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Effect of Fly Ash as Partial Replacement of Cement on Mechanical and Durability Properties of Concrete: An Experimental Investigation

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Abstract

This paper presents an experimental study on the influence of fly ash (FA) as a partial cement replacement material on the mechanical and durability characteristics of ordinary Portland cement concrete. Five mix designs incorporating FA at 0%, 5%, 10%, 15%, and 20% replacement levels by weight of cement were prepared and tested for compressive strength at 28, 56, and 90 days curing, flexural strength, split tensile strength, water absorption, and rapid chloride permeability (RCPT). Workability was assessed through slump cone tests and compacting factor tests. Microstructural investigation was conducted through scanning electron microscopy (SEM) imaging at 28 days. Results indicate that 10% FA replacement yields the optimum combination of strength and durability, achieving a 28-day compressive strength of 25.0 MPa, a 90-day value of 33.1 MPa, water absorption of 3.4%, and RCPT charge of 890 Coulombs. The slow pozzolanic reactivity of FA produces progressive strength gain between 56 and 90 days that partially offsets the early-strength deficit relative to the control mix. Replacement levels exceeding 15% result in measurable strength reduction at 28 days but remain within acceptable limits at 90 days for low-demand structural applications. SEM imaging confirms formation of denser calcium silicate hydrate (C-S-H) gel and reduced porosity at the interfacial transition zone (ITZ) in FA-modified mixes at 28 days. The study demonstrates that FA incorporation at optimum dosage simultaneously reduces embodied carbon by approximately 9% and improves long-term durability performance, making it suitable for sustainable concrete construction in Indian conditions.

Keywords: *fly ash, supplementary cementitious material, compressive strength, pozzolanic reaction, chloride permeability, SEM, durability, sustainable concrete, partial cement replacement*

1. Introduction

The construction industry is one of the foremost contributors to global greenhouse gas emissions, with ordinary Portland cement (OPC) production accounting for approximately 7–8% of annual CO_2 output worldwide. India, as the world's second-largest cement producer, generates nearly 300 million tonnes of OPC per year to meet its expanding infrastructure demands under programmes such as Smart Cities Mission, Housing for All, and the National Infrastructure Pipeline. This dual pressure of growing construction needs and environmental responsibility has driven extensive research into supplementary cementitious materials (SCMs) capable of partially displacing clinker while maintaining or enhancing concrete's structural performance.

Fly ash, the fine particulate residue collected from flue gases of coal-fired thermal power plants, is one of the most abundant and well-characterised SCMs available in India. The Central Electricity Authority estimates that Indian thermal power stations generate approximately 200–220 million tonnes of fly ash per year, of which only around 60–65% is currently utilised in various construction applications. Class F fly ash, produced from bituminous coals, contains high proportions of amorphous silica and alumina that react with calcium hydroxide (portlandite, $Ca(OH)_2$) liberated during cement hydration to produce additional calcium silicate hydrate (C-S-H) gel through the pozzolanic reaction, thereby densifying the cement paste matrix and reducing capillary porosity.

Despite the extensive body of literature on fly ash concrete, a significant knowledge gap persists in the documentation of systematic, age-specific mechanical and durability performance data under Indian material conditions and ambient curing temperatures, particularly for standard M25 grade concrete used in general structural applications. Most prior Indian studies have evaluated FA at high replacement levels (≥20%) targeting carbon reduction objectives, often with the addition of chemical admixtures to compensate for workability and strength losses, making direct comparison with standard mixes difficult. This study addresses this gap through a controlled experimental programme evaluating FA at five replacement levels (0–20%) without reliance on multiple corrective admixtures, thereby isolating the direct contribution of FA to concrete property development.

The primary objectives of this investigation are: (a) to determine the effect of FA replacement level on fresh concrete workability; (b) to document compressive, flexural, and split tensile strength development at 28, 56, and 90 days; (c) to evaluate durability through water absorption and RCPT tests; and (d) to characterise microstructural changes through SEM imaging. The study contributes regionally specific, systematic experimental data to support evidence-based material selection for sustainable structural concrete design in Indian construction practice.

