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Comparative Experimental Study on Ordinary Portland Cement and Portland Pozzolana Cement in M35 Concrete and Performance Evaluation of Fly Ash-Based Cement Bricks

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ABSTRACT

The construction sector's rapid growth has significantly increased the demand for sustainable and high-performance building materials. Cement, a primary construction binder, contributes approximately 5–8% of global CO_2 emissions. To address this environmental challenge, this study investigates the mechanical performance and environmental viability of Ordinary Portland Cement (OPC) and Portland Pozzolana Cement (PPC), alongside the fabrication and testing of fly ash-based cement bricks. OPC and PPC concretes were cast with M35 design mix, and their compressive strengths were evaluated after 3, 7, and 28 days of curing. The results showed that OPC exhibited superior early-age strength, achieving a maximum compressive strength of 43.02 N/mm² at 28 days, whereas PPC attained a peak value of 39.02 N/mm², demonstrating competitive long-term performance. With better workability (slump value: 98 mm) and compaction factor (0.98). Additionally, three types of fly ash bricks were cast with increasing fly ash content (20%, 35%, and 50%) by weight, maintaining a fixed cement ratio. These bricks were tested for compressive strength, water absorption, soundness, efflorescence, and structural integrity. The best-performing mix (35% fly ash) achieved a compressive strength of 7.2 N/mm² and water absorption below 12%, meeting IS:3495 standards for non-load-bearing applications. The results confirm that PPC is a more sustainable alternative to OPC in long-term structural applications, and fly ash bricks offer an eco-friendly, cost-effective substitute for traditional clay bricks, supporting the circular use of industrial by-products in civil infrastructure.

Keywords: Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), fly ash bricks, compressive strength, water absorption, sustainable construction materials

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1. INTRODUCTION

1.1 General Overview

Concrete remains the most extensively used construction material globally, forming the backbone of modern infrastructure development. In India alone, the annual consumption of concrete exceeds 370 million cubic meters, with projections indicating a yearly increase of 30 million cubic meters to meet the demands of rapid urbanization and infrastructure expansion. However, the conventional cement and concrete industry is currently challenged by the depletion of high-quality natural raw materials and the environmental impact of cement manufacturing, which contributes significantly to global CO_2 emissions.

Concurrently, various industrial sectors are generating large volumes of waste by-products, many of which have demonstrated potential for reuse as supplementary cementitious materials. Among these, **fly ash**, a finely divided residue resulting from the combustion of pulverized coal in thermal power plants, has emerged as a widely adopted mineral admixture. Fly ash predominantly comprises silica (SiO_2), alumina (Al_2O_3), calcium oxide (CaO), and iron oxides (Fe_2O_3), which contribute to its pozzolanic reactivity with typical concentrations of silica and alumina ranging between 75% and 95%. Depending on the combustion process, the mineralogy of fly ash may include crystalline and amorphous phases such as quartz, mullite, hematite, magnetite, and fused silicates.

Cement, particularly **Ordinary Portland Cement (OPC)**, plays a pivotal role as a binding material in the production of concrete and mortar. Known for its rapid setting and early strength development, OPC is extensively used in residential, commercial, and infrastructural construction. However, **Portland Pozzolana Cement (PPC)**, which incorporates pozzolanic materials like fly ash, is increasingly favoured for its long-term durability, reduced permeability, and lower environmental impact.

As the industry evolves towards sustainable construction practices, evaluating alternative cement types and integrating industrial by-products into cement-based materials becomes essential. The selection of appropriate cementitious systems is critical to ensuring structural performance, durability, cost-efficiency, and environmental stewardship in modern construction.

