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A Comparative and Synergistic Study on the Performance of Reinforced Concrete Incorporating Basalt Powder and Recycled Steel Filings

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***Abstract:** The pursuit of high-performance and sustainable construction materials has driven significant research into supplementary cementitious materials (SCMs) and industrial by-products. This study presents a comprehensive comparative analysis of the individual and combined effects of basalt powder (BP) and recycled steel filings (SF) on the mechanical and durability properties of reinforced concrete. An experimental program was designed incorporating four concrete mixtures: a control mix (M0), mixes with 15% cement replacement by BP (M1) and SF (M2) individually, and a hybrid mix with 10% BP and 10% SF (M3). The properties evaluated include workability, density, compressive strength (at 7, 14, and 28 days), splitting tensile strength, and water absorption. Results indicate that both additives enhance concrete performance, albeit through distinct mechanisms. The BP mix (M1) demonstrated superior durability characteristics, reducing water absorption by 10.8% compared to the control, attributed to pozzolanic activity and pore refinement. The SF mix (M2) showed the most significant improvement in mechanical strength, with a 17.1% increase in 28-day compressive strength, owing to improved packing density and crack-arresting capabilities. The hybrid mix (M3) exhibited a synergistic effect, achieving the optimal balance of properties, including the highest compressive strength (43 MPa), tensile strength (4.0 MPa), and the lowest water absorption (5.4%). This suggests that the combination of BP and SF leverages the microstructural densification of the former and the mechanical reinforcement of the latter. The findings advocate for the integrated use of these sustainable materials to produce concrete with enhanced performance and a reduced environmental footprint, promoting the recycling of industrial waste.*
***Keywords:** Basalt Powder, Steel Filings, Sustainable Concrete, Mechanical Properties, Durability, Hybrid Additive, Supplementary Cementitious Material*

I. INTRODUCTION

Reinforced concrete stands as the cornerstone of modern civil infrastructure due to its versatility, structural efficacy, and economic viability. However, its widespread use is tempered by inherent limitations, including quasi-brittle behavior under tension, susceptibility to crack propagation, and permeability to deleterious agents like chlorides and sulfates, which can precipitate premature deterioration and compromise service life [1]. In tandem with performance challenges, the global construction industry faces mounting pressure to mitigate its environmental impact, particularly the substantial carbon dioxide emissions associated with Portland cement production [2, 3].

This dual imperative enhancing performance while improving sustainability has catalyzed extensive research into alternative binder systems and the incorporation of supplementary cementitious materials (SCMs). SCMs, often industrial by-products or naturally occurring materials, can partially replace cement, thereby reducing the carbon footprint and frequently enhancing specific concrete properties through physical and chemical interactions [4, 5].

Among naturally derived SCMs, basaltic rocks, when finely ground, exhibit promising pozzolanic activity. Basalt powder (BP), a by-product of basalt rock processing, contains amorphous silica and alumina that can react with portlandite ($Ca(OH)_2$) from cement hydration to form additional calcium-silicate-hydrate (C-S-H) gel [6, 7]. This reaction contributes to microstructural densification, pore refinement, and a consequent improvement in durability metrics such as reduced permeability and increased resistance to chemical attack.

Conversely, the incorporation of metallic waste materials, such as recycled steel filings (SF) a residue from machining and grinding operations offers a pathway to enhance mechanical properties. SF particles act primarily as a micro-reinforcement and filler. They improve the packing density of the concrete matrix, provide crack-bridging at the micro-scale, and can enhance toughness and impact resistance [8, 9]. Utilizing SF also aligns with circular economy principles by diverting industrial waste from landfills.

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While the individual effects of BP and SF have been explored separately in prior studies, a direct comparative assessment of their influence on a common concrete matrix, and more importantly, an investigation into their potential synergistic effects in a hybrid system, remains relatively underexplored. This represents a significant research gap. A hybrid approach could potentially amalgamate the durability benefits of BP with the mechanical reinforcement of SF, leading to a more holistically superior concrete composite.

Therefore, the primary objectives of this research are threefold: (1) to compare the individual effects of BP and SF on the fresh, mechanical, and durability properties of concrete at comparable replacement levels; (2) to investigate the performance of a hybrid mix incorporating both BP and SF; and (3) to elucidate the underlying mechanisms responsible for the observed behavior through a discussion of physical and chemical interactions. The outcomes of this study aim to provide actionable insights for developing high-performance; sustainable concrete mixes for demanding infrastructure applications.