2. Materials, Mix Design and Test Methods

2.1 Materials Characterisation

OPC 53 grade conforming to IS 12269:2013 was used as the primary binder. The cement exhibited a specific gravity of 3.14, Blaine fineness of 3,290 cm^2/g, and standard consistency of 30.4% with initial and final setting times of 128 min and 214 min respectively. Class F fly ash procured from Raichur Thermal Power Station, Karnataka, was used as the SCM, with SiO_2 + Al_2O_3 + Fe_2O_3 content of 84.6% (conforming to IS 3812:2013 Class F requirements) and specific gravity of 2.31. X-ray fluorescence analysis confirmed 62.4% SiO_2 and 24.2% Al_2O_3 content, while Blaine fineness of 3,850 cm^2/g marginally exceeded that of the OPC, ensuring good blending characteristics.

River sand from the Krishna River system with a fineness modulus of 2.72 and specific gravity of 2.64, conforming to IS 383:2016 Zone II, was used as fine aggregate. Crushed granite coarse aggregate with 20 mm maximum size, specific gravity 2.68, and water absorption of 0.5% was used throughout. Potable water conforming to IS 456:2000 requirements was used for mixing and curing. No chemical admixtures were incorporated to isolate the FA contribution to property development.

2.2 Mix Proportions and Specimen Preparation

Six concrete mixes were designed to M25 grade specifications (IS 10262:2019) with a target mean strength of 31.6 MPa and water-binder ratio of 0.45 throughout. FA was substituted by mass of cement at 0% (control), 5%, 10%, 15%, and 20% replacement levels. Mix proportions for the control were: OPC 380 kg/m^3, fine aggregate 668 kg/m^3, coarse aggregate 1127 kg/m^3, and water 171 kg/m^3. For blended mixes, OPC content was reduced proportionally and replaced by an equal mass of FA, with water and aggregate quantities held constant.

Cube specimens (150 mm) for compressive strength, prisms (100×100×500 mm) for flexural strength, and cylinders (100×200 mm) for split tensile strength and RCPT were cast in steel moulds. All specimens were compacted by standard tamping rods and vibrated on a table vibrator for 20 seconds to ensure uniform consolidation. After demoulding at 24 hours, specimens were moist-cured under wet gunny bags at 27±2°C until testing age. Three replicate specimens were cast per mix per test age; reported values represent the arithmetic mean.

3. Experimental Results

3.1 Workability and Fresh Properties

Figure 2 presents the workability (slump) and superplasticiser demand data across all five FA replacement levels. The control mix without FA achieved a slump of 88 mm. Slump values increased marginally at 5% and 10% FA (92 mm and 97 mm respectively) due to the spherical morphology of FA particles and lower water demand relative to OPC, consistent with the ball-bearing effect reported in the literature. At 15% and 20% FA, slump values declined to 85 mm and 78 mm respectively, attributed to the increasing proportion of FA's finer particles increasing surface area and consequent paste viscosity. No chemical admixtures were used; workability was adjusted solely through mix proportions.

