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Review IJCT

Laboratory Scale Study on Fly Ash Replacement to Cement in High-Strength Concrete

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Abstract

Concrete, the cornerstone of modern infrastructure, faces increasing environmental impact of cement production calls for sustainable alternatives in construction materials. Primarily due to the high carbon footprint associated with Portland cement production. This review synthesizes existing research and the findings from an experimental study investigating the partial replacement of Ordinary Portland Cement (OPC) with fly ash in high-strength concrete (HSC) of grade M60. The study specifically examines a 50% replacement level of cement with Class C fly ash, evaluating its influence on compressive strength development over 7, 14, and 28 days. Furthermore, this review delves into the broader implications of fly ash utilization in concrete, encompassing sustainability benefits, enhanced durability, cost-effectiveness, and long-term performance. The experimental results indicate a gradual strength gain in fly ash-amended concrete, achieving a 28-day compressive strength of 45 MPa. While this is below the target strength of 70 MPa, the trend suggests potential for long-term strength development, aligning with findings from reviewed literature. This paper underscores the necessity for optimized mix designs and extended curing regimes to fully leverage the benefits of fly ash in high-strength applications, contributing to a more sustainable and resilient construction industry.

Keywords: Fly ash, partial cement replacement, high-strength concrete (HSC), M60 grade, compressive strength, sustainability, durability, pozzolanic reaction

INTRODUCTION

India's infrastructure sector stands as a cornerstone of national development, driving rapid urbanization, employment generation, and economic growth. With the nation's population crossing 1.4 billion and expanding urban footprints encroaching on resource availability, the demand for sustainable construction practices has never been more critical. Concrete remains the backbone of modern infrastructure – be it highways, bridges, high-rise buildings, or dams. However, the core component of concrete – Ordinary Portland Cement (OPC) – is a highly energy-intensive material, the production of which is responsible for nearly 7–8% of global CO_2 emissions. In the face of growing environmental concerns and the urgent need for climate-resilient infrastructure, finding alternatives to reduce the dependency on cement without compromising performance is a priority for engineers, researchers, and policymakers alike.

One such alternative that has emerged prominently over the past few decades is *fly ash*, a fine by-product generated from coal combustion in thermal power plants. India, being one of the largest producers of coal-based energy, generates

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an enormous amount of fly ash – much of which remains underutilized and poses a serious environmental hazard. Fly ash, when used as a supplementary cementitious material (SCM), not only helps in waste management but also enhances the properties of concrete through pozzolanic reactions. Its use in concrete, particularly in high-performance grades, such as M60, can lead to significant environmental, technical, and economic advantages.

High-strength concrete (HSC), such as M60 grade, is widely used in the construction of high-rise buildings, precast elements, and long-span bridges where both strength and durability are paramount. However, the high cement content typically required for such mixes results in increased cost and carbon footprint. Replacing cement with fly ash in such applications offers a dual benefit – reduction in environmental impact and improved long-term mechanical performance due to the gradual pozzolanic activity that enhances strength over time. The successful incorporation of Class C fly ash in high-strength concrete mixes can significantly lower the heat of hydration, improve workability, and enhance resistance to chemical attacks – qualities that are increasingly demanded in modern-day infrastructure projects [1–3].

Despite its known advantages, the practical application of fly ash at high cement-replacement levels still faces several challenges. These include variability in chemical composition, dependence on power plant source, lack of codal clarity for high-volume fly ash concrete (HVFAC), and limited awareness among site engineers and contractors. Additionally, the early-age strength of fly ash-blended concrete tends to be lower compared to conventional mixes, which often leads to hesitation in their use for fast-tracking construction projects. There is also a need for more field-level data, standardization of mix design procedures, and long-term durability testing under varying climatic exposures.

Over the years, a growing body of research has investigated the mechanical behavior, durability, and microstructural properties of fly ash-blended concrete, with encouraging results. Studies have shown that with proper curing, mix design optimization, and quality control, it is feasible to replace even up to 50% of cement in M60-grade concrete without compromising performance. This review-based study, coupled with experimental validation, seeks to provide a holistic perspective on the use of fly ash in high-strength concrete, particularly with respect to compressive strength development over 7, 14, and 28 days.

