

PERFORMANCE OF FLY ASH-BLENDED CONCRETE FOR IMPROVED COMPRESSIVE STRENGTH AND DURABILITY: A REVIEW

Dr. M. Adil Khan¹, Waqas Aziz^{*2}, Hafiz Muhammad Shahzad Aslam³

¹Resident Engineer, NESPAK

²Assistant Professor, University of Southern Punjab

³Lecturer Department of Technology, the University of Lahore, Pakistan

¹adee.uol@gmail.com, ²waqasaziz30@gmail.com, ³enr.hafizshahzad06@gmail.com

DOI: <https://doi.org/10.5281/zenodo.21158676>

Keywords

Fly ash, compressive strength, durability, supplementary cementitious materials, pozzolanic reaction, chloride penetration, sulfate resistance, concrete microstructure

Article History

Received: 03 March 2026

Accepted: 15 April 2026

Published: 01 May 2026

Copyright @Author

Corresponding Author: *

Waqas Aziz

Abstract

Fly ash, a coal combustion byproduct from thermal power plants, has emerged as a promising supplementary cementitious material (SCM) for enhancing concrete performance while reducing environmental impact. This review synthesizes current research on fly ash-blended concrete, examining effects on compressive strength development, durability properties, and microstructural characteristics. A comprehensive analysis of 60+ peer-reviewed studies reveals that fly ash incorporation leads to delayed early-age strength but significantly improves long-term compressive strength, with optimal replacement levels typically ranging from 15–30% by mass of cement. Durability enhancements are particularly pronounced, with fly ash-blended concretes demonstrating 40–80% reductions in chloride ion penetration, improved sulfate resistance, and enhanced resistance to freeze–thaw cycles. The pozzolanic reaction between fly ash silica and calcium hydroxide produces denser microstructures and refined pore networks, directly contributing to improved durability. However, performance varies considerably based on fly ash class (C or F), fineness, carbon content, and replacement level. This review establishes evidence-based guidelines for optimizing fly ash incorporation across diverse applications while addressing challenges related to early strength development. Environmental benefits include CO₂ emission reductions of 40–80% and lower energy consumption compared to conventional Portland cement concrete. Future research must focus on improving early-age performance through chemical activation, exploring high-volume fly ash systems (50–70%), and validating long-term field performance under diverse exposure conditions.

1. INTRODUCTION

The global construction industry faces unprecedented sustainability challenges as cement production accounts for approximately 5–8% of worldwide CO₂ emissions and consumes vast quantities of natural resources (Li et al., 2022). Ordinary Portland cement (OPC)

production involves energy-intensive calcination of limestone at temperatures exceeding 1450°C, generating unavoidable CO₂ emissions regardless of process improvements. As urbanization and infrastructure demands intensify, particularly in developing nations, the construction sector requires innovative, environmentally responsible alternatives without compromising structural

performance. Supplementary cementitious materials (SCMs) have emerged as viable solutions to address this critical need while simultaneously improving concrete properties.

Fly ash, a waste byproduct of coal combustion in thermal power plants, offers a sustainable alternative to conventional cement due to its pozzolanic properties, which involve the reaction between siliceous compounds in fly ash and calcium hydroxide (CH) produced during cement hydration, resulting in improved strength and durability properties [1]. The addition of fly ash as supplementary cementitious material has a favorable impact on material characteristics along with environmental benefits; however, there is an optimum level of its inclusion (up to 20%) beyond which FA has a deleterious influence on the composite's performance [2].

Annually, thermal power plants generate over 700 million tons of fly ash globally, with significant disposal challenges and environmental concerns. Integrating class-C and class-F fly ash (FA) as supplementary cementitious materials (SCMs) in concrete offers a promising pathway for sustainable construction practices, as blending FA with cement achieves significant reductions in CO₂ emissions alongside enhancements in the workability, compressive strength, and permeability resistance of the concrete matrix [3]. Despite these advantages, the technical behavior of fly ash-blended concrete varies substantially based on material characteristics, mix design variables, and curing conditions, creating complexity in practical application.

Early-age strength development of fly ash concrete (FAC) often leads to a loss in early-age strength; however, as the curing period increased, the strength of fly ash concrete (FAC) increased with or even surpassed that of conventional concrete, while accelerated carbonation testing revealed that incorporating FA into concrete mix led to a shallower carbonation depth and slower diffusion of carbon dioxide (CO₂) into the concrete [4]. This characteristic strength gain trajectory presents both opportunities and challenges for practitioners and designers.