1.2 Objectives of the Study

This research is undertaken with the following key objectives:

1. **Comparative Evaluation of Cement Types**
   To conduct a comparative analysis of the physical and chemical characteristics of OPC and PPC in compliance with Indian Standard (IS) specifications.
2. **Strength Development Assessment**
   To assess the development of compressive strength in concrete mixes prepared with OPC and PPC at three distinct curing intervals: 3 days, 7 days, and 28 days.
3. **Workability and Durability Analysis**
   To examine the workability, setting time, and durability characteristics (including water absorption and resistance to chemical attacks) of both cement types under standardized environmental and mixing conditions.
4. **Environmental Impact Comparison**
   To evaluate the carbon footprint and sustainability implications of OPC versus PPC production and use in construction.

5. **Performance in Aggressive Environments**
   To explore the long-term behaviour of OPC and PPC-based concrete when exposed to chemically aggressive or moisture-laden environments.
6. **Construction Suitability Recommendations**
   To provide practical recommendations for the appropriate selection and application of OPC and PPC in various construction scenarios, based on experimental findings.

2. MATERIALS AND METHODOLOGY

This chapter outlines the key materials employed and the experimental approach adopted to investigate the comparative behaviour of Ordinary Portland Cement (OPC) and Portland Pozzolana Cement (PPC), as well as the structural performance of fly ash-based cement bricks. All procedures were performed in accordance with relevant Indian Standard (IS) codes to ensure consistency, reliability, and adherence to civil engineering best practices.

2.1.1 Cement

Two types of commercially available cement were selected for the experimental study:

- **Ordinary Portland Cement (OPC – 43 Grade):** Known for its high early strength and rapid setting properties, OPC was chosen to represent conventional cement used in construction.
- **Portland Pozzolana Cement (PPC):** This type incorporates pozzolanic materials such as fly ash, offering enhanced long-term durability and sustainability advantages.

Both cements were tested for their standard properties as per **IS 4031**, including consistency, setting times, fineness, and compressive strength.

2.1.2 Fly Ash

Fly ash, an industrial by-product from thermal power plants, was used as a supplementary cementitious material in both PPC and fly ash bricks. Its pozzolanic nature contributes to improved durability and strength gain in concrete. The material conformed to the requirements of **IS 3812 (Part 1):2003**.

2.1.3 Aggregates

- **Fine Aggregate:** Clean, well-graded river sand confirming to **Zone II** classification as per **IS 383:2016** was used. It was free from silt, clay, and organic impurities.
- **Coarse Aggregate:** Angular crushed granite of 20 mm maximum size, meeting the specifications in **IS 383**, was used as the coarse aggregate. The material was clean, hard, and suitably graded.

2.1.4 Water

Potable water, free from harmful salts and suspended solids, was used throughout the study for mixing and curing. It satisfied the quality standards outlined in **IS 456:2000**.

ISSN: 2583-6129
DOI: 10.55041/ISJEM04558

2.1.5 Chemical Admixture

To improve the workability of concrete without increasing the water content, a high-performance water-reducing admixture—**Conplast SP430ES2**—was used. This admixture belongs to the sulphonated naphthalene formaldehyde (SNF) group and complies with **IS 9103:1999**.

2.2 Concrete Mix Design

A concrete mix of **M35 grade** was designed using the guidelines of **IS 10262:2019**. A consistent water-cement ratio was maintained across all mixes to enable direct comparison between OPC and PPC-based concretes.

Table 2.1: Mix Proportions for M35 Concrete

Material	**Quantity (kg/m³)**
Cement	420
Fine Aggregate	652
Coarse Aggregate	816
Water	180
Admixture (SP430)	2.35 (0.56% of cement)

Note:A consistent mix design was maintained across both cement types to ensure that variations in performance could be attributed solely to cement composition.

2.3 Fabrication of Fly Ash Bricks

Fly ash bricks were prepared in three different compositions by varying the fly ash content while maintaining a constant cement ratio. The goal was to assess the optimal mix for structural performance and sustainability.