In the broader context of sustainable construction and circular economy principles, this research is both timely and relevant. It not only supports environmental conservation through industrial waste utilization but also promotes innovations in concrete technology that align with the goals of green building certifications like IGBC, GRIHA, and LEED. As infrastructure demand continues to rise, integrating sustainable materials, like fly ash into mainstream concrete practice, can play a pivotal role in reducing India's carbon footprint while maintaining the structural integrity and service life of its built environment.

LITERATURE REVIEW

This chapter presents the critical analysis of the existing literature which is relevant to the "Effects of partial replacement of steel and polypropylene with cement in some concrete." Though the literature consists of many research contributions, here, some of the research and review papers are being analyzed. The existing approaches are categorized based on the basic concepts involved in percentage replacement and needed best strength. Finally, the findings are summarized related to the scanned and analyzed research papers. Chapter concludes with the motivation behind the identified problem [4].

Partial Replacement of Cement by Fly-Ash in Concrete

The study "Partial Replacement of Cement by Fly Ash in Concrete" explores using fly ash (10%, 20%, and 30%) to replace cement in M10, M20, and M30 concrete. It highlights environmental benefits by reducing CO_2 emissions and improving concrete durability. Tests on 27 concrete cubes at 7-, 28-, and 56-days show that fly ash concrete gains strength over time, with a 10–15% increase after 28 days. The Fly ash also enhances workability, reducing water and admixture needs. However, higher fly ash content slightly delays early strength development [5].

The research supports fly ash as a sustainable, cost-effective alternative in concrete production.

1. *Effect on Compressive Strength with Partial Replacement of Fly Ash:* The researcher conducted a study on the compressive strength of concrete by partially replacing cement with fly ash sourced from various locations. The research analyzed the effect of varying fly ash content on concrete strength development over time. The results showed mixed effects – some replacements increased strength, while others reduced it. When 10% of cement was replaced with fly ash, the concrete lost 20% comprehensive strength at 7 days and 50% at 28 days. However, using 20% fly ash made the concrete 7% stronger at 7 days and 11% stronger at 28 days. With 30% fly ash, the compressive strength increased by 23% at 7 days and 25% at 28 days. The study also found that concrete strength improved as it aged [6].
2. *Structural Applications Of 100 Percent Fly Ash Concrete:* This study investigates 100% fly ash concrete, where Class C fly ash replaces Portland cement, emphasizing environmental sustainability through reduced CO_2 emissions and use of industrial by-products. The material proved promising early strength (20 MPa at 2 days) and exceptional long-term strength (55 MPa at 1 year), comparable to conventional concrete. Key engineering properties – Young's modulus, splitting tensile strength, and shrinkage – were evaluated, revealing tensile strength as 15–30% lower than predicted by Portland cement models. Structural elements (beams, columns) showed similar strength and ductility to traditional concrete, confirming design equations for flexural ability. Field trials confirmed feasibility using standard equipment, achieving target slump (127 mm), set time (120 minutes), and compressive strength (33 MPa at 28 days). However, durability data and refined anchorage requirements for reinforcement remain critical gaps for broader adoption [7].
3. *Partial Replacement of Cement with Fly Ash in Concrete and Its Effect:* This study explores partial cement replacement with fly ash in M25-grade concrete, emphasizing environmental sustainability through industrial waste use. Class F and C fly ash were analyzed, differing in calcium content and self-cementing properties. Experimental trials with 10%, 20%, and 30% fly ash replacement at a 0.35 water-cement ratio revealed that 10–20% fly ash enhanced 28-day compressive strength (up to 43.24 MPa), while 30% replacement reduced performance. Higher water-cement ratios increased slump but lowered strength. Findings highlight the viability of 10–20% fly ash as best for structural applications, balancing eco-efficiency with mechanical performance [8].
4. *Replacement of Cement by Fly Ash in Concrete:* The study explores the use of fly ash as a partial replacement for cement in concrete, analyzing its impact on strength, workability, and sustainability. Concrete mixes (M25, M35, M50, M60) with fly ash levels from 0% to 65% were evaluated for compressive strength at 7, 28, and 60 days. Results show that while early strength decreases, long-term strength improves, with the best replacement level of up to 45%. Fly ash enhances durability, reduces cement consumption, and lowers costs, making it an eco-friendly alternative. However, excessive use (>45%) negatively affects early strength, limiting its application in high-strength early-load structures [9].