II. LITERATURE REVIEW

A. Basalt Powder as a Supplementary Cementitious Material

Basalt, a common extrusive volcanic rock, is primarily composed of plagioclase, pyroxene, and olivine minerals. When ground to a fine powder (typically with a Blaine fineness exceeding 400 m^2/kg), its amorphous silicate content becomes reactive in the high-pH environment of hydrating cement. Research by Wang et al. (2021) demonstrated that replacing 15% of cement with BP led to a 12% increase in 28-day compressive strength, attributed to the secondary pozzolanic C-S-H formation that densifies the interfacial transition zone (ITZ) between paste and aggregate. Beyond strength, the durability benefits are pronounced. Al-Salloum et al. (2020) reported that BP incorporation significantly reduced water sorptivity and chloride ion penetration, while also enhancing resistance to sulfate attack. This is due to the reduction in capillary pore connectivity and total porosity. Furthermore, Li et al. (2019) observed that BP effectively mitigated autogenous shrinkage in high-performance concrete mixes, reducing early-age cracking potential. The optimal replacement level is generally cited between 10% and 20% by weight of cement, beyond which workability may decrease substantially due to the high surface area of the powder, and the dilution effect may outweigh pozzolanic benefits if the curing conditions are not favorable [6].

B. Recycled Steel Filings as a Micro-Reinforcement

Steel filings, a waste product from metalworking industries, are characterized by their high density, strength, and irregular, elongated particle shape and their incorporation into concrete functions through physical mechanisms rather than chemical reactivity. Reddy & Kumar (2019) found that a 10-20% volumetric replacement of fine aggregate with SF increased compressive strength by up to 15% and flexural strength by up to 25%. The enhancement is credited to three key factors: (1) the excellent packing effect, reducing void content; (2) the high modulus of elasticity of steel, which provides superior load transfer; and (3) the ability of steel particles to intercept and arrest micro-cracks, thereby increasing fracture energy [16, 17]. Studies on dynamic performance, such as those by Khan et al. (2023), indicate that SF-reinforced concrete exhibits improved impact and abrasion resistance, making it suitable for industrial floors and pavements. A critical consideration is the potential for corrosion of the steel particles, which could lead to expansive pressures and cracking. However, research suggests that in a dense, high-quality concrete matrix with low permeability, the filings remain effectively passivated, especially when used as a partial fine aggregate replacement rather than a cement replacement [20, 21].

C. Hybrid Systems and Synergistic Potential

The concept of using hybrid additives to tailor concrete properties is gaining traction. A limited number of studies have explored combinations similar to BP and SF. For instance, Hussein et al. (2023) investigated a mix with 10% BP and 10% SF and reported a balanced improvement in both strength and durability, outperforming single-additive mixes. The postulated synergy arises from the complementary roles: the BP refines the microstructure and strengthens the cementitious binder, creating a denser and less permeable matrix that better protects the steel filings from corrosion. Simultaneously, the SF provides a robust skeletal framework that reinforces this improved matrix, enhancing its load-bearing capacity and toughness. This body of work, while promising, is nascent and warrants further systematic investigation to optimize proportions and fully understand the interaction mechanisms, which is the core contribution of the present study.

TABLE I
SUMMARY OF KEY PREVIOUS STUDIES ON BP AND SF IN CONCRETE

REFRENCE	Material	Replacement Level (%)	Key Finding
Wang et al. (2021)	Basalt Powder	15% (Cement)	12% increase in 28-day compressive strength
Al-Salloum et al. (2020)	Basalt Powder	10-20% (Cement)	Reduced permeability and enhanced sulfate resistance
Li et al. (2019)	Basalt Powder	15% (Cement)	Reduced autogenous shrinkage, improved durability
Reddy & Kumar (2019)	Steel Filings	10-20% (Sand)	15% increase in compressive strength
Ahmed et al. (2022)	Steel Filings	15% (Sand)	Improved dynamic load and impact resistance
Hussein et al. (2023)	BP + SF (Hybrid)	10% + 10%	Balanced enhancement of strength and durability
Çelik et al. (2022)	Basalt Powder	20% (Cement)	Enhanced long-term strength and chloride resistance
Khan et al. (2023)	Steel Filings	25% (Sand)	Significant increase in abrasion and impact resistance

III. MATERIALS AND EXPERIMENTAL METHODOLOGY

A. Materials

Cement: Ordinary Portland Cement (OPC) Type I conforming to ASTM C150.