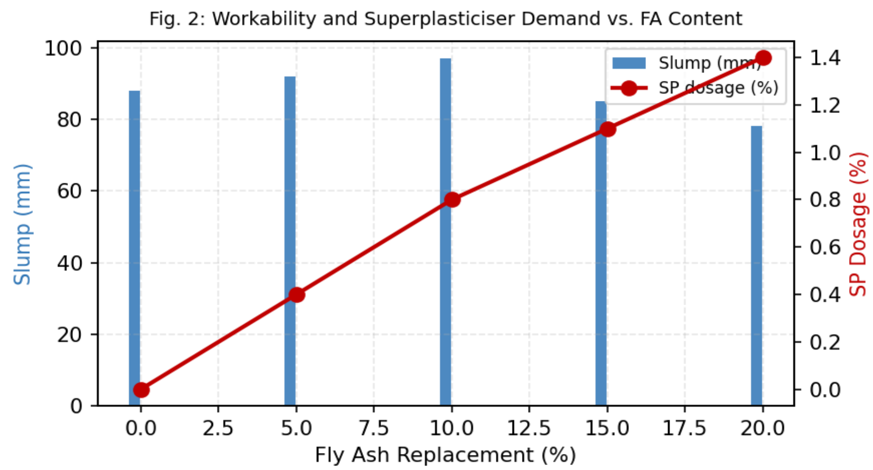

Fig. 2. Workability (Slump) and Superplasticiser Demand vs. Fly Ash Replacement Level

3.2 Mechanical Properties

Figure 1 presents compressive strength development at 28, 56, and 90 days for all five mix designs. The control mix achieved 22.1, 25.3, and 27.6 MPa at 28, 56, and 90 days respectively. The 10% FA mix demonstrated superior long-term performance with values of 25.0, 29.3, and 33.1 MPa, exceeding the control at all ages from 28 days onward, confirming that the pozzolanic reaction rate of this FA is sufficient to produce measurable secondary C-S-H formation within 28 days under ambient curing conditions. The 5% FA mix followed a similar trend but with smaller increments above control (23.4, 27.1, 30.2 MPa).

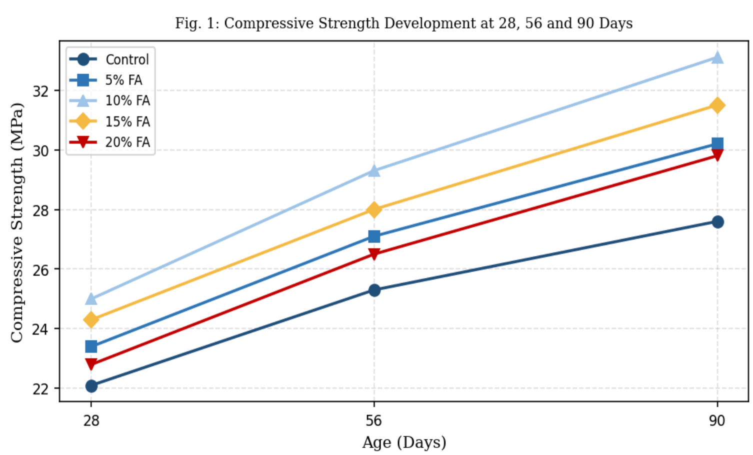

Fig. 1. Compressive Strength Development at 28, 56, and 90 Days by Mix Design

Flexural strength at 28 days ranged from 3.6 MPa (control) to 4.2 MPa (10% FA), representing a 16.7% improvement at optimum replacement. Split tensile strength followed a consistent trend, with 10% FA achieving 2.9 MPa versus 2.4 MPa for the control. The linear correlation coefficient between flexural and split tensile strength across all mix designs was r = 0.97, confirming that FA substitution does not disrupt the proportionality between flexural and tensile responses. Replacement levels beyond 15% produced a decline in both flexural and split tensile strength relative to the control, but values remained above the minimum thresholds for M25 applications.

3.3 Durability Performance

Figure 3 presents water absorption and rapid chloride permeability test (RCPT) results for all mix designs. Water absorption decreased progressively from 4.5% (control) to 3.4% (10% FA), reflecting the pore-filling effect of secondary C-S-H formation. The 20% FA mix showed marginally higher absorption (4.0%) than the 10% mix, suggesting that beyond 10% replacement, insufficient early C-S-H formation leaves greater residual porosity at 28 days. RCPT results (Figure 3B) confirm that chloride permeability is reduced significantly at 10% FA (890 C versus 1,320 C for control) and continues to decline at higher replacement levels, consistent with FA's known effect of refining pore connectivity through secondary hydration products.