- *Strength Characteristics of Concrete with Partial Replacement of Cement by Fly Ash and Activated Fly Ash:* This study investigates the partial replacement of cement with fly ash (FA) and chemically activated fly ash (AFA) in M30-grade concrete. Experimental results show that 40% AFA replacement (using sodium silicate and calcium oxide) significantly enhances compressive, tensile, and flexural strengths, outperforming conventional concrete (CVC) by 6.16% and regular FA concrete by 12.5% at 28 days. While 30% of FA replacement reduces strength by 6.8%, AFA perfects pozzolanic reactivity, improving workability and durability. The findings highlight 40% AFA as the best replacement, balancing mechanical performance with environmental benefits through reduced cement use and CO_2 emissions [10].

5. *On Effects of Fly Ash as a Partial Replacement of Cement on Concrete Strength:* Fly ash, a cost-effective and eco-friendly cement substitute, reduces CO_2 emissions and landfill waste while enhancing concrete's long-term strength. Though early strength development is slower, studies find a best replacement ratio where fly ash concrete surpasses conventional mixes over time due to improved aggregate bonding. Conflicting results at higher ratios highlight the need for balanced mix design, driven by sustainability goals in modern construction [11].
6. *A Review Paper on Partial Replacement of Cement by Fly Ashin High-Strength Concrete:* This review evaluates the partial replacement of cement with fly ash in M65-grade high-strength concrete (HSC), emphasizing environmental and mechanical benefits. Studies show that 15–20% fly ash replacement enhances durability by reducing drying shrinkage, sorptivity, and chloride permeability while achieving target compressive strength (74.9 MPa). Mix design adhering to IS 10262-2019 standards integrates superplasticizers for workability and perfects water–cement ratios (0.31). Research by Kuo et al. noted reduced strength with piezoelectric materials, while Baeza et al. proved improved performance using ternary waste blends (fly ash, marble dust). Chan's work highlighted cost-effective, durable concrete with non-reactive waste like silt. Rodriguez found reservoir sludges as practical pozzolans, and Khmiri validated ground glass pozzolanic activity. Overall, fly ash and industrial by-products offer sustainable solutions for HSC, balancing [12].
7. *Partial Replacement of Cement with Fly Ash in Concrete Mix Design:* Fly ash, a coal combustion by-product, reduces cement use in concrete, addressing CO_2 emissions from cement production. Its pozzolanic properties enhance long-term strength via CSH gel formation. Studies show activated fly ash (treated with sodium silicate/calcium oxide) outperforms conventional mixes, achieving 40% replacement as best for compressive (42.2 N/mm^2), tensile (5.12 N/mm^2), and flexural (5.88 N/mm^2) strength. Government initiatives in India target 600 million tons of fly ash utilization by 2032. Benefits include improved workability, reduced permeability, and thermal resistance. Challenges involve slower early strength gain, requiring extended curing. Activated variants mitigate strength lag, offering eco-friendly, durable alternatives aligned with sustainability goals [13].
   - *Partial Replacement of Cement with Fly Ash to Produce Environmentally Friendly Concrete:* Fly ash, a coal combustion by-product, reduces cement use and CO_2 emissions. Classified as Class F (pozzolanic) or Class C (self-cementing) per ASTM C618, it enhances concrete properties. Optimal 15% replacement achieves peak compressive (3699 psi) and split tensile strength (343 psi) via pozzolanic CSH formation. Fly ash improves durability by reducing water permeability (23 mm at 30% replacement) and enhances workability through spherical particles. India targets 600 million tons of fly ash utilization by 2032 to mitigate environmental hazards. Challenges include slower early strength gain, requiring extended curing [14]. This study explores how fly ash affects concrete properties, focusing on strength, workability, and durability. Fly ash often increases long-term strength but may slightly reduce early strength, enhancing durability by reducing permeability and chemical attack. It improves workability due to its spherical particles but can delay setting times, which is advantageous in large placements.
8. *Fly Ash and Pozzolanic Concrete:* This foundational work details fly ash's pozzolanic reactions in concrete, where it forms calcium silicate hydrate (C–S–H), enhancing microstructure, density, and resistance to chemical attacks. It's a key resource for understanding the role of fly ash in sustainable concrete [15].
9. *Mix Design for Optimal Strength Development of Fly Ash Concrete:* This research focuses on designing concrete mixes with fly ash to achieve best strength, adjusting proportions for water–cementitious materials ratio and aggregate grading. Proper curing is vital to maximize fly ash's pozzolanic benefits.
10. *Compressive Strength of Low Cement/High Fly Ash Concrete:* Investigating concrete with minimal cement and high fly ash content, this study shows the potential for significant cement reduction, which is crucial for lowering CO_2 emissions in construction.