Table 2.2: Fly Ash Brick Mix Ratios

Mix ID	**Cement**	**Sand**	**Fly Ash**
Mix A	1.6	5.2	1.2
Mix B	1.6	4.4	2.0
Mix C	1.6	3.6	2.8

Bricks were cast using metallic Moulds, compacted manually, and cured under moist conditions for 28 days before testing. The curing environment was carefully controlled to simulate field conditions.

ISSN: 2583-6129
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2.4 Experimental Testing Program

2.4.1 Cement Testing

Standard laboratory tests were conducted to assess the quality of OPC and PPC:

- **Fineness**: Determined by air permeability method (IS 4031 Part 2).
- **Standard Consistency**: Measured using Vicat apparatus (IS 4031 Part 4).
- **Initial and Final Setting Times**: Evaluated as per IS 4031 Part 5.
- **Compressive Strength**: Cement mortar cubes were tested at 3, 7, and 28 days (IS 4031 Part 6).

2.4.2 Workability of Fresh Concrete

Two workability tests were performed:

- **Slump Test**: Assessed concrete flow using slump cone (IS 1199:1959).
- **Compaction Factor Test**: Used for mixes with medium to low workability.

2.4.3 Compressive Strength of Concrete

Concrete cubes measuring 150 mm × 150 mm × 150 mm were cast and tested at curing intervals of 3, 7, and 28 days. The compressive strength was determined using a calibrated compression testing machine in line with **IS 516:1959**.

2.4.4 Testing of Fly Ash Bricks

The fly ash bricks were subjected to the following tests:

- **Compressive Strength**: Tested on 28-day cured bricks following **IS 3495 (Part 1):1992**.
- **Water Absorption**: Measured to evaluate porosity and durability (IS 3495 Part 2).
- **Efflorescence Test**: Assessed for salt deposits on drying (IS 3495 Part 3).
- **Soundness and Structural Integrity**: Verified by striking the bricks and inspecting for cracks or delamination.

2.5 Instruments and Apparatus

The following laboratory apparatus were used during the experimental program:

- Vicat apparatus (consistency & setting time)
- Blaine's air permeability tester (fineness)
- Slump cone and compaction factor setup
- Concrete cube moulds and CTM
- Fly ash brick moulds
- Water bath and curing tanks

3. RESULTS AND DISCUSSION

This chapter presents a comprehensive analysis of the experimental results obtained from the investigation of Ordinary Portland Cement (OPC) and Portland Pozzolana Cement (PPC) concretes, as well as fly ash-based cement bricks. The discussion emphasizes comparative performance in terms of workability, compressive strength, water absorption, soundness, efflorescence, and material structure. The results were interpreted using both tabular and graphical methods in accordance with Indian Standard specifications.

3.1 Workability Characteristics

Workability was assessed using slump and compaction factor tests on fresh concrete mixes prepared with OPC and PPC. Two samples of each were tested to account for variability.

Table 3.1: Workability Test Results

Cement Type	Sample	Slump (mm)	Compaction Factor
OPC	1	85	0.90
OPC	2	92	0.93
PPC	1	94	0.98
PPC	2	98	0.94

Discussion:
PPC-based concrete demonstrated superior workability, as indicated by higher slump values and compaction factors, owing to the lubricating effect of the spherical fly ash particles, which reduce inter-particle friction and promote cohesive flow without compromising stability.

