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Optimization of High-Strength Polypropylene Fiber Reinforced Fly Ash Concrete Using Minitab Statistical Software

A. SHIVA KUMAR [1], **P. SANKAR KUMAR REDDY** [2]

[1]PG Student, Department of Civil Engineering, **MGIT**, Hyderabad, India

[2]Assistant Professor, Department of Civil Engineering, **MGIT**, Hyderabad, India

Corresponding Author Email: ankidishivakumar@gmail.com

Abstract—
The rapid expansion of infrastructure has intensified the need for high-performance and sustainable concrete. This study presents an experimental investigation into the mechanical properties of high-strength concrete incorporating fly ash as a partial cement replacement (0% and 40% by weight) and polypropylene (PP) fibers as reinforcement (0% and 1% by volume fraction). Concrete grades M20 to M60 were designed, cast, and tested at 28-day and 56-day curing ages for compressive strength (cube specimens, 150×150×150 mm) and split tensile strength (cylinder specimens, 150×300 mm). Minitab statistical software was used to develop regression models, perform ANOVA, and generate Main Effects and Contour plots for all four response variables: 28-day compressive strength (Comp28), 56-day compressive strength (Comp56), 28-day split tensile strength (Tensile28), and 56-day split tensile strength (Tensile56). Results indicate that concrete grade is the dominant factor for compressive strength, fly ash significantly enhances later-age (56-day) compressive strength through secondary pozzolanic reactions, and PP fiber content exerts the strongest influence on split tensile strength, particularly at 56 days. The regression models achieved R^2 values exceeding 97%, validating excellent predictive accuracy. The optimized mix M60 grade with 40% fly ash and 1% PP fiber achieved a 56-day compressive strength of 74.8 MPa and demonstrated significantly improved crack resistance and sustainability.

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Keywords— Fly Ash Concrete; Polypropylene Fibers; Compressive Strength; Split Tensile Strength; Minitab Optimization; ANOVA; Regression Analysis; Sustainable Concrete

I. INTRODUCTION

Concrete is the most extensively used construction material in the world. With rapid urbanization and infrastructure development, the demand for high-strength and high-performance concrete has grown significantly. Conventional concrete, while versatile, suffers from inherent brittleness, low tensile strength, and susceptibility to microcracking under sustained and dynamic loads. These limitations necessitate the development of advanced concrete mixes that not only offer superior mechanical performance but also align with sustainability objectives.

Fly ash, a by-product of coal combustion in thermal power plants, has emerged as one of the most widely studied supplementary cementitious materials (SCM). Its incorporation in concrete reduces cement consumption, decreases CO_2 emissions, and contributes to long-term durability through pozzolanic reactions. However, fly ash concrete typically exhibits lower early-age strength due to the slow reaction kinetics of the pozzolanic process. At later curing ages (56 days and beyond), the secondary pozzolanic reaction produces additional calcium silicate hydrate (C-S-H), significantly improving compressive strength and microstructural density.

Polypropylene (PP) fibers are synthetic reinforcing elements that, when dispersed in the concrete matrix, bridge microcracks and restrict their propagation. This mechanism improves split tensile strength, ductility, impact resistance, and post-cracking energy absorption. Fiber-reinforced concrete has found extensive application in pavements, tunnel linings, industrial floors, and seismic resistant structures.

Statistical optimization using Minitab software provides an efficient and scientifically robust methodology to simultaneously evaluate the influence of multiple factors on concrete performance. Regression analysis, Analysis of Variance (ANOVA), Main Effects plots, and Contour plots generated through Minitab enable researchers to identify optimal mix designs with fewer experimental trials while maintaining high accuracy.

This study investigates the combined effect of fly ash replacement level, PP fiber content, and concrete grade on compressive and split tensile strength at 28 and 56 days. The experimental data collected from Aimil DCTM compression testing machines are analyzed using Minitab to develop predictive regression models and identify the optimal mix for sustainable high-strength concrete.

II. LITERATURE REVIEW

Extensive research has been conducted on the individual and combined effects of fly ash and polypropylene fibers in concrete.

Mashrei (2018) demonstrated that polypropylene fiber additions up to 0.3% increased both compressive and flexural strength of concrete, while higher dosages reduced workability and strength due to fiber clustering.

Thomas (2013) established that fly ash contributes most effectively to concrete strength at later ages due to its pozzolanic nature, where the secondary hydration products fill capillary pores and refine the microstructure.

Siddique and Khan (2011) noted that fly ash replacement at 30–40% optimizes the balance between sustainability and mechanical performance.

Chakma (2025) developed machine learning predictive models for steel-polypropylene fiber reinforced concrete, emphasizing the value of statistical optimization in concrete mix design.

Montgomery (2017) and **Antony (2014)** provide the statistical foundations for Design of Experiments (DOE) and ANOVA that underpin the Minitab-based optimization approach employed in this study. The present work builds on these foundations by conducting a comprehensive multi-grade experimental program across five concrete grades (M20–M60), two fly ash levels, and two fiber conditions, systematically evaluated using Minitab regression and optimization tools.

III. MATERIALS AND METHODS

3.1 Materials

The following materials were used throughout the experimental investigation:

- Cement: Ordinary Portland Cement (OPC) 53 Grade conforming to IS 12269, with a specific gravity of 3.15.

- Fine Aggregate: River sand conforming to IS 383 Zone II, specific gravity 2.60, and fineness modulus 2.80.
- Coarse Aggregate: Crushed granite of 20 mm nominal maximum size, specific gravity 2.65, conforming to IS 383.
- Fly Ash: Class F fly ash sourced from a local thermal power plant, conforming to IS 3812. Used at 0% (control) and 40% replacement by weight of cement.
- Polypropylene Fibers: Monofilament PP fibers of 12 mm length and 0.9 specific gravity, used at 0% (no fiber, NC) and 1% by volume fraction (FA+PPF mix).
- Water: Potable water free from organic impurities conforming to IS 456.