11. *Effect of Source of Fly Ash on Abrasion Resistance of Concrete:* This study highlights that fly ash source impacts concrete's abrasion resistance, affecting durability in structures exposed to wear (Figures 1-4). Selecting the right fly ash is key for enhancing concrete's longevity.

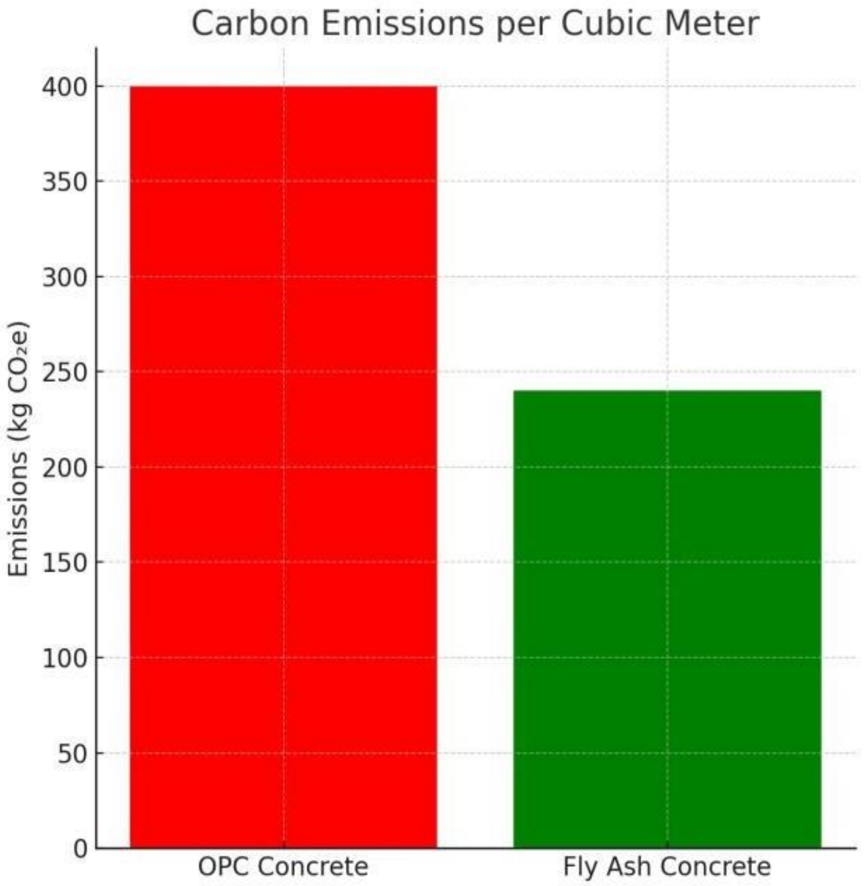

Figure 1. Carbon emission per cubic meter.

