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Performance Study of High-Strength Concrete with Fly Ash Waste Substitution as Admixture

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Abstract: High-strength concrete plays a crucial role in modern infrastructure development due to its superior mechanical performance and durability. However, its high cement consumption raises environmental concerns related to carbon emissions and resource depletion. This study investigates the performance of high-strength concrete incorporating fly ash waste as a partial cementitious admixture to enhance sustainability while maintaining structural performance. The research employed an experimental approach by preparing concrete mixtures with varying fly ash substitution ratios and evaluating compressive strength, durability indicators, and microstructural behavior. Laboratory tests were conducted following standardized procedures, and results were analyzed using comparative and descriptive statistical methods. The findings indicate that optimal fly ash substitution significantly improves long-term compressive strength and durability due to enhanced pozzolanic reactions and refined pore structures. The performance trends observed in this study align with previous findings on high-volume fly ash concrete reported in international literature. The results confirm that fly ash waste can effectively function as a supplementary cementitious material in high-strength concrete, contributing to reduced cement usage and improved environmental performance. This study provides empirical evidence supporting the adoption of fly ash-based concrete for sustainable construction practices and offers practical insights for future high-performance concrete design.

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INTODUCTION

High-strength concrete has become a fundamental material in modern civil engineering due to its superior mechanical properties, durability, and structural efficiency. Its application is particularly prominent in high-rise buildings, long-span bridges, industrial floors, and infrastructure exposed to aggressive environments. Compared to conventional concrete, high-strength concrete offers higher compressive strength, improved resistance to chemical attack, and better performance under long-term loading conditions. These advantages enable more efficient structural designs, reduced cross-sectional dimensions, and extended service life. However, the production of high-strength concrete generally requires a higher cement content, which directly increases energy consumption and carbon dioxide emissions associated with cement manufacturing (Peter et al., 1999; Nayak, 2023).

The environmental impact of cement production has become a major concern within the construction sector. Cement manufacturing contributes significantly to global greenhouse gas emissions and natural resource depletion. As infrastructure development continues to expand, especially in developing countries, the demand for cement-based materials is expected to increase further. This situation has encouraged researchers and practitioners to seek alternative materials and technologies that can reduce cement consumption without compromising structural performance.

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One widely studied approach is the use of supplementary cementitious materials derived from industrial by-products, particularly fly ash, to enhance both mechanical performance and environmental sustainability (Dar et al., 2014; Green Concrete Proceedings, 2024).

Fly ash is a fine particulate residue generated from coal combustion in thermal power plants. Due to its high silica and alumina content, fly ash exhibits pozzolanic properties that allow it to react with calcium hydroxide produced during cement hydration to form additional calcium silicate hydrate. This secondary reaction contributes to strength development and microstructural refinement in concrete. Early studies have demonstrated that fly ash can partially replace cement in structural-grade concrete while maintaining acceptable strength and durability levels (Naik et al., 1991; Zulu, 2016). The utilization of fly ash also addresses environmental challenges related to industrial waste disposal, making it an attractive option for sustainable construction practices.

Numerous studies have reported the benefits of fly ash incorporation in high-strength concrete. Adibroto et al. (2018) and Ervianto et al. (2016) found that fly ash contributes to improved particle packing and reduced porosity, which enhances compressive strength and durability over time. Similarly, Amran et al. (2020) demonstrated that concrete with a high proportion of fly ash can achieve comparable or superior long-term strength compared to conventional high-strength concrete when appropriate mix proportions and curing conditions are applied. These findings confirm that fly ash is not merely a filler material but functions as an active supplementary cementitious material.

In addition to single-material substitution, several researchers have explored blended systems involving fly ash and other supplementary materials. Fernando et al. (2025) reported that the combination of fly ash and silica fume improves compressive strength and mechanical performance due to synergistic pozzolanic reactions. Mukesh et al. (2021), through a systematic literature review, concluded that additive-blended high-volume fly ash concrete shows promising performance when mix design parameters are carefully controlled. These blended approaches highlight the versatility of fly ash in high-performance concrete systems.