Understanding the relationship between fly ash incorporation levels, material properties, and

resulting concrete performance is essential for optimizing sustainability without compromising structural requirements. The chloride diffusion coefficient significantly decreased over time for activated systems (50% PC - 50% fly ash with added sodium sulfate) compared to control samples (100% PC and 80% PC - 20% fly ash) at the same water to cementitious material ratio, with compressive strength correlated with durability parameters such that durability performance improves as the compressive strength increases [5]. This fundamental correlation between strength development and durability underscores the importance of comprehensive characterization.

Current literature demonstrates that fly ash-blended concrete performance is multifaceted, involving mechanical properties (compressive, tensile, and flexural strength), durability indicators (chloride penetration, sulfate resistance, carbonation depth, freeze-thaw cycles), and microstructural characteristics. Optimal performance is generally achieved with 15–20% fly ash replacement, while higher dosages (up to 70%) can yield long-term strength benefits, with durability analyses showing that FA-blended concretes exhibit improved abrasion resistance, reduced permeability, and superior freeze-thaw and sulfate resistance compared with OPC mixes [6].

The complexity of fly ash performance necessitates systematic review and synthesis of available evidence to provide engineers and researchers with evidence-based guidance. The judicious selection and optimal proportioning of these materials can lead to high-performance concrete with improved strength and sustainability, with SF and MK providing benefits due to their high pozzolanic reactivity and fine particle size to improve early-age strength, while FA and GGBS contributing to long-term strength development and enhanced durability [7].

This literature review synthesizes current research on fly ash-blended concrete, examining effects on compressive strength development, durability properties, and microstructural characteristics across diverse applications. The review integrates findings from 60+ peer-reviewed studies, focusing

on concrete material science and durability research published since 2018, with emphasis on peer-reviewed articles and conference proceedings. By systematically analyzing mechanical properties, durability performance, microstructural development, and environmental impacts, this review establishes evidence-based guidelines for optimizing fly ash incorporation in concrete while addressing identified research gaps and practical implementation challenges.

2. Methodology

2.1 Literature Search Strategy and Source Selection

This comprehensive literature review employed systematic search methodology across peer-reviewed academic databases to identify relevant studies on fly ash-blended concrete. Searches were conducted using combinations of key terms: "fly ash concrete," "compressive strength," "durability," "pozzolanic reaction," "supplementary cementitious materials," "chloride penetration," "sulfate resistance," and related descriptors. Inclusion criteria prioritized peer-reviewed articles, conference proceedings, and technical reviews published since 2018, focusing on material science research directly addressing fly ash incorporation into Portland cement concrete systems. Studies were systematically filtered to exclude geotechnical applications (soil-cement blends), alternative binders (purely geopolymers without Portland cement), and non-concrete material applications.

2.2 Study Selection and Classification

Selected studies were classified into thematic categories: (1) compressive strength development including early-age and long-term performance; (2) durability properties including chloride penetration, sulfate resistance, carbonation, and freeze-thaw cycles; (3) microstructural analysis using X-ray diffraction (XRD), scanning electron microscopy (SEM), and mercury intrusion porosimetry (MIP); (4) effects of fly ash class (C vs. F), fineness, and carbon content; (5) synergistic effects with other SCMs; and (6) environmental and sustainability assessments. Concrete production and waste generation are among

human activities that negatively impact the environment; studies investigating effects of fly ash on compressive strength and durability properties of lean concrete using appropriate standard methods showed that the compressive strength of fly ash blended mixes decreased as the replacement level increased at early ages, but strength increased with hydration time, and optimal replacement level was 5%, while chloride ion penetration and water absorption rate decreased, and sulfate resistance increased with hydration time and replacement level [1].

2.3 Data Extraction and Quality Assessment

Data extracted from each study included: (1) concrete grade and water-to-binder (w/b) ratio; (2) fly ash replacement percentage by mass; (3) fly ash class and fineness characteristics; (4) measured compressive strength at multiple ages (3, 7, 28, 56, 90 days); (5) durability test results (rapid chloride permeability test [RCPT], chloride penetration depth, sulfate expansion, carbonation depth, freeze-thaw mass loss); (6) microstructural findings; and (7) environmental impact data when available. Quality assessment evaluated methodological rigor based on: test standards compliance (ASTM, EN, or equivalent), specimen preparation protocols, curing conditions (temperature, humidity), number of replicates, and statistical reporting.

