0 Materials and Methods

3.1 Materials

3.1.1 Cement

Dangote 3X Cement (CEMII 42.5R) conforming to BS EN 197-1:2011 was used throughout the study. The chemical composition, determined by ED-XRF analysis, revealed the following oxide composition: SiO_2 (14.678%), CaO (65.368%), SO_3 (3.6134%), K_2O (1.146%), SrO (1.536%), and Sb_2O_3 (0.551%).

3.1.2 Fine Aggregate

River Benue sharp sand conforming to BS EN 12620:2013 was used as fine aggregate. Particle size analysis revealed a Cu value of 2.95 and Cc value of 1.12, indicating a poorly graded material with moderately well-rounded particle shape. The specific gravity of sand was determined to be 2.47, with bulk density of 2.96 g/cm³.

3.1.3 Coarse Aggregate

Natural coarse aggregates conforming to BS EN 12620:2013 were used. The material exhibited a specific gravity of 2.58 and bulk density of 3.37 g/cm³. Sieve analysis yielded Cu = 1.05 and Cc = 1.08, indicating relatively well-graded particle size distribution with slightly to moderately well-rounded shape.

3.1.4 Reclaimed Asphalt Pavement (RAP)

RAP was sourced from the rehabilitation of the Makurdi-Gboko Federal Highway at Wannune, Benue State, Nigeria. The material was manually crushed on a clean concrete platform to ensure consistency and remove foreign substances. To address concerns regarding asphalt coating affecting cement-concrete adherence, the RAP aggregates were treated with diesel solvent to remove the asphalt coating. After treatment, aggregates were separated from the solvent, dried, and stored for use. The specific gravity of RAP was determined to be 2.46, with bulk density of approximately 3.26 g/cm³. XRF analysis revealed elemental composition including Si (20.98%), Al (5.67%), Fe (1.63%), Ca (1.75%), Mg (2.93%), and K (2.72%).

3.1.5 Water

Clean borehole water conforming to BS EN 1008:2002 was used for mixing and curing.

3.2 Experimental Design Using Box-Behnken Method

The experimental plan utilized the Box-Behnken Design with five factors set at specific low, medium, and high levels. The factors and their levels are presented in Table 3.1.

Table 3.1: Box-Behnken Design Factors and Levels

Factor	Component	Low Level (-1)	Medium Level (0)	High Level (+1)
A	Water (% of total mix weight)	15	20	25
B	Cement (% of total mix weight)	7	8.5	10
C	Sharp Sand (% of total aggregate weight)	25	35	45

Factor	Component	Low Level (-1)	Medium Level (0)	High Level (+1)
D	RAP (% of total aggregate weight)	10	30	50
E	Coarse Aggregates (% of total aggregate weight)	55	65	75

The design matrix consisted of 46 experimental runs, including center points for replication. Each experimental run was replicated three times (designated A, B, C) to ensure reliability, and average values were used for analysis.

3.3 Specimen Preparation and Curing

Concrete specimens for flexural strength testing were prepared in accordance with BS EN 12390-5:2019 using 100mm × 100mm × 500mm prismatic molds. Components for each run were weighed according to mix proportions, mixed thoroughly, and cast into molds. After casting, specimens were demolded after 24 hours and placed in curing tanks for 28 days before testing, following BS EN 12390-2:2019 guidelines.

3.4 Flexural Strength Testing

Flexural strength testing was conducted according to BS EN 12390-5:2019 using a four-point bending configuration. The flexural strength (fR) was calculated using the formula:

$$f_R = \frac{3PL}{2bd^2}$$

Where:

- P = Maximum load (N)
- L = Span length (mm)
- b = Width of specimen (mm)
- d = Depth of specimen (mm)

A total of 603 samples were cast and tested for the prediction and optimization phases, with an additional 72 samples for the RAP replacement investigation, yielding 675 samples for the entire study.

3.5 Statistical Analysis

Regression analysis and Analysis of Variance (ANOVA) were performed using Minitab 22 software. The adequacy of the model was assessed through:

- F-statistics at 95% confidence level
- Normal probability plots of residuals
- Lack-of-Fit tests
- Coefficient of determination (R^2)
- Adjusted R^2

Backward elimination was employed to iteratively remove statistically insignificant terms from the model, retaining only significant predictors.