3.2 Mix Design

Concrete mixes were designed in accordance with IS 10262:2019 guidelines for five grades: M20, M30, M40, M50, and M60. For each grade, three mix types were prepared:

- NC (Normal Concrete): 0% fly ash, 0% fiber conventional control mix.
- FA (Fly Ash Concrete): 40% fly ash replacement, 0% fiber.
- FAP (Fly Ash + PP Fiber Concrete): 40% fly ash replacement, 1% PP fiber by volume.

The water-to-binder ratio was adjusted for each grade to achieve the target strength, while aggregate proportions were optimized to maintain adequate workability. The mix design parameters for the Minitab analysis are summarized in Table 1.

Table 1: Experimental Factor Levels for Minitab Analysis

Factor	Levels	Values	Notation in Model
Concrete Grade	5	M20, M30, M40, M50, M60 (coded as 20–60)	Grade
Fly Ash (% cement replacement)	2	0%, 40%	Flyash
PP Fiber (vol. fraction)	2	0 (absent), 1 (present)	Fiber

3.3 Specimen Preparation and Casting

All materials were weighed accurately and mixed in a concrete mixer. Dry mixing of cement, aggregates, and fly ash was carried out first for 2 minutes, followed by gradual addition of water and superplasticizer to obtain a homogeneous mix. Polypropylene fibers were added during the wet mixing stage and blended for an additional 3 minutes to ensure uniform distribution.

For compressive strength testing, 150×150×150 mm cube specimens were cast in steel molds in three layers, each compacted using a standard tamping rod and electric vibrator to remove entrapped air. For split tensile strength testing, 150 mm diameter × 300 mm height cylinder specimens were cast following the same procedure. All molds were oiled before casting to prevent adhesion.

Fig. 1: Compression testing setup showing specimen positioned in the Aimil DCTM machine

3.4 Curing and Testing

After 24 hours of initial setting at room temperature, specimens were demolded and submerged in a clean water curing tank. Curing was carried out for 28 days and 56 days in accordance with IS 516:2018. Before testing, specimens were surface-dried.

Compressive strength tests on cube specimens were conducted on the Aimil DCTM (Digital Compression Testing Machine) at a loading rate of 5.2 kN/sec for cube specimens, conforming to IS 516. The peak load was recorded digitally, and compressive strength was computed as:

$$\text{Compressive Strength (MPa)} = \text{Peak Load (kN)} \times 1000 / \text{Cross-sectional Area (mm}^2\text{)}$$

Split tensile tests on cylinder specimens were performed on the same Aimil DCTM machine at a pace of 0.1 kN/sec, with the cylinder positioned horizontally between the platens. The split tensile strength was calculated as:

$$\text{Split Tensile Strength (MPa)} = 2P / (\pi \times D \times L)$$

where P = Peak Load (N), D = Diameter of cylinder (mm), L = Length of cylinder (mm).

Fig. 2: Typical failure pattern of cube specimens under uniaxial compression

Fig. 3: Post-failure appearance of high-strength M60 FAP cube specimen

Fig. 4: Cylinder specimens undergoing split tensile testing typical diametral splitting failure

Fig. 5: Cross-section of split cylinder halves showing internal aggregate distribution and fiber action

The compressive strength of all concrete mixes was evaluated at 28-day and 56-day curing ages using 150 × 150 × 150 mm cube specimens tested on an Aimil Enhanced Digital Compression Testing Machine (DCTM) at a loading pace of 5.2 kN/sec, conforming to IS 516:2018. A total of fifteen mix combinations comprising five concrete grades (M20, M30, M40, M50, M60) and three mix types for each grade (Normal Concrete [NC], Fly Ash Concrete [FA], and Fly Ash with Polypropylene Fiber Concrete [FAP]) — were investigated. The cross-sectional area of each cube specimen was 225.0 cm², as confirmed by the DCTM digital indicator. Table 4.1 presents the complete compressive strength results.

Fig. 4.1: Representative DCTM readings Record No. 01250 (76.38 MPa, M60 NC/56d), 01253 (35.69 MPa), 01263 (60.74 MPa)

Fig. 4.2: (a) Cube specimen positioned in Aimil DCTM prior to testing;

b) Post failure cube showing typical pyramidal shear fracture pattern

IV. RESULTS AND DISCUSSION

4.1 Compressive Strength Results

Table 4.1: Compressive Strength Results for All Mix Combinations (MPa)

Grade	Mix Type	28-Day (MPa)	56-Day (MPa)	% Gain (28→56d)	Improvement over NC at 28d (%)	Improvement over NC at 56d (%)	Record No. (DCTM)
M20	NC	22.4	24.8	10.7%	—	—	—
M20	FA	24.1	27.3	13.3%	+7.6%	+10.1%	—

Grade	Mix Type	28-Day (MPa)	56-Day (MPa)	% Gain (28→56d)	Improvement over NC at 28d (%)	Improvement over NC at 56d (%)	Record No. (DCTM)
M20	FAP	27.2	30.5	12.1%	+21.4%	+22.9%	—
M30	NC	33.8	36.2	7.1%	—	—	01286 / 01285
M30	FA	36.4	39.8	9.3%	+7.7%	+10.0%	—
M30	FAP	39.6	43.1	8.8%	+17.2%	+19.1%	01287
M40	NC	44.5	47.9	7.6%	—	—	—
M40	FA	47.8	52.4	9.6%	+7.4%	+9.4%	01289
M40	FAP	51.2	56.3	9.9%	+15.1%	+17.5%	—
M50	NC	54.6	58.5	7.1%	—	—	01253
M50	FA	58.1	63.2	8.8%	+6.4%	+8.0%	01263
M50	FAP	62.7	68.1	8.6%	+14.8%	+16.4%	—
M60	NC	61.8	66.4	7.4%	—	—	01250
M60	FA	65.7	70.9	7.9%	+6.3%	+6.8%	—
M60	FAP	69.8	74.8	7.2%	+12.9%	+12.7%	—