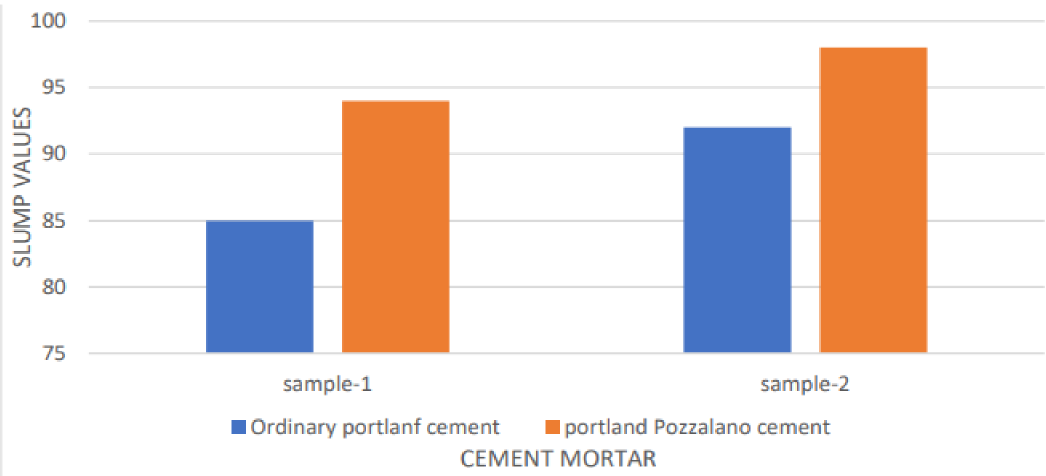

Figure 1: Comparative Study on the Workability of Ordinary Portland Cement and Portland Pozzolana Cement Mortars Using Slump Tests

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3.2 Compressive Strength of Concrete

Concrete cubes were tested at three different curing intervals—3, 7, and 28 days. The results for OPC and PPC mixes are tabulated below.

Figure 2: A Comparative Study on the Mechanical Properties of OPC and PPC-Based Cement Mortars

Table 3.2: 3-Day Compressive Strength

Sample	OPC (N/mm²)	PPC (N/mm²)
1	14.98	15.90
2	16.23	16.08
3	17.20	17.40

Table 3.3: 7-Day Compressive Strength

Sample	OPC (N/mm²)	PPC (N/mm²)
1	25.20	25.00
2	26.56	26.10
3	27.96	26.80

Table 3.4: 28-Day Compressive Strength

Sample	OPC (N/mm²)	PPC (N/mm²)
1	40.94	37.28
2	42.10	38.66
3	43.02	39.02

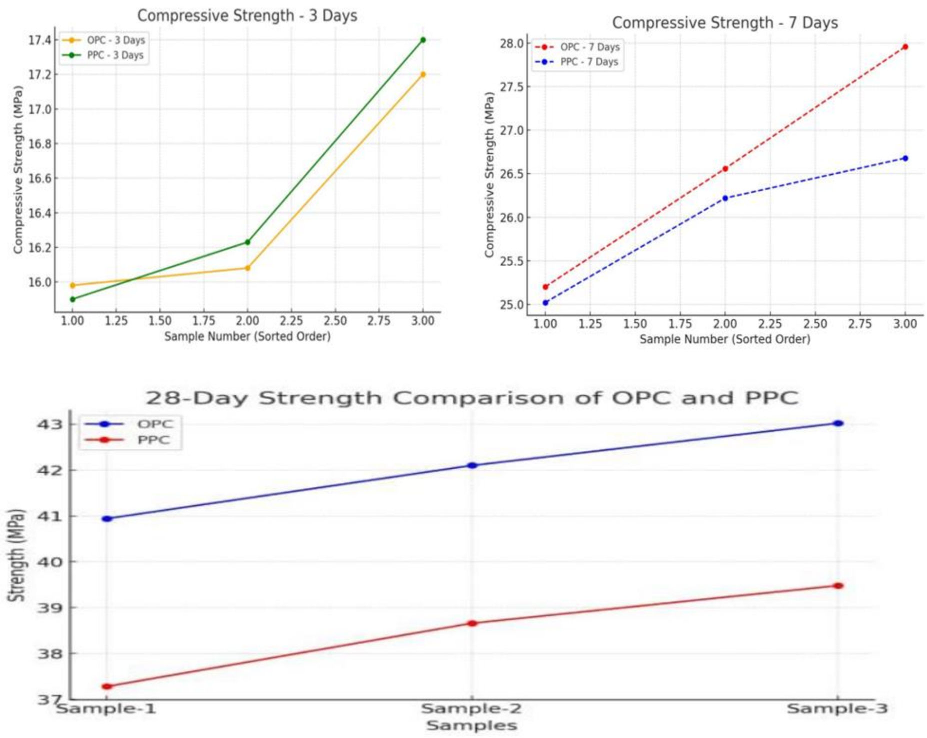

Figure 3: Compressive Strength Development of OPC and PPC Concrete at 3, 7, and 28 Days