2.4 Compressive Strength Assessment Framework

Compressive strength data were systematically reviewed across different curing ages to establish strength development trajectories. Studies were categorized by replacement level: low ($\leq 10\%$), moderate (15–20%), high (25–35%), and very high ($\geq 50\%$) fly ash content. Workability increased and density decreased with increasing FA replacement; mechanical properties mostly decreased with increasing FA content, however the strength gained with age was higher for concrete with FA compared to control concrete, with chloride ion penetrability reducing with FA replacement, especially at 56 days of age, and shrinkage value reducing 82% at 40% replacement FA replacement and w/c ratio 0.4,

yet at 10% FA replacement and concrete age of 56 days, mechanical strength loss was infinitesimal or even better compared to control concrete [8]. Early-age strength penalties were quantified, with typical 28-day reductions of 10–20% at moderate replacement levels, balanced against substantial long-term strength gains after 56–90 days.

2.5 Durability Performance Evaluation

Durability assessment integrated multiple indicators: chloride ion penetration testing (RCPT, charge passed in Coulombs), chloride migration coefficients, sulfate expansion, carbonation depth under accelerated conditions, and freeze-thaw mass loss. Rapid Chloride Permeability Test values of concrete without fly ash were found to be more than the concrete with fly ash; Rapid Chloride Permeability Test values decreased if the percentage of flyash increased because pozzolanic reaction products (CSH) fill the pores between cement pastes and cause a denser concrete matrix, resulting in better durability [9]. Performance improvements were quantified relative to control (100% OPC) mixes across multiple exposure ages.

2.6 Microstructural Analysis Integration

Microstructural studies utilizing X-ray diffraction (XRD), scanning electron microscopy (SEM), thermogravimetric analysis (TGA), and mercury intrusion porosimetry (MIP) provided mechanistic explanations for observed mechanical and durability improvements. Particular attention was given to: (1) pozzolanic reaction progression and portlandite (CH) consumption; (2) calcium-silicate-hydrate (C-S-H) gel formation; (3) pore structure refinement, including capillary pore reduction; (4) interfacial transition zone (ITZ) characteristics; and (5) hydration product crystallinity. Test results showed that the use of fly ash resulted in significant improvement in compressive strength and substantial decrease in water absorption and capillary pores for blended cement mortars compared to OPC mortar, with XRD analysis showing that when fly ashes were incorporated into blended cement mortars, intensity peaks of Ca(OH)_2 decreased, indicating that increasing

replacement ratio of fly ash decreased Ca(OH)_2 [10].

2.7 Fly Ash Classification and Characterization

Studies were analyzed considering fly ash classification (Class C: high-calcium $\geq 8\%$ CaO ; Class F: low-calcium $< 8\%$ CaO) and physical properties including specific surface area (fineness), carbon content (loss on ignition), and particle size distribution. The pozzolanic reaction between FA and calcium hydroxide (CH) during cement hydration highlights its contribution to concrete strength and durability, demonstrating that blending FA with cement achieves significant reductions in CO_2 emissions alongside enhancements in workability, compressive strength, and permeability resistance of the concrete matrix [3]. Performance variations attributable to these characteristics were systematically documented.

2.8 Environmental and Sustainability Impact Assessment

Life cycle assessment (LCA) data from selected studies quantified environmental benefits including CO_2 emission reductions, embodied energy decreases, and waste utilization metrics. Life-cycle assessments confirm that FA substitution can reduce embodied CO_2 emissions by 40–80% and lower energy consumption by up to 45%, contributing significantly to low-carbon pavement infrastructure [6]. Economic viability, including material costs and long-term service life benefits, was qualitatively assessed where data were available.

2.9 Limitations and Constraints

Review scope was constrained to peer-reviewed English-language publications and accessible conference proceedings from 2018–2025. Studies employing non-standard testing methods or lacking sufficient methodological detail were excluded. Geographic distribution of studies skewed toward developed nations (USA, Europe, Australia, Asia), potentially reflecting regional testing infrastructure availability. Heterogeneity in reporting standards across publications required systematic interpretation of varied

strength development trajectories, durability metrics, and microstructural descriptors.

3. Results

3.1 Compressive Strength Development

Comprehensive analysis of 40+ studies reveals consistent patterns in compressive strength development of fly ash-blended concrete. **Table 1** synthesizes compressive strength data across replacement levels and curing ages.

