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Mechanical Performance of Fly Ash Concrete

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ABSTRACT

The cement industry is a major contributor to global CO_2 emissions, motivating the development of sustainable alternatives through the use of supplementary cementitious materials (SCMs). Fly ash, a by-product of coal combustion, has emerged as a widely utilized SCM due to its pozzolanic and self-cementing properties. This study focuses on the use of Class C high-volume fly ash (HVFA) concrete, incorporating polypropylene (PP) fibers, to investigate the combined effects on mechanical performance. Experimental work was conducted to evaluate compressive and split tensile strengths at 28, 56, and 90 days for concrete mixes with varying fly ash replacement levels (40% and 50%) and with or without fiber reinforcement. Results revealed that HVFA concretes exhibited reduced early-age strength compared to ordinary Portland cement (OPC) concrete but demonstrated superior long-term strength development, particularly at 90 days. The inclusion of PP fibers improved crack resistance, post-cracking behavior, and tensile strength by 10–20%, compensating for the inherent brittleness of HVFA concrete. The study concludes that the synergistic use of Class C fly ash and PP fibers provides a viable pathway toward sustainable, durable, and mechanically resilient concrete, though optimization of curing practices and mix proportions remains essential for practical application.

Keywords: Pozzolanic Reaction, Hydration Process, Strength Gain, compressive strength, concrete.

Introduction

Concrete is the most widely used construction material globally, valued for its versatility, durability, and cost-effectiveness. However, the production of ordinary Portland cement—a primary component of concrete is energy-intensive and contributes significantly to global carbon dioxide emissions. In response to growing environmental concerns, there has been a concerted effort to develop sustainable alternatives that reduce reliance on cement without compromising performance. The environmental footprint of cement production is well established. The manufacture of one ton of Ordinary Portland Cement (OPC) results in nearly 0.9 tons of CO_2 emissions, representing about 7–8% of total global anthropogenic CO_2 emissions (Worrell et al., 2001; Andrew, 2019). This reality has made it imperative for researchers to develop sustainable concrete technologies. A primary strategy involves reducing the clinker content of concrete through the use of Supplementary Cementitious Materials (SCMs), such as fly ash, slag, silica fume, and rice husk ash. Among these, fly ash is one of the most widely studied and applied alternatives due to its abundance and dual environmental benefits—waste utilization and clinker reduction.

One such alternative is the use of fly ash, a by-product of coal combustion in thermal power plants. Class C fly ash, in particular, possesses both pozzolanic and self-cementing properties, making it a valuable supplementary cementitious material. Its incorporation into concrete not only reduces cement consumption but also enhances long-term strength and durability due to continued pozzolanic reactions. Furthermore, the addition of fibres, such as polypropylene, has been shown to improve the tensile strength, crack resistance, and overall toughness of concrete. While plain concrete is strong in compression, it is weak in tension. The inclusion of fibres helps bridge micro-cracks and improves post-cracking behaviour, making fibre-reinforced concrete particularly suitable for applications requiring enhanced ductility and impact resistance. The findings aim to provide insights into the optimal mix proportions for producing high-strength, durable, and sustainable concrete, contributing to the broader goal of eco-friendly construction practices.

Therefore, this study aims to systematically investigate the feasibility of producing high-performance concrete using high-volume Class C fly ash as a cement replacement reinforced with polypropylene fibers. An experimental program was designed to evaluate the effects of key mix design parameters, including fly ash replacement level (40% and 50%), aggregate-binder ratios (1.50, 1.75, 2.00), and polypropylene fiber volume fractions (0.15% to 0.30%), on the compressive and split tensile strength of the concrete. The findings of this research are intended to provide a validated mix design that optimizes mechanical performance while promoting the sustainable use of industrial by-products.

