

Optimisation of Concrete Reinforced with Recycled Polypropylene Fibre from Cement Bags and Fly Ash using Scheffe Method



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ABSTRACT: Recent developments in sustainable concrete technology emphasise reducing cement usage and integrating waste-derived materials. This study examines the combined effects of fly ash and recycled polypropylene fibre (RPPF) obtained from cement bags on grade 20 concrete, utilising the Scheffé (6,2) simplex lattice method for modelling and optimisation. Twenty-one concrete mixtures were prepared with water, cement, river sand, crushed granite, fly ash, and RPPF. Fly ash replaced cement at proportions from 0% to 25%, and RPPF was added at 0% to 2.5% by cement weight. Cube and beam specimens were cast, cured, and tested for strength at 7 and 28 days. The 28-day compressive strengths ranged from 6.3 to 19.7 N/mm², while flexural strengths varied from 0.42 to 3.04 N/mm². Optimal mechanical properties were observed with moderate fly ash substitution and low RPPF content. The Scheffé model demonstrated high predictive accuracy, with R² values of 99.98% for compressive strength and 99.97% for flexural strength. The optimal mix ratio, 0.50:0.95:2.00:0.05:0.01:3.00 (Water: Cement: Fine Aggregate: Fly Ash: RPPF: Coarse Aggregate), yielded 28-day strengths of 19.17 N/mm² (compressive) and 2.59 N/mm² (flexural), thereby advancing sustainability goals while ensuring adequate mechanical performance.

KEYWORDS: Fly ash, recycled polypropylene fibre, cement bag fibres, Scheffé method, Mix optimisation, Compressive and Flexural strength.

[Received Dec. 17, 2025; Revised Jan. 15, 2026; Accepted Jan. 25, 2026]

Print ISSN: 0189-9546 | Online ISSN: 2437-2110

I. INTRODUCTION

The rapid growth of the construction industry has intensified global concerns regarding sustainability, particularly the environmental impact of cement production. Cement manufacturing accounts for approximately 5% to 8% of global anthropogenic CO₂ emissions due to its energy-intensive processes (Mohamad et al., 2021; Alobaydy, 2024). This has driven research into alternative materials and optimisation strategies aimed at reducing the carbon footprint of concrete while maintaining structural performance (Duchesne, 2021; Muñoz-Pérez et al., 2023).

Fly ash, a by-product of coal combustion, is one of the most widely used supplementary cementitious materials (SCMs) in concrete. Its utilisation supports waste valorisation and reduces clinker demand, thereby lowering CO₂ emissions (Duchesne, 2021; Li et al., 2022). In addition, fly ash improves concrete properties such as workability, sulphate resistance, and durability, although its effectiveness depends on replacement level and material characteristics (Samani et al., 2018; Akbulut et al., 2024). Excessive replacement may reduce early strength, highlighting the need for optimised proportions.

In parallel, recycling plastic waste for construction applications has gained increasing attention. Polypropylene fibre (PPF) is commonly used to improve tensile and flexural performance, control cracking, and enhance ductility (Song et

al., 2021). When sourced from waste cement bags, recycled polypropylene fibre (rPPF) offers a low-cost and environmentally sustainable alternative to virgin fibres (Lamba et al., 2022; Marthong, 2019). Previous studies have confirmed that fibres derived from cement bags improve crack resistance and mechanical performance while diverting plastic waste from landfills.

Recent studies have reported benefits from combining fly ash and polypropylene fibre in concrete systems. Akid et al. (2021) and Beskopylny et al. (2023) demonstrated improved flexural performance and durability when both materials are used together. However, the effectiveness of such hybrid systems is highly dependent on proportioning, as interactions between constituents significantly influence mechanical behaviour. Conventional mix design approaches are often inadequate for optimising multivariable concrete systems. Consequently, advanced statistical techniques such as Scheffé's simplex lattice method have been adopted to model and optimise concrete mixtures efficiently (Agunwamba et al., 2024). This has been successfully applied to concretes containing alternative aggregates and SCMs (Ndububa and Ogbo, 2022; Abah et al., 2023; Ogbo et al., 2023).

