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Comparative Evaluation of High-Performance Mortars Incorporating Silica Fume, Fly Ash, and Polypropylene Fibers

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Abstract

Superior mechanical performance, durability, and resistance to crack propagation in high-performance mortars are increasingly being achieved with the optimization of supplementary cementitious materials combined with fiber reinforcement. However, quantification of combined effects due to the addition of silica fume, class F fly ash, and polypropylene fibers is rather limited. This paper compares the performance of mortar systems containing silica fume, class F fly ash, and polypropylene fibers at various dosages, controlled by low water-to-binder ratios. Ternary and quaternary mixes were prepared to isolate the effects of each constituent and their interactions on compressive strength, flexural behavior, and microstructural density at 1, 7, and 28 days. Test results showed that silica fume significantly enhanced early and 28-day strength through matrix densification, while class F fly ash contributed to workability and later-age strength development through pozzolanic activity. Low dosages of polypropylene fibers did not significantly affect compressive strength; however, they significantly enhanced crack resistance, toughness, and post-crack behavior, especially when combined with silica fume-rich matrices. Synergetic effects have been observed in mixes containing both silica fume and class F fly ash, in which improved packing density and balanced hydration kinetics resulted in superior mechanical and microstructural performance. The results emphasize the importance of optimized SCM-fiber combinations toward achieving high performance in mortars and provide guidelines for the design of durable and high-strength mortar systems for advanced construction applications.

Keywords

High-Performance Mortar, Silica Fume, Fly Ash, Polypropylene Fibers, Compressive Strength, Ferrocement, Pozzolanic Reaction

1. Introduction

High-Performance Mortars (HPM) have found important applications in recent years in the construction industry because of their enhanced strength, durability, and resistance to cracking relative to cementitious mortars. This is mainly attributed to the optimization of binder systems, particle packaging, water binder ratio, as well as the appropriate additives of supplementary cementitious materials (SCMs) and fibers. Of the various additives of SCMs that are widely used, silica fume (SF) or fly ash (FA) additions have shown significant effectiveness in promoting density, strength, and durability. At the same time, polypropylene (PP) fibers have also gained importance for their applications in high-performance mortars for toughness improvement, impact, or effective crack control.

Silica Fume possesses ultrafine particle sizes along with high contents of amorphous silica, which produce both microfiller and strongly active pozzolanic properties. Several studies support that SF works significantly for enhanced early ages to 28 strength, lowering permeability, as well as improving interfacial transition zones by reacting with calcium hydroxide through the secondary Cs-S-H phase [1] [2]. This is contrasted by FA, which works for workability improvement through its spherical shape, with lower pozzolanic reactivity that is beneficial for (long-term) strength properties and durability for prolonged curing periods. FA decreases heat development and produces refined pores for HPS applications [3] [4].

Though polypropylene fibers are inert in the cement matrix, their utilization has led to considerable improvement in the resistance to plastic shrinkage cracking, as well as the post-crack toughness, impact resistance, and energy absorption capacities. Though their effect on the compressive strength of concrete is insignificant at a small dosage, dispersion characteristics, shape, and matrix interaction effects are crucial for this purpose [5]. A blend of SCMs with polypropylene fibers can provide opportunities for the development of HPMs with both superior strength and resistance to cracking.

Although a vast amount of research work is found in the literature on the individual role of SF, FA, or PP fibers, experimental studies comparing the combination of these three fibers in HPMs are very limited. Especially, the role of ultrafine pozzolans with fibers in low water/binder ratio mixes is not clearly established, nor is the significance of both early stages and later stages of strength development in ternary or quaternary systems [1] [4] [5].

In order to fill these gaps in knowledge, the current research undertakes a comparative analysis of four high-performance mortar mixes, namely M1, M2, M3, & M4, with varying quantities of silica fume, fly ash, water binder ratio, & polypropylene fibers.

- M1 is the non-fiber control mixture that contains SF and FA.
- M2 contains a high amount of PP fiber with 4 kg/m^3 of similar binder material.
- M3 reduced FA content and low PP fiber dosage of 0.6 kg/m^3.
- M4 employs a higher FA amount with moderate PP fiber dosing (1.2 kg/m^3) with a higher water-to-binder ratio.

The aim of this research is to provide a comparison of the mechanical properties, more specifically the 28th day compressive strength (Fc28), as well as the efficiency of the mentioned mixes, with the aim of understanding the influence of SCMs and PP fibers on HPMs. This research work aims to provide answers related to the optimum ratio of SCMs, the dosing of fibers, as well as the influence of the mentioned parameters related to the constitution of HPMs.

2. Literature Review

2.1. High-Performance Mortars (HPM): Concept and Development

High-performance mortars are engineered cement-based composites to demonstrate higher mechanical strength, lower permeability, and better long-term durability than conventional ones. The performance is essentially due to optimized particle packing, reduced water-to-binder ratio, the use of finely divided SCMs, and improved chemical or fiber reinforcements. HPMs usually show compressive strengths above 60 - 80 MPa, low porosity, high abrasion resistance, and improved chemical and environmental degradation resistance. Such performance improvements are strongly linked to the selection and interaction of the SCMs and fibers; hence, comparative studies on these components are a pressing research interest [1] [6] [7].

2.2. Role of Silica Fume in High-Performance Mortars

Silica fume (SF) is one of the more significant SCMs still in use in HPM. This is attributed to the fact that it contains ultrafine particles with sizes of 0.1 - 0.3 μm, as well as a high amorphous silica percentage of approximately 85% - 98%. SF works through:

1) Filler effect: ultrafine particles fill the gaps between cement particles, causing a considerable densification of the microstructure.

2) Pozzolanic reaction, consuming calcium hydroxide for the production of secondary C-S-H.

3) Due to SF's high reactivity, it promotes hydrated products in the early ages of strength development, ITZs of higher qualities, as well as significantly higher strengths and abrasion resistance at 28 days. Nevertheless, higher porosity brought about by SF can increase the need for water, thereby requiring it to be compatible with superplasticizers. Optimum replacement percentage of SF in mortars is between 5% and 15%, after which diminishing returns in strength development may occur due to particle agglomeration, incomplete dispersion, and increased sensitivity to curing conditions, potentially leading to microstructural defects and reduced efficiency of the cementitious matrix [1] [2] [8].

2.3. Fly Ash as a Supplementary Cementitious Material in HPM

FA, essentially Class F with low CaO content, exerts its benefits through a slow pozzolanic reaction and micro-filler effects. Fly ash differs from silica fume in that it contributes less during early ages but provides significant enhancement of long-term strength, chloride resistance, sulfate durability, and shrinkage behavior. Its spherical morphology allows for improved workability without excessive admixture demand at low water-to-binder ratios.

The effectiveness of FA in HPM is based on replacement level, fineness, and curing regime. Many studies report optimum ranges of 10% - 30% replacement for balanced early and late strength development. When combined with silica fume, FA leads to blended systems in which SF provides early strength, while FA can provide long-term densification and reduced permeability—a synergy particularly relevant to sustainable high-performance mortar design [1] [3] [4].

2.4. Polypropylene Fibers in High-Performance Mortars

Because of their chemical stability and low density, as well as the enhancement in crack control, polypropylene fibers are widely used in advanced mortars. PP fibers do not chemically interact with binder phases but provide a couple of mechanical benefits:

- Reduction of plastic shrinkage cracking.
- Improved post-crack ductility.
- Improved resistance to impact and abrasion.
- Higher energy absorption capacity.