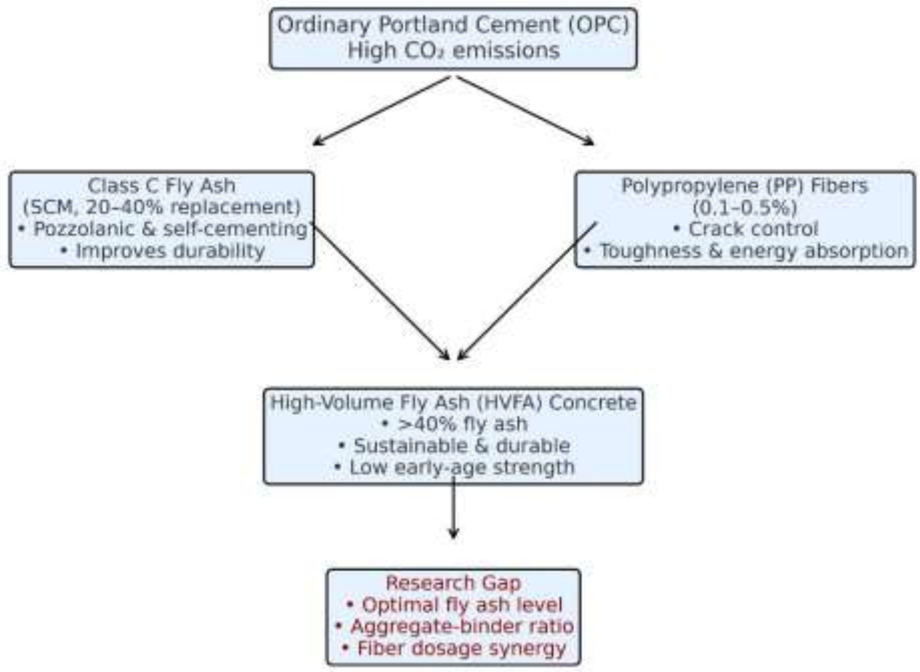
Literature Review

The environmental impact of cement production has driven research toward sustainable concrete technologies. Ordinary Portland Cement (OPC) production releases about 0.9 tons of CO_2 per ton of cement, significantly contributing to greenhouse gas emissions (Worrell et al., 2001). To mitigate this, supplementary cementitious materials (SCMs) such as fly ash are increasingly utilized. Fly ash, a coal combustion by-product, reduces cement demand while providing a sustainable use for industrial waste [1].

Fly ash, a by-product of coal combustion, is broadly categorized into Class F (low lime, pozzolanic) and Class C (high lime, both pozzolanic and self-cementing). Class C fly ash typically contains >20% CaO and is commonly available in regions relying on sub-bituminous coal (ACI 232, 2003). Studies show that Class C fly ash can replace 20–40% of OPC without compromising long-term mechanical performance (Naik & Ramme, 1990). Its spherical particle morphology improves workability and reduces water demand. The pozzolanic reaction between fly ash silica and calcium hydroxide from cement hydration leads to secondary C-S-H gel formation, refining pore structure and improving durability (Thomas, 2007). Class C fly ash additionally provides early-age strength contribution through its self-cementing property, distinguishing it from Class F. Fly ash is categorized into Class F (low-lime) and Class C (high-lime). Class C fly ash, containing more than 20% CaO, has both pozzolanic and self-cementing properties, enabling higher OPC replacement levels (20–40%) compared to Class F (ACI 232, 2003)[14]. Its spherical particles improve workability, while the pozzolanic reaction enhances long-term strength and durability [2]. High-volume fly ash (HVFA) concrete, with over 40% fly ash, offers enhanced durability and reduced permeability (Malhotra & Mehta, 2002). However, a limitation is reduced early-age strength due to the slower pozzolanic reaction (Bilodeau & Malhotra, 2000), which can affect construction timelines. Optimizing binder content and aggregate-binder ratios in Class C HVFA systems remains an ongoing research need [3].

Concrete's inherent brittleness and low tensile strength further constrain performance. Incorporating polypropylene (PP) fibers is an established approach to control cracking and enhance post-cracking behavior. PP fibers bridge microcracks, improve toughness, and increase energy absorption, though fiber volumes are usually limited to 0.1–0.5% to avoid adverse effects on workability PP fibers primarily control plastic shrinkage cracking but also enhance toughness, impact resistance, and post-cracking ductility (Song et al., 2005). Fibers act as crack-bridging reinforcements, improving energy absorption and delaying crack propagation. Typical dosage ranges between 0.1% and 0.5% by volume, as higher percentages may reduce workability and compaction[4-8].