Nevertheless, most existing Scheffé-based studies focus on single-material modifications, with limited experimental application to hybrid systems incorporating both fly ash and recycled polypropylene fibre. Despite substantial global efforts

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to develop more sustainable concretes, few studies have rigorously optimised such hybrid systems using the Scheffé model. Most existing research evaluates each material separately or employs conventional mix-design methods that lack predictive capability for multi-component interactions. In addition, recycled polypropylene fibre sourced from waste cement bags has received very little research attention, despite its potential as a low-cost and sustainable reinforcement material. Therefore, the present study focuses on optimising the mechanical performance of concrete reinforced with rPPF derived from waste cement bags and fly ash using the Scheffé (6,2) simplex lattice method. The model is used to predict and optimise mix proportions for maximum compressive and flexural strength, supported by material characterisation and 7-day and 28-day strength testing.

The specific objectives of the study were to: characterise the constituent materials, with particular emphasis on fly ash and RPPF; design concrete mixtures with varying proportions of fly ash and RPPF using the Scheffé simplex lattice method; evaluate compressive and flexural strengths at 7 and 28 days, and optimise the mixture proportions to improve mechanical performance using Scheffé's regression models. This study advances sustainable concrete technology by presenting an optimisation-based framework for a hybrid concrete system incorporating fly ash and recycled polypropylene fibre derived from waste cement bags. The contribution of this study lies in the systematic application of a six-component Scheffé mixture design to optimise the combined use of these materials, validated through experimental compressive and flexural strength testing. The findings provide practical guidance for engineers in designing hybrid concrete mixes with predictable mechanical performance while prioritising the reuse of plastic waste from cement bags. The remainder of the paper is organised as follows: Section 2 presents the theoretical analysis; Section 3 describes the materials and methods; Section 4 discusses the results; and Section 5 concludes with key findings and recommendations for future research.

II. THEORETICAL ANALYSIS

A. Mixture Theory and Scheffé Design

Optimising concrete mixtures containing multiple interacting constituents requires a modelling approach that captures the combined effect of the constituents. Conventional optimisation methods often fail to adequately represent nonlinear interactions in systems incorporating fly ash and recycled polypropylene fibres. Mixture theory addresses this limitation by expressing concrete performance as a function of component proportions rather than absolute quantities. For a mixture with q components, the proportions X_i are constrained as shown in equation (1).

$$\sum_{i=1}^q X_i = 1, \text{ with } 0 \leq X_i \leq 1 \quad (1)$$

where X_i represents the pseudo-component proportion of the i^{th} mixture component and q is the total number of components in the mixture. This constraint ensures that the mixture proportions are non-negative and collectively sum to unity,

consistent with Scheffé's mixture theory (Agunwamba et al., 2024).

The Scheffé simplex lattice design offers a systematic approach for modelling mixture behaviour and predicting response variables such as compressive and flexural strengths. The second-degree Scheffé model represents the mixture response Y as indicated in equation (2):

$$Y = \sum_{i=1}^q \beta_i X_i + \sum_{i<j} \beta_{ij} X_i X_j \quad (2)$$

with β_i representing the linear blending effect of the i th component and corresponds to the predicted response at the vertex of the simplex where that component dominates. The interaction coefficient β_{ij} captures the combined effect of components i and j . Positive values indicate synergistic interactions that enhance strength development, while negative values indicate antagonistic interactions that reduce mechanical performance. This formulation accounts for nonlinear effects arising from pozzolanic reactions, fibre-matrix interaction, and aggregate packing (Ndububa and Ogbo, 2022). Equation (3) defines the number of mixture points necessary to estimate all model coefficients:

$$N = \frac{(m+q-1)!}{m!(q-1)!} \quad (3)$$

where m denotes the degree of the Scheffé polynomial and q represents the number of mixture components. In this study, a quadratic model ($m = 2$) was adopted for a six-component concrete system ($q = 6$).