Aggregates: Natural River sand (fine aggregate with fineness modulus of 2.8) and crushed granite coarse aggregate with a maximum nominal size of 20 mm. Both met ASTM C33 requirements.

Basalt Powder (BP): Obtained from a local quarry, ground to a Blaine fineness of 420 m²/kg. Its specific gravity was 2.9. X-ray fluorescence (XRF) analysis indicated a high content of SiO_2 (45.2%) and Al_2O_3 (14.5%).

Recycled Steel Filings (SF): Collected from a local machining workshop, sieved to pass a 1.18 mm sieve and retained on a 150 µm sieve. The particles were irregular and elongated. To prevent rust, they were washed with a rust inhibitor and dried before use. Specific gravity was 7.85.

Water: Potable tap water.

Superplasticizer: A polycarboxylate-ether based high-range water reducer (HRWR) was used to maintain adequate workability, conforming to ASTM C494 Type F.

TABLE II
CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF BINDER MATERIALS

Property/Oxide (%)	OPC	Basalt Powder
SiO2	20.1	45.2
Al2O3	5.2	14.5
Fe2O3	3.5	12.8
CaO	63.0	9.1
MgO	2.1	6.3
SO3	2.4	0.2
LOI	2.5	1.5
Specific Gravity	3.15	2.90
Blaine Fineness (m²/kg)	350	420

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B. Mix Proportions and Design

Four concrete mixtures were designed with a target characteristic strength of 35 MPa and a constant water-to-binder (w/b) ratio of 0.45. The binder includes OPC and the replacement material(s). The control mix (M0) contained 100% OPC. In mix M1, 15% of OPC by weight was replaced with BP. In mix M2, 15% of the fine aggregate volume was replaced with SF (this volumetric equivalence was chosen to match the mass-based cement replacement roughly and to avoid excessive weight in the SF mix). The hybrid mix M3 contained 10% BP (cement replacement) and 10% SF (sand replacement). A constant dosage of superplasticizer (0.8% by weight of binder) was used in all mixes containing additives to achieve comparable workability.

TABLE III
CONCRETE MIX PROPORTIONS (KG/M³)

Component	M0 (Control)	M1 (15% BP)	M2 (15% SF)	M3 (10%BP+10%SF)
Cement	400	340	400	360
Basalt Powder	0	60	0	40
Water	180	180	180	180
Fine Aggregate (Sand)	720	720	612	648
Steel Filings	0	0	175	117
Coarse Aggregate	1100	1100	1100	1100
Superplasticizer	03.2	3.2	3.2	3.2
Water/Binder Ratio	0.45	0.45	0.45	0.45

C. Sample Preparation and Curing

For each mix, cubes (150 mm) were cast for compressive strength and density tests, cylinders (150 mm diameter × 300 mm height) for splitting tensile strength, and disks (100 mm diameter × 50 mm height) for water absorption. All materials were mixed in a laboratory pan mixer following ASTM C192 procedures. The fresh concrete was compacted on a vibrating table, demolded after 24 hours, and subsequently cured in a water tank at 23±2°C until the day of testing.

D. Testing Procedures

Fresh Properties: Slump test (ASTM C143) and fresh density (ASTM C138) were measured immediately after mixing.
Compressive Strength: Tested on 150 mm cubes at ages of 7, 14, and 28 days using a compression testing machine (ASTM C39). The average of three specimens is reported
Splitting Tensile Strength: Determined on 28-day cured cylinders as per ASTM C496
Water Absorption: Conducted on 28-day cured, oven-dried disk samples following ASTM C642. The percentage increase in mass after 24-hour immersion was recorded.
Dry Density: The oven-dry density of hardened cubes was calculated at 28 days.

IV. RESULTS AND ANALYSIS

A. Fresh Concrete Properties

The results of the slump test and fresh density are presented in Figure 1and Table 4. The control mix (M0) exhibited the highest slump of 75 mm. The incorporation of additives reduced workability: M1 (BP) showed a slight reduction to 72 mm, attributed to the high surface area of the fine powder. M2 (SF) had a more noticeable drop to 70 mm due to the angular shape and high friction of the steel particles. The hybrid mix M3 recorded the lowest slump of 68 mm, reflecting the combined effect of both additives. Despite the reductions, all mixes remained within an acceptable workability range (65-100 mm) for typical reinforced concrete placements, aided by the superplasticizer. The fresh density increased progressively from 2400 kg/m³ (M0) to 2425 kg/m³ (M1), 2480 kg/m³ (M2), and 2495 kg/m³ (M3), directly correlating with the higher specific gravity of the added materials, especially steel.