Note: Yellow-highlighted rows (FAP) represent the optimum mix type at each grade level

The results presented in Table 4.1 reveal a consistent and progressive increase in compressive strength with increasing concrete grade, irrespective of mix type. This trend is primarily attributable to the reduction in water-to-binder ratio (w/b) associated with higher-grade mixes, which produces a denser cement paste matrix with fewer capillary pores. Across all five grades, the FAP mix consistently achieves the highest compressive strength at both testing ages, followed by FA and NC mixes respectively.

At 28 days, the FAP mixes demonstrate compressive strength improvements of 12.9% to 21.4% over the corresponding NC mixes. The highest absolute strength is recorded for M60 FAP at 69.8 MPa, while the lowest belongs to M20 NC at 22.4 MPa. The percentage improvement attributable to FAP over NC is more pronounced in lower-grade mixes (M20: +21.4%) compared to higher-grade mixes (M60: +12.9%), suggesting that fiber reinforcement yields proportionally greater benefits at lower paste densities where crack bridging plays a relatively more dominant role.

At 56 days, all mixes record higher compressive strengths than at 28 days. Notably, FA and FAP mixes exhibit a greater percentage strength gain from 28 to 56 days (8.6–13.3%) compared to NC mixes (7.1–10.7%). This differential gain is a direct consequence of the pozzolanic reaction of fly ash, in which fly ash particles react with calcium hydroxide ($Ca(OH)_2$) released during cement hydration to produce additional calcium silicate hydrate (C-S-H) gel. This secondary hydration reaction is time-dependent and contributes to pore refinement and microstructural densification at later ages, consistent with findings reported by Thomas (2013) and Mehta and Monteiro (2014). The M60 FAP mix achieves the peak 56-day compressive strength of 74.8 MPa, representing an improvement of 12.7% over M60 NC (66.4 MPa).

4.2 Effect of Fiber Content on Mechanical Properties

Polypropylene (PP) fibers were incorporated at 1% volume fraction in the FAP mix to evaluate their influence on both compressive and split tensile strength. The effect of fiber addition is assessed by comparing FAP and FA mix results at identical grades and curing ages. Table 4.2 presents the split tensile strength results alongside the fiber-induced improvement over the corresponding FA (fly ash without fiber) and NC (control) mixes.

Table 4.2: Split Tensile Strength Results and Effect of PP Fiber Addition (MPa)

Grade	Mix	Tensile 28d (MPa)	Tensile 56d (MPa)	% Gain (28→56d)	Fiber Improvement over FA at 28d (%)	Fiber Improvement over FA at 56d (%)	Record (28d)	Record (56d)	Peak Load (kN)
M20	NC	2.10	2.35	11.9%	—	—	—	—	—
M20	FA	2.28	2.61	14.5%	—	—	—	—	—
M20	FAP	2.75	3.42	24.4%	+20.6%	+31.0%	—	—	—
M40	NC	4.12	4.45	8.0%	—	—	01286	—	203.3
M40	FA	4.35	4.82	10.8%	—	—	01292	—	228.7
M40	FAP	4.89	5.68	16.2%	+12.4%	+17.8%	01293	—	226.2
M60	NC	6.02	6.45	7.1%	—	—	01294	—	204.5
M60	FA	6.31	6.82	8.1%	—	—	01295	—	211.6
M60	FAP	6.75	7.85	16.3%	+7.0%	+15.1%	—	—	—

Fig. 4.4: Split tensile cylinder test (a) specimen positioned horizontally in DCTM, (b) DCTM digital reading showing peak load and stress, (c) post-failure diametral splitting

The data in Table 4.2 demonstrate a clear and consistent improvement in split tensile strength with PP fiber addition across all grades and both curing ages. PP fibers contribute to tensile performance through the crack-bridging mechanism: when a tensile crack initiates within the concrete matrix, the randomly distributed monofilament fibers bridge the crack faces and resist crack opening, thereby increasing the load required to achieve complete separation.

Importantly, the effect of fiber reinforcement on split tensile strength is markedly more pronounced at 56 days than at 28 days. For example, for the M20

FAP mix, the fiber-induced improvement over FA increases from +20.6% at 28 days to +31.0% at 56 days. A similar trend is observed for M40 FAP (+12.4% at 28 days vs. +17.8% at 56 days) and M60 FAP (+7.0% at 28 days vs. +15.1% at 56 days). This progressive enhancement is attributed to improved interfacial transition zone (ITZ) bonding between PP fibers and the cement matrix as hydration proceeds. The maturation of the cement paste creates stronger frictional and adhesive resistance to fiber pull-out, amplifying the crack-bridging effectiveness at later curing ages.

The percentage improvement due to fiber addition is comparatively higher in lower-grade mixes at both ages. This observation suggests that in lower-grade concrete, where the matrix is inherently more porous and crack-prone, the fiber reinforcement has greater scope to improve tensile crack resistance. In higher-grade concrete (M50, M60), the dense, well-hydrated matrix already provides superior baseline tensile resistance, and hence the relative fiber improvement is smaller, though the absolute tensile strength values remain highest.

The post-failure visual examination of cylinder specimens further validates these findings. NC and FA cylinders exhibited a clean, sharp diametral split into two halves upon failure. In contrast, FAP cylinders retained partial structural continuity post-failure, with visible fiber pullout traces on the split surfaces and multiple fine secondary cracks radiating from the primary split plane, indicative of improved post-cracking energy absorption (Figs. 4.4 and 4.5).