The linear transformation described in equation (4) converts normalised pseudo-components into concrete batch values:

$$Z = X.A \quad (4)$$

where Z represents the actual mixture proportions, and A is the transformation matrix that maps pseudo-components into real concrete mix constituents while satisfying predefined practical bounds for cement, fly ash, recycled polypropylene fibre, aggregates, and water (Agunwamba et al., 2024).

1. Numerical illustration of pseudo-component transformation

The relationship between the pseudo-components X_i and the actual mixture components Z_i is expressed in equation (4). For the Scheffé N(6,2) design used in this study, the transformation matrix is:

$$A = \begin{bmatrix} 0.50 & 0.50 & 0.50 & 0.50 & 0.50 & 0.50 \\ 1.00 & 0.95 & 0.90 & 0.85 & 0.80 & 0.75 \\ 2.00 & 2.00 & 2.00 & 2.00 & 2.00 & 2.00 \\ 0.00 & 0.05 & 0.10 & 0.15 & 0.20 & 0.25 \\ 0.00 & 0.01 & 0.01 & 0.02 & 0.02 & 0.03 \\ 3.00 & 3.00 & 3.00 & 3.00 & 3.00 & 3.00 \end{bmatrix}$$

Consider an optimised pseudo-component vector:

$$\{X\} = [0.30 \ 0.20 \ 0.15 \ 0.15 \ 0.10 \ 0.10]^T$$

which satisfies Equation (1), substitution into Equation (4) yields the corresponding actual mixture proportions for cement, fine aggregate, coarse aggregate, fly ash, recycled

polypropylene fibre, and water. This transformation ensures that all optimised mixtures remain within practical mix-design limits while satisfying Scheffé mixture constraints.

2. Regression Analysis and Optimisation

Model coefficients are estimated by fitting experimental data to the Scheffé polynomial using the least-squares method. Model adequacy is evaluated using the coefficient of determination (R^2), as defined in equation (5)

$$R^2 = 1 - \frac{\sum(Y_{exp} - Y_{pred})^2}{\sum(Y_{exp} - \bar{Y}_{exp})^2} \quad (5)$$

High R^2 values indicate strong agreement between experimental and predicted responses, confirming the suitability of the model for mixture optimisation. The optimisation procedure identifies mixture proportions that maximise compressive and flexural strength within the defined simplex domain, providing a robust framework for analysing and improving sustainable concrete mixtures incorporating fly ash and recycled polypropylene fibre.

III. MATERIALS AND METHODS

A. Materials

Concrete mixes were produced using six constituents: cement, fine aggregate, coarse aggregate, fly ash, recycled polypropylene fibre (RPPF) sourced from waste cement bags, and water. All materials, except fly ash, were obtained locally in Abuja, Nigeria. Fly ash was sourced from a tile manufacturing facility in Ajaokuta, Kogi State, Nigeria.

1. Cement

Ordinary Portland Cement (OPC) of the Dangote brand (Grade 42.5N) was used. The cement was visually inspected to confirm it was free from lumps and visible impurities. Further characterisation tests were conducted to verify its compliance with concrete production requirements in accordance with the relevant British Standard (BS EN 197-1).

2. Fine aggregate

Well-graded natural river sand passing the 4.75 mm sieve was used as fine aggregate. The sand was free from organic impurities that could adversely affect the quality of the concrete.

3. Coarse aggregate

Crushed granite served as the coarse aggregate. The material was free from dust, clay, and deleterious substances. Sieve analysis was conducted using standard sieves in accordance with BS 812-103.1:1985 to determine particle size distribution.

4. Fly ash

The fly ash (Figure 1) was obtained in a dry powdered form and stored in an airtight bag. Its chemical composition was determined using Energy-Dispersive X-ray Fluorescence (EDXRF) analysis to confirm suitability as a supplementary cementitious material.