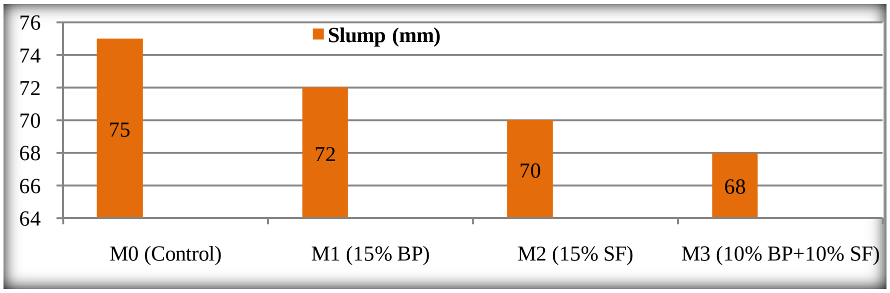

Fig 1: Slump Value of the Fresh Concrete

B. Compressive Strength Development

The compressive strength development over time is a critical performance indicator, as shown in Figure 2 and Table 4. At all ages, all modified mixes outperformed the control.

M0 (Control): Showed strengths of 22, 29, and 35 MPa at 7, 14, and 28 days, respectively.

M1 (15% BP): Achieved strengths of 24, 32, and 40 MPa. The 28-day strength represents a 14.3% increase over M0. This enhancement is more pronounced at later ages, consistent with the slower pozzolanic reaction of BP.

M2 (15% SF): Recorded strengths of 25, 33, and 41 MPa, corresponding to a 17.1% increase at 28 days. The improvement is evident even at early ages (7 days), highlighting the immediate physical filler effect of SF.

M3 (Hybrid): Demonstrated the highest performance across all ages, with strengths of 26, 35, and 43 MPa a 22.9% increase over the control at 28 days. This result unequivocally demonstrates a synergistic effect, where the combined mix outperforms the arithmetic sum of individual improvements.

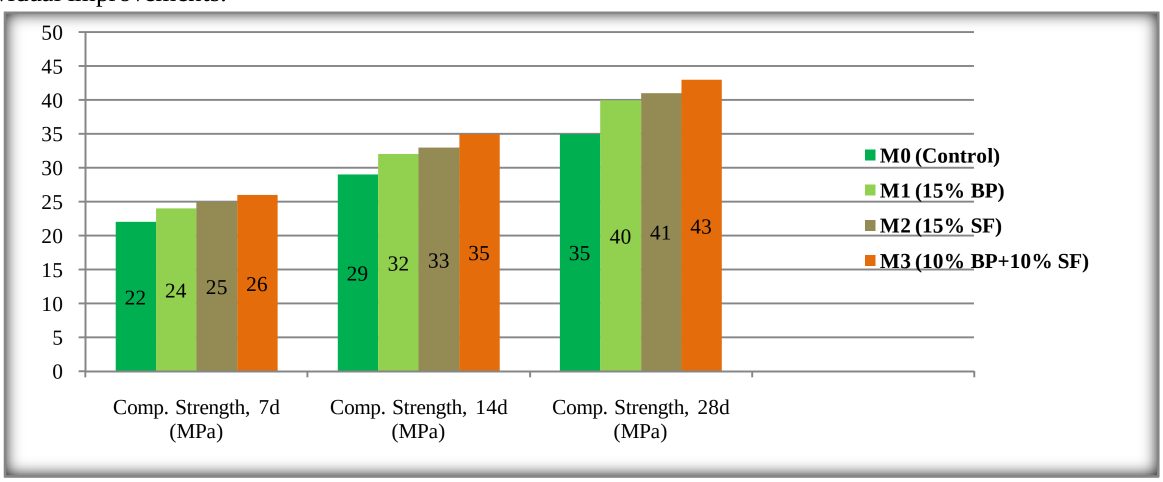

Fig 2:Comp. Strength at Study Ages

C. Splitting Tensile Strength

The 28-day splitting tensile strength results are depicted in Table 4. The trend mirrors that of compressive strength but with even more significant percentage gains, as tensile strength is more sensitive to micro-reinforcement.