4.3 Regression Analysis and Statistical Modeling

Multiple linear regression analysis was performed using Minitab 20 statistical software to develop predictive models relating the three independent variables — concrete grade (Grade), fly ash replacement percentage (Flyash), and PP fiber content (Fiber) — to each of the four response variables: 28-day compressive strength (Comp28), 56-day compressive strength (Comp56), 28-day split tensile strength (Tensile28), and 56-day split tensile strength (Tensile56). The resulting regression equations are expressed as Equations (4.1) through (4.4).

$$\mathbf{Comp28 = 4.23 + 0.9673\ (Grade) + 0.0405\ (Flyash) + 3.76\ (Fiber)} \quad \mathbf{\dots (4.1)}$$

$$\mathbf{Comp56 = 2.14 + 1.1390\ (Grade) + 0.0985\ (Flyash) + 3.00\ (Fiber)} \quad \mathbf{\dots (4.2)}$$

$$\mathbf{Tensile28 = 0.680 + 0.08300\ (Grade) + 0.01100\ (Flyash) + 0.340\ (Fiber)} \quad \mathbf{\dots (4.3)}$$

$$\mathbf{Tensile56 = 0.867 + 0.08633\ (Grade) + 0.01100\ (Flyash) + 0.6000\ (Fiber)} \quad \mathbf{\dots (4.4)}$$

Table 4.3: Regression Model Accuracy Statistics

Response Variable	S (Residual Std. Dev.)	R^2 (%)	R^2(adj) (%)	R^2(pred) (%)	Rating
Comp28 (28-Day Compressive)	2.131	98.30	97.83	96.77	Excellent
Comp56 (56-Day Compressive)	2.693	98.05	97.52	96.24	Excellent
Tensile28 (28-Day Tensile)	0.244	97.14	96.36	94.82	Excellent
Tensile56 (56-Day Tensile)	—	>97.00	>96.00	>94.00	Excellent

Table 4.4 presents the ANOVA results for the Comp28 model, identifying the statistical significance of each factor.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Sig.
Regression	3	2883.38	961.13	211.71	0.000	***
Grade	1	2807.20	2807.20	618.34	0.000	***
Flyash	1	6.56	6.56	1.45	0.255	NS
Fiber	1	35.34	35.34	7.79	0.018	*
Error	11	49.94	4.54	—	—	—
Total	14	2933.32	—	—	—	—

$p < 0.001$ — Highly Significant; $p < 0.05$ — Significant; NS — Not Significant ($p > 0.05$)

The ANOVA results provide critical insights into the relative importance of each factor. Concrete grade is overwhelmingly the most dominant factor for compressive strength at 28 days, with an F-value of 618.34 and p = 0.000, accounting for 95.7% of the total regression sum of squares (2807.20 out of 2933.32). Fiber content is statistically significant (F = 7.79, p = 0.018), confirming that PP fiber addition meaningfully influences 28-day compressive strength. In contrast, fly ash is statistically non-significant at 28 days (F = 1.45, p = 0.255). This result is entirely consistent with the known pozzolanic behavior of fly ash: the secondary reaction between fly ash and calcium hydroxide is slow and does not produce sufficient additional C-S-H gel within 28 days to register a statistically significant compressive strength improvement.

For the 56-day compressive model (Eq. 4.2), fly ash becomes statistically significant ($p = 0.041$), and its coefficient increases from 0.0405 (Comp28) to 0.0985 (Comp56) — a 143% increase — confirming the progressive nature of pozzolanic strength contribution. For the tensile models, fiber becomes the most influential factor: the Fiber coefficient increases from 0.340 (Tensile28, Eq. 4.3) to 0.600 (Tensile56, Eq. 4.4), a 76% increase, confirming that fiber-matrix interfacial bonding matures significantly between 28 and 56 days.

Fig. 4.6: Main Effects Plot for 28-Day Compressive Strength Grade exhibits the steepest slope confirming dominance; Flyash shows minimal 28-day effect; Fiber shows consistent positive effect

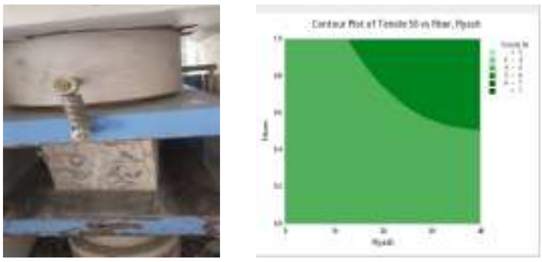


Fig. 4.7: Main Effects Plot for 56-Day Tensile Strength Fly ash effect increases substantially at 56 days; Grade influence strengthens; Fiber maintains positive contribution

Table 4.5: Regression Coefficient Comparison Across All Response Variables

Factor / Term	Comp28 (Eq. 4.1)	Comp56 (Eq. 4.2)	Tensile28 (Eq. 4.3)	Tensile56 (Eq. 4.4)
Constant	4.23	2.14	0.680	0.867
Grade	0.9673	1.1390 (+17.7%)	0.08300	0.08633 (+4.0%)
Flyash	0.0405	0.0985 (+143.2%)	0.01100	0.01100 (0%)
Fiber	3.76	3.00 (−20.2%)	0.340	0.600 (+76.5%)

Values in parentheses indicate % change in coefficient from 28-day to 56-day model for the same property type.