Figure 1 Fly ash in a sack

5. Recycled polypropylene fibre (from cement bags)

The recycled polypropylene fibres, illustrated in Figure 2, were obtained from used cement bags collected at construction sites. The bags were washed, dried, and cut into fibre strips approximately 30 mm in length before incorporation into the concrete mixes.



Figure 2 Recycled polypropylene fibres shredded and cut to size

6. Water

Clean potable water, free of oil and suspended impurities, was used for mixing and curing to ensure proper cement hydration and strength development.

B. Methods

1. Material characterisation

The physical, chemical, and mechanical properties of all constituent materials were evaluated in accordance with relevant British Standards to confirm their suitability for concrete production. Sieve analysis was conducted on river sand and crushed granite in accordance with BS 812-103.1:1985 to determine particle size distribution and fineness modulus, while specific gravity was determined following BS 1377-2:1990. Ordinary Portland Cement was tested for standard consistency and setting times using a Vicat apparatus in accordance with BS EN 196-3:2016. Fly ash was characterised for chemical composition using Energy-Dispersive X-ray Fluorescence (EDXRF), and its specific gravity and surface area were determined to confirm its suitability as a supplementary cementitious material. Recycled polypropylene fibre (RPPF) obtained from discarded cement bags was tested for tensile strength using a Universal Testing Machine by axially loading individual

fibres to failure. These tests confirmed that all materials met the requirements for producing fly ash-modified, fibre-reinforced concrete optimised using Scheffé's method.

2. Mix design and sample preparation

Concrete mixes were first designed using the conventional mix design method. Scheffé's second-degree (6, 2) simplex lattice design model was then applied to generate mixture points. The target grade was C20, characterised by a 28-day compressive strength of 20 N/mm². The mix consisted of six components: cement, river sand (fine aggregate), crushed granite (coarse aggregate), fly ash, RPPF and water. Fly ash was incorporated as a partial replacement for cement at 0%, 5%, 10%, 15%, 20%, and 25% by weight of cement, while RPPF was added at 0%, 0.5%, 1%, 1.5%, 2%, and 2.5% by weight of cement.

Substituting m=2 and q=6 into the relevant expression for determining the number of mixture points in equation (3) yielded the number of mixture points, as shown in equations (6) and (7):

$$N = \frac{(2+6-1)!}{2!(6-1)!} \quad (6)$$

$$N = \frac{7!}{2!(5)!} = \frac{5040}{2 \times 120} = 21 \quad (7)$$

This produced 21 mixes: one control (S1) without fly ash or fibre, and 20 variations (S2–S21) with different fly ash and RPPF contents. All batches were mixed manually using a consistent sequence and duration to minimise variability. Cement, fine aggregate, and fly ash were first dry-mixed, followed by gradual addition of RPPF to ensure uniform fibre dispersion. Coarse aggregate and water were subsequently added and mixed to achieve a homogeneous concrete. Slump tests were conducted immediately after concrete mixing. Fresh concrete was cast into cube moulds for compressive strength testing and beam moulds for flexural strength testing. After 24 h, specimens were demoulded and water-cured for 7 and 28 days.

3. Compressive strength test

Compressive strength was determined using 150 × 150 × 150 mm cube specimens at 7 and 28 days in accordance with standard procedures. Specimens were tested using a Universal Testing Machine, and compressive strength was calculated using Equation (8). The average value of three specimens was recorded for each mix.

$$\text{Compressive strength} = \frac{\text{Maximum Load}}{\text{Cross-section Area}} \quad (8)$$

4. Flexural strength test

Flexural strength was assessed using beam specimens of dimensions 100 × 125 × 225 mm after 7 and 28 days of curing. Testing was conducted under a three-point loading arrangement, and flexural strength was calculated using Equation (9). The beam dimensions and loading configuration were maintained consistently for all specimens to enable a reliable comparative evaluation of flexural performance among the different concrete mixtures. The same specimen geometry and loading procedure were applied throughout the study to ensure consistency of the flexural

strength results. For each mix, the average flexural strength value obtained from three tested specimens was recorded.