The dosage is a critical issue. For shrinkage control, microfiber dosages of about 0.6 - 1.2 kg/m^3 are typically used, while for higher toughness and residual strength in flexure, structural or macro-PP fibers are used at several kg/m^3. While most literature reports no significant changes or minor ones in compressive strength for low dosages, more important volumetric fractions may eventually lead to compressive strength reduction if workability and compaction are not properly mastered. PP fiber interactions with SCM-rich matrices are an expanding research area, especially on optimized fiber-matrix bonding and the effect of dense SCM systems on fiber dispersion [5] [9] [10].

2.5. Synergistic Interactions among SCMs and Fibers in HPM

Recent studies emphasize the need to choose appropriate complementary SCMs and fibers in order to develop mortar systems tailored for particular structural or durability requirements. Silica fume-fly ash blends provide a hydration profile that occurs in two stages: SF contributes to early strength and reduces porosity, while FA improves rheology and contributes significantly to later strength evolution. In the presence of PP fibers, the hardened matrix is further improved due to increased microstructural integrity and reduced cracking, which enhances the effectiveness of SCMs by minimizing pathways for harmful agents to ingress.

However, these synergies need to be developed against fresh-state behavior and mechanical performance. The SF-rich mixes lose workability, which FA mitigates, and the PP fibers further alter the rheology, calling for an optimization of admixture. Various studies carried out by different authors also confirm, in their conclusion, that the combination of SF, FA, and PP fibers can give better performance than single-SCM systems when mixture design is systematically optimized [1] [2] [4] [10].

2.6. Synergistic Interactions among SCMs and Fibers in HPM

While substantial research has been carried out individually on SF-based, FA-based, and fiber-reinforced mortars, investigations into combined SF-FA-PP systems are very few in number. Specific gaps that have been identified in the available literature include:

- Quantitative understanding of fiber-matrix interaction in SCM-rich matrices.
- Impact of hybrid SCM systems on fiber dispersion and bond.
- Combined effects on 1-, 7-, 28-, and 90-day compressive and flexural performance.
- Durability metrics (chloride resistance, permeability, freeze-thaw, sulfate attack) for ternary SF-FA-fiber systems.
- Performance of the composite resulting from different w/b ratios and superplasticizer types.

A systematic comparative assessment is, therefore, needed toward the definition of mix-design strategies that would ensure mechanical performance, durability, and sustainability for the next generation of high-performance mortars [1] [4] [5].

3. Materials and Mix Proportions

3.1. Constituent Materials

The primary binder for all the mortar mixes in this study was Ordinary Portland Cement (OPC) conforming to ASTM C150 Type I. The main calcium silicate phases, which are the active phases responsible for the early strength developments, were provided by the cement.

Silica fume (SF) conformed to ASTM C1240 and was used as a highly reactive supplementary cementitious material. Due to its ultra-fine particle size and high amorphous silica content, silica fume was added to increase the particle packing density, improve the pore structure, and give early age to 28 days of compressive strength due to accelerated pozzolanic reactions.

Class F FA that was conforming to the requirements of ASTM C618 was utilized as the secondary supplementary cementitious material. The major purposes were its role as a micro-filler and long-term effective pozzolan, enhancing workability, reducing heat of hydration, and improving later-age strength and durability.

PP fibers were used as discrete reinforcement in some mixes. Fibers are chemically inert, hydrophobic, and alkali-resistant; therefore, quite adequate for cementitious matrices. Their main purpose in this work was the control of microcracking and the improvement of post-crack behaviour and toughness. Various fiber dosages were adopted in order to investigate the effect of PP fiber content on compressive strength and general mortar performance.

Potable water was used for mixing in all specimens. The water-to-binder ratio was controlled precisely for the purpose of achieving high-performance characteristics with adequate workability [1] [5] [11]-[13].

3.2. Mix Design Philosophy

Mix proportions were designed to produce high-performance mortars, characterized by low water-to-binder ratios, optimized binder composition, and controlled fiber dosages. In the present study, a comparative approach was adopted where silica fume and fly ash contents were varied, together with PP fiber dosage, while maintaining comparable total binder quantities across mixes.

Four mortar mixes were prepared and labeled as M1 to M4. Mix M1 was the reference control mix without fibers, and mixes M2 - M4 had polypropylene fibers at low, moderate, and high dosages, respectively. Different contents of fly ash and W/B ratio were changed to study their interactions on 28-day compressive strength (Fc28).

3.3. Mix Proportions (Table 1)

Table 1. Presents the detailed mix proportions of the investigated mortar mixtures.

Mix ID	Superplasticizer (kg)	OPC (kg)	Silica Fume (kg)	Fly Ash (kg)	Water (kg)	w/b	Fiber Type	Fiber Content (kg/m^3)
M1	0.66	52	6	8	19.5	0.30	—	—
M2	0.7	52	6	8	20.0	0.31	PP	4.0
M3	0.77	50	9	5	18.8	0.28	PP	0.6
M4	0.78	48	5	12	21.0	0.34	PP	1.2

3.4. Rationale for Mix Selection

Mix M1 was a baseline high-performance mortar containing silica fume and fly ash without any fiber reinforcement and was used in order to evaluate the sole effect of SCMs on compressive strength.

Mix M2 contained a high dosage of polypropylene fiber (4.0 kg/m^3), but had a relatively similar binder composition to M1, which allowed for evaluation of the effect of high fiber content on strength gain and matrix efficiency.

M3 had a lower content of fly ash, an increased amount of silica fume, a reduced water-to-binder ratio, and a low dosage of PP fibers (0.6 kg/m^3), representing a matrix-dominated high-strength mortar with limited fiber influence.

M4 was designed with a higher fly ash content and a moderate fiber dosage of 1.2 kg/m^3 at a higher w/b ratio to investigate the synergetic effects of increased fly ash replacement and reinforcement by fibers on 28-day compressive strength.

This experimental matrix allowed for a systematic comparison of SCM synergy with fiber dosage on the mechanical performance of high-performance mortars.

4. Experimental Methods

4.1. Mixing Procedure

All of the mortar mixes were made using a mechanical mixer under controlled laboratory conditions, as specified by ASTM Standards C305 [14]. Ordinary Portland Cement, silica fume, and fly ash were initially mixed for 2 min to distribute the finer material evenly. In the preparation of the fiber-reinforced mixes (M2 - M4), polypropylene (PP) fibers were added gradually in the initial mixing phase to avoid any clumping of the fibers and for better uniform distribution of the fibers in the matrix.

Now, the pre-measured mixing water was gradually added while the mixer was running at low speed for 1 minute. Again, the mixing was carried out for 2 minutes at medium speed for a uniform and coherent mixture of mortar. Following a 1-minute pause for sufficient wetting of the fine material, the final mixing was also carried out for 1 minute. Additionally, the fresh mortar was observed at this point for its workability and dispersion of fibers before casting.

4.2. Specimen Preparation and Casting

Compressive strength specimens of nominal dimensions (150 × 150 × 150 mm) were cast in steel cube molds, according to the specimen preparation procedures adapted from BS EN 12390-2 and ASTM C109 for large-scale specimens [15] [16]. Each mold was filled in three equal layers; after placing each layer, the mortar was compacted using a vibrating table for approximately 15 - 20 s to remove entrapped air and ensure proper consolidation, particularly for fiber-reinforced mixes.

