**Enhancing Concrete Performance Using Supplementary Cementitious Materials and Air-Cooled Blast Furnace Slag**

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**Abstract**
This research investigates the enhancement of concrete performance by partially replacing cement with fly ash and metakaolin, and coarse aggregates with air-cooled blast furnace slag (ACBFS). The study evaluates the compressive and flexural strengths of M30 grade concrete in binary, ternary, and quaternary mixes, aiming to promote sustainability and resource conservation. Experimental results indicate that an optimal mix with 10% fly ash, 15% metakaolin, and 60% ACBFS achieves superior mechanical properties, with a compressive strength of 39.59 MPa and flexural strength of 6.0 MPa at 28 days, alongside a 7.3% cost reduction compared to the reference mix. These findings underscore the potential of supplementary cementitious materials (SCMs) and ACBFS in producing sustainable, high-performance concrete.

**Keywords**: Sustainable concrete, fly ash, metakaolin, ACBFS, compressive strength, flexural strength, supplementary cementitious materials

**1. Introduction**

Concrete is the most widely used construction material globally due to its high compressive strength, durability, and versatility. However, traditional concrete production relies heavily on cement and natural aggregates, contributing to significant environmental impacts, including CO₂ emissions and depletion of natural resources. To address these challenges, supplementary cementitious materials (SCMs) such as fly ash and metakaolin, along with industrial by-products like air-cooled blast furnace slag (ACBFS), have been increasingly utilized to enhance concrete performance while promoting sustainability.

Fly ash, a by-product of coal combustion, improves workability and long-term strength through pozzolanic reactions but often reduces early-age strength. Metakaolin, a highly reactive aluminosilicate, enhances strength and durability by forming additional calcium silicate hydrate (C-S-H) gel. ACBFS, a by-product of steel production, serves as a viable substitute for coarse aggregates, offering comparable mechanical properties while reducing the demand for natural resources.

This study aims to investigate the combined effects of fly ash, metakaolin, and ACBFS on the compressive and flexural strengths of M30 grade concrete. The research explores binary (fly ash), ternary (fly ash and metakaolin), and quaternary (fly ash, metakaolin, and ACBFS) mixes to identify an optimal mix design that balances performance, cost, and sustainability.

**1.1 Objectives**

* Evaluate the impact of partial cement replacement with fly ash on concrete strength.
* Assess the effect of replacing coarse aggregates with ACBFS in fly ash-based concrete.
* Investigate the influence of metakaolin as a partial replacement for fly ash in binary and ternary mixes.
* Compare the mechanical properties and cost-effectiveness of various mix designs.

**2. Literature Review**

The use of SCMs and industrial by-products in concrete has been extensively studied to improve mechanical properties and sustainability. Davis (1937) demonstrated that fly ash, due to its pozzolanic properties, can replace up to 30% of cement, enhancing long-term strength and reducing water demand. Haque et al. (1984) noted that high-volume fly ash concrete (HVFC) improves workability but may experience slump loss, necessitating careful mix design.

Metakaolin has gained attention since the 1960s for its ability to enhance concrete strength and durability. Its fine particle size and high reactivity promote the formation of secondary C-S-H gel, reducing porosity and improving resistance to chemical attacks (Siddique, 2003). ACBFS, characterized by its angular and porous structure, has been shown to yield comparable compressive strength to natural aggregates, making it a sustainable alternative (Berry et al., 1986).

Previous studies primarily focused on binary mixes, with limited research on ternary and quaternary combinations. The combined effect of fly ash, metakaolin, and ACBFS on both compressive and flexural strengths remains underexplored, justifying the need for this study.

**3. Materials and Methods**

**3.1 Materials**

The materials used in this study were tested per Indian Standards (IS) and included:

* **Cement**: Ordinary Portland Cement (OPC) conforming to IS 8112.
* **Fly Ash**: Class F fly ash with low carbon content, sourced locally.
* **Metakaolin**: High-reactivity aluminosilicate with fine particle distribution.
* **ACBFS**: Angular, porous coarse aggregate substitute with 20% lower density than natural aggregates.
* **Aggregates**: Natural sand and coarse aggregates conforming to IS 383.
* **Superplasticizer**: Polycarboxylate-based admixture to enhance workability.
* **Water**: Potable water meeting IS 456 requirements.

Physical properties of the materials were determined, with key parameters such as specific gravity, fineness, and water absorption recorded.

**3.2 Experimental Design**

The reference mix (M0) was designed for M30 grade concrete per IS 10262-2009, with a water-cement ratio optimized for workability and strength. Sixteen additional mixes (M1–M16) were prepared, varying the replacement levels:

* Fly ash: 10%–25% of cement.
* Metakaolin: 5%–15% of cement (replacing fly ash in ternary/quaternary mixes).
* ACBFS: 20%–60% of coarse aggregates.

The mixes were categorized as:

* **Binary**: Cement replaced by fly ash (e.g., M1: 25% fly ash).
* **Ternary**: Cement replaced by fly ash and metakaolin (e.g., M5: 20% fly ash, 5% metakaolin).
* **Quaternary**: Cement replaced by fly ash and metakaolin, coarse aggregates by ACBFS (e.g., M16: 10% fly ash, 15% metakaolin, 60% ACBFS).

**3.3 Specimen Preparation and Testing**

Concrete specimens (cubes for compressive strength, beams for flexural strength) were cast, cured for 7 and 28 days under moist conditions, and tested per IS 516. Compressive strength tests were conducted using a compression testing machine, while flexural strength was measured via a three-point bending test. Mix proportions were adjusted for moisture content and water absorption, ensuring consistency.