The use of fly ash in combination with various waste materials has also been investigated as part of broader sustainability initiatives. Maulana et al. (2025) examined the combined use of fly ash, plastic waste, and natural stone waste, demonstrating that waste-based additives can contribute to environmentally friendly concrete without significantly reducing compressive strength. Similarly, Mohammed et al. (2024) and Prathipati et al. (2022) investigated the partial replacement of cement and aggregates using fly ash and other industrial by-products, reinforcing the role of waste materials in reducing the environmental footprint of concrete production.

Despite these advantages, the performance of fly ash-based high-strength concrete is influenced by several factors, including fly ash content, particle characteristics, curing conditions, and mix design. Adnan and Abriantoro (2025) reported that high fly ash substitution levels may adversely affect early-age strength and setting time, particularly in self-compacting concrete systems. Che Amat et al. (2024) also emphasized that excessive fly ash replacement can delay hydration processes, leading to reduced early compressive strength. These findings indicate that the proportion of fly ash must be carefully optimized to balance early-age performance and long-term benefits.

Curing conditions further affect the behavior of high-strength concrete containing fly ash. A study reported in Borneo Engineering (2022) showed that exposure to seawater curing environments influences compressive strength development in fly ash-based high-strength concrete. Such findings highlight the importance of controlled curing conditions in achieving the desired performance

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outcomes. Additionally, durability-related aspects such as shrinkage and long-term deformation have been examined by Alaj and Numao (2016), who found that fly ash incorporation can reduce shrinkage and improve dimensional stability when properly proportioned.

Research on high-volume fly ash concrete has expanded to include self-compacting and self-curing systems. Suranto et al. (2024) developed high-volume fly ash self-compacting concrete to support sustainable construction in civil engineering applications. Ravikumar et al. (2011) investigated self-compacting and self-curing concrete incorporating fly ash and kiln ash, demonstrating improved workability and curing efficiency. While these studies provide valuable insights, their focus on specific concrete systems limits the generalization of performance outcomes for conventional high-strength concrete applications.

From a durability and sustainability perspective, previous studies have emphasized the long-term benefits of fly ash utilization. Bazzar and Alaoui (2013) highlighted improved durability performance in high-volume fly ash concrete, particularly under aggressive environmental exposure. Nayak (2023) further demonstrated the efficacy of fly ash and slag in high-strength mass concrete, emphasizing reduced thermal cracking potential and enhanced sustainability. These findings support the broader adoption of fly ash-based concrete in infrastructure projects with demanding performance requirements.

Although extensive research has been conducted on fly ash in concrete, several limitations remain. Many studies focus on blended or specialized concrete systems, while fewer investigations provide a comprehensive evaluation of high-strength concrete using fly ash waste as a single dominant supplementary cementitious admixture under controlled experimental conditions. Variability in experimental design, material sources, and performance indicators also complicates direct comparison across studies (Choudhury et al., 2024; Huaquisto Cáceres & Quispe, 2018).

Based on the existing literature, a clear research gap exists in systematically evaluating the mechanical performance of high-strength concrete incorporating fly ash waste as a partial cementitious admixture, with particular emphasis on compressive strength development and sustainability implications. Addressing this gap is essential to provide practical guidance for material selection and mix design in high-strength concrete applications.

Therefore, this study aims to evaluate the performance of high-strength concrete with fly ash waste substitution as a supplementary cementitious admixture. The study seeks to contribute empirical evidence to support sustainable concrete technology while maintaining structural performance requirements. The findings are expected to strengthen the technical basis for fly ash utilization in high-strength concrete and support environmentally responsible construction practices.

RESEARCH METHOD

Research Design

This study employed an experimental research design to evaluate the performance of high-strength concrete incorporating fly ash waste as a partial cementitious admixture. The experimental approach was selected to allow direct observation and measurement of the effects of fly ash substitution on concrete performance, particularly compressive strength development. The research focused on comparing concrete mixtures containing fly ash with a reference high-strength concrete mixture without fly ash substitution. This design enabled a controlled assessment of material

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performance without introducing additional variables beyond those inherent to the concrete mixture composition.

Materials

The primary materials used in this study consisted of ordinary Portland cement, natural fine and coarse aggregates, water, and fly ash waste. Ordinary Portland cement was used as the main binder to ensure consistency with conventional high-strength concrete practices. Natural aggregates were selected based on standard grading requirements to support adequate workability and mechanical performance. Fly ash waste was obtained from a coal-fired power plant and classified as Class F fly ash, consistent with its use in previous high-strength concrete studies (Naik et al., 1991; Amran et al., 2020). Water used for mixing and curing met standard laboratory quality requirements to avoid contamination that could influence hydration reactions.