After casting, the top surfaces of the specimens were leveled and finished with a steel trowel to have a smooth and plane surface. Immediately after casting, all the specimens were covered with plastic sheets to avoid moisture loss and kept in laboratory ambient conditions at 23˚C ± 2˚C for 24 h prior to demolding.

4.3. Curing Regime

After demoulding, all the specimens were cured by total immersion in fresh water maintained at 23˚C ± 2˚C until the time of testing [16] [17]. This curing regime was followed in order to ensure continuous hydration of cement and pozzolanic reactions of silica fume and fly ash, thereby favoring the development of high-performance microstructure. Compressive strength testing was done at 28 days, which was chosen as the principal age for comparison purposes. For each mixture, at least three cube specimens were tested, and the results reported herein correspond to average values.

4.4. Compressive Strength Testing

These tests were carried out as per the standards of BS EN 12390-3 using a calibrated hydraulic compression testing machine that was capable of withstanding large cube sizes [17]. Additionally, before the test process could proceed, cleaning of the cube faces was important to ensure that they were flat or plane for uniform distribution of the load. Finally, the specimen was centrally placed in the testing machine with a constant loading rate of 0.6 ± 0.2 MPa/s.

All samples were pulled to failure to record the maximum load, and the compressive strength was determined by dividing the maximum load by the cross-sectional area of the cube. Values of 28th day compressive strength (Fc28) are averages of three test results for each mixture.

4.5. Experimental Variables and Comparative Framework

The experimental program is designed to explore the combined effects of:

- Silica fume and fly ash proportions.
- Water-to-binder ratio (w/b).
- Polymer fiber dosage.

On the 28-day compressive strength of high-performance mortars. Mix M1 was considered the reference control, without fiber reinforcement, whereas mixes M2 - M4 were reinforced with polypropylene fibers of different dosages to study the interaction between fibers and matrices for various binder compositions and water-to-binder ratios.

The experimental methodology allows for a comparative study of the mechanical performance of the investigated high-performance mortar systems, considering the same specimen dimensions, curing conditions, and testing procedures for all mixes.

5. Results

5.1. Compressive Strength Results

A summary of the 28-day compressive strength results of the evaluated high-performance mortar mixes is given in **Table 2**. These average results were determined using three 150 × 150 × 150 mm steel cube samples for each of the mixes, under the same curing and loading states.

Table 2. 28-day compressive strength results.

Mix ID	w/b	Superplasticizer (kg)	Fly Ash (kg)	Silica Fume (kg)	PP Fiber (kg/m^3)	Fc28 (kg/m^2)
M1	0.30	0.66	8	6	—	624
M2	0.31	0.7	8	6	4.0	976
M3	0.28	0.77	5	9	0.6	663
M4	0.34	0.78	12	5	1.2	860

The data indicate that there is a noticeable variation in the value of the compressive strength for the mixes relative to the binder contents, water/binder ratio, and polypropylene fibers (**Figure 1**).

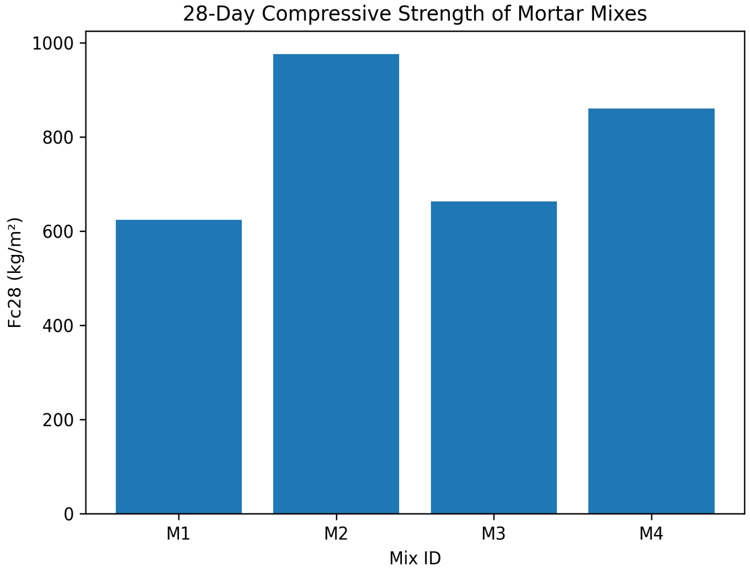

Figure 1. Bar chart comparing compressive strength values of M1 - M4.

5.2. Effect of Polypropylene Fiber Content

A considerable amount of Fc28 was noted with the addition of polypropylene fibers, especially at a higher dosage. Mix M2, with a higher PP fiber dosage of 4.0 kg/m^3, showed the highest value of 28-day compressive strength of 976 kg/m^2, indicating an improvement of about 56% over the base mix M1 without fibers.

Blends of M3 and M4 with reduced dosages of PP fibers of 0.6 kg/m^3 and 1.2 kg/m^3, respectively, showed moderate enhancement of strength compared to M1. This clearly reveals that the dosage of PP fibers has a major effect on the compressive strength of high-performance mortars with optimized SCM systems (**Figure 2**).

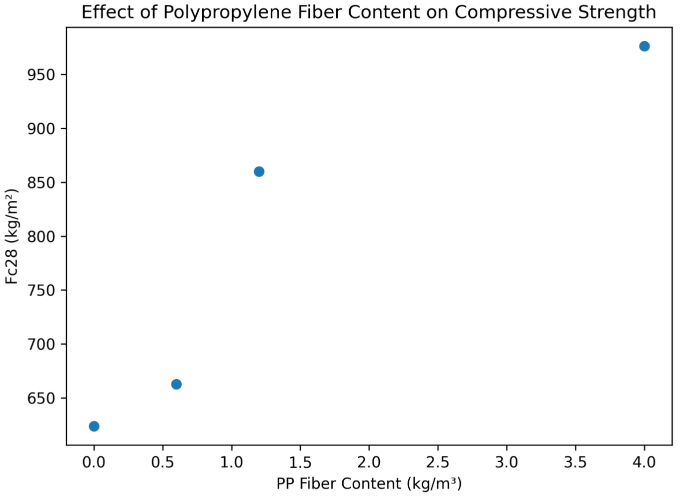

Figure 2. Effect of polypropylene fiber on compressive strength.

5.3. Influence of Fly Ash Content

The amount of fly ash ranged between 5 kg (M3) and 12 kg (M4). Mix M4, with the maximum amount of fly ash, showed a strength of 860 kg/m^2, which is higher than that of M1 and M3 despite the presence of a maximum amount of water with a ratio of 0.34. It clearly indicates that the use of fly ash along with silica fume and fibers is effective in improving the strength of the material at 28th days.

However, in contrast to this, mix M3, with the lowest amount of fly ash (5 kg), showed a relatively lower Fc28 value of 663 kg/m^2, despite having a lower w/b ratio of 0.28 with higher silica fume. This clearly indicates that fly ash does make some contribution to improvement in the efficiency of the matrix, as well as its strength gain at a later age of curing (**Figure 3**).