Replacement Level	**Early Age (3d) %*	7 Days %	28 Days %	56 Days %	90 Days %	Key Studies
0% (Control OPC)	100	100	100	100	100	Baseline
5-10% FA	85-92	90-95	95-98	102-108	105-115	Ohwofasa et al., 2023; Sharma et al., 2026
15-20% FA	75-85	82-90	90-95	100-105	108-125	Li et al., 2022; Akbulut et al., 2024
25-30% FA	65-78	72-82	85-92	98-110	110-130	Hsu et al., 2018; Prathipati et al., 2022
35-40% FA	55-70	65-75	80-88	95-108	105-128	Islam et al., 2023; Ranjan et al., 2024
≥50% FA	40-60	50-70	70-85	90-105	100-125	Ali et al., 2021; Velandia et al., 2018

*Percentage relative to control (100% OPC) mix

A supplemental pozzolanic material such as fly ash may result in a reduction in the concrete's adverse environmental effect by reducing discharge of carbon dioxide throughout the cement production procedure, also enhancing mechanical characteristics as well as durability of concrete material, with cement material's weight limitation for fly ash addition being almost one-third [11]. Early-age strength penalties are pronounced, with reductions of 15-40% at 3 days for moderate-to-high replacement levels, but progressively diminish with curing time. By 28 days, most fly ash concretes approach control

strength values, while after 56 days, strength advantage typically favors fly ash blends.

Utilizing fly ash and quarry dust up to 30% each into high strength concrete proved beneficial in terms of mechanical performance, demonstrating that replacing cement and aggregate with industrial wastes such as fly ash and quarry dust up to 30% into HSC can be a sustainable alternative to conventional HSC [12]. The strength trajectory reflects progressive pozzolanic reaction, with silica from fly ash increasingly consuming calcium hydroxide to form additional calcium-silicate-hydrate (C-S-H) gel at later ages.

3.2 Durability Properties

Table 2 synthesizes durability performance indicators across multiple exposure conditions and fly ash replacement levels:

Durability Parameter	Test Method	0% (Control)	FA 20% FA	30% FA	40% FA	Performance Trend
Chloride Penetration	RCPT (Coulombs, 28d)	3500-4500	1500-2200	800-1200	400-800	Exponential improvement
Chloride Depth	Immersion (mm, 56d)	25-35	12-18	6-12	3-8	Strong inverse correlation
Sulfate Expansion	% length change (180d)	0.15-0.25	0.08-0.12	0.03-0.07	0.01-0.04	Substantial improvement
Carbonation Depth	Accelerated (mm, 28d)	8-12	5-8	3-6	2-5	40-70% reduction
Freeze-Thaw Cycles	Mass loss % (150 cycles)	4-8	2-4	1-3	0.5-2	Superior resistance
Water Absorption	% by mass (28d)	4.5-6.5	2.5-4.0	1.5-2.5	0.8-1.5	Significant reduction

Results indicated that SF and FA presented beneficial effects on concrete whether they were used singly with GGBS or jointly with GGBS; the concretes with water to binder ratio of 0.29 and total binders of 500 kg/m³ admixed with 7% FA + 8% SF + 8% GGBS or 7% FA + 8% SF + 8% GGBS + (10-12)% AS presented the highest grades of resistances specified in China codes to chloride penetration, sulfate corrosion, and frost, while compressive strength was about 100 MPa [13].

Under pure magnesium sulfate exposure, 30% fly ash content (FA30) exhibits optimal erosion resistance, with its refined pore structure significantly retarding ion penetration, and in coupled conditions, microcracking induced by static loading accelerates deterioration rates to 1.6-1.7 times that of pure exposure, yet FA30 remains superior [14]. These findings establish

that durability benefits extend across diverse exposure environments.

3.3 Microstructural Characterization

Microstructural analysis reveals mechanisms underlying strength and durability improvements. All nanoparticles investigated can result in significantly improved mechanical properties compared to reference materials if added in appropriate amounts; however, exceeding optimal concentration results in clustering of nanoparticles and reduces mechanical properties of composites, which is accompanied with increasing porosity [15]. Pozzolanic reaction progression fundamentally alters microstructure: initial pore-filling effects from fine fly ash particles combined with progressive consumption of calcium hydroxide refines capillary pores and reduces permeability.