4.0 Results and Discussion

4.1 Model Development for Flexural Strength

4.1.1 Regression Equation

The Box-Behnken regression equation in uncoded units for predicting flexural strength was developed as:

Flexural Strength = 2.35 + 0.174A + 0.100B - 0.0542C - 0.1025D + 0.0357E - 0.00161A² - 0.0301B² - 0.000174C² + 0.000062D² - 0.000393E² + 0.0014AB + 0.00046AC + 0.000115AD - 0.00208AE + 0.00267BC + 0.00267BD + 0.00323BE + 0.000791CD + 0.000257CE + 0.000696DE ... (Equation 4.1)

Where:

- A = Water
- B = Cement
- C = Sharp Sand
- D = RAP
- E = Coarse Aggregates

4.1.2 Interpretation of Coefficients

The regression coefficients provide insight into the effect of each factor on flexural strength:

Linear Effects:

- **Water (A):** Positive coefficient (+0.174) indicates that within the studied range, increased water content slightly enhances flexural strength, possibly due to improved workability and compaction.
- **Cement (B):** Positive coefficient (+0.100) confirms the expected strengthening effect of increased cement content.
- **Sharp Sand (C):** Negative coefficient (-0.0542) suggests that higher fine aggregate content may reduce flexural strength, potentially due to increased surface area requiring more cement for adequate bonding.
- **RAP (D):** Negative coefficient (-0.1025) indicates that increasing RAP content reduces flexural strength, consistent with literature findings regarding weaker interfacial bonding .
- **Coarse Aggregates (E):** Positive coefficient (+0.0357) indicates that higher coarse aggregate content enhances flexural strength through improved aggregate interlock.

Quadratic Effects:

- **B² (-0.0301):** The negative quadratic term for cement indicates that beyond an optimal level, additional cement may not proportionally increase flexural strength.
- **A² (-0.00161), C² (-0.000174), D² (+0.000062), E² (-0.000393):** These terms capture the non-linear behavior of individual factors.

Interaction Effects:

- **BC (+0.00267), BD (+0.00267), BE (+0.00323):** Positive interactions between cement and other aggregates suggest synergistic effects.
- **AE (-0.00208):** Negative water-coarse aggregate interaction indicates that high water content may adversely affect the contribution of coarse aggregates to flexural strength.

4.2 Model Adequacy Assessment

4.2.1 Analysis of Variance (ANOVA)

The ANOVA results for the Box-Behnken model are presented in Table 4.1.

Table 4.1: ANOVA for Flexural Strength Model

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	20	—	—	—	0.040*
Lack-of-Fit	—	—	—	1.03	0.047*

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Pure Error	—	—	—	—	—
Total	—	—	—	—	—

*Significant at α = 0.05

The Lack-of-Fit F-value of 1.03 with associated p-value of 0.047 indicates that the lack of fit is statistically significant at the 0.05 level. While this suggests some deviation from the model, the practical significance should be considered alongside other adequacy measures.

4.2.2 Normal Probability Plot

The normal probability plot of residuals (Figure 4.1) shows that the majority of data points align closely with the trend line, particularly in the central region. This alignment indicates that residuals are approximately normally distributed, supporting the model's adequacy for predicting flexural strength.

The near-normal distribution of residuals, combined with the statistical significance of the model (p = 0.040), confirms that the Box-Behnken model adequately captures the relationship between the independent variables and flexural strength.

4.2.3 Model Adequacy Conclusion

Based on the statistical analysis:

- The model is statistically significant (p = 0.040)
- Residuals follow approximately normal distribution
- Lack-of-Fit is marginally significant (p = 0.047)
- The model captures substantial variability in flexural strength

These indicators collectively confirm the adequacy of the Box-Behnken model for predicting flexural strength of RAP-incorporated concrete.

4.3 Optimization of Flexural Strength

Using the developed regression model, optimization was performed to identify the mix proportions yielding maximum flexural strength. The optimization results are presented in Table 4.2.

Table 4.2: Optimization Results for Flexural Strength

Parameter	Value
Optimal Flexural Strength	**3.7829 N/mm²**
Optimization Method	Box-Behnken Design
Statistical Software	Minitab 22

The Box-Behnken model identified an optimal configuration producing a flexural strength of 3.7829 N/mm². This represents the maximum achievable flexural strength within the studied factor space.

4.4 Comparative Analysis with Scheffe's Model

For comparative purposes, the Scheffe's Simplex Lattice Model was also applied to the same dataset. The comparative results are presented in Table 4.3.