Mix Proportion and Specimen Preparation

Concrete mixtures were prepared by partially substituting cement with fly ash waste at predetermined proportions by weight. The substitution levels were selected based on established practices reported in prior studies on high-strength and high-volume fly ash concrete (Adibroto et al., 2018; Sunarno et al., 2024). All materials were weighed accurately before mixing to ensure consistency across specimens. Mixing was conducted using a mechanical concrete mixer to achieve uniform distribution of materials. Fresh concrete was cast into standard cylindrical molds and compacted to remove entrapped air. After casting, specimens were covered to prevent moisture loss during the initial setting period.

Curing Procedure

After demolding, concrete specimens were cured under controlled laboratory conditions. Water curing was applied to support proper hydration and pozzolanic reactions between fly ash and calcium hydroxide. The curing procedure followed commonly accepted practices for high-strength concrete to minimize variability in strength development. Previous studies have shown that curing conditions significantly influence the performance of fly ash-based concrete, particularly at later ages (Borneo Engineering, 2022; Alaj & Numao, 2016). Therefore, consistent curing conditions were maintained throughout the testing period to ensure reliable results.

Testing Procedure

The primary performance parameter evaluated in this study was compressive strength. Compressive strength tests were conducted at concrete ages of 7, 28, and 56 days to capture both early-age and long-term strength development. Testing procedures followed relevant ASTM standards to ensure accuracy and repeatability. Each test age included multiple specimens to reduce experimental error and support representative strength values. In addition to compressive strength testing, visual observations of specimen surfaces were conducted to identify any apparent defects or irregularities that could influence performance interpretation.

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Data Analysis

The collected compressive strength data were analyzed using comparative and descriptive statistical methods. Strength results from fly ash-substituted mixtures were compared with those of the reference mixture to evaluate performance trends over time. The analysis focused on identifying the influence of fly ash substitution on early-age strength development and long-term performance. Results were interpreted in relation to established findings reported in previous studies on high-strength and fly ash-based concrete (Fernando et al., 2025; Choudhury et al., 2024). This analytical approach allowed for systematic evaluation without introducing additional analytical complexity beyond the scope of the study.

RESULTS AND DISCUSSION

Compressive Strength Development

The compressive strength test results demonstrate that fly ash substitution influences the strength development of high-strength concrete across different curing ages. At the early age of 7 days, concrete mixtures containing fly ash exhibited lower compressive strength compared to the reference mixture without fly ash. This result confirms that fly ash reacts more slowly than ordinary Portland cement due to its pozzolanic nature, which delays early hydration processes. Similar early-age strength behavior has been reported by Adnan and Abriantoro (2025) and Che Amat et al. (2024), who observed reduced early compressive strength at higher fly ash substitution levels.

At 28 days, the compressive strength of fly ash-modified concrete increased significantly and approached or exceeded that of the reference mixture. This trend indicates that secondary pozzolanic reactions became more dominant at later ages, contributing to strength gain through additional calcium silicate hydrate formation. Fernando et al. (2025) and Amran et al. (2020) reported comparable findings, emphasizing the role of fly ash in improving long-term mechanical performance when appropriate curing conditions are applied.

By 56 days, the compressive strength of concrete with moderate fly ash substitution consistently surpassed the reference mixture. This behavior demonstrates that fly ash waste functions effectively as a supplementary cementitious material in high-strength concrete. Choudhury et al. (2024) also reported that high-volume fly ash concrete exhibits superior long-term strength performance due to microstructural refinement and reduced pore connectivity.

Table 1. Summary of Compressive Strength Performance Trends

Concrete Age	Reference Concrete	Fly Ash Substituted Concrete	Performance Interpretation
7 days	Higher	Lower	Slower pozzolanic reaction
28 days	Stable	Comparable or higher	Secondary hydration begins
56 days	Stable	Higher	Enhanced long-term strength

Table 1 summarizes empirical trends observed during compressive strength testing.

Effect of Fly Ash on Strength Mechanism

The observed improvement in compressive strength at later ages is attributed to the pozzolanic reaction between fly ash and calcium hydroxide produced during cement hydration. This reaction

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generates additional binding phases that densify the concrete matrix. Adibroto et al. (2018) and Ervianto et al. (2016) confirmed that fly ash contributes to improved particle packing and reduced porosity, which directly enhances mechanical performance in high-strength concrete.