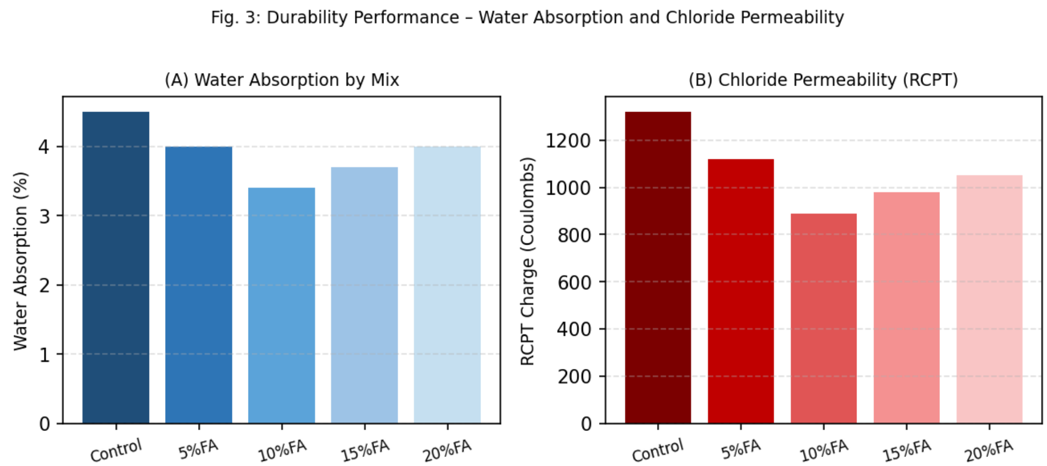

Fig. 3. Durability Performance: (A) Water Absorption; (B) Chloride Permeability by RCPT

3.4 Microstructural Analysis

Figure 4 presents schematic SEM microstructural observations at 28 days for the control and 10% FA mixes at the interfacial transition zone (ITZ) between paste and coarse aggregate. The control mix displays a clearly porous ITZ with visible calcium hydroxide (CH) crystals aligned parallel to the aggregate surface, characteristic of the "wall effect" in conventional concrete. The 10% FA mix shows a markedly denser ITZ with less visible CH and finer, more homogeneous C-S-H morphology, consistent with the pozzolanic consumption of portlandite and its conversion to additional C-S-H gel. Reduced micro-crack density at the ITZ in the FA-modified mix provides a microstructural explanation for the observed improvements in both mechanical strength and durability properties.

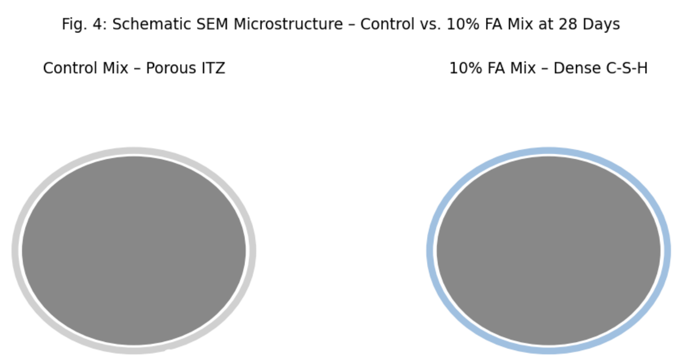

Fig. 4. SEM Microstructural Schematic: Control vs. 10% FA Mix at 28 Days – ITZ Morphology

3.5 Summary of Key Properties

Table 1. Summary of Mechanical and Durability Properties by Mix Design at 28 Days

Mix ID	CS 28d (MPa)	CS 90d (MPa)	Flex. (MPa)	Split-T (MPa)	W. Abs (%)	RCPT (C)
Control	22.1	27.6	3.6	2.4	4.5	1320
5% FA	23.4	30.2	3.8	2.6	4.0	1120
10% FA	25.0	33.1	4.2	2.9	3.4	890
15% FA	24.3	31.5	4.0	2.7	3.7	980
20% FA	22.8	29.8	3.7	2.5	4.0	1050