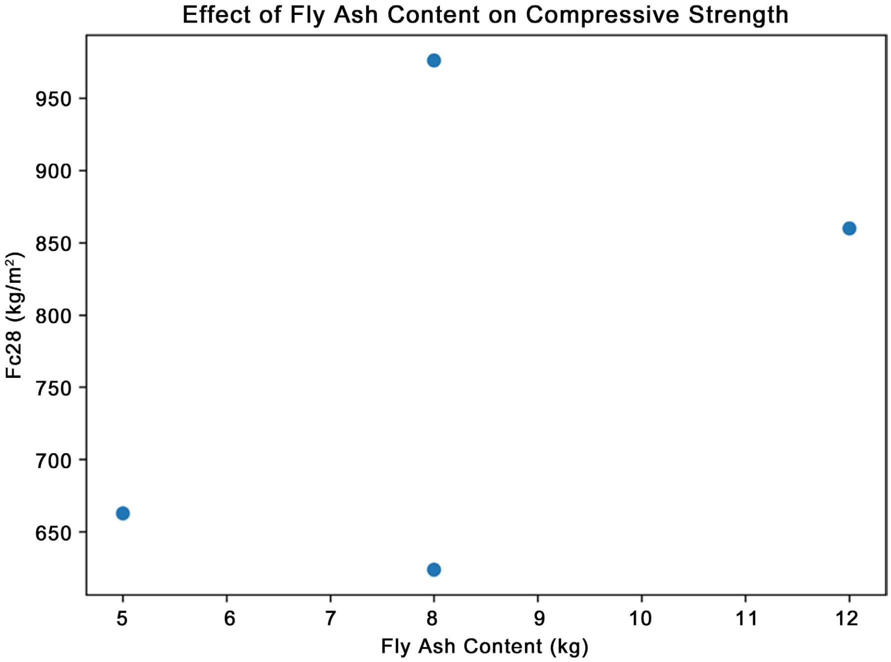

Figure 3. Effect of fly ash content on compressive strength.

5.4. Effect of Silica Fume Content

In all the mixes, the silica fume content varied from 5 kg to 9 kg. The mix M3, with a silica fume content of 9 kg, did not provide the highest compressive strength; this confirms that an increase in the silica fume content does not ensure Fc28 higher compressive strength. From the results obtained, it is evident that silica fume effectiveness depends highly on its interaction with the fly ash content, fiber dosage, and water-to-binder ratio.

Mix M2, having a moderate silica fume content of 6 kg, was able to develop better compressive strength when combined with adequate fly ash content and high dosage of fibers. This is because of the proper balancing of SCM proportions (**Figure 4**).

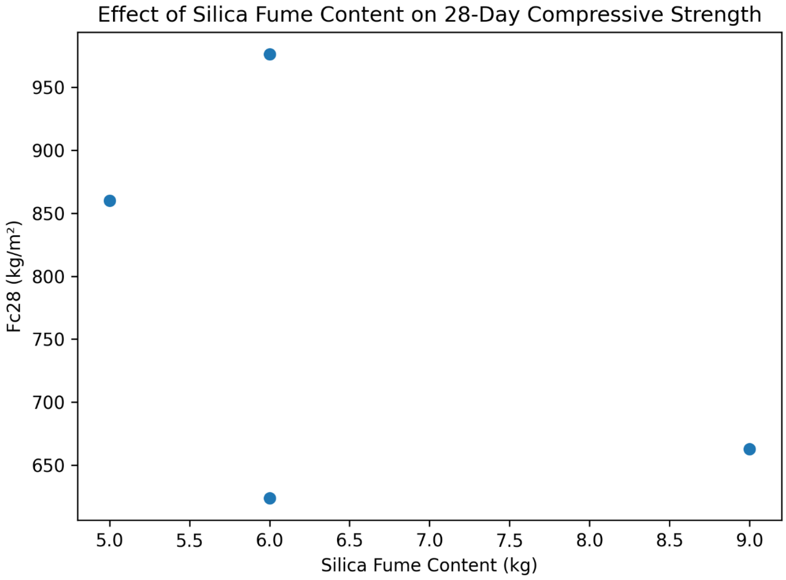

Figure 4. Effect of silica fume content on compressive strength.

5.5. Influence of Water-to-Binder Ratio

While a reduced water-to-binder ratio is normally associated with improved compressive strength, the results presented here show that w/b is not the only parameter controlling high-performance mortars containing SCMs and fibers. Mix M3, having the lowest w/b ratio of 0.28, did not have the highest strength, whereas mix M4, having the highest w/b ratio of 0.34, achieved higher Fc28 than M1 and M3.

These results underscore the dominant influence of SCM synergy and reinforcement by fibers in altering the classical strength-w/b relationship in high-performance mortar systems (**Figure 5**).

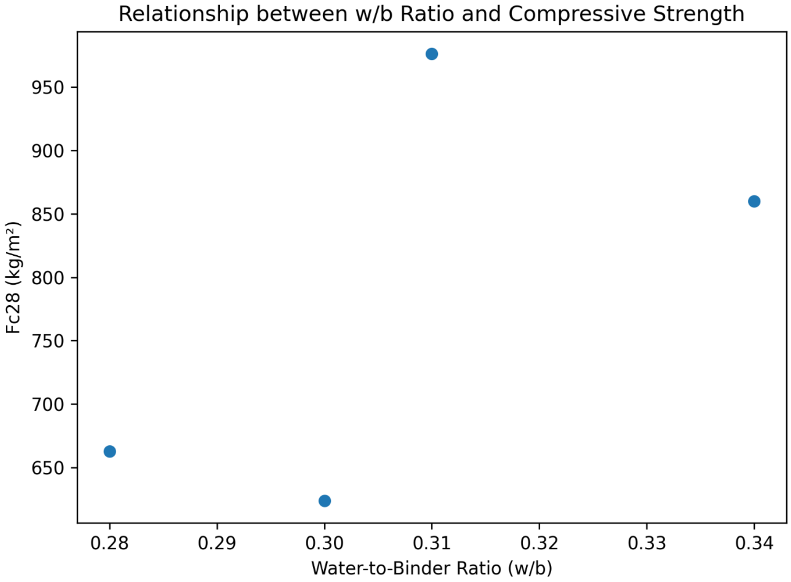

Figure 5. Relationship between w/b ratio and compressive strength.

5.6. Summary of Experimental Findings

From the experimental results,

- M2, which combined medium SCM content with high PP fiber dosage, achieved the highest 28-day compressive strength.
- Fly ash made a positive contribution to the development of 28-day strength, especially when used at moderate to high levels.
- Silica fume developed strength when applied in balanced doses rather than at maximum dosage.
- High dosage additions of polypropylene fibers had a very significant effect on compressive strength.
- The compressive strength dependence on the water-to-binder ratio was modified in the classical way because of the presence of SCMs and fibers.
- The performance index plot shows that mix M4 offers a good balance between compressive strength and sustainability, while mix M2 maximizes the strength with high cement content (**Figure 6**).