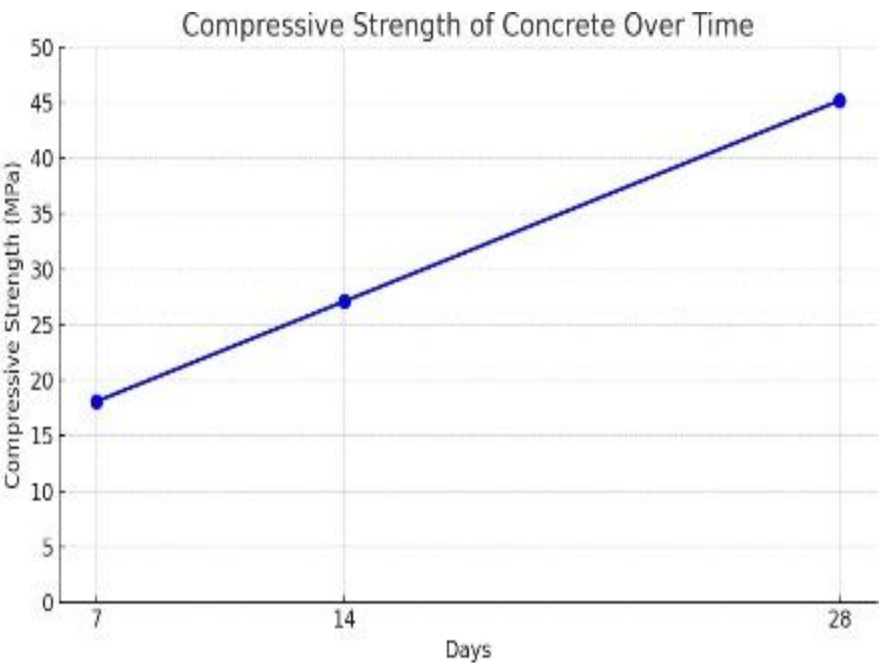

Figure 2. Compressive strength concrete over time.