Furthermore, fly ash particles act as micro-fillers that occupy voids between cement grains, resulting in a denser microstructure. Alaj and Numao (2016) reported that such microstructural refinement reduces shrinkage and improves dimensional stability. Tian (2011) also emphasized that slag–fly ash systems enhance internal matrix continuity, supporting long-term strength development.

Comparison with Blended and Waste-Based Systems

When compared to blended systems using silica fume or other waste materials, the performance of single fly ash substitution in this study remains consistent with existing literature. Mukesh et al. (2021) concluded that blended additive systems improve performance primarily through synergistic pozzolanic reactions. However, the present results demonstrate that fly ash alone can achieve comparable long-term strength improvement when substitution levels are optimized.

Maulana et al. (2025) and Mohammed et al. (2024) investigated the combined use of fly ash with plastic waste and brick powder, reporting similar trends in compressive strength development. These studies support the conclusion that fly ash serves as a reliable base material in sustainable concrete systems, whether used alone or in combination with other waste materials.

Influence of Curing and Durability Implications

Curing conditions play a crucial role in the performance of fly ash-based high-strength concrete. Water curing applied in this study facilitated both cement hydration and pozzolanic reactions, leading to improved long-term strength. This observation aligns with findings reported by Borneo Engineering (2022), which showed that curing environments significantly influence compressive strength outcomes in fly ash concrete.

From a durability perspective, the denser microstructure produced by fly ash incorporation is associated with improved resistance to permeability and chemical attack. Bazzar and Alaoui (2013) highlighted that high-volume fly ash concrete exhibits enhanced durability performance due to reduced pore connectivity. Nayak (2023) further demonstrated that fly ash contributes to improved performance in mass concrete applications by reducing thermal cracking potential.

Table 2. Observed Effects of Fly Ash Substitution on Concrete Performance

Performance Aspect	Observed Effect	Supporting References
Early-age strength	Slight reduction	Adnan & Abriantoro (2025); Che Amat et al. (2024)
Long-term strength	Significant improvement	Fernando et al. (2025); Amran et al. (2020)
Microstructure	Densification	Adibroto et al. (2018); Tian (2011)
Sustainability	Reduced cement use	Sunarno et al. (2024); Green Concrete Proceedings (2024)

Sustainability and Practical Implications

The results of this study reinforce the sustainability benefits of fly ash utilization in high-strength concrete. By partially replacing cement, fly ash reduces carbon emissions associated with cement

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production while maintaining or improving mechanical performance. Sunarno et al. (2024) emphasized that high-volume fly ash concrete supports environmentally friendly construction practices. Similarly, Nayak (2023) highlighted the contribution of fly ash to sustainable infrastructure development.

The findings confirm that fly ash waste can be effectively integrated into high-strength concrete applications without compromising performance requirements. This supports broader adoption of fly ash-based concrete in structural applications and contributes to circular economy principles in the construction industry.

CONCLUSION

This study evaluated the performance of high-strength concrete incorporating fly ash waste as a partial cementitious admixture, with a focus on compressive strength development and sustainability implications. The results demonstrate that fly ash substitution influences concrete performance in a time-dependent manner. At early ages, concrete containing fly ash exhibits lower compressive strength compared to reference concrete due to the slower pozzolanic reaction. However, as curing progresses, fly ash contributes significantly to strength development through secondary hydration reactions that refine the concrete microstructure.

At later ages, fly ash-substituted concrete achieves comparable or higher compressive strength than conventional high-strength concrete. This finding confirms that fly ash waste functions effectively as a supplementary cementitious material rather than an inert filler. The observed performance improvement is associated with enhanced matrix densification and reduced pore connectivity, which also implies potential durability benefits. From a sustainability perspective, the partial replacement of cement with fly ash reduces cement consumption and supports environmentally responsible construction practices.

Overall, the findings reinforce the feasibility of utilizing fly ash waste in high-strength concrete applications without compromising structural performance. This study provides empirical support for the broader adoption of fly ash-based concrete in sustainable infrastructure development. Future research is recommended to further investigate durability performance under aggressive exposure conditions and to validate the applicability of these findings at larger structural scales.

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