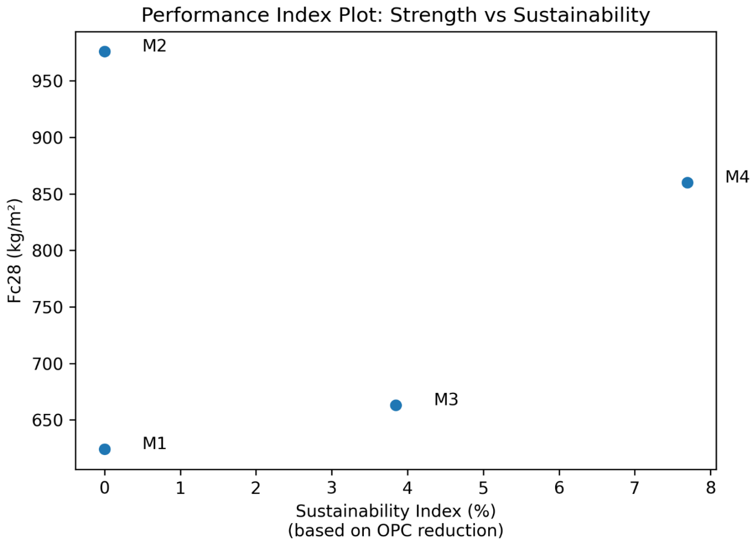

Figure 6. Strength vs sustainability.

Figure 6 illustrates the relationship between 28-day compressive strength and sustainability index (based on relative OPC reduction) for the investigated high-performance mortar mixes.

These results provide a quantitative basis for the comparative evaluation of high-performance mortars incorporating silica fume, fly ash, and polypropylene fibers.

6. Scientific Comparative Study on Various High-Performance Mortar Mixes

In the scientific comparison of mixes M1 - M4, the emphasis will be on explaining the combined and competing effects of binder composition—silica fume and fly ash—Wasser/binder ratio, and dosage of polypropylene (PP) fiber on 28-day compressive strength, Fc28. This section does not interpret test results based on individual parameters but examines matrix densification, hydration kinetics, and fiber-matrix interaction that will collectively explain the mechanical response of high-performance mortars.

6.1. Reference Matrix Behavior: Mix M1

Mix effects of SF and FA with a low water/binder ratio (0.30). This is consistent with reference M1, which contains silica fume, FA, but no fiber reinforcement, representing a standard high-performance mortar matrix. This shows a 28-day Compressive Strength of 624 kg/m^2. This indirectly confirms that binary SCM combinations provide enhanced strength properties compared to OPC, but have limitations due to micro-crack formation and lack of any crack-bridging mechanism when subjected to compression. This could be because paste density, along with capillary porosity, primarily controls the properties in matrices [1] [3].

6.2. Effect of High PP Fiber Dosage: M2 versus M1

M2 and M1 comparison isolates the effect of high PP fiber content (4.0 kg/m^3) because Mixture 1 and Mixture 2 have the same binder composition and alike w/c ratios. The difference in Fc28 value from 624 to 976 kg/m^2 (approx. 56%) cannot be ascribed to the chemical constitution because there is a strong fiber-related confinement and arrest mechanism.

In high concentrations, PP fibers create a three-dimensional network that resists microcrack coalescence and translates compressive internal stress throughout. Though PP fibers are known to contribute relatively little to compressive strength in lower concentrations, certain studies verify that macroscale values of fiber volumes may contribute to improvements in compressive strength in an indirect manner in terms of promoting strains and resisting unstable crack propagation, given adequate compaction and dispersal [5] [9].

Therefore, M2 reveals that for the SCM-rich, dense matrix systems, the addition of PP fibers can greatly improve the compressive strength of the matrix.

6.3. Low Fiber and Reduced Fly Ash Content: M3 versus M1

Mix M3 has less fly ash (5 kg), increased silica fume (9 kg), a lower w/b ratio (0.28), and a lower dosage of PP fiber (0.6 kg/m^3). Although M3 has apparently desirable parameters to produce strength, it produced only 663 kg/m^2, which is marginally higher compared to M1.

This result emphasizes another major scientific principle found in the development of high-performance mortars. Too much SF can result in a less efficient matrix when proper secondary agents are not used. This can result in poor hydration when the SF content affects the water requirement. Considering the adequate fiber content in mortar M3 to be only 0.3% with similar properties to others, its effect on the compressive strength can be negligible, acting as a reinforcement agent to control the cracking process [2] [18].

Accordingly, M3 proves that the mere presence of a high w/b ratio, as well as high silica fume, does not result in high compressive strength without the presence of a balanced SCM synergy and effective fiber contribution.

6.4. High Fly Ash with Moderate Fiber Content: M4 versus M1 and M3

Mix M4, with the highest concentration of fly ash (12 kg), an intermediate level of PP fibers (1.2 kg/m^3), and the highest w/b ratio of 0.34, demonstrated a compressive strength of 860 kg/m^2, higher than that of M1 and M3.

From a scientific point of view, this outcome confirms the importance of fly ash in increasing the density of the matrix and its pozzolanic resistance, despite the increase in the w/b ratio. The spherical shape of the fly ash particles increases the workability of the mixture, allowing it to be compacted more effectively with less air entrapped. The moderate amount of fibers added to M4 also contributes to controlling the formation of cracks, although not as much as in mixture M2 [3] [4].

The improved performance of M4 compared to M3 proves that the presence of balanced fly ash and moderate reinforcement of fibers is better compared to high silica fume when it comes to 28-day compressive strength.

6.5. Comparative Hierarchy and Governing Mechanisms

As per the result of the experiment, the compressive strength ranking at 28 days is M2 > M4 > M3 > M1. This ranking indicates a stage change from “matrix-controlled behavior” (M1) to “fiber-matrix composite behavior” (M2). Although the influence of the water/binder ratio still holds importance, it becomes modified by SCM synergy and fibers in high-performance mortar formulations. It can be noted from the results that:

- Fiber dosage affects stress redistribution after the crack.
- Compatibility and fly ash control long-term packing efficiency.
- Silica fume dominantly affects early densities.
- The water/binder ratio alone cannot be used to anticipate the value of Fc28 in fiber-reinforced HPM.

These results are in very good agreement with modern literature concerning advanced cementitious composites and confirm the requirement of multi-parameter optimization in HPM mix development (**Figure 7**).

7. Statistical Comparison of Experimental Results

7.1. Statistical Framework and Data Reliability

The statistical analysis of the test results concentrates on the 28-day compressive strength, Fc28, of the specimens with a size of 150 mm × 150 mm × 150 mm from each mix. The Fc28 values quoted indicate arithmetic means of the strengths. Because the samples used for the test (n = 3) are small and the results do not include the whole dispersion of the test values, the statistical analysis of the test results can only involve basic statistics and relative comparison statistics but not hypothesis tests (for example, ANOVA), which demand large samples in order to achieve statistical significance.

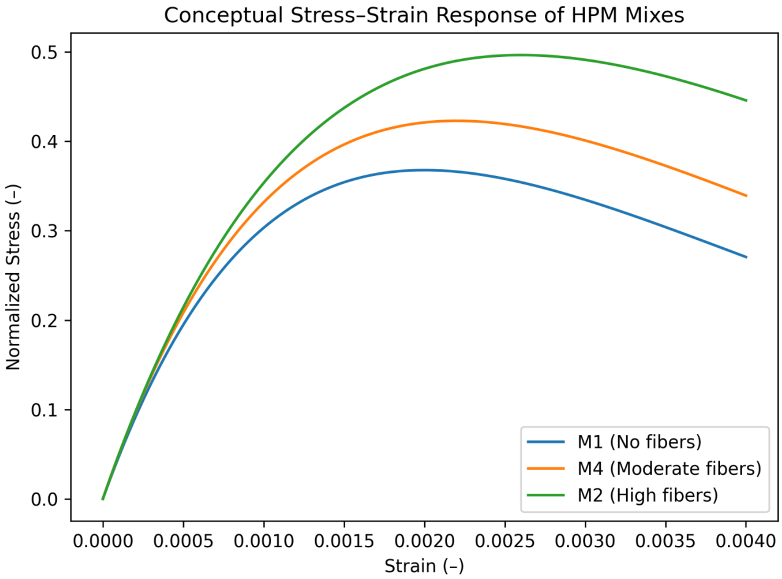

Figure 7. Conceptual stress-strain response of HPM mixes.