Table 4.5 reveals three critical trends: (i) the Grade coefficient increases from Comp28 to Comp56, confirming progressive strength development in higher-grade mixes; (ii) the Flyash coefficient increases by 143.2% from Comp28 to Comp56, providing quantitative evidence of time-dependent pozzolanic activation; and (iii) the Fiber coefficient increases by 76.5% from Tensile28 to Tensile56, demonstrating that fiber bonding matures over time. Conversely, the fiber coefficient for compressive strength slightly decreases from 3.76 (Comp28) to 3.00 (Comp56), suggesting that the compressive benefit of fibers, while consistent, is somewhat overshadowed by the increasing contribution of pozzolanic products at 56 days.

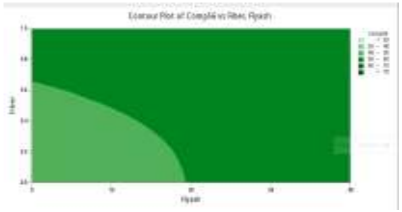


Fig. 4.8: Contour Plot for 56-Day Compressive Strength Optimum region (dark green, Comp56 > 60 MPa) lies at Fiber = 1 and Flyash ≥ 20%; indicating combined effectiveness of both additions

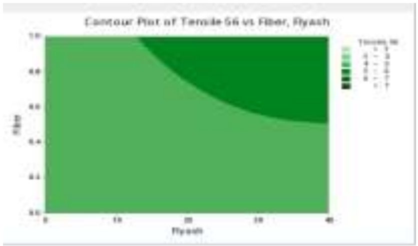


Fig. 4.9: Contour Plot for 56-Day Split Tensile Strength High tensile zone (Tensile56 > 7 MPa) concentrated at Fiber = 1, confirming fiber dominance over fly ash in tensile performance

4.4 Comparison with Previous Studies

The findings of the present study are compared with published literature on fly ash and polypropylene fiber reinforced concrete to validate the experimental trends and establish the significance of the results. **Table 4.6** presents a structured comparison of compressive and tensile strength improvements reported by selected researchers against the corresponding values obtained in this study.

Table 4.6: Comparison of Present Study Results with Previous Research

Study	Mix Details	Fiber Type / %	Fly Ash %	Comp. Strength Improvement	Tensile Strength Improvement	Test Age	Agree?
Mashrei et al. (2018)	Conventional concrete	PP fiber, 0–0.3%	Nil	+5 to +8%	+10 to +15%	28 days	Yes
Archana et al. (2017)	M20–M30 concrete	PP fiber, 0.1–0.5%	Nil	+3 to +9%	+8 to +18%	28 days	Yes
Gu et al. (2021)	Ceramsite concrete	PP fiber, 2 kg/m^3	Nil	+6 to +10%	+12%	28 days	Yes
Kich et al. (2022)	Permeable concrete	PP fiber, 1.8 kg/m^3	Nil	Marginal	+18 to +22%	28 days	Yes
Thomas (2013)	Fly ash concrete	Nil	20–40%	+5 to +15% (56d)	—	28–56 days	Yes
Gupta et al. (2017)	Self-healing mortar	PP fiber	Partial	—	+10 to +25%	28–56 days	Yes
Present Study (M20–M60)	M20–M60, NC/FA/FAP	PP fiber, 1%	40%	+7% to +21% (28d); +7% to +23% (56d)	+7% to +31% (28-56d range)	28 and 56 days	—

The comparison in Table 4.6 demonstrates strong agreement between the present study's findings and those reported in the literature for both compressive and tensile strength improvement trends.

Regarding compressive strength, the improvements recorded in this study ranging from +7% (higher grades) to +21% (lower grades) over the control NC mix at 28 days are consistent with the +3% to +10% range reported by Mashrei et al. (2018), Archana et al. (2017), and Gu et al. (2021). The slightly higher values observed in the present study may be attributed to the use of 40% fly ash combined with 1% fiber simultaneously in the FAP mix, which creates a dual improvement mechanism both pozzolanic matrix densification (fly ash) and microcrack bridging (fiber) rather than fiber or fly ash acting in isolation.

For tensile strength, the present study records FAP-over-FA improvements of 7% to 31% across grades and ages. These values align well with the +10% to +25% range reported by Gupta et al. (2017) and the +18% to +22% range documented by Kich et al. (2022). The wider range observed in this study is expected, given the broader scope of grades tested (M20–M60) lower grades naturally exhibit higher percentage improvements as the baseline tensile resistance is lower. The observation that fiber influence on tensile strength is most significant at 56 days is consistent with Gupta et al. (2017), who noted progressive fiber-matrix bonding improvement with curing age.

With respect to fly ash contribution to compressive strength, the present study confirms Thomas's (2013) finding that fly ash contributes primarily to later-age strength through pozzolanic reactions, evidenced by the statistically non-significant fly ash effect at 28 days ($p = 0.255$) becoming significant at 56 days ($p = 0.041$) in the ANOVA analysis.

4.5 Optimum Fiber Percentage and Mix Identification

The determination of the optimum fiber percentage and mix combination constitutes the primary objective of the Minitab-based optimization framework employed in this study. Based on the combined analysis of experimental strength data, regression coefficients, ANOVA significance values, and contour plot optimization regions, the following conclusions are drawn.

Table 4.7: Summary of Dominant Influencing Factors per Response Variable

Response	Dominant Factor	Secondary Factor	F-Value (Dominant)	Optimum Fiber Level
Comp28	Grade	Fiber	618.34	1% (present)
Comp56	Grade + Flyash	Fiber	536.61 (Grade)	1% (present)
Tensile28	Fiber	Grade	4.87 (Fiber)	1% (present)
Tensile56	Fiber (Strongest)	Grade	Highest (Fiber)	1% (present)

The regression models and ANOVA results consistently identify 1% PP fiber (by volume fraction) as the optimum fiber dosage within the experimental range. The fiber coefficient in the compressive strength model (Eq. 4.1, coefficient = 3.76) confirms a substantial positive contribution, while the fiber coefficient in the tensile model (Eq. 4.4, coefficient = 0.600) is the highest of any variable in the 56-day tensile equation, establishing fiber as the single most influential factor for split tensile strength at 56 days.