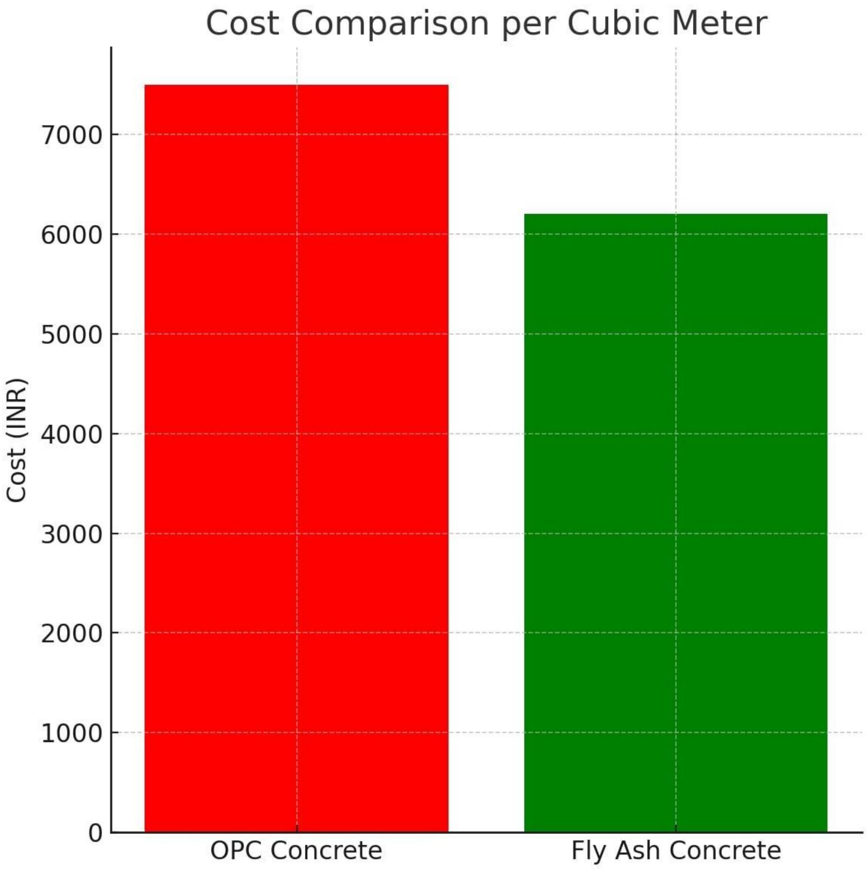

Figure 3. Cost comparison.

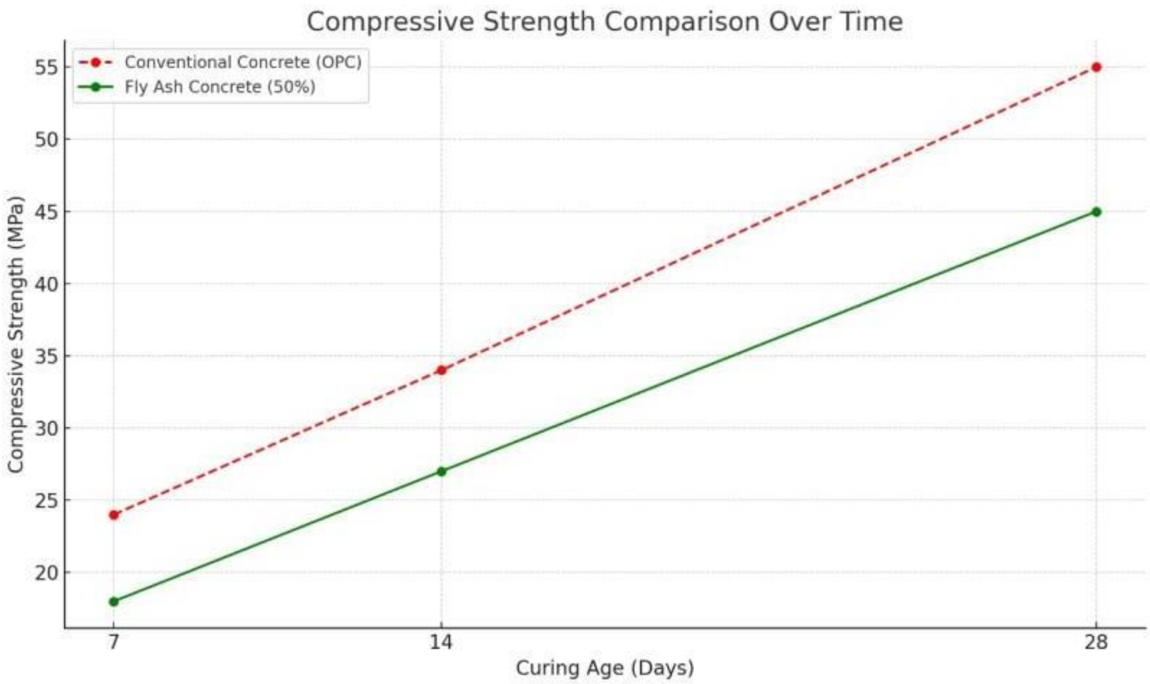

Figure 4. Compressive strength concrete over time curing days.

PROPOSED METHODOLOGY

This chapter details the methodology employed to investigate the effects of partial cement replacement with fly ash in M60 grade concrete. The methodology encompasses the materials used, mix design, specimen preparation, curing, and testing procedures.