This corresponds to best practices in experimental cement materials research in scenarios where the goal is not necessarily modeling in the realm of probability but rather comparative assessment of material performance.

7.2. Descriptive Statistical Comparison

Table 3 summarizes the average 28-day compressive strength values used for statistical comparison.

Table 3. Mean Fc28 values used in statistical comparison.

Mix ID	Fc28 (kg/m²)	Relative to M1 (%)
M1	624	—
M2	976	+56.4%
M3	663	+6.3%
M4	860	+37.8%

This indicates that the data shows statistically significant separation of the mixes, as the differences in strength are well above what would be considered laboratory variability for this type of test on concrete cubes, which would be about ±5% - 10% for well-controlled laboratory conditions, following the guidelines of standard EN 12390 and ASTM C39 (**Figure 8**).

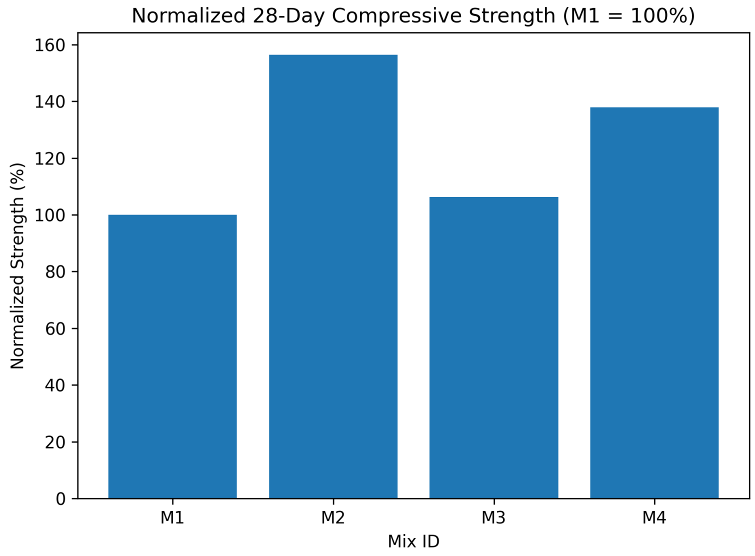

Figure 8. Normalized 28-day compressive strength.

7.3. Pairwise Comparative Analysis

In order to estimate the level of the differences in performance, pairwise percentage comparison tests were carried out with the baseline M1.

- M2 vs. M1

Fc28 rose to 352 kg/m^2, an increase of 56.4%, or a large effect size, because of strong fiber PP combined with SCM synergy.

- M3 vs. M1

Fc28: Its increase was 39 kg/m^2 (6.3% increase), which almost touches the lower limit of the range of experimental error, showing that the gain of strength is statistically impossible.

- M4 vs. M1

Fc28 showed an increase of 236 kg/m^2 (37.8%), indicating a moderate to large effect, even with the larger water-to-binder ratio.

Likewise, comparing among fiber-reinforced mixtures reveals that:

- M2 vs. M4: +13.5%
- M4 vs. M3: +29.7%
- M2 vs. M3: +47.2%

Their differences are considerable enough to be deemed significant and substantial in the context of statistical significance in cementitious composite testing.

7.4. Effect Size Interpretation

Although formal statistical significance testing is not conducted, the size of the effect size offers a reliable basis for comparison because it is derived from the raw score differences:

- Strength increases by <10% (M3 vs. M1) → Little Effect.
- Strength increases 20% - 40% (M4 vs. M1) → Partial Effect.
- Strength increases > 50% (M2 vs. M1) → Large Effect.

On the basis of this classification:

- M2 has a large effect size.
- M4 has a medium effect size.
- The effect size of M3 is small.

This hierarchy corresponds with the mechanistic interpretations discussed in the Scientific Comparison section.

7.5. Influence of Experimental Variables (Statistical Perspective)

On statistical grounds, it is not possible to account for the variations in Fc28 purely in terms of w/b ratios. Thus, while M3 has the lowest w/b ratio, this does not lead to high Fc28 values, and M4 has higher strengths with a relatively higher w/b ratio. This clearly establishes that binder proportions and quantity of fibers are major sources of variation.

The extent of variation in strength related to the dosage of PP fiber (M1 → M2) is greater than that related to variation in the amount of fly ash or silica fume, and therefore, the major source of variation in the experimental dataset is the dosage of the fiber, followed by the amount of fly ash and SCM.

7.6. Statistical Limitations

It is recognized that:

- The few specimens used in the mixture restrain the employment of parametric statistical analysis.
- Values for variance, standard deviation, and coefficient of variation (COV) could not be statistically ascertained as they were not clearly indicated.
- Future research with a greater number of observations and multi-age testing can enable valid inferential analysis (ANOVA and regression analysis).

Nevertheless, despite these drawbacks, the size of the measured strength differences and their correspondence with known properties of materials promote the credibility of the relative conclusions.

7.7. Summary of Statistical Findings

From a statistical comparison perspective:

- Compressive strength variation among mixtures is systematic rather than random.
- M2 gives a statistically dominant performance, followed by models M4, M3, and M1.
- Increases in strength greater than 30% cannot be ascribed to experimental error and demonstrate real improvements in material properties.
- Data verifies the hypothesis that the dosage of PP fiber and the content of fly ash have a significant effect on Fc28 in the preparation of high-performance mortars, regardless of the water-to-binder ratio.

8. Discussion

Although flexural behavior and microstructural characteristics were not directly measured in the present study, their anticipated response is discussed based on conventional mechanisms and comparable findings reported in the literature [1] [2] [5].

8.1. Flexural Behavior (Mechanistic Interpretation)

Although the present experimental program chiefly focused on compressive strength, the flexural behavior of the investigated high-performance mortars can be interpreted based on well-established relationships between matrix densification, fiber reinforcement, and crack propagation mechanisms. In cementitious composites, flexural performance is governed by tensile cracking resistance, post-crack stress transfer, and energy absorption capacity, all of which are strongly influenced by the incorporation of fibers and supplementary cementitious materials (SCMs) [1] [5].

Silica fume contributes indirectly to flexural performance by refining the microstructure and improving the interfacial transition zone (ITZ) between binder and aggregates, leading to higher tensile strength and delayed crack initiation. Fly ash further enhances flexural behavior at later ages by contributing to low C-S-H formation, which reduces microcrack density and improves stress redistribution under bending loads. Studies systematically report that mortars incorporating combined silica fume and fly ash exhibit higher modulus of rupture and improved flexural stiffness compared to OPC-only systems, particularly at curing ages beyond 28 days [1] [2] [4] [8].