$$\text{Flexural strength (N/mm}^2\text{)} = \frac{3PL}{2bd^2} \quad (9)$$

$$L = 225\text{mm, } b = 100\text{mm, } d = 125\text{mm}$$

5. Regression modelling and mix optimisation

A second-degree Scheffé simplex lattice regression model was employed to relate mixture proportions to mechanical properties. The six mixture components were cement (x_1), fine aggregate (x_2), coarse aggregate (x_3), fly ash (x_4), recycled polypropylene fibre (x_5), and water (x_6). The responses were the 7-day and 28-day compressive and flexural strengths. The general form of the second-degree Scheffé model for a six-component system is expressed in equation (10) as:

$$Y(X) = \sum_{i=1}^6 \beta_i X_i + \sum_{i=1}^5 \sum_{j=i+1}^6 \beta_{ij} X_i X_j \quad (10)$$

Experimental results from the 21 mixes were used to compute blending and interaction coefficients, producing predictive models for compressive and flexural strengths. Predicted strengths for each mix were compared with experimental values to validate the model. The mix with the highest predicted strength within the fly ash and rPPF limits was selected as optimal.

II. RESULTS AND DISCUSSION

A. Materials Characterisation

The constituent materials satisfied standard requirements for concrete production. The Ordinary Portland Cement (OPC) had a standard consistency of 32% and setting times of 50 and 230 minutes, ensuring adequate workability. The fine aggregate (river sand) had a fineness modulus of 2.83 and a specific gravity of 2.57. The coarse aggregate (crushed granite) had a maximum particle size of 19 mm and a specific gravity of 2.69, indicating a well-graded aggregate. The fly ash possessed a specific gravity of 2.50 and a specific surface area of 3822 cm²/g. Its major oxide composition in Table 1 consisted of SiO₂ (51.98%), Al₂O₃ (11.39%), and Fe₂O₃ (15.13%), giving a combined total of 78.50%, which exceeds the ASTM C618 requirement of 70% for Class F fly ash. The CaO content of 2.28% in Table 1 further confirmed its Class F classification, indicating that it contributes primarily to long-term pozzolanic activity. The RPPF from discarded cement bags exhibited tensile breaking loads of 0.26–0.53 N, providing sufficient crack-bridging capacity and demonstrating its suitability as a sustainable secondary reinforcement in concrete (Lamba et al., 2022).

Table 1 Major Oxide Composition of Fly Ash Used

Oxide	Content (%)
SiO ₂	51.979
Al ₂ O ₃	11.388
Fe ₂ O ₃	15.132
Total (SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃)	78.499
CaO	2.2786

B. Compressive and Flexural Strength Results

1. Compressive strength

The compressive strength of all concrete mixes increased with curing time, reflecting cement hydration and the delayed pozzolanic activity of fly ash (Figure 3). At 7 days, strengths ranged from 2.4 N/mm² (Mix S5) to 10.3 N/mm² (Mix S1), while at 28 days they ranged from 6.3 N/mm² (Mix S6) to 19.7 N/mm² (Mix S1). The control mix (S1), with 100% cement, achieved the highest 28-day strength of 19.7 N/mm², consistent with the C20 target strength. Comparable strengths were observed for S2, S8, and S19 (≈19.2 N/mm²), which included moderate fly ash replacement (≤15%) and low RPPF content (≤1%). This demonstrates that appropriately proportioned fly ash and fibres can yield compressive strengths similar to conventional concrete.

Mixes with high fly ash replacement (≥20%) and RPPF content (>2%), such as S5, S6, and S18, exhibited the lowest 28-day strengths (6.3–8.4 N/mm²). The reductions are attributed to the delayed pozzolanic reaction of Class F fly ash and compaction challenges due to excessive fibre content, consistent with prior observations in polypropylene fibre-reinforced concretes (Song et al., 2021; Akid et al., 2021). These results indicate that compressive strength is governed by the balance between fly ash replacement and RPPF dosage, rather than the effect of either material alone. Moderate fly ash improved matrix packing, and low fibre content did not hinder compaction. Higher fibre contents increased void formation, while excessive fly ash reduced the effective binder at 28 days, lowering strength.