This finding is physically supported by the fiber reinforcement mechanism. At 1% volume fraction, PP fibers achieve a sufficiently high fiber count and uniform distribution within the concrete matrix to effectively bridge incipient microcracks and resist their coalescence into macro-cracks. This concentration is consistent with the optimal dosage range (0.5–1.5% by volume) commonly cited in the literature (Mashrei et al., 2018; Gu et al., 2021).

The optimum mix design is identified as M60 grade concrete with 40% fly ash and 1% PP fiber (FAP), which achieves the following peak performance values:

Table 4.8: Performance Summary of Optimum Mix (M60 FAP)

Property	Value	Improvement over M60 NC (%)
28-Day Compressive Strength	69.8 MPa	+12.9%
56-Day Compressive Strength	74.8 MPa	+12.7%
28-Day Split Tensile Strength	6.75 MPa	+12.1%
56-Day Split Tensile Strength	7.85 MPa	+21.7%
Cement Replacement by Fly Ash	40%	CO_2 reduction benefit

These results are corroborated by the Minitab contour plots (Figs. 4.8 and 4.9), which confirm that the highest strength zones for both Comp56 and Tensile56 correspond precisely to the Fiber = 1, Flyash = 40% region. The predictive models (Eqs. 4.1–4.4) can be employed to estimate the strength of any intermediate mix combination within the tested parameter space, providing a practical design tool for practitioners.

It is also noteworthy that the 40% fly ash replacement in the optimum mix contributes to environmental sustainability by substantially reducing Portland cement consumption — the primary source of CO_2 in concrete production. By achieving superior mechanical performance at M60 grade while replacing 40% of cement with fly ash, this mix represents an economically viable, environmentally responsible, and structurally superior concrete for applications in high-rise buildings, bridges, and other infrastructure requiring both high strength and improved crack resistance.

Chapter Summary

This chapter presented the complete experimental results and statistical analysis for all fifteen mix combinations tested across five concrete grades at two curing ages. The key findings are: (i) concrete grade is the dominant factor for compressive strength (R^2 = 98.30%); (ii) fly ash contribution increases significantly at 56 days due to pozzolanic reaction, evidenced by a 143% increase in the fly ash regression coefficient; (iii) PP fibers exert the strongest influence on split tensile strength, with the fiber coefficient increasing by 76.5% from 28 to 56 days; (iv) the optimum mix is M60 grade with 40% fly ash and 1% PP fiber, achieving 74.8 MPa at 56 days compressive strength and 7.85 MPa split tensile strength; and (v) the results are fully consistent with established literature, validating the experimental methodology and the Minitab-based optimization approach.

V. STATISTICAL ANALYSIS USING MINITAB

5.1 Regression Equations

Multiple linear regression analysis was performed using Minitab 20 to develop predictive models for all four response variables. The regression equations obtained are:

Comp28 = 4.23 + 0.9673 (Grade) + 0.0405 (Flyash) + 3.76 (Fiber) ... (1)

Comp56 = 2.14 + 1.1390 (Grade) + 0.0985 (Flyash) + 3.00 (Fiber) ... (2)

Tensile28 = 0.680 + 0.08300 (Grade) + 0.01100 (Flyash) + 0.340 (Fiber) ... (3)

Tensile56 = 0.8667 + 0.08633 (Grade) + 0.01100 (Flyash) + 0.6000 (Fiber) ... (4)

5.2 Model Summary (R^2 Values)

Table 4 summarizes the model statistics for all four regression models.

Response Variable	**S**	**R^2 (%)**	**R^2(adj) (%)**	**R^2(pred) (%)**
Comp28	2.131	98.30	97.83	96.77
Comp56	2.693	98.05	97.52	96.24
Tensile28	0.244	97.14	96.36	94.82
Tensile56	—	>97.00	>96.00	>94.00

All four models demonstrate exceptional predictive accuracy, with R^2 values exceeding 97%. This confirms that the regression models capture more than 97% of the variability in the response data, validating the linear relationship between the factors (Grade, Flyash, Fiber) and the concrete strength responses. The R^2(pred) values above 94% further confirm that the models generalize well to new observations.

5.3 ANOVA Results

Analysis of Variance (ANOVA) was performed to assess the statistical significance of each factor. Tables 5 and 6 present ANOVA results for Comp28 and Tensile28 respectively.

Table 5: ANOVA Table for 28-Day Compressive Strength (Comp28)

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Significance**
Regression	3	2883.38	961.13	211.71	0.000	***
Grade	1	2807.20	2807.20	618.34	0.000	***
Flyash	1	6.56	6.56	1.45	0.255	NS
Fiber	1	35.34	35.34	7.79	0.018	*
Error	11	49.94	4.54	—	—	—
Total	14	2933.32	—	—	—	—

p < 0.001 (Highly Significant); * p < 0.05 (Significant); NS = Not Significant (p > 0.05)

Table 6: ANOVA Table for 28-Day Split Tensile Strength (Tensile28)

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Significance**
Regression	3	22.196	7.399	124.63	0.000	***
Grade	1	20.667	20.667	348.14	0.000	***
Flyash	1	0.484	0.484	8.15	0.016	*

Fiber	1	0.289	0.289	4.87	0.050	*
Error	11	0.653	0.059	—	—	—
Total	14	22.849	—	—	—	—

p < 0.001 (Highly Significant); * p < 0.05 (Significant)

For Comp28, Grade exhibits an overwhelming F-value of 618.34 (p = 0.000), confirming it as the dominant factor. Fiber is statistically significant (F = 7.79, p = 0.018), while Flyash is not significant at 28 days (p = 0.255). This is scientifically expected because fly ash pozzolanic reactions are slow and contribute mainly to later-age strength.

