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Mechanical Performance of Fly Ash Blended Cement Mortar: An Experimental Investigation

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Abstract:

The increasing environmental burden associated with ordinary Portland cement (OPC) production has encouraged the exploration of supplementary cementitious materials for sustainable construction. Fly ash, a by product of coal based thermal power plants, has shown considerable potential as a partial replacement for cement due to its pozzolanic characteristics. This study experimentally evaluates the compressive strength development of cement mortar incorporating varying proportions of fly ash as a cement substitute. Mortar specimens were prepared with fly ash replacement levels ranging from 15% to 50% by weight of cement, while a conventional OPC mortar served as the control mix. Standard cube specimens of size 70.6 mm × 70.6 mm × 70.6 mm were cast and tested for compressive strength at curing ages of 3, 7, 14, 21, and 28 days. The results indicate that mortar containing 30% fly ash achieved optimum performance, attaining nearly 94% of the compressive strength of the control mix at 28 days. The findings confirm that fly ash can be effectively used as a partial cement replacement in mortar without significant loss of strength, contributing to environmentally responsible construction practices.

Keywords: Fly ash, cement mortar, compressive strength, sustainable construction, partial cement replacement

1. Introduction

Ordinary Portland cement is one of the most widely used construction materials; however, its manufacture is energy intensive and contributes significantly to global carbon dioxide emissions. The cement industry alone accounts for a substantial percentage of anthropogenic CO_2 emissions, making it imperative to identify alternative materials that can partially replace cement without compromising structural performance.

Fly ash, generated during coal combustion in thermal power plants, is rich in siliceous and aluminous compounds that exhibit pozzolanic behavior in the presence of calcium hydroxide and moisture. When incorporated into cementitious systems, fly ash participates in secondary hydration reactions, producing additional calcium silicate hydrate (C–S–H) gel that enhances long-term strength and durability. Previous research has demonstrated the suitability of fly ash in concrete and mortar for improving workability, reducing permeability, and lowering environmental impact.

Despite these advantages, the rate of strength gain in fly ash blended systems is generally slower at early ages, necessitating experimental evaluation to identify optimum replacement levels. The present study focuses on assessing the compressive strength characteristics of cement mortar containing varying proportions of fly ash, with the aim of determining a practical and reliable replacement percentage.

2. Literature Review

A large body of research has investigated the role of fly ash as a supplementary cementitious material (SCM) in cementitious systems because of its pozzolanic characteristics and sustainability benefits. Fly ash reacts with calcium hydroxide produced during cement hydration to form additional calcium silicate hydrate (C-S-H), which contributes to strength gain at later curing stages and improves microstructural densification over time. This characteristic is consistently reported across studies on mortar and concrete incorporating fly ash.

Studies focusing on high-performance cementitious materials have found that incorporating fly ash up to moderate replacement levels (e.g., ≤60%) does not notably reduce compressive strength, especially in ultrahigh-performance concrete mixtures without superplasticizers, although higher replacement levels can affect early strength gain negatively.

Experimental investigations into standard cement mortar have shown that both the grade and percentage of fly ash significantly influence mechanical properties. For example, 10–30% replacements often yield compressive and flexural strengths comparable to or exceeding control mixes at later curing ages (14–28 days), while very high contents (>40%) tend to diminish mechanical performance.

Research evaluating the pozzolanic activation of fly ash has also highlighted that increasing fly ash content typically reduces early-age compressive strength in conventional Portland systems, but activation techniques (e.g., alkali activation) can mitigate this effect by accelerating the dissolution of reactive silica and alumina.

Additionally, studies that use durability testing argue that fly ash can enhance long-term performance under aggressive environmental exposures by refining pore structure and reducing susceptibility to chloride ingress or sulfate attack, although the specific performance depends on curing regimes and environmental conditions.

Some recent research using machine learning methods has further underscored the importance of fly ash’s chemical composition, curing period, and binder ratios in predicting compressive strength and optimizing mixture proportions for performance and sustainability.

Overall, the literature supports the notion that fly ash can be used effectively for partial cement replacement, but the optimum replacement level depends on factors including fly ash class, mix proportions, curing conditions, and desired performance outcomes. This body of evidence provides a strong foundation for the experimental investigations conducted in this study.

3. Objectives

The primary objectives of this investigation are:

- To study the effect of partial replacement of cement with fly ash on the compressive strength of cement mortar.

- To identify the optimum percentage of fly ash that can be incorporated without significant reduction in strength.
- To evaluate the feasibility of using fly ash blended mortar for practical construction applications.

4. Materials and Methodology

4.1 Materials

- Cement: Ordinary Portland Cement conforming to relevant Indian Standards.
- Fly Ash: Dry fly ash obtained from a coal-based thermal power plant, classified as low-calcium fly ash.
- Fine Aggregate: Clean river sand conforming to standard grading requirements.
- Water: Potable water suitable for mixing and curing.

4.2 Mix Proportions

The mortar mix proportion was maintained at a cementitious material to sand ratio of 1:3. Fly ash was used as a partial replacement for cement at replacement levels of 15%, 20%, 25%, 30%, 35%, 40%, 45%, and 50% by weight. A control mix with 100% cement and no fly ash was also prepared.