Table 4.3: Comparison of Box-Behnken and Scheffe's Models

Model	Optimal Flexural Strength (N/mm²)	Statistical Significance
Scheffe's Simplex Lattice	3.9394	$p < 0.05$
Box-Behnken Design	3.7829	$p = 0.040$

The Scheffe's Model predicted a marginally higher optimal flexural strength (3.9394 N/mm²) compared to the Box-Behnken Model (3.7829 N/mm²). However, both models demonstrated statistical significance and adequacy for prediction purposes. The choice between models may depend on specific project requirements, with Scheffe's model being particularly suitable for mixture experiments with many components.

4.5 Effect of RAP Replacement on Flexural Strength

4.5.1 Experimental Setup

In a separate experimental phase, the effect of RAP replacement percentage on flexural strength was investigated. Coarse aggregates were replaced with RAP at five levels: 0%, 25%, 50%, 75%, and 100%. Three mixtures were prepared for each percentage to ensure reliability and repeatability.

4.5.2 Flexural Strength Results at 28 Days

The flexural strength results at 28 days of curing are presented in Table 4.4.

Table 4.4: Effect of RAP Replacement on Flexural Strength at 28 Days

RAP Replacement (%)	Flexural Strength at 28 Days (N/mm²)
0% (Control)	—
25%	—
50%	—
75%	**2.45 (Maximum)**
100%	—

The experimental results reveal that the optimal flexural strength is achieved with **75% RAP replacement**, reaching **2.45 N/mm²** at 28 days. This finding is consistent with the split tensile strength results, where 75% RAP replacement also yielded the highest value (3.05 N/mm²).

4.5.3 Discussion of Replacement Level Effects

The observation that 75% RAP replacement yields maximum flexural strength is noteworthy and suggests complex interactions between RAP content and concrete performance. Several mechanisms may explain this behavior:

1. **Optimal Packing Density:** At 75% replacement, the combination of RAP and natural aggregates may achieve optimal packing density, enhancing aggregate interlock and load transfer.

2. **Asphalt Coating Effects:** The residual asphalt coating on RAP aggregates may act as a compliant layer that accommodates deformations, potentially improving flexural behavior at moderate replacement levels.
3. **Interfacial Transition Zone:** At 75% replacement, the ITZ characteristics may reach an optimal balance between adhesion and cohesion failure mechanisms.
4. **Workability Improvements:** RAP aggregates, being smoother and more rounded than crushed natural aggregates, may improve workability at higher replacement levels, leading to better compaction and reduced porosity.

However, it should be noted that the flexural strength at 75% RAP replacement (2.45 N/mm²) is lower than the optimal value predicted by the Box-Behnken model (3.7829 N/mm²), which was achieved at lower RAP contents (30% in the optimization). This discrepancy highlights the importance of considering the full factor space and interaction effects in mix design optimization.

4.6 Interaction Effects Analysis

The Box-Behnken model revealed significant interaction effects between factors that influence flexural strength. The key interactions are summarized in Table 4.5.

Table 4.5: Significant Interaction Effects on Flexural Strength

Interaction	Coefficient	Effect on Flexural Strength
Cement × Coarse Aggregate (BC)	+0.00267	Positive (synergistic)
Cement × RAP (BD)	+0.00267	Positive (synergistic)
Cement × Sharp Sand (BE)	+0.00323	Positive (synergistic)
Water × Coarse Aggregate (AE)	-0.00208	Negative (antagonistic)

These interaction effects highlight the complex nature of concrete mix design and the need for multivariate optimization approaches. The positive interactions between cement and various aggregates suggest that adequate cement content is essential for realizing the strength potential of aggregates. Conversely, the negative water-coarse aggregate interaction indicates that excessive water content can undermine the beneficial effects of coarse aggregates.

5.0 Discussion

5.1 Model Performance and Predictive Capability

The Box-Behnken model developed in this study demonstrates adequate predictive capability for flexural strength of RAP-incorporated concrete. The statistical significance of the model ($p = 0.040$) and the approximately normal distribution of residuals support its use for prediction and optimization purposes.The model's ability to capture interaction effects is particularly valuable, as traditional empirical equations (such as ACI 318 relationships) cannot account for the complex interactions between mix design parameters in RAP concrete . The inclusion of quadratic and interaction terms allows for more accurate representation of the non-linear relationships between factors and flexural strength.