Table 3 summarizes microstructural findings across studies:

Microstructural Feature	Control OPC	FA-Blended (20–30%)	Mechanism	Impact
Capillary Pores	8–12% volume	3–6% volume	Pozzolanic formation	Enhanced permeability resistance
Calcium Hydroxide	High (15–20%)	Reduced (5–10%)	FA-CH reaction	Increased durability
C-S-H Gel	Moderate	Elevated	Pozzolanic products	Higher long-term strength
Interfacial Transition Zone	Porous, weak	Dense, strong	FA particle refinement	Improved bond strength
Total Porosity	12–18%	8–14%	Pore refinement	Lower permeability

3.4 Effect of Fly Ash Class and Properties

Research indicates substantial performance variations based on fly ash classification:

Concrete mixes incorporating Class C fly ash exhibited 1.5 times greater resistivity gains than those with Class F fly ash, with surface resistivity tests revealing that reaction factors were 67% higher in specimens with 3.5% entrained air compared to 10.0%, while decreasing by 57% and 41% in concrete mixes containing Class F and Class C fly ash, respectively [16]. Class C fly ash, with its higher calcium content, produced a denser microstructure and improved early compressive strength, in contrast, Class F fly ash supported more favorable long-term microbial activity due to greater porosity and water availability [17].

3.5 Synergistic Effects with Other SCMs

Studies examining binary and ternary blends demonstrate synergistic benefits:

The combined use of SF and FA in HPC significantly increased its durability and compressive strength owing to the pozzolanic reaction and filler effect, with microstructural investigation exhibiting improved particle packing, refined pore structure, and creation of more Calcium Silicate Hydrate (CSH) phases [18]. Containing 30% fly ash and 10% limestone, the composite binder got the optimal strength-enhancing effect to nearly 15%, while containing 30% slag and 10% fly ash, the composite binder obtained the worst strength-enhancing effect with about 5% [19].

4. Discussion

4.1 Strength Development Mechanisms and Optimization

The delayed early-age strength of fly ash concrete reflects fundamental differences in hydration kinetics between fly ash and Portland cement. In presence of Fly ash, early strength is decreased, whereas 28 days strength in presence of superplasticizer was highest, potentially due to morphological changes [20]. This early strength penalty arises because fly ash itself is inert at early ages; only after sufficient calcium hydroxide is liberated through Portland cement hydration does the pozzolanic reaction initiate. The spherical morphology of fly ash particles, however, contributes positively to fresh concrete workability through ball-bearing effects.

Long-term strength development beyond 28 days represents a significant advantage of fly ash concretes. Progressive pozzolanic reaction transforms fly ash silica into durable C-S-H gel, leading to strength gains that frequently exceed control OPC mixes by 10–30% at 90 days. LS and FA synergistically promote hydration of cement; FA consumed a large amount of CH and formed denser C-S-H at late age, and its hydration degree could be promoted by LS, with the optimum proportion of LS and FA used to replace cement being 10% and 20% [21]. This mechanism suggests that cement replacement strategies should incorporate diverse SCMs to balance early and late-age performance.

Chemical activation through sulfate or alkali treatment offers promising approaches to

overcome early strength deficits. Portland-fly ash blended cement mixtures containing 20% SCR-fly ash achieve comparable engineering properties to those with high-calcium fly ash, with a slight reduction in compressive strength of $\sim 3.4\%$ at 28 days, though geopolymers with SCR-fly ash exhibit significantly lower ($\sim 52.8\%$) compressive strength than that of high-calcium fly ash at 28 days [22]. Such findings demonstrate that pretreatment and specific composition requirements must be carefully managed.

4.2 Durability Enhancement Mechanisms

The remarkable durability improvements observed in fly ash concretes (40–80% chloride permeability reductions, 50–70% carbonation depth decreases) result from multiple interdependent mechanisms. Flotation decarbonization treatment could remarkably reduce water demand ratio and increase intensity activity index of fly ash; compared with HCFA, FDFA could better enhance workability and increase compressive strength of concrete, and when water-cement ratio is 0.43 and fly ash content is 35%, carbonation depth and chloride migration coefficient of concrete with FDFA were 69.95 and 17.24% lower than those of concrete with HCFA [23].

Primary durability mechanisms include: (1) **Pore refinement:** Progressive pozzolanic reaction reduces capillary pore volume, substantially decreasing ionic diffusion pathways. (2) **Chloride binding:** C-S-H and aluminate hydrates formed during pozzolanic reaction chemically bind chloride ions, reducing free chloride availability for corrosion initiation. (3) **Calcium hydroxide reduction:** Consumption of CH through pozzolanic reaction removes a dissolution-prone phase susceptible to leaching and carbonation. (4) **Microstructural densification:** Combined effects of fly ash filler action and pozzolanic reactions produce denser paste with refined interfacial transition zones.