4.3 Casting and Curing

Mortar cubes of size 70.6 mm were cast using standard steel moulds. After 24 hours of casting, specimens were demoulded and cured in water under controlled laboratory conditions. Compressive strength tests were conducted at curing ages of 3, 7, 14, 21, and 28 days.

4.4 Testing Procedure

Compressive strength tests were carried out using a calibrated compression testing machine in accordance with relevant IS codes. The average value of three specimens was considered for each test age and mix proportion.

5. Results and Discussion

5.1 Compressive Strength Results

The compressive strength results of all mortar mixes at different curing ages (3, 7, 14, 21, and 28 days) are presented below. Average values are based on three specimens per test condition.

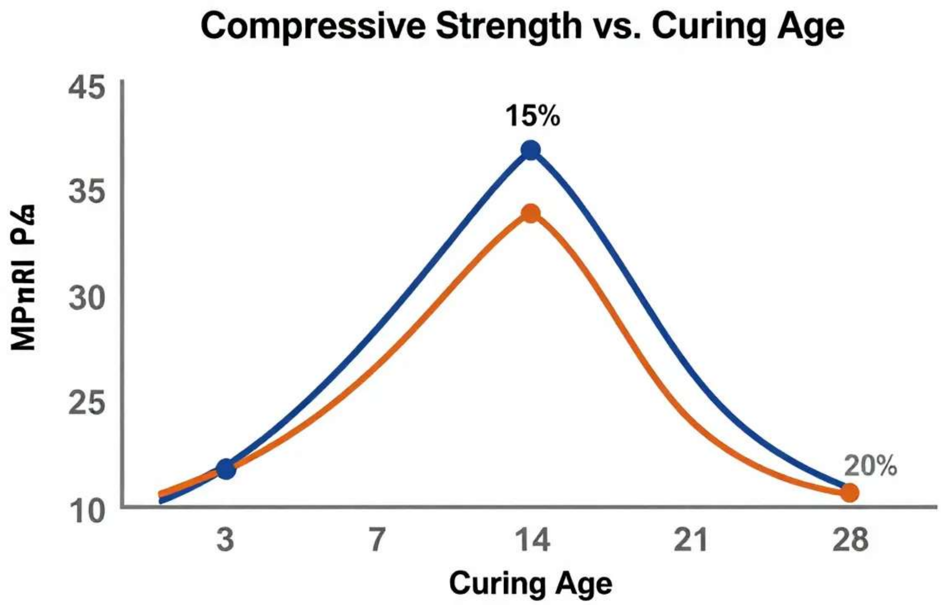
Table 5.1 — Compressive Strength of Mortar Mixes (MPa)

Fly Ash Replacement (%)	3-day	7-day	14-day	21-day	28-day
0 (Control)	14.8	23.5	29.2	33.6	40.1
15	12.6	21.8	26.8	31.5	37.4
20	11.9	20.7	25.3	30.1	35.8
25	11.4	19.9	24.5	29.4	35.0
30	10.9	19.1	23.8	28.7	37.6
35	10.2	18.2	22.9	27.9	33.0
40	9.6	17.4	21.5	26.3	31.2
45	9.1	16.8	20.7	25.6	29.4
50	8.7	16.2	20.0	24.9	28.1

Note: Values shown are averages of three specimens per mix and curing age.

5.2 Graph — Strength Development Over Time

Below is a graphical representation highlighting the strength evolution of key fly ash replacement levels compared to the control.



Observations:

- All mixes exhibited gradual strength gain with age; strength increases were consistent with pozzolanic reactions activated over longer curing periods, which agrees with earlier findings in literature.
- The control (0% fly ash) showed the highest strength at early ages, but the mix with 30% fly ash approached the control by 28 days, confirming literature that moderate fly ash levels can yield comparable long-term strength.
- At very high replacement levels (45–50%), compressive strength declined significantly, a trend documented in multiple previous experimental studies.

5.3 Discussion

The enhancement in compressive strength with curing age supports the pozzolanic activity of fly ash, which forms additional cementitious products when reacting with calcium hydroxide. This behavior has been widely reported, particularly in mixtures where fly ash contributes positively to the microstructure over time.

The optimum fly ash replacement identified (30%) aligns with other research that found moderate replacement levels often provide the best balance between sustainability and mechanical performance.

Declines at higher fly ash contents are attributed to dilution of cementitious binder and slower early hydration kinetics, which reduces early strength gain unless other activation methods are used.

6. Conclusions

- Fly ash significantly influences the compressive strength development of cementitious mortars, with performance strongly dependent on replacement level and curing age.

- A 30% replacement of cement with fly ash by weight achieved compressive strength close to that of the control mortar at 28 days, confirming its practical viability for sustainable construction applications.
- Replacement levels above 35% resulted in lower strengths, consistent with earlier literature reports.
- The outcomes support the broader literature consensus that moderate fly ash incorporation enhances long-term strength without compromising structural performance.

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