M0 (Control): 3.2 MPa.

M1 (BP): 3.6 MPa (12.5% increase). The improvement is due to ITZ strengthening and matrix densification.

M2 (SF): 3.8 MPa (18.8% increase). The crack-arresting capability of the steel particles provides a direct mechanical benefit against tensile failure.

M3 (Hybrid): 4.0 MPa (25.0% increase). This superior performance suggests that the dense matrix provided by BP effectively transfers stress to the well-distributed SF particles, which then resist crack opening more efficiently.

D. Durability Indicator: Water Absorption

Water absorption, an indicator of porosity and permeability, is shown in Figure 3.

M0 (Control): 6.5%.

M1 (BP): 5.8% (10.8% reduction). This is the most significant reduction among all mixes, confirming BP's primary role in enhancing durability by refining the pore structure.

M2 (SF): 6.0% (7.7% reduction). The reduction, while notable, is less than that of BP. SF improves packing but does not chemically reduce porosity.

M3 (Hybrid): 5.4% (16.9% reduction). The hybrid mix achieved the lowest absorption, indicating that the SF particles are integrated into a matrix already densified by BP, leading to the least permeable composite.

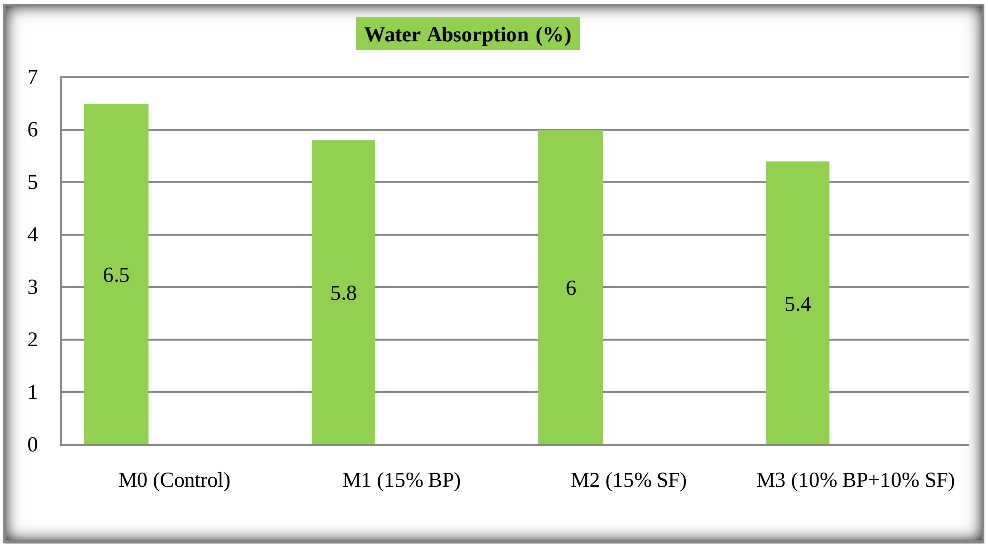

Fig 3: Durability Indicator for all mixes

TABLE IV

SUMMARY OF TEST RESULTS FOR ALL CONCRETE MIXES

Property	M0 (Control)	M1 (15% BP)	M2 (15% SF)	M3 (10% BP+10% SF)
Fresh Density (kg/m³)	2400	2425	2480	2495
% Inc. in 28d Comp. Str	Baseline	+14.3%	+17.1%	+22.9%
Splitting Tensile Str. (MPa)	3.2	3.6	3.8	4.0

V. DISCUSSION

A. Mechanism of Enhancement by Basalt Powder

The performance improvement in M1 is predominantly chemical and microstructural. The fine BP particles serve a dual purpose: (1) as a micro-filler, they occupy spaces between cement grains, leading to a denser particle packing in the fresh state; (2) more importantly, the reactive SiO_2 and Al_2O_3 in BP undergo a pozzolanic reaction with calcium hydroxide (CH) liberated during cement hydration. This reaction, which progresses over weeks, generates additional C-S-H gel, the primary phase that provides strength. This secondary C-S-H not only increases the solid volume but, more critically, refines the pore structure converting large, interconnected capillary pores into smaller, discontinuous gel pores. This refinement is the direct cause of the significant reduction in water absorption. It is expected to translate to superior long-term durability against chloride ingress, sulfate attack, and freeze-thaw cycles.