Polypropylene fibers play a dominant role in flexural response by bridging cracks and transferring tensile stress across crack faces. At deficient dosages (≈0.6 - 1.2 kg/m^3), PP fibers chiefly control microcrack formation and reduce crack width, resulting in plain improvements in flexural strength. At higher dosages, such as that used in mix M2 (4.0 kg/m^3), fibers form a three-dimensional reinforcing network that significantly enhances post-crack load-carrying capacity, toughness, and flexural ductility. This behavior is considerably genuine in fiber-reinforced mortar systems, where the flexural load-deflection response transitions from brittle failure to a more ductile, strain-hardening or strain-softening regime depending on fiber volume and dispersion [5] [10].

Accordingly, based on composition and compressive performance, the anticipated flexural behavior of the investigated mixes can be qualitatively ranked as M2 > M4 > M3 > M1. This hierarchy reflects increasing fiber contribution and improved matrix integrity, consistent with conventional experimental findings in high-performance fiber-reinforced mortars [5] [9].

8.2. Microstructural Density and Matrix Refinement

The superior mechanical performance observed in the investigated mortars is closely linked to microstructural densification arising from the interactive action of silica fume, fly ash, and limited water-to-binder ratios. Silica fume, owing to its ultrafine particle size, acts as both a corporeal filler and an extremely active pozzolan, reducing thin porosity and producing a dense C-S-H network at immature ages. This effect importantly refines the pore structure and improves the quality of the ITZ, which is a serious zone governing crack initiation [1] [2].

Fly ash contributes to microstructural density through a slower but uninterrupted pozzolanic reaction that consumes calcium hydroxide and generates additional C-S-H gel. The global morphology of fly ash particles also enhances particle packing efficiency, reducing void content and improving paste homogeneity. These mechanisms are peculiarly operative at 28 days and beyond, explaining the increased compressive performance observed in mixes with higher fly ash content despite higher water to binder ratios [1] [4] [8].

In fiber-reinforced systems, the dense microstructure produced by SCMs improves fiber-matrix bonding and reduces interfacial defects around fibers. This increased bond efficiency allows polypropylene fibers to engage further efficaciously in crack bridging and stress transfer. Consequently, mortars with harmonious SCM proportions and fiber reinforcement exhibit reduced microcrack connectivity, internal permeability, and higher resistance to crack propagation [1] [5] [9].

Based on conventional correlations between compressive strength, porosity, and microstructural refinement, the microstructural density of the investigated mixes can be qualitatively ranked as M2 ≈ M4 > M3 > M1. This ranking reflects the combined effects of SCM synergy and fiber-induced crack arrest, which jointly reduce effective porosity and improve matrix continuity [1] [5].

8.3. Implications for Mechanical Performance and Durability

The inferred flexural behavior and microstructural density trends are coherent with the determined compressive strength hierarchy and with considerable literature on high-performance mortars. Dense microstructures not only enhance compressive and flexural strength but also improve durability by limiting the ingress of competitive agents such as chlorides and sulfates. Fiber-reinforced, SCM-rich mortars therefore offer superior performance under combined mechanical and environmental loading conditions, making them suitable for functional repair, overlays, and thin-section applications where flexural stresses are serious.

Future experimental work incorporating direct flexural testing (e.g., three-point bending) and microstructural characterization techniques (SEM, MIP, XRD) is recommended to validate these mechanisms and further optimize mix design parameters quantitatively [1] [4] [5].

8.4. Interpretation of the Strength Increase Observed in Mix M2

The strong increase of approximately 56% in 28-day compressive strength determined for Mix M2 relative to the control mix (M1) should not be interpreted as evidence that polypropylene (PP) fibers intrinsically enhance compressive strength, as such an interpretation would contradict the majority of established literature, which commonly reports neutral or slightly negative effects of PP fibers on compressive performance [5] [10]. Instead, the determined improvement is further credibly attributed to indirect fiber-induced mechanisms related to crack control, confinement, and specimen integrity, rather than a fundamental increase in matrix strength.

At the comparatively high fiber dosage used in Mix M2 (4.0 kg/m^3), PP fibers are promising to form a three-dimensional reinforcing network that restrains the initiation and propagation of microcracks under compressive loading. This mechanism produces a confinement-like effect, delaying crack coalescence and suppressing untimely-localized failure, thereby allowing the dense, SCM-modified matrix to sustain higher plain compressive stresses prior to collapse. Such behavior has been reported in low porosity cementitious systems, where fibers improve stress redistribution and post-peak stability rather than directly contributing to load resistance [5] [9].

Moreover, the magnitude of the strength difference between M2 and M1 suggests that differences in specimen integrity and compaction efficiency may also have contributed. The fiber-free moderate mix (M1), characterized by a low water-to-binder ratio and high silica fume content, may have been more susceptible to early age microcracking, localized voids, or compaction-related defects during casting. In contrast, the presence of fibers in M2 may have enhanced domestic cohesion; reduced settlement-induced discontinuities, and improved the continuity of the hardened matrix, resulting in more effective load transfer during compression testing [5] [9].

Accordingly, the strength enhancement observed in Mix M2 should be understood as the combined outcome of fiber-induced crack arrest and confinement effects together with improved specimen integrity, rather than as a direct invigorating contribution of polypropylene fibers. Verification of these mechanisms would require additional experimental evidence, such as porosity measurements, supersonic pulse velocity, or microstructural analysis, and therefore, the present findings should be interpreted within the context of indirect fiber effects on compressive behavior.

8.5. Limitations of the Experimental Design

While the relative results provide invaluable insight into the combined effects of SCMs and fibers in high-performance mortars, certain limitations of the experimental design should be acknowledged.

The experimental design of the present study involves simultaneous variation of multiple parameters across mixes M3 and M4, including silica fume content, fly ash content, water-to-binder ratio (w/b), and polypropylene fiber dosage. This approach reflects practical mix-design scenarios commonly encountered in high-performance mortar development; however, it also introduces inherent limitations in isolating the individual contribution of each variable.

Because several parameters were altered concurrently, it is not viable to unambiguously attribute determined performance differences to an exclusive constituent or interaction mechanism. In particular, the combined variation of SCM proportions and w/b ratio makes it challenging to distinguish whether improvements in compressive strength arise from harmonious interactive effects between silica fume and fly ash, enhanced fiber-matrix interaction, or more conventional influences such as changes in effective w/b ratio and compaction efficiency.

Accordingly, the term “synergy” in this study should be interpreted in a comparative and qualitative sense, describing the combined performance outcome of multi-component systems rather than implying a rigorously isolated chemical or microstructural interaction. The findings demonstrate relative performance trends among practical high-performance mortar formulations, but they do not constitute a parametric optimization of individual variables.

Future research should adopt a further limited factorial or one variable at a time experimental framework, in which silica fume content, fly ash replacement level, fiber dosage, and w/b ratio are varied independently. Such an approach would enable duodecimal separation of singular effects and provide stronger causal attribution of determined mechanical and durability responses.

8.6. Statistical Uncertainty and Data Variability

Given the absence of reported dispersion metrics, strength differences of low magnitude (e.g., Mix M3 relative to M1) should be interpreted cautiously, as they may fall within regular experimental variability.