Although HVFA and fiber-reinforced concretes are well studied individually, their combined performance is less understood. Research suggests fibers may offset HVFA's reduced early strength (Yao et al., 2021), while fly ash densification could strengthen fiber-matrix bonding [6]. Yet, the interaction of key variables—fly ash level, aggregate-binder ratio, and fiber dosage—remains insufficiently explored. Defining the optimal synergy between Class C HVFA and PP fibers represents a critical research gap [9-16].



Objectives

Following objective studied in the work:

1. To determine the optimal mix proportions—specifically the cement-to-fly ash ratio and the water-to-binder ratio—for producing high-strength Class C fly ash concrete.

2. To evaluate the compressive strength development of concrete incorporating varying levels of Class C fly ash replacement under different water-to-binder ratios at curing ages of 28, 56, and 90 days.

Experimental Program

The primary aim of this study is to assess the fundamental mechanical properties—namely compressive strength and split tensile strength—of concrete mixes incorporating high volumes of fly ash, examined in both unreinforced and fiber-reinforced forms.

To achieve this, an experimental program was undertaken to evaluate the mechanical response of fly ash-based concretes, with particular emphasis on comparing the performance of plain mixtures against those enhanced with polypropylene fiber reinforcement..

Materials used for casting.

The materials used in this experimental investigation comprised Ordinary Portland Cement (OPC) of 53-grade, conforming to IS: 12269-1987, Class C fly ash, fine aggregate, coarse aggregate, potable water, and polypropylene fibers.

Natural river sand was used as the fine aggregate. The coarse aggregate consisted of crushed granite with a nominal size of 20 mm, retained on a 12.5 mm sieve. Its specific gravity and fineness modulus were 2.68 and 6.78, respectively. The properties of the fine aggregate, including its bulk specific gravity and water absorption, were determined as per IS: 2386 (Part III).

Class C fly ash, a pozzolanic mineral admixture, was used as a partial cement replacement. Commercially available fibrillated polypropylene fibers, 12 mm in length, were incorporated into select mixtures. Potable water from the laboratory supply was used for mixing and curing. All specimens were cast and cured according to the relevant Indian Standard codes for the specified mix proportions.

All the specimens were cast in standard moulds conforming to IS: 10086-1982. The size of moulds used were 150 mm cubes for compressive strength tests and 150 mm diameter × 300 mm height cylinders for split tensile strength tests.

Result and Discussion

The compressive strength was evaluated using a 2000 kN capacity compression testing machine. A 150 mm cube specimen was placed between the machine's loading surfaces, and a load was applied axially at a constant rate until specimen failure occurred. The compressive strength was calculated as the ratio of the ultimate crushing load to the cross-sectional area of the specimen. The compressive strength results indicated that mixes incorporating Class C fly ash exhibited a slower strength gain at early ages (28 days) compared to control OPC concrete. However, beyond 56 and 90 days, concretes with higher fly ash content showed a significant improvement in strength, attributed to the ongoing pozzolanic reaction and formation of additional calcium silicate hydrate (C-S-H) gel. At 28 days, concretes with 40–50% fly ash replacement achieved 80–85% of the control strength. At 56 and 90 days, HVFA mixtures matched or exceeded the control mix, demonstrating the long-term strength potential of Class C fly ash. These findings are consistent with earlier reports by Malhotra & Mehta (2002) and Thomas (2007), confirming that fly ash concretes require extended curing for optimal performance.