Discussion:
OPC-based concrete demonstrated marginally higher early and ultimate strength compared to PPC-based mixes. However, the strength gap narrowed significantly at 28 days, highlighting the latent pozzolanic activity of fly ash in PPC. These results affirm PPC's viability in long-term performance, especially in structures where sustainability and durability are critical.

3.3 Performance of Fly Ash Cement Bricks

3.3.1 Compressive Strength of Bricks

Bricks made with three varying mix proportions were tested for compressive strength at 7 and 28 days.

Table 3.5: Fly Ash Brick Strength

Mix Ratio (C:S:FA)	7-Day Strength (MPa)	28-Day Strength (MPa)
1:3.25:0.75	5.3	7.8
1:2.75:1.25	4.9	7.3
1:2.25:1.75	4.4	6.6

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Discussion:
The first mix (1:3.25:0.75), having lower fly ash and higher sand content, exhibited the highest strength. Increasing fly ash content beyond optimal levels led to reduced strength due to the dilution of cementitious material, although the bricks remained structurally sound and suitable for use in non-load bearing applications.

3.3.2 Water Absorption Test

Water absorption was measured after 24-hour submersion, indicating porosity and resistance to moisture ingress.

Table 3.6: Water Absorption Results

Mix No.	Initial Weight (g)	Soaked Weight (g)	Absorption (%)
1	3181	3583	12.68
2	3055	3470	13.58
3	3062	3398	10.97

Discussion:
All mixes exhibited water absorption within the acceptable range of 10–15% as per IS guidelines. Mix 3 had the lowest absorption, indicating enhanced compaction and reduced voids due to the optimal fly ash content. Lower water absorption implies better long-term durability.

3.3.3 Soundness Test

Bricks were assessed for soundness by striking two bricks together and observing the acoustic response.

Observation:
Bricks from mixes with balanced fly ash content produced a sharp, metallic ringing sound, indicating good integrity and compaction. Bricks with higher fly ash content gave a dull sound, suggesting reduced density but no visible structural damage.

3.3.4 Efflorescence Test

Bricks were partially submerged in water and dried to identify salt deposit formation.

Results:

- Some bricks showed **moderate efflorescence**, with white salt deposits covering 10–50% of the surface.
- Other samples, particularly from Mix 1, displayed **no visible efflorescence**, indicating good chemical stability and low soluble salt content.

3.3.5 Structural Integrity of Bricks

Broken bricks were visually inspected for internal flaws, pores, and material distribution.

ISSN: 2583-6129
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Findings:

- The internal matrix appeared homogeneous across all mixes.
- No segregation or unreacted cement/fly ash pockets were observed.
- Very few micro-pores were present, confirming effective mixing and compaction during casting.

3.4 Effect of Fly Ash on Brick Performance

The inclusion of fly ash in brick manufacturing offers several technical and environmental benefits:

1. **Enhanced Strength**: Pozzolanic reaction contributes to improved long-term strength.
2. **Lightweight**: Reduced density lowers transportation and structural loads.
3. **Improved Durability**: Better resistance to weathering and chemical exposure.
4. **Sustainability**: Utilizes industrial waste, reducing dependence on natural clay.
5. **Cost-Efficiency**: Lower production costs due to reduced energy requirements.
6. **Thermal Performance**: Offers better insulation, reducing energy consumption in buildings.