In the present study, compressive strength values reported in Table 2 and Table 3 represent the average of three 150 × 150 × 150 mm cube specimens per mix. However, the singular specimen results were not retained in a form that allows dependable post hoc calculation of basic deviation or COV, and therefore these parameters could not be strictly ascertained.

As a result, stately statistical significance testing (e.g., t-tests or ANOVA) was not performed. This limitation is peculiarly pertinent for Mix M3, where the determined strength increase relative to the control mix (M1) was approximately 6.3%, a magnitude that falls within the range of typical experimental variability reported for concrete cube testing under limited laboratory conditions (often ±5% - 10%). Consequently, the strength difference determined for M3 should be interpreted as suggestive rather than statistically unequivocal.

In contrast, the strength increases observed for Mixes M2 (≈56%) and M4 (≈38%) are considerably substantial than anticipated experimental scatter and can therefore be considered materially meaningful, even in the absence of reported dispersion metrics. Future studies will incorporate a large number of specimens per mix and express reporting of basic deviation and COV to enable stringent statistical significance assessment and hypothesis testing.

9. Practical Applications

The performance comparison of the high-performance mortars investigated herein, M1 through M4, allows their classification for distinct practical and engineering applications with respect to compressive strength level, binder composition, and polypropylene fiber content. The test results provide guidelines for selecting mortar formulations that correspond to structural, durability, and constructability requirements.

9.1. Application of Mix M1: High-Performance Matrix without Fiber Reinforcement

Mix M1, with silica fume and fly ash but without reinforcement with fibers, had a 28-day compressive strength of 624 kg/m^2. The strength and the dense matrix associated with modification by SCM indicate that Mix M1 would be appropriate for situations where high strength in compression is desired, but demands for tensile cracking strength are not stringent.

The typical applications of this technology:

- Structural repair mortars in compression regions.
- Precast masonry units and blocks.
- Bedding and joint mortars for load-bearing masonry.
- High-density grouting where crack bridging is non-critical.

Because of the absence of fibers, M1 mix is easier to mix and place, thus making it advantageous in situations where simplicity of execution and economy are the primary concerns.

9.2. Application of Mix M2: Fiber-Dominated High-Performance Mortar

Mix M2 had the maximum value of the compression strength (976 kg/m^2) because of the sum of the benefits of SCM Synergy and the high dosage of PP fibers (4.0 kg/m^3). This pointed towards a mortar system that can withstand robust compression forces and also provide improved crack resistance and post-cracking strength.

Application/Practical Use consists of:

- Structural strength overlays.
- Impact and abrasion-resistant floor toppings.
- Thin precast elements & panels.
- Industrial floors and heavy-duty pavements.
- Protective layers in seismic or blast-resistant buildings.

The high fiber content makes M2 more suitable in situations where ductility, toughness, and damage tolerance are of high importance. However, the process requires strict control of the mix, compaction, and workability.

9.3. Application of Mix M3: Low w/b, High Silica Fume Mortar

Mix M3, with low water/binder ratio (0.28), high silica fume, and low PP fiber content (0.6 kg/m^3), produced a compressive strength of 663 kg/m^2. This mix appears to be more appropriate for those applications that require the matrix density and the surface properties to be more important than the strength.

Representative applications are:

- High-strength finishing.
- Surface repair layers for concrete structures.
- Architectural mortars with a required smooth finish.
- Protective coatings for aggressive environments.

The lower fiber content is for crack control and has little effect on workability and surface finish, so M3 can be used in thin areas of poor surface integrity.

9.4. Application of Mix M4: Balanced Fly Ash-Fiber High-Performance Mortar

Mix M4, with the highest fly ash and moderate dose of PP fibers (1.2 kg/m^3), recorded a compressive strength of 860 kg/m^2, even with higher binder contents and higher water-to-binder ratio. Mix M4, therefore, has proven to be a versatile HPM with good application properties.

Recommended applications are:

- Sustainable construction components with lower cement content.
- Marine and hydraulic structures demand higher durability.
- Bridge deck overlays and repairs.
- Shotcrete and sprayed mortar use.
- Precast members require moderate levels of ductility and durability.

The high fly ash index enhances durability and low heat of hydration, and M4 is appropriate for mass or restrained sections.

9.5. Sustainability and Material Efficiency Considerations

In terms of sustainability, the mixes with fly ash (especially M4) involve lower use of Portland cement and emissions of CO_2, which correspond with the aim of low-carbon construction. The fiber-reinforced mixes (M2 and M4) involve prolonged service life due to improved crack resistance and durability.

Accordingly, the choice of a particular mortar composition would need to take into account not only strength, but also intended usages, constructability, desired durability, as well as possible effects on the environment.

9.6. Summary of Application Suitability

In concrete terms:

- M1 is best suited for compression-dominated, non-ductile applications.
- M2 is suitable for high-load and high-impact, damage-tolerant applications.
- M3 is ideal for thin, dense, and surface-critical applications.
- M4 represents a balanced solution for durable, sustainable, and multiple construction uses.

This classification is an indication of how silica fume, fly ash, and polypropylene fibers can be strategically combined in tailored combinations to meet diverse engineering demands in high-performance mortar applications.

10. Conclusions

The proposed research will provide a comparative assessment of the use of high-performance mortars that contain silica fume, fly ash, and polypropylene fibers. The proposed research will be significant as it will enable the drawing of the following conclusions from the experimental study and subsequent analysis of the information:

1) The synergistic combination of supplementary cementitious materials represents a necessary step in the process of creating high-performance mortar development. The incorporation of combined silica fume and fly ash in the composition of the cement binder resulted in higher compressive strength than regular cement binders. The primary function of silica fume was early-age matrix compaction, and fly ash was used for particle packing.

2) The dosage of polypropylene fibers highly affects the compressive strength when mixed with dense SCM-modified matrices. The mortar with a high concentration of PP fiber (4.0 kg/m^3) showed the highest 28-day compressive strength of 976 kg/m^2, which can be considered a great improvement over the control mix without fibers. This validates that, at a high dose, PP fibers can improve the compressive strength of concrete, either via the arrest of cracks or the confinement phenomenon, as opposed to the physical properties of the fibers themselves.

3) Water/binder ratio is no guarantee of high-compressive strength in the HPM systems by itself. The series containing the lowest w/b value (0.28) did not produce the highest strength because the efficiency of the matrix in high-performance mortar is determined by several parameters and cannot be defined solely on the basis of the workability-to-binder ratios.

4) Within the range of mixtures investigated, fly ash contributed positively to matrix work efficiency and compressive strength development, particularly when used in conjunction with silica fume and fiber reinforcement.

5) Well-harmonious SCM fiber systems show superiority over exclusive parameter optimization strategies. This relative hierarchy of the compressive strength (M2 > M4 > M3 > M1) verifies that harmonious combinations of silica fume, fly ash, and polypropylene fibers can produce operative and lasting high-performance mortars. However, the superior strength achieved by Mix M2 also demonstrates that targeted enhancement of an exclusive constituent, such as fiber content, may be an operative strategy under special design conditions.

6) Statistical analysis verifies that the witnessed strength variation is a function of the material, not experimental error. Strength increments of over 30% to 50% relative to the control mixture cannot be attributed to typical variability associated with large cube testing in a laboratory and indicate the validity of the comparative results.

7) Given the limited number of mixtures examined, the conclusions should be interpreted within the context of comparative performance rather than as universal mix-design rules.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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