B. Mechanism of Enhancement by Steel Filings

The enhancement from SF is primarily physical and mechanical. The high-density, high-modulus steel particles improve the granular skeleton of the concrete. They act as rigid filler, reducing the volume of voids and increasing the composite's density and elastic modulus. Under load, these particles interact with the propagating micro-cracks in the brittle cement matrix. Their presence creates a more tortuous crack path, and their high strength allows them to bridge these micro-cracks, delaying their coalescence into a critical macro-crack. This crack-arresting and bridging mechanism is responsible for the notable improvements in both compressive and, especially, tensile strength, as well as the potential for increased fracture energy and impact resistance. The early-age strength gain in M2 supports the argument that this is an immediate physical effect, unlike the slower pozzolanic process.

C. Synergistic Effects in the Hybrid Mix (M3)

The superior all-around performance of the hybrid mix M3 points to a compelling synergy, not merely an additive effect. The postulated mechanism is sequential and complementary:

1) *Matrix Optimization:* The BP first refines the cementitious paste, creating a denser, stronger, and less permeable binder phase.
2) *Reinforcement Embedment:* This optimized matrix then provides a superior medium for embedding the SF particles. The stronger ITZ between the paste and the steel (enhanced by the BP's pore refinement) ensures more effective stress transfer from the matrix to the reinforcing particles.
3) *Mutual Protection:* The dense, low-permeability matrix from BP reduces the ingress of water and oxygen, thereby offering better corrosion protection to the embedded SF. In turn, the SF particles provide mechanical "armor" to the now-improved matrix, making it more resistant to cracking under mechanical and environmental stresses.

This synergy explains why M3 achieved the highest compressive strength (the strong matrix is well-reinforced), the highest tensile strength (the cracks are effectively bridged in a dense medium), and the lowest water absorption (the matrix is dense, and the steel filler reduces capillary channels).

D. Practical Implications and Sustainability

From a practical standpoint, the hybrid mix offers a balanced property profile suitable for demanding applications such as bridge decks, marine structures, industrial floors, and pavements, where both high strength/durability and sustainability are required. Environmentally, using 20% less cement (as in M3) directly reduces the associated CO_2 emissions. Furthermore, utilizing BP (a quarry by-product) and SF (an industrial waste) valorizes materials that would otherwise require disposal, contributing to a circular economy. The slight reduction in workability is easily manageable with modern chemical admixtures.

VI. CONCLUSIONS

Based on the experimental investigation and analysis, the following conclusions can be drawn:

1) Both basalt powder (BP) and recycled steel filings (SF) are effective in enhancing concrete properties. BP excels at improving durability by reducing water absorption by 10.8% through pore refinement driven by pozzolanic activity. SF excels in improving mechanical strength, increasing 28-day compressive strength by 17.1% through physical filler and crack-bridging effects.
2) A synergistic effect was observed in the hybrid mix containing both BP (10%) and SF (10%). This mix (M3) achieved the highest performance in all tested categories: compressive strength (43 MPa, +22.9%), splitting tensile strength (4.0 MPa, +25.0%), and the lowest water absorption (5.4%, -16.9%).
3) The synergy is attributed to the complementary mechanisms: BP creates a dense, impermeable matrix that efficiently transfers stress and protects the SF, while the SF provides robust micro-reinforcement to this enhanced matrix.
4) The use of these materials promotes sustainable construction by reducing cement consumption and recycling industrial by-products, without compromising—and in fact enhancing—the technical performance of concrete.

VII. RECOMMENDATIONS FOR FUTURE WORK

1) To build upon this research, the following studies are recommended:
2) Conduct microstructural analyses using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) to visually confirm the pozzolanic reaction products, ITZ improvement, and steel-matrix bonding.
3) Perform long-term durability tests, including rapid chloride penetration (RCPT), sulfate resistance, and accelerated corrosion tests, especially for the steel-filling mixes.
4) Investigate the performance under dynamic loads (impact, fatigue) and elevated temperatures.
5) Explore the economic feasibility and lifecycle assessment (LCA) of producing concrete with these hybrid additives on a commercial scale.
6) Optimize the replacement ratios using response surface methodology (RSM) to find the global optimum for specific performance criteria.

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