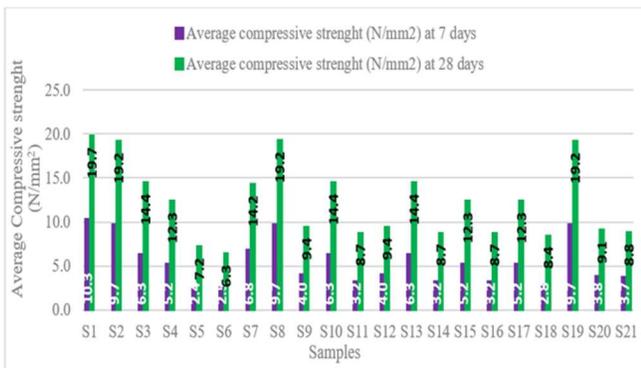


Figure 3 Average compressive strength of samples at 7 and 28 days of curing

2. Flexural strength

The flexural strength increased from 7 to 28 days, reflecting the combined effects of cement hydration, the pozzolanic contribution of fly ash, and fibre bridging within the concrete matrix. As shown in Figure 4, the 7-day strengths ranged from 0.26 to 2.91 N/mm², while the 28-day strengths varied between 0.42 and 3.04 N/mm². The highest 28-day strength (3.04 N/mm²) was achieved by S7, which combined moderate fly ash replacement with low RPPF content, demonstrating that limited fibre inclusion improves crack control and post-cracking behaviour. Moderate-performing mixes, including S2, S8, and S19, recorded approximately 2.59 N/mm², indicating that moderate fly ash and fibre enhance matrix continuity without compromising bond strength.

Mixes with high fly ash (≥20%) and RPPF (≥2%), such as S4, S5, and S18, showed the lowest 28-day strengths (<0.75 N/mm²). Reduced performance is attributed to delayed pozzolanic reaction and fibre clustering, which impair workability and increase void formation. Overall, flexural strength is governed by both matrix integrity and fibre effectiveness, consistent with previous reports that moderate fibre inclusion improves flexural behaviour, whereas excessive fibre and high supplementary cementitious material contents hinder stress transfer (Song et al., 2021; Lamba et al., 2022; Akid et al., 2021).

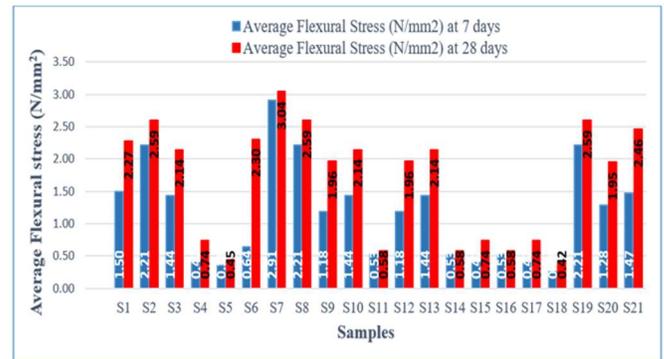


Figure 4 Average flexural stress of samples at 7 and 28 days of curing

All beam specimens exhibited failure patterns characteristic of flexural behaviour under three-point loading. Cracking initiated at the tensile face near the mid-span and propagated vertically through the depth of the beam, resulting in a dominant flexural crack at failure. No inclined cracking near the supports or other indicators of shear-dominated failure were observed. These observations confirm that the measured flexural strength values are representative of flexural tensile behaviour, consistent with the representative failure pattern shown in Figure 5.



Figure 5 Typical flexural failure pattern of concrete beam specimen under three-point loading, showing dominant mid-span cracking.

C. Scheffe Optimisation Analysis

The experimental results were analysed using Scheffe’s simplex lattice design model to develop predictive equations for compressive and flexural strengths, and to identify optimal mix proportions.