**4. Results and Discussion**

**4.1 Compressive Strength**

The compressive strength results for key mixes at 7 and 28 days are summarized in Table 1.

**Table 1: Compressive Strength of Selected Mixes**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Mix** | **Fly Ash (%)** | **Metakaolin (%)** | **ACBFS (%)** | **Compressive Strength (MPa)** |  |
|  |  |  |  | 7 Days | 28 Days |
| M0 | 0 | 0 | 0 | 26.01 | 38.48 |
| M1 | 25 | 0 | 0 | 16.06 | 28.92 |
| M4 | 25 | 0 | 60 | 22.92 | 36.30 |
| M8 | 20 | 5 | 60 | 26.26 | 38.16 |
| M12 | 15 | 10 | 60 | 26.96 | 38.48 |
| M16 | 10 | 15 | 60 | 29.05 | 39.59 |

* **Binary Mixes (M1)**: Replacing 25% of cement with fly ash reduced compressive strength by 25% at 28 days (28.92 MPa vs. 38.48 MPa for M0), attributed to slower pozzolanic reactions.
* **Ternary/Quaternary Mixes**: Adding metakaolin and ACBFS significantly improved strength. Mix M16 (10% fly ash, 15% metakaolin, 60% ACBFS) achieved the highest strength (39.59 MPa at 28 days), surpassing the reference mix by 2.9%. This enhancement is due to metakaolin’s fine particles and pozzolanic reactivity, combined with ACBFS’s contribution to C-S-H gel formation.
* **Effect of ACBFS**: Increasing ACBFS from 0% to 60% in fly ash mixes (M1 to M4) boosted strength by up to 25%, reflecting improved matrix packing and chemical reactions.

**4.2 Flexural Strength**

Flexural strength results followed a similar trend, as shown in Table 2.

**Table 2: Flexural Strength of Selected Mixes**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Mix** | **Fly Ash (%)** | **Metakaolin (%)** | **ACBFS (%)** | **Flexural Strength (MPa)** |  |
|  |  |  |  | 7 Days | 28 Days |
| M0 | 0 | 0 | 0 | 4.05 | 5.90 |
| M1 | 25 | 0 | 0 | 3.30 | 4.90 |
| M4 | 25 | 0 | 60 | 3.60 | 5.30 |
| M8 | 20 | 5 | 60 | 3.56 | 5.39 |
| M12 | 15 | 10 | 60 | 3.96 | 5.76 |
| M16 | 10 | 15 | 60 | 4.30 | 6.00 |

* **Binary Mixes**: Fly ash reduced flexural strength by 17% at 28 days (M1: 4.90 MPa vs. M0: 5.90 MPa).
* **Quaternary Mixes**: Mix M16 exhibited the highest flexural strength (6.0 MPa), comparable to or exceeding the reference mix, due to the synergistic effects of metakaolin and ACBFS.
* **Trend**: Flexural strength increased with higher metakaolin and ACBFS content, mirroring compressive strength trends.

**4.3 Cost Analysis**

A cost comparison between the reference mix (M0) and the optimal quaternary mix (M12) revealed a 7.3% cost reduction for M12 (Table 3). This saving is attributed to reduced cement and aggregate quantities, offset by the lower cost of fly ash and ACBFS.

**Table 3: Cost Analysis (per m³)**

|  |  |  |  |
| --- | --- | --- | --- |
| **Material** | **M0 (Rs)** | **M12 (Rs)** | **Rate (Rs/kg)** |
| Cement | 2887.5 | 2021.2 | 7 |
| Fly Ash | 0 | 69.3 | 1.2 |
| Sand | 381 | 381 | 0.5 |
| Aggregates | 689.4 | 275.56 | 0.6 |
| ACBFS | 0 | 275 | 0.4 |
| Metakaolin | 0 | 462 | 12 |
| Superplasticizer | 102.5 | 102.5 | 38 |
| **Total** | **3868** | **3587** |  |
| **Savings** | - | **7.3%** |  |

**5. Conclusions**

This study demonstrates that the strategic use of fly ash, metakaolin, and ACBFS in concrete enhances mechanical properties and promotes sustainability. Key conclusions include:

1. Partial replacement of cement with 25% fly ash reduces compressive and flexural strengths by 25% and 17%, respectively, at 28 days.
2. Incorporating ACBFS (up to 60%) increases strength by up to 25% in fly ash mixes, due to improved matrix packing and chemical reactions.
3. Metakaolin significantly enhances strength, with the optimal mix (M16: 10% fly ash, 15% metakaolin, 60% ACBFS) achieving 39.59 MPa compressive strength and 6.0 MPa flexural strength at 28 days.
4. The quaternary mix (M12) offers comparable strength to the reference mix with a 7.3% cost reduction, making it economically viable.

These findings highlight the potential of SCMs and ACBFS in producing high-performance, sustainable concrete suitable for infrastructure applications.

**6. Future Scope**

Future research could explore:

* The effect of varying aggregate sizes (e.g., 40 mm) on mix performance.
* Incorporation of additional SCMs (e.g., alccofine, rice husk ash) for high-performance concrete.
* Long-term durability, split tensile strength, and shrinkage properties beyond 28 days.
* Higher ACBFS replacement levels and their impact on mechanical properties.

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