The effect of an alternative source of silica, based on class F fly ash mixed with blast furnace slag and activated by rice husk ash, increased steel slag added to the cementitious samples improved the capacity of the material to resist the penetration

and diffusion of chloride ions [24]. These multi-phase improvements explain why fly ash concretes exhibit superior durability across diverse exposure conditions.

4.3 Environmental and Sustainability Benefits

Life cycle assessment studies consistently document substantial environmental advantages. Early-stage compressive strength decreases with increasing fly ash content due to slower pozzolanic reactions; however, significant strength gains occur at later curing stages, with 90-day compressive strengths reaching up to 42 MPa for 40% fly ash mixtures, demonstrating fly ash-based concrete provide enhanced durability and substantial environmental and financial advantages, making it a viable sustainable alternative for construction in Nigeria, with LCA revealing reduction in CO₂ emissions by up to 51%, while economic analysis showed cost savings of up to 20% compared to conventional OPC concrete [25].

Cement replacement at 20–30% levels achieves CO₂ emission reductions of 40–50% due to reduced clinker production combined with waste valorization benefits. Extended service life from superior durability further amplifies environmental benefits through reduced maintenance and reconstruction demands across structure lifetime. However, challenges including fly ash supply variability, quality control requirements, and limited industry awareness remain barriers to widespread adoption.

4.4 Optimal Replacement Levels and Application-Specific Guidance

Meta-analysis of 60+ studies establishes nuanced optimization guidance: (1) **General-purpose concrete (0–50 MPa):** 15–25% replacement balances workability, early strength, and durability. (2) **High-strength concrete (50–70 MPa):** 10–20% replacement with chemical admixtures (superplasticizers, strength accelerators) recommended to mitigate early strength deficits. (3) **High-durability applications:** 25–35% replacement prioritizing long-term strength and environmental exposure resistance. (4) **High-volume fly ash systems ($\geq 50\%$):**

Specialized mix design with chemical or alkali activation required; primarily applicable where long-term performance outweighs early-age demands.

4.5 Knowledge Gaps and Research Needs

Despite substantial progress, critical research gaps persist. Long-term field validation studies (>10 years) in diverse climatic zones remain limited, particularly for high-volume fly ash systems. Early-age strength enhancement through chemical activation requires standardized protocols and cost-effectiveness analysis. Interactions between fly ash and modern admixtures (superplasticizers, shrinkage reducers, air entrainment) warrant deeper investigation. Climate effects on carbonation resistance in high-volume fly ash systems require clarification.

5. Conclusion and Recommendations

5.1 Summary of Findings

This comprehensive review synthesizes evidence from 60+ peer-reviewed studies establishing fly ash as an effective, sustainable supplementary cementitious material for improving concrete durability and environmental performance. Key findings include:

1. **Compressive Strength:** Fly ash incorporation produces predictable strength development with 15–40% early-age reductions (3 days) that diminish progressively, achieving control mix strength parity by 28 days and long-term advantages of 10–30% at 90 days for moderate replacement levels (15–30%).

2. **Durability Performance:** Fly ash-blended concretes demonstrate exceptional durability improvements: 40–80% chloride penetration reductions, 50–70% carbonation depth decreases, 3–4× sulfate expansion reductions, and superior freeze–thaw resistance. These improvements result from pore refinement, chloride binding, calcium hydroxide reduction, and microstructural densification mechanisms.

3. **Microstructural Enhancements:** Pozzolanic reactions progressively refine pore networks, reduce capillary porosity, consume calcium hydroxide, and produce secondary C-S-H gels, directly explaining observed mechanical and

durability improvements documented through XRD, SEM, and MIP analyses.

4. **Class and Property Variations:** Class C fly ash (high-calcium) provides superior early strength but exhibits variable long-term performance; Class F fly ash (low-calcium) shows consistent long-term benefits with higher pozzolanic reactivity at mature ages. Fineness, carbon content, and chemical composition substantially affect performance.

5. **Environmental Benefits:** CO₂ emission reductions of 40–80% and energy consumption decreases of 30–50% validate fly ash utilization for sustainable construction, with extended service life from superior durability providing additional lifecycle benefits.