1. Strength response and mixture component modelling

The six-component mixtures: cement, fine aggregate, coarse aggregate, fly ash, recycled polypropylene fibre

(RPPF), and water, were modelled using a quadratic Scheffé polynomial across 21 experimental points.

The compressive strength response was determined and is presented in Equation 11 as follows:

$$n_c(X) = 19.70X_1 + 19.17X_2 + 14.43X_3 + 12.33X_4 + 7.17X_5 + 6.33X_6 - 10.27X_1X_2 + 4.71X_1X_3 - 12.93X_1X_4 + 0.46X_1X_5 - 12.53X_1X_6 - 19.54X_2X_3 + 0.46X_2X_4 - 12.94X_2X_5 - 2.01X_2X_6 - 12.93X_3X_4 + 0.46X_3X_5 - 0.06X_3X_6 - 0.06X_4X_5 + 0.87X_4X_6 - 0.06X_5X_6 \quad (11)$$

The coefficient of determination $R^2 = 99.98$

The flexural strength response was determined and is expressed in Equation 12 as follows:

$$n_f(X) = 2.27X_1 + 2.59X_2 + 2.14X_3 + 0.74X_4 + 0.45X_5 + 2.30X_6 + 1.50X_1X_2 + 1.50X_1X_3 + 0.88X_1X_4 + 1.50X_1X_5 - 2.38X_1X_6 - 1.50X_2X_3 - 0.88X_2X_4 - 1.50X_2X_5 - 2.38X_2X_6 - 0.88X_3X_4 - 0.88X_3X_5 - 2.38X_3X_6 - 0.88X_4X_5 + 0.88X_4X_6 - 2.38X_5X_6 \quad (12)$$

The coefficient of determination $R^2 = 99.97$.

The high coefficients of determination indicate excellent agreement between experimental and predicted responses, consistent with prior applications of Scheffé’s method in multi-component optimisation (Song et al., 2021). Such values are expected for mixture models developed within a simplex lattice design, as experimental points are generated from the design space itself. Twenty-one mixture points were used, which is sufficient to support a quadratic model of the six-component system and to perform optimisation within the established mixture constraints.

The mixture component transformation was applied to convert the optimised pseudo-component proportions obtained from

the Scheffé model into practical batching quantities. This was achieved using the A-matrix formulation described in Section 2, which maps the normalised pseudo-components to actual mixture proportions of cement, fine aggregate, coarse aggregate, fly ash, recycled polypropylene fibre, and water. The transformation ensured that all recommended mixes satisfied the mixture constraints and predefined practical bounds, enabling direct implementation for laboratory batching and strength evaluation.

2. *Strength optimisation and validation*

The experimental 28-day compressive and flexural strengths of the 21 concrete mixes ranged from 6.33 to 19.70 N/mm² and 0.42 to 3.04 N/mm², respectively. Scheffé’s quadratic model was used to optimise mix proportions for maximum strength while incorporating fly ash and recycled polypropylene fibre (RPPF). As shown in Table 2, the optimal pseudo-component mix for compressive strength was $X_1 = 0.60$, $X_2 = 0.40$ (others = 0), predicting 19.65 N/mm². For flexural strength, $X_1 = 0.50$, $X_2 = 0.50$ yielded 3.04 N/mm². The corresponding real mix proportions (Z-values) were identical for both responses: $Z_1 = 0.50$, $Z_2 = 0.98$, $Z_3 = 2.00$, $Z_4 = 0.03$, $Z_5 = 0.00$, $Z_6 = 3.00$, facilitating practical batching. The model validation showed strong agreement between predicted and experimental results ($R^2 = 99.98\%$ for compressive, 99.97% for flexural), confirming model robustness. Optimal performance was achieved with $\leq 15\%$ fly ash and $\leq 1\%$ RPPF, consistent with S2, S7, S8, and S19, which recorded 28-day compressive strengths of 19.2–19.7 N/mm² and flexural strengths of 2.6–3.0 N/mm². Higher fly ash or fibre contents reduced performance.