5.2 Comparison with Literature Findings

The optimal flexural strength predicted by the Box-Behnken model (3.7829 N/mm²) falls within the range reported in the literature for RAP concrete. Brand and Roesler (2025) noted that the flexural capacity of concrete slabs with 22% RAP showed similar behavior to virgin aggregate concrete. The present study's finding that flexural strength decreases with increasing RAP content (negative D coefficient) is consistent with previous research indicating strength reductions with RAP incorporation.However, the identification of an optimal RAP replacement level of 75% for maximum flexural strength in the replacement study contrasts with most literature suggesting

monotonic strength reduction with increasing RAP. This discrepancy may be attributed to the specific treatment methods (diesel washing) employed in this study, which removed the asphalt coating and potentially improved aggregate-cement bonding. Additionally, the use of RAP with specific gradation characteristics may have contributed to improved packing density at high replacement levels.

5.3 Practical Implications for Concrete Mix Design

The findings of this study have several practical implications for concrete mix design:

1. **Predictive Tool:** The Box-Behnken regression equation provides a practical tool for engineers to estimate flexural strength based on mix proportions, facilitating preliminary mix design and optimization.
2. **RAP Utilization:** The study demonstrates that RAP can be effectively utilized in concrete production, with appropriate mix design optimization. The identification of 75% RAP replacement as optimal for flexural strength (within the experimental conditions) suggests potential for high-volume RAP utilization.
3. **Factor Interactions:** The significant interaction effects highlight the importance of considering multiple factors simultaneously in mix design. Single-factor optimization approaches may miss opportunities for synergistic improvements.
4. **Treatment Methods:** The diesel treatment employed to remove asphalt coating from RAP aggregates appears to have contributed to improved performance, suggesting that preprocessing of RAP may be beneficial for enhancing concrete properties.

5.4 Limitations and Future Research

Several limitations of this study should be acknowledged:

1. **Single Response Focus:** While flexural strength was the focus of this analysis, multi-objective optimization considering compressive strength, durability, and cost would provide more comprehensive mix design guidance.
2. **Laboratory Conditions:** The study was conducted under controlled laboratory conditions; field validation would be necessary to confirm practical applicability.
3. **RAP Variability:** The RAP used in this study came from a single source; variability in RAP characteristics from different sources could affect model generalizability.
4. **Long-term Performance:** Only 28-day strength was considered; long-term durability and strength development beyond 28 days warrant investigation.

Future research should address:

- Multi-objective optimization incorporating strength, durability, and sustainability metrics
- Field validation of optimized mixes
- Investigation of RAP from multiple sources
- Long-term performance monitoring
- Comparison with other optimization methods (e.g., machine learning approaches)

6.0 Conclusion

This study successfully developed and validated a Box-Behnken Design model for predicting and optimizing the flexural strength of cement concrete containing Reclaimed Asphalt Pavement. The key conclusions are:

1. **Model Development:** A statistically significant regression model ($p = 0.040$) was developed for flexural strength prediction, incorporating linear, quadratic, and interaction effects of five mix design parameters.
2. **Model Adequacy:** The model demonstrated adequate fit, with normal probability plots confirming approximately normal distribution of residuals. The Lack-of-Fit test ($F = 1.03$, $p = 0.047$) indicated acceptable model performance.
3. **Optimization Result:** The Box-Behnken model identified an optimal flexural strength of **3.7829 N/mm²** through systematic optimization of mix proportions.

4. **RAP Replacement Effects:** In the replacement study, **75% RAP replacement** yielded the maximum flexural strength of **2.45 N/mm²** at 28 days, suggesting potential for high-volume RAP utilization with appropriate mix design.
5. **Comparative Performance:** While Scheffe's Simplex Lattice Model predicted a marginally higher optimal value (3.9394 N/mm²), the Box-Behnken Model demonstrated its own efficacy and statistical significance, offering a robust alternative for concrete optimization.
6. **Practical Implications:** The developed model provides a valuable predictive tool for engineers and researchers, facilitating the design of RAP-incorporated concrete mixtures with optimized flexural performance.

The study contributes to the growing body of knowledge on sustainable concrete production, demonstrating that with appropriate mix design optimization, RAP can be effectively utilized as a partial replacement for natural aggregates in concrete, contributing to resource conservation and environmental sustainability in the construction industry.

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