4. Conclusion and Recommendations

Based on the systematic evaluation of Ordinary Portland Cement (OPC) and Portland Pozzolana Cement (PPC), and the investigation into fly ash-based bricks, the following conclusions are drawn:

1. **Chemical and Physical Comparison**
   OPC demonstrated higher lime content and faster hydration, leading to quicker setting times and greater early strength. PPC, containing pozzolanic fly ash, showed superior fineness and long-term micro structural stability. Both cement types complied with Indian Standard specifications.
2. **Compressive Strength Trends**
   At early curing intervals (3 and 7 days), OPC exhibited approximately 53–55% higher compressive strength compared to PPC. However, by 28 days, PPC nearly matched OPC's strength, confirming its effectiveness for applications that allow longer curing durations.
3. **Workability and Durability Performance**
   PPC mixes displayed better workability (higher slump and compaction factor) due to the spherical particle shape of fly ash. Durability tests, including water absorption and efflorescence evaluations, showed that PPC and fly ash bricks have improved resistance to environmental degradation.
4. **Environmental Sustainability**
   PPC manufacturing significantly reduces CO_2 emissions by partially substituting clinker with fly ash. Fly ash bricks further enhance sustainability by utilizing industrial waste, reducing clay consumption, and minimizing landfill pressure.
5. **Aggressive Environment Suitability**
   PPC concrete and fly ash bricks performed better under aggressive exposure conditions such as sulphate and moisture attack. Their lower permeability and enhanced chemical resistance make them suitable for coastal, underground, or chemically harsh applications.
6. **Practical Construction Applications**
   OPC is ideal for high-rise buildings, precast structures, and other load-bearing applications where early strength is critical. PPC is more suitable for residential structures, masonry work, and long-life components where environmental performance and cost-effectiveness are priorities. Fly ash bricks

exceeded strength benchmarks and were found to be lightweight, durable, and environmentally favourable.

4.2 Recommendations

In light of the experimental data and performance analysis, the following recommendations are proposed:

1. **Material Use Based on Structural Needs**
   - Use **OPC** in applications requiring rapid strength development, such as high-rise structural elements, roads, and precast components.
   - Use **PPC** in masonry, plastering, and durability-focused applications like water tanks, basements, and infrastructure exposed to chemicals or moisture.
2. **Promotion of Fly Ash Bricks**
   - Encourage use in government and private construction through incentives and policy mandates.
   - Adopt fly ash bricks in low-cost housing schemes, green building projects, and energy-efficient infrastructure.
3. **Optimization of Material Mix Ratios**
   - Conduct further studies to optimize cement–sand–fly ash ratios for improved compressive strength, water resistance, and thermal performance.
   - Evaluate the use of higher-grade cements to enhance the load-bearing capability of bricks.
4. **Incorporation of Admixtures and Fibrous Reinforcement**
   - Experiment with natural and synthetic fibres (e.g., coconut fibre, glass fibre) to enhance tensile strength and crack resistance.
   - Evaluate chemical admixtures for faster setting and improved bonding, especially in PPC-based systems.
5. **Durability Testing Under Real-World Conditions**
   - Perform extended durability tests such as freeze-thaw resistance, chloride permeability, and carbonation depth to validate long-term performance.
   - Implement pilot field trials to monitor real-life behaviour under varying climatic and usage conditions.
6. **Aesthetic and Structural Refinements in Bricks**
   - Improve fly ash bricks using pigments, textures, and surface finishes for better architectural appeal.
   - Standardize size and shape for better interlocking and mortar bonding.
7. **Policy Alignment and Sustainability Integration**
   - Incorporate PPC and fly ash products into sustainable building certification programs.
   - Provide industry training and capacity building to enhance the adoption of eco-friendly alternatives.

Final Remark:
The findings of this study reinforce the value of PPC and fly ash bricks as sustainable, durable, and cost-effective alternatives in construction. With proper application, optimization, and policy support, these materials can contribute significantly to the future of environmentally responsible and high-performance infrastructure development.

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