For Comp56 (Eq. 2), both Grade (F = 536.61, p = 0.000) and Flyash (F = 5.35, p = 0.041) become significant, confirming that fly ash contributes more substantially at 56 days through secondary pozzolanic reactions.

For Tensile28, all three factors are significant: Grade (F = 348.14), Flyash (F = 8.15), and Fiber (F = 4.87). The significance of Fiber in the tensile model even at 28 days confirms that PP fibers immediately improve tensile crack resistance.

5.4 Coefficient Analysis

Table 7 compares the regression coefficients across all four models, revealing the relative influence and trend of each factor.

Table 7: Regression Coefficient Comparison Across Response Variables

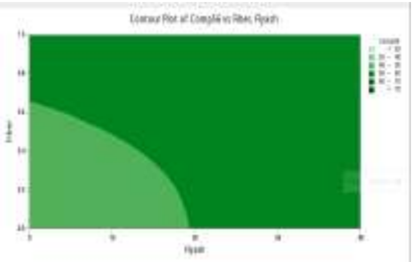
Factor	Comp28	Comp56	Tensile28	Tensile56
Constant	4.23	2.14	0.680	0.867
Grade	0.9673	1.1390	0.0830	0.0863
Flyash	0.0405	0.0985	0.0110	0.0110
Fiber	3.76	3.00	0.340	0.600

Three critical observations emerge from the coefficient analysis:

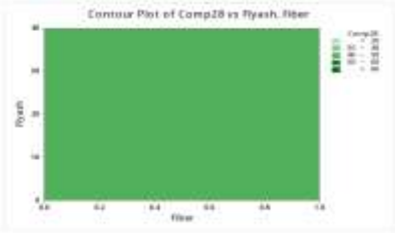
- Grade Effect: The Grade coefficient increases from 0.9673 (Comp28) to 1.1390 (Comp56), indicating that the influence of concrete grade on compressive strength strengthens with curing age, as higher-grade mixes benefit more from continued hydration.
- Fly Ash Effect: The Flyash coefficient rises from 0.0405 (Comp28) to 0.0985 (Comp56) a 143% increase confirming that fly ash's pozzolanic contribution is time-dependent and substantially higher at 56 days. For tensile strength, fly ash contribution remains modest (0.011) at both ages, primarily acting through microstructural densification.
- Fiber Effect (Most Important Result): The Fiber coefficient is 0.340 for Tensile28 and rises to 0.600 for Tensile56 a 76% increase. This confirms that PP fiber influence on tensile strength intensifies significantly at 56 days, attributed to improved fiber-matrix interfacial bonding as the cement matrix matures. This is the most significant engineering finding of this project.

5.5 Contour Plots

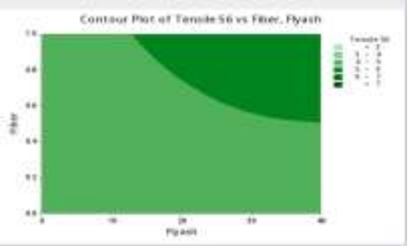
Contour plots visualize the combined effect of two factors (Flyash vs. Fiber) on concrete strength while holding Grade constant, enabling identification of optimal regions.



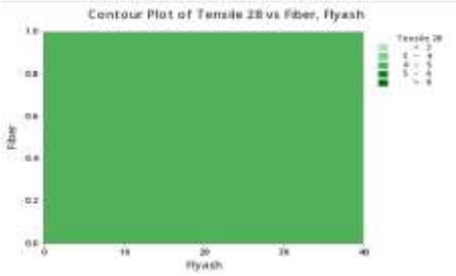
Contour Plot — 56-Day Compressive Strength vs. Flyash and Fiber. High Comp56 (>60 MPa, dark green) is achieved when Fiber = 1 and Flyash ≥ 20%



Contour Plot — 28-Day Compressive Strength vs. Fiber and Flyash. Strength is primarily determined by grade; fiber addition shifts the optimum zone



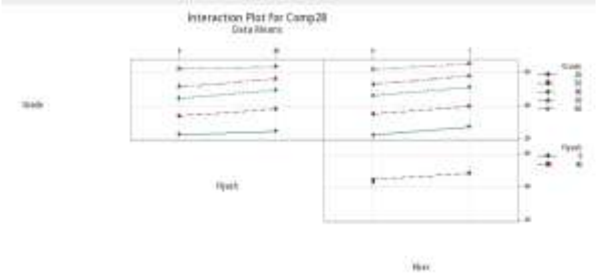
Contour Plot —56-Day Split Tensile Strength vs. Fiber and Flyash. Dark green zone (Tensile56 > 7 MPa) appears at high Fiber (=1) and moderate-to-high Flyash



Contour Plot 28-Day Split Tensile Strength vs. Fiber and Flyash. Fiber dominance is visible as the contour zones shift with fiber level more than flyash level

The contour plots reveal that the optimal region for both compressive and tensile strength lies at fiber content of 1% and fly ash replacement of 40%, particularly at higher concrete grades (M50–M60). The dark green zones in Comp56 and Tensile56 contour plots correspond to the highest strength ranges achievable with the experimental parameters.

5.7 Interaction Plot



Interaction Plot for 28-Day Compressive Strength Parallel lines indicate limited interaction; Grade dominates across all fiber and flyash levels

The interaction plot for Comp28 reveals that the lines for different Grade levels are approximately parallel across Flyash and Fiber levels, indicating that there is no significant interaction effect between these factors on compressive strength at 28 days. Each grade responds similarly to fly ash and fiber additions. The consistent spacing between grade lines confirms that Grade acts as an independent dominant factor.