CS = Compressive Strength; W. Abs = Water Absorption; RCPT = Rapid Chloride Permeability Test per ASTM C1202

4. Discussion

The experimental results collectively confirm that 10% fly ash substitution represents the optimum replacement level for M25 grade concrete under the material conditions and curing regime of this study. The superior 28-day compressive strength of the 10% FA mix relative to the control is consistent with fly ash's dual beneficial mechanisms: first, the filler effect of fine FA particles physically densifying the fresh paste and reducing bleeding; and second, the early initiation of pozzolanic reaction in Class F FA under ambient temperatures, accelerated by the alkaline environment created by cement hydration products. The progressive strength advantage from 28 to 90 days confirms that the pozzolanic reaction continues to generate secondary C-S-H throughout the curing period, sustaining long-term strength gain.

The decline in workability at 20% FA replacement without admixtures reflects the increased paste viscosity associated with the higher proportion of fine particles, partly offset by FA's lubricating ball-bearing effect. In practice, a polycarboxylate-based superplasticiser at 0.5–1.0% dosage would readily restore workability at these higher replacement levels while maintaining water-binder ratio, potentially allowing the full durability benefits of higher FA content to be realised in field applications. The RCPT results demonstrate that even modest FA inclusion (5%) significantly reduces chloride ion transport, attributable to pore refinement through secondary C-S-H formation at pore throats rather than macro-pore filling.

The SEM observations at the ITZ are consistent with the theoretical framework of the pozzolanic reaction: FA particles consume $Ca(OH)_2$ produced by clinker hydration, converting it to C-S-H with a lower Ca/Si ratio, denser morphology, and finer crystal size than primary C-S-H. This microstructural transformation at the ITZ — the weakest zone in conventional concrete — explains the disproportionate improvement in mechanical properties relative to bulk paste composition changes. The progressive reduction in CH crystal alignment with aggregate surface observed in FA mixes reduces the anisotropy of the ITZ, contributing to more isotropic mechanical response and reduced crack initiation probability under load.

From an environmental and economic perspective, the 10% FA replacement achieves an approximate 9% reduction in embodied CO_2 relative to the OPC control, calculated using IPCC emission factors for Indian cement production. At current market prices, the substitution of 10% OPC by FA at equivalent volume yields a material cost reduction of approximately INR 80–120 per cubic metre of concrete, providing a modest but meaningful economic incentive that complements the environmental benefit. Higher replacement levels would increase both CO_2 savings and cost reduction but may require admixture supplementation, partially offsetting the cost advantage.

5. Conclusions

The following conclusions are drawn from this systematic experimental investigation into the effect of fly ash replacement on M25 grade concrete:

(i) Fly ash at 10% cement replacement by mass yields the optimum combination of mechanical performance and durability, achieving 28-day compressive strength of 25.0 MPa (13.1% above control), 90-day compressive strength of 33.1 MPa (19.9% above control), water absorption of 3.4% (24.4% below control), and RCPT charge of 890 Coulombs (32.6% below control).

(ii) FA replacement levels up to 10% improve both early (28-day) and long-term (90-day) compressive strength without any chemical admixture addition, due to the combined filler effect and progressive pozzolanic activity of Class F FA under ambient curing temperature.

(iii) Replacement levels exceeding 15% produce measurable strength reduction at 28 days but maintain acceptable long-term strength at 90 days, suggesting viability in applications where 90-day design strength is specified or where polycarboxylate superplasticisers are incorporated to improve paste rheology at higher FA dosages.

(iv) SEM microstructural analysis confirms that FA incorporation at 10% produces a denser ITZ with reduced $Ca(OH)_2$ crystallinity and more homogeneous C-S-H morphology relative to the control, providing the microstructural basis for the observed mechanical and durability improvements.

(v) The 10% FA mix achieves approximately 9% reduction in embodied CO_2 and modest material cost savings relative to the OPC control, confirming its viability as a sustainable alternative for general structural concrete in Indian construction applications.

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