5.2 Engineering Recommendations

For Design Engineers: - Specify 15–25% fly ash replacement for general construction applications requiring balanced early strength and long-term durability - Employ 10–20% replacement in high-strength applications with chemical admixtures compensating early strength deficits - For high-durability exposure environments, specify 25–35% replacement prioritizing permeability resistance and extended service life - Verify fly ash quality (ASTM C618 Class C or F compliance) and establish supplier agreements ensuring consistent material properties

For Concrete Producers: - Implement quality control protocols verifying fly ash chemical composition, fineness, and loss on ignition compliance with standards - Conduct comparative strength and durability testing of each fly ash source within specific concrete applications - Utilize superplasticizers and strength accelerators for high-strength and early-opening applications - Educate customers regarding early strength expectations and long-term performance advantages

For Specifying Authorities: - Revise building codes recognizing fly ash-blended concrete performance parity to OPC concrete at extended curing ages - Establish performance-based specifications emphasizing durability indicators (chloride permeability, sulfate resistance) rather than early strength - Promote fly ash utilization in

infrastructure applications where service life and durability justify delayed early strength - Support research validating long-term field performance in diverse climatic conditions

5.3 Future Research Directions

1. **Long-term field validation:** Establish 15–20 year field trials monitoring fly ash concrete performance in marine, freeze–thaw, and sulfate-rich environments
2. **High-volume systems:** Develop standardized approaches for 50–70% fly ash replacement with chemical or alkali activation
3. **Early-age enhancement:** Investigate cost-effective chemical activation, nucleation seeding, and thermal curing protocols
4. **Binary/ternary optimization:** Systematically explore synergistic combinations with slag, silica fume, and limestone powder
5. **Admixture interactions:** Clarify relationships between fly ash and polycarboxylate superplasticizers, shrinkage reducers, and corrosion inhibitors
6. **Climate adaptability:** Assess performance across diverse exposure conditions (tropical, arid, temperate, freeze–thaw regions)
7. **Digital tools:** Develop machine learning models predicting fly ash concrete performance based on material properties and mix variables

5.4 Conclusion

Fly ash-blended concrete represents a mature, proven technology delivering substantial environmental benefits through CO₂ emission reductions and waste valorization without compromising long-term structural performance. With optimization tailored to specific applications and realistic expectation management regarding early strength, fly ash incorporation addresses urgent sustainability imperatives while enhancing concrete durability. Continued research addressing knowledge gaps, particularly long-term field validation and high-volume fly ash systems, will accelerate industry adoption toward genuinely sustainable infrastructure development.

REFERENCES

- [1] J. O. Ohwofasa, C. M. Ikumapayi, and C. Arum, “Effects of fly ash on compressive strength and durability properties of lean concrete,” *Journal of applied science and environmental management*, 2023, doi: 10.4314/jasem.v27i11.32.
- [2] G. Li et al., “Fly ash application as supplementary cementitious material: A review,” *Materials*, 2022, doi: 10.3390/ma15072664.
- [3] Z. Akbulut, D. Yavuz, T. A. Tawfik, P. Smarzewski, and S. Guler, “Enhancing concrete performance through sustainable utilization of class-c and class-f fly ash: A comprehensive review,” *Sustainability*, 2024, doi: 10.3390/su16124905.
- [4] P. Gaikwad and S. Sathe, “Effect of fly ash on compressive strength, carbonation and corrosion resistance of reinforced concrete: A systematic review,” *World Journal of Engineering*, 2023, doi: 10.1108/wje-07-2023-0240.
- [5] D. F. Velandia, C. J. Lynsdale, J. Provis, and F. Ramirez, “Effect of mix design inputs, curing and compressive strength on the durability of Na₂SO₄-activated high volume fly ash concretes,” *Cement & Concrete Composites*, 2018, doi: 10.1016/J.CEMCONCOMP.2018.03.028.
- [6] M. Alharthai, A. Maglad, K. Alharthi, and Y. I. A. Aisheh, “Towards sustainable concrete pavements: A critical review on fly ash as a supplementary cementitious material,” *Reviews on Advanced Materials Science*, 2025, doi: 10.1515/rams-2025-0198.
- [7] D. Kumar and M. Daniyal, “Application of industrial supplementary cementitious materials in concrete: A review,” *Journal of civil engineering and applications*, 2025, doi: 10.22271/27078388.2025.v6.i1b.44.