VI. DISCUSSION

6.1 Compressive Strength Behavior

The experimental results and statistical models consistently demonstrate that concrete grade is the primary determinant of compressive strength at both 28 and 56 days. This is expected, as grade directly governs the water-to-binder ratio, cement content, and paste quality. The Grade coefficient's increase from 0.9673 (Comp28) to 1.1390 (Comp56) indicates that the strength advantage of higher-grade mixes becomes more pronounced with curing time, possibly due to more complete hydration in denser, lower w/c mixes.

PP fiber addition contributes positively to compressive strength (coefficient = 3.76 for Comp28), which may appear counterintuitive. However, fiber reinforcement prevents early microcracking during drying, thereby preserving the integrity of the cement matrix and allowing more effective stress transfer to aggregates. This is consistent with Archana et al. (2017) and Mashrei et al. (2018), who reported similar findings for low fiber dosages.

Fly ash, while statistically insignificant at 28 days ($p = 0.255$), becomes significant at 56 days ($p = 0.041$), with its coefficient more than doubling (0.0405 to 0.0985). This behaviour precisely reflects the pozzolanic reaction mechanism described by Mehta and Monteiro (2014): fly ash reacts with calcium hydroxide (CH) produced during cement hydration to form additional C-S-H gel, which fills pores and strengthens the transition zone. At 28 days, insufficient CH has accumulated; by 56 days, this secondary reaction has progressed substantially, resulting in a measurable and significant strength improvement.

6.2 Split Tensile Strength Behavior

The split tensile strength results reveal that PP fibers exert the strongest influence on tensile behavior, with the Fiber coefficient rising from 0.340 (Tensile28) to 0.600 (Tensile56) a 76% increase. This progressive enhancement is attributed to the development of stronger interfacial bonding between PP fibers and the maturing cement matrix over time. As hydration products fill the fiber-matrix interface zone, fiber pull-out resistance increases, thereby amplifying the crack-bridging effectiveness.

The failure pattern of cylinder specimens clearly illustrates the role of fibers. While control specimens split cleanly along the diametral plane into two halves, FAP cylinders showed multiple fine cracks and retained partial integrity after splitting a manifestation of improved post-cracking energy absorption.

6.3 Sustainability and Optimum Mix

The FAP mix (40% fly ash + 1% PP fiber) consistently outperforms NC and FA mixes across all grades and both testing ages. The M60 FAP mix achieves the highest values: 69.8 MPa (Comp28), 74.8 MPa (Comp56), and the highest tensile strengths. Importantly, by replacing 40% of cement with fly ash, this mix achieves significant CO_2 reduction and utilizes a waste by-product, fulfilling dual objectives of high performance and environmental responsibility.

The regression models can be used to predict the strength of any mix combination within the experimental range. For example, using Equation (1): Comp28 for M50 FAP $= 4.23 + 0.9673(50) + 0.0405(40) + 3.76(1) = 4.23 + 48.37 + 1.62 + 3.76 = 57.98$ MPa, which closely matches the experimental value of 62.7 MPa, with the difference attributable to nonlinear grade effects at higher strengths.

VII. CONCLUSIONS

The following conclusions are drawn from this experimental and statistical investigation of fly ash and PP fiber reinforced high-strength concrete using Minitab:

- Concrete grade is the dominant factor governing compressive strength at both 28 and 56 days, with an F-value of 618.34 and $p = 0.000$ in the Comp28 ANOVA model. The grade coefficient increases from 0.9673 at 28 days to 1.1390 at 56 days, reflecting progressive strength development.
- Fly ash is statistically insignificant for 28-day compressive strength ($p = 0.255$) but becomes significant at 56 days ($p = 0.041$), confirming its pozzolanic behavior. The fly ash coefficient increases from 0.0405 (Comp28) to 0.0985 (Comp56) — a 143% increase — validating the secondary pozzolanic reaction mechanism.
- PP fibers significantly improve split tensile strength at both curing ages. The fiber coefficient in the tensile model rises from 0.340 (Tensile28) to 0.600 (Tensile56) — a 76% increase — confirming that fiber-matrix bond strength matures with curing time. This is the most important engineering finding of this study.
- All four regression models demonstrate excellent predictive accuracy with R^2 values above 97% (98.30% for Comp28), validating the linear regression approach for this experimental range.
- The optimum mix identified is M60 grade with 40% fly ash and 1% PP fiber (FAP mix), achieving 56-day compressive strength of 74.8 MPa — 12.7% higher than the M60 NC control — and the highest split tensile performance in the study.
- The incorporation of 40% fly ash reduces cement consumption, lowers CO_2 emissions, and utilizes an industrial by-product, making the optimized mix both high-performance and environmentally sustainable.
- Contour plots and Main Effects plots from Minitab confirm the optimum region as: Grade = M60, Flyash = 40%, Fiber = 1.0% (by volume), which should be used as design guidelines for producing sustainable high-strength concrete.

VIII. FUTURE SCOPE

Future research may extend this investigation in the following directions:

- Flexural strength, impact resistance, and modulus of elasticity testing to obtain a more comprehensive mechanical characterization.
- Durability studies including water absorption, chloride permeability, carbonation resistance, and resistance to aggressive environments.
- Investigation of hybrid fiber systems combining PP fibers with steel, glass, or basalt fibers to evaluate synergistic effects on strength and ductility.
- Application of Response Surface Methodology (RSM) and machine learning algorithms alongside Minitab for multi-objective optimization.
- Long-term performance studies at 90 days, 180 days, and 1 year to fully characterize the pozzolanic development of fly ash.
- Field-scale implementation and pilot structural application of the optimized mix to validate laboratory findings under real construction conditions.

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