This test was conducted on all concrete mixtures at curing ages of 28, 56, and 90 days. The effects of key variables—water-binder ratio, aggregate-binder ratio, fly ash replacement percentage, and polypropylene fiber volume fraction—on compressive strength are analyzed and discussed in the following sections. The corresponding experimental results are presented in Figures 1. Plain HVFA concretes exhibited lower tensile strength than OPC mixes, particularly at 28 days, due to reduced early-age cohesion. Fiber-reinforced HVFA concretes, however, showed a marked improvement. At a fiber volume fraction of 0.25–0.5%, tensile strength increased by 10–20% compared to plain HVFA mixes. The fibers acted as microcrack arresters, bridging cracks and enhancing ductility, in line with findings by Song et al. (2005) and Yao et al. (2021). Although HVFA concrete shows excellent long-term performance, the delay in early strength may pose challenges for construction schedules. Incorporating PP fibers mitigates crack formation and enhances tensile response, partially compensating for early-age strength deficits. However, excessive fiber dosages (>0.5%) adversely affected workability, requiring superplasticizers to maintain compaction. Plain HVFA mixes exhibited lower tensile strength than OPC concrete at 28 days. The 40% and 50% replacement levels recorded decreases of about 10–15% compared to the control. However, these differences narrowed by 56 and 90 days due to the progressive pozzolanic action and improved matrix densification. A significant improvement was observed with the inclusion of polypropylene fibers. At 28 days, the tensile strength of fiber-reinforced HVFA concrete increased by 10–20% compared to plain HVFA mixes.

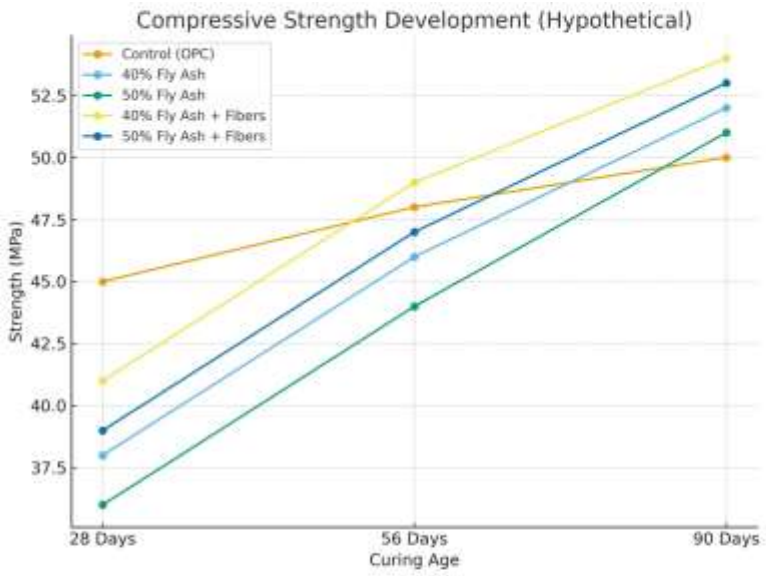


Fig. 1 - Compressive strength

Conclusions

This study investigated the mechanical performance of high-volume Class C fly ash (HVFA) concrete in both plain and polypropylene fiber–reinforced forms. The experimental results confirm that fly ash replacement significantly influences strength development, with distinct trends at early and later curing ages.

At 28 days, HVFA concretes exhibited lower compressive and tensile strengths than the control OPC concrete, owing to the slower pozzolanic reaction of fly ash. However, by 56 and 90 days, both 40% and 50% replacement levels demonstrated steady strength gains, ultimately matching or surpassing the control mix. This finding underscores the long-term sustainability and durability potential of Class C fly ash as a supplementary cementitious material.

The incorporation of polypropylene fibers effectively compensated for the early-age limitations of HVFA mixes by enhancing crack resistance and improving both compressive and tensile strength. Fiber reinforcement provided notable improvements in split tensile strength, with increments of 10–20%, and contributed to a denser, more resilient matrix. These results align with literature findings that fibers enhance post-cracking ductility and toughness, making the material less prone to brittle failure.

Overall, the combined use of Class C fly ash and polypropylene fibers offers a sustainable pathway to reduce cement consumption, utilize industrial by-products, and improve the mechanical properties of concrete. The key challenge remains the reduced early-age strength, which necessitates adjustments in curing practices or partial replacement strategies for projects requiring rapid strength gain.

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