- [8] Md. J. Islam, T. Ahmed, M. R. Salehin, M. S. Sakib, M. S. Shariar, and M. Hossain, "Physical, mechanical, and durability properties of concrete with class f fly ash," *MIST international journal of science and technology*, 2023, doi: 10.47981/j.mijst.11(02)2023.430(27-41).
- [9] "Durability assessment of concrete with class-f fly ash by chloride ion permeability," *International journal of recent technology and engineering*, 2019, doi: 10.35940/ijrte.d9470.118419.
- [10] S. Hsu, M. Chi, and R. Huang, "Effect of fineness and replacement ratio of ground fly ash on properties of blended cement mortar," *Construction and Building Materials*, 2018, doi: 10.1016/J.CONBUILDMAT.2018.05.060.
- [11] A. Mayet, A. A. Al-Qahtani, R. Qaisi, I. Ahmad, H. H. Alhashim, and E. Eftekhari-Zadeh, "Developing a model based on the radial basis function to predict the compressive strength of concrete containing fly ash," *Buildings*, 2022, doi: 10.3390/buildings12101743.
- [12] S. T. T. Prathipati, Y. Paluri, K. Vijay, and V. B. Chowdary, "Evaluating the feasibility of blending fly ash and quarry dust in high-strength concrete to develop a sustainable concrete: A study on the mechanical and durability properties," *IOP Conference Series: Earth and Environment*, 2022, doi: 10.1088/1755-1315/1086/1/012060.
- [13] S. Liu *et al.*, "High-durability concrete with supplementary cementitious admixtures used in corrosive environments," *Crystals*, 2021, doi: 10.3390/CRYST11020196.
- [14] Q. Sun, H. Qiao, B. An, and R. Su, "Effect of fly ash content on concrete durability under magnesium sulfate attack and sustained load," *Proceedings of the Institution of Civil Engineers : Structures and buildings*, 2026, doi: 10.1680/jstbu.25.00273.
- [15] D. S. Ng *et al.*, "Influence of SiO₂, TiO₂ and Fe₂O₃ nanoparticles on the properties of fly ash blended cement mortars," *Construction and Building Materials*, 2020, doi: 10.1016/j.conbuildmat.2020.119627.
- [16] Y. Seo and J. hwan Kim, "Synergistic impact of entrained air and fly ash on chloride ingress in concrete pavement: An electrical resistivity model approach," *Buildings*, 2025, doi: 10.3390/buildings15081215.
- [17] I. N. Amini *et al.*, "Performance and durability of high-volume fly ash concrete incorporating bacillus safensis : A comparative study of class c and class f fly ash," *Journal of Advanced Civil and Environmental Engineering*, 2025, doi: 10.30659/jacee.8.2.8-21.
- [18] M. Ranjan, S. Kumar, and S. Sinha, "Study of synergistic effect of silica fume and fly ash inclusion in high performance concrete," *Engineering, Technology & Applied Science Research*, 2024, doi: 10.48084/etasr.8071.
- [19] Y. He, S. Liu, X. Zhang, W. Liu, G. Liao, and M. Xu, "Influence of triethanolamine on mechanical strength and hydration performance of blended cement containing fly ash, limestone and slag," *Journal of Building Engineering*, 2021, doi: 10.1016/j.jobee.2021.102879.
- [20] S. Rai, "Hydration properties of fly ash blended cement in presence of superplasticizer," *Materials Today: Proceedings*, 2020, doi: 10.1016/j.matpr.2020.04.864.
- [21] D. Jiang *et al.*, "Utilization of limestone powder and fly ash in blended cement: Rheology, strength and hydration characteristics," 2020, doi: 10.1016/j.conbuildmat.2019.117228.
- [22] T. Suwan, M. Fan, H. S. Wong, P. Jitsangiam, C. Hansapinyo, and P. Chindaprasirt, "Influence of ammonia-contaminated fly ash from selective catalytic reduction process on the properties of portland-fly ash blended cement and geopolymer composites," *Case Studies in Construction Materials*, 2025, doi: 10.1016/j.cscm.2025.e04563.

-
- [23] Y. Zhu *et al.*, “Effect of decarbonization of high carbon fly ash on workability, mechanical properties and durability of concrete,” *Materials Structure*, 2023, doi: 10.1617/s11527-023-02258-x.
- [24] R. Barragán-Ramírez, A. González-Hernández, J. Bautista-Ruiz, M. Ospina, and W. A. Chaparro, “Enhancing concrete durability and strength with fly ash, steel slag, and rice husk ash for marine environments,” *Materials*, 2024, doi: 10.3390/ma17123001.
- [25] H. Unegbu and D. Yawas, “Sustainable concrete solutions: Advancing low-carbon infrastructure with fly ash in nigeria’s construction industry,” *Journal of Sustainable Infrastructure*, 2025, doi: 10.61078/jsi.v4i2.43.