Table 2: Optimised Mix Proportions

Strength Type	X1	X2	X3	X4	X5	X6	Z1	Z2	Z3	Z4	Z5	Z6	Strength (N/mm ²)
Compressive	0.60	0.40	0	0	0	0	0.50	0.98	2.00	0.03	0.00	3.00	19.65
Flexural	0.50	0.50	0	0	0	0	0.50	0.98	2.00	0.03	0.00	3.00	3.04

3. *Material composition optimisation and recommended mix*

The experimental strengths in Figure 3 and Figure 4 show that Sample S1 (control sample) achieved the highest compressive strength (19.7 N/mm², 2.27 N/mm² flexural), while Sample S7 recorded the highest flexural strength (3.04 N/mm², 14.2 N/mm² compressive). Mixes S2, S8, and S19 showed balanced performance (19.2 N/mm² compressive, 2.59 N/mm² flexural), confirming that peak compressive and flexural strengths did not occur in the same mix.

The Scheffe model produced three optimised mixes presented in Table 3. Mix 1 achieved the highest strengths (19.65 N/mm² in compression, 3.04 N/mm² in flexure) but excluded RPPF, contrary to the study’s goal of evaluating waste fibre. Mix 2 included both fly ash and RPPF, achieving 19.17 N/mm²

compressive and 2.59 N/mm² flexural strength, slightly below Mix 1 but still satisfying Grade 20 requirements.

The selection of the optimal mix prioritised a balance between mechanical performance and sustainability rather than maximising individual strength values. While Mix 1 achieved the highest compressive and flexural strengths, it excluded recycled polypropylene fibre (RPPF), contrary to the study’s objective of promoting waste material utilisation. Mix 2 incorporated both fly ash as partial cement replacement and RPPF derived from waste cement bags, achieving compressive and flexural strengths of 19.17 N/mm² and 2.59 N/mm², respectively, which satisfy the requirements for Grade 20 concrete. The inclusion of fly ash and RPPF in Mix 2 reduces cement demand and promotes plastic waste reuse, making it the preferred mix when both structural performance and sustainability considerations are jointly evaluated.

Table 3: Recommended Mix Proportions

Mixes	Z1	Z2	Z3	Z4	Z5	Z6	Compressive Strength (N/mm ²)	Flexural Strength (N/mm ²)
Mix 1	0.50	0.98	2.00	0.03	0.00	3.00	19.65	3.04
Mix 2	0.50	0.95	2.00	0.05	0.01	3.00	19.17	2.59
Mix 3	0.50	0.94	1.98	0.05	0.00	2.97	19.17	2.59

IV. CONCLUSION

This study demonstrated the effectiveness of Scheffé's simplex lattice method in optimising concrete incorporating fly ash and recycled polypropylene fibre derived from waste cement bags. The results confirmed that sustainable Grade 20 concrete can be produced by appropriately balancing fly ash replacement and fibre inclusion, maintaining compressive strength while enhancing flexural performance. The developed Scheffé regression models exhibited strong predictive capability for both compressive and flexural strength, providing a reliable framework for mixture optimisation in multi-component concrete systems. Mechanical performance was found to depend on the continuity of the cementitious matrix, enhanced by fly ash replacement, and the crack-bridging efficiency of recycled polypropylene fibres, with overall strength governed by their synergistic interaction. These findings indicate that optimal concrete performance is achieved through proportioning synergy rather than the dosage of individual components in isolation. The results demonstrate that hybrid concrete incorporating fly ash and recycled polypropylene fibres from waste cement bags can achieve reliable mechanical performance while supporting the reuse of plastic waste. The predictive models, validated through experimental testing, provide practical guidance for the design of sustainable concrete mixes with predictable mechanical performance. Future research should focus on the durability and microstructural performance of these optimised mixtures under varying environmental conditions to confirm their long-term suitability for sustainable construction applications.

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