- *Overview of Experimental Procedure:* The study involves preparing and testing concrete cube specimens with a specific focus on M60 grade concrete where 50% of the cement is replaced by fly ash. The compressive strength of these specimens will be evaluated at 7, 14, and 28 days to determine the impact of fly ash replacement on strength development.
- *Materials:* The materials used in this study and their key properties are:
  - *Cement:* Ordinary Portland Cement (OPC) of 53 grade conforming to relevant Indian Standards (IS). Physical and chemical properties of the cement were determined as per standard procedures.
  - *Fly Ash:* Class C fly ash obtained as a by-product of coal combustion from a thermal power plant. Physical and chemical properties of the fly ash were evaluated.
  - *Fine Aggregate:* Natural sand, the properties of which, including grading and fineness modulus, were determined.
  - *Coarse Aggregate:* Crushed angular aggregate of 20 mm maximum size, with its properties (e.g., impact value, crushing value, specific gravity, water absorption) tested as standard procedures.
  - *Water:* Clean potable water used for mixing concrete with W/C 0.32.
  - *Admixtures:* Polytancrete NGT, Super Plasticizing Admixture dosage with 1%
  - *Concrete Mix Proportioning:* The mix design for M60 grade concrete was carried out as per IS 10262 guidelines. A control mix (without fly ash replacement) was designed, and then a modified mix was prepared with 50% cement replaced by an equal volume of fly ash. The water–cement ratio was carefully controlled to achieve the desired workability and strength. The quantities of cement, fly ash, fine aggregate, coarse aggregate, and water were accurately measured for each batch.
  - *Specimen Preparation:* Concrete cube specimens of 150 mm x 150 mm x 150 mm dimensions were cast for compressive strength testing. The concrete was placed in molds in layers and compacted to ensure proper consolidation. Specimens were labelled and cured under controlled laboratory conditions (temperature and humidity) for 7, 14, and 28 days.

Testing Procedures

- *Fresh Concrete Tests:* Workability of fresh concrete was assessed using the slump test and compaction factor test.
- *Hardened Concrete Tests:* Compressive strength tests were conducted on the cube specimens at 7, 14, and 28 days of curing using a compression testing machine. The failure load was recorded, and the compressive strength was calculated.
- *Material Tests:* Tests were conducted on individual materials (cement, fly ash, aggregates) to determine their physical and chemical properties as per relevant IS codes.
- *Data Analysis:* The compressive strength test results were recorded and analyzed to evaluate the effect of fly ash replacement on strength development. The data was presented in tables and graphs to facilitate comparison and interpretation.

CONCLUSIONS

The utilization of fly ash as a partial replacement for cement in concrete presents a multifaceted opportunity to advance sustainable construction practices. The findings of this review, synthesizing a range of research from laboratory experiments to field applications, highlight that incorporating fly ash can offer distinct advantages in terms of both concrete performance and environmental conservation. The average compressive strength values obtained for the M60 grade concrete with 50% fly ash replacement at different curing ages were:

- 7 Days: 18.09 MPa.
- 14 Days: 27.10 MPa.
- 28 Days: 45.18 MPa.

These results indicate a progressive gain in compressive strength over time for the fly ash-amended concrete. However, the strength development is notably slower compared to typical OPC concrete, especially at early ages. The 28-day compressive strength of 45.18 MPa, while significant, is below the target mean strength of 70 MPa for M60 grade concrete. While studies consistently demonstrate the potential for enhanced long-term strength and durability in fly ash concrete, the impact on early strength development necessitates careful consideration in mixed design and curing practices. The optimal percentage of fly ash replacement is shown to vary depending on the specific application and desired concrete properties, requiring a balanced approach to achieve both structural integrity and ecological benefits.

This review underscores that the successful implementation of fly ash in concrete requires a holistic understanding of material science, mix proportioning, and construction practices. Further research and standardization are essential to address concerns regarding variability in fly ash quality and to develop comprehensive guidelines for its use in diverse construction scenarios.

In conclusion, the partial replacement of cement with fly ash represents a vital step towards a more sustainable and resilient built environment. By strategically leveraging this industrial by-product, the construction industry can mitigate its environmental footprint, conserve natural resources, and produce concrete structures with improved longevity and performance. Achieving widespread adoption, however, will depend on continued collaboration among researchers, industry professionals, and policymakers to promote informed decision-making and best practices in fly ash concrete technology.

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