International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 12s,2025
https://theaspd.com/index.php

Durability And Mechanical Synergy Of High-Performance Concrete With Hybrid Pozzolanic Binders Under Aggressive Environments

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Abstract
*This study explores the mechanical and durability characteristics of high-performance concrete (HPC) incorporating a ternary blend of **Fly Ash (FA)**, **Ground Granulated Blast Furnace Slag (GGBS)**, and **Metakaolin (MK)** as supplementary cementitious materials (SCMs). The objective is to assess the **synergistic effects** of these pozzolanic binders in enhancing the long-term performance of HPC exposed to aggressive environmental conditions such as **acidic, sulfate-rich, and chloride-laden environments**. The results demonstrate that the ternary blended concrete exhibits superior **compressive strength, lower permeability, and enhanced resistance to chemical attack**, validating its application in durability-critical infrastructure.*
Keywords: *Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), and Metakaolin (MK) compressive strength, lower permeability, and enhanced resistance to chemical attack,*

1. INTRODUCTION

Concrete structures are increasingly exposed to harsh environmental conditions, necessitating improvements in durability and performance. High-performance concrete (HPC), when engineered with **SCMs**, offers improved strength and reduced permeability, making it a viable choice for durable construction.
Individually, **Fly Ash**, **GGBS**, and **Metakaolin** have shown considerable promise in improving concrete characteristics. However, **limited studies exist on their synergistic behavior** when used together in ternary combinations. This research aims to evaluate the **combined effects** of these materials in enhancing HPC performance in aggressive environments such as sulfate attack, acid exposure, and chloride penetration.

2. MATERIALS

2.1 Cement and Supplementary Cementitious Materials (SCMs)

- **Ordinary Portland Cement (OPC) 53 Grade**
- **Fly Ash (FA)** – Class F, sourced from local thermal plant
- **Ground Granulated Blast Furnace Slag (GGBS)** – Grade 120
- **Metakaolin (MK)** – High-reactivity, purity > 95%

Figure 2.1.a – *Raw SCMs: (left to right) Fly Ash, GGBS, and Metakaolin powders)*

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2.2 Aggregates and Water

- **Fine Aggregate**: Natural river sand (Zone II), fineness modulus 2.6
- **Coarse Aggregate**: Crushed granite (10–20 mm), water absorption < 2%

Figure 2.1.b – *Aggregate gradation setup in the concrete materials lab*

Water: Potable, conforming to IS 2386 standards

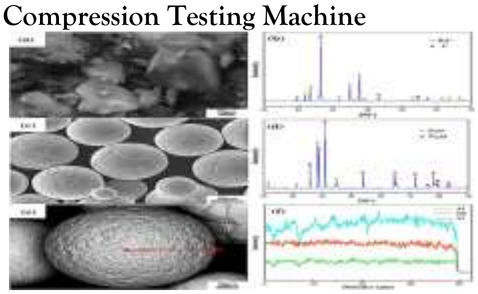
- **Superplasticizer**: Polycarboxylate-based, 1% by binder weight

2.3 Equipment

- **Laboratory Pan Mixer** – for uniform mixing (photo below)
- **Compression Testing Machine** – up to 600 kN capacity for 150 mm cubes
- **RCPT Setup** – for evaluating chloride permeability
- **Environmental Chambers** – pH-controlled baths for acid/sulfate exposure
- **SEM/XRD** – for microstructure and phase analysis

2.3.a Compression Testing Machine

2.3.b RCPT Setup



2.3c SEM/XRD

2.3.d Laboratory Pan Mixer

3. METHODOLOGY

3.1 Mix Design and Preparation

- Designed four concrete mixes (M0–M3, W/B = 0.30) targeting **60 MPa at 28 days**.
- Mixing steps:
    1. Dry blend cement and SCMs (FA, GGBS, MK).
    2. Add fine and coarse aggregate, dry-mix 2 min.
    3. Introduce water with superplasticizer, mix 3 min.
    4. Rest 1 min; final mix 2 min.

Figure 3.1 – *Laboratory mixer during fresh concrete preparation*

3.2 Specimen Casting and Curing

- Cast specimens in 150×150×150 mm steel molds for compression; cylindrical molds for RCPT.
- Demold after 24 h and cure in:
    - Moist chamber (95 ± 5 % RH, 23 ± 2 °C).
    - Acid (5 % H_2SO_4) and sulfate (5 % Na_2SO_4) baths.

Figure 3.2 – *Specimens immersed in sulfate and acid exposure baths* (insert your photo)

3.3 Test Methods

3.3.1 Compressive Strength (ASTM C39)

- Tested at 7, 28, 56, and 90 days.
- Load applied at 0.3 MPa/s until failure.
- Average of three specimens per age.

Figure 3.3 – *Compression test for 150 mm cubes*

3.3.2 Chloride Permeability (RCPT, ASTM C1202)

- Vacuum saturate 50 mm thick specimens.
- Apply 60 V DC, record coulombs passed in 6 h.

Figure 3.4 – *RCPT apparatus during testing* (insert your photo)

3.3.3 Durability Tests

- **Acid Resistance**: 28-day mass loss after immersion in 5 % H_2SO_4.
- **Sulfate Resistance**: Linear expansion measured at 30-day intervals for 90 days.
- **Water Absorption / Sorptivity**: ASTM C1585—mass gain and capillary rise measured.

3.3.4 Microstructure Analysis

- **SEM**: Use fractured pieces of 28-day samples (gold-coated).
- **XRD**: Powder analysis (Cu Kα, 10°–70° 2θ) for C–S–H and portlandite content.

Figure 3.5 – *SEM image of sample showing dense C–S–H matrix* (insert actual image)

3.4 Test Procedure Flowchart

1. SCMs characterization (chemical & physical properties).
2. Mix design preparation (M0–M3).
3. Casting and curing as per schedule.
4. Compressive strength & RCPT at specified ages.
5. Durability tests in acid/sulfate media.
6. Microstructural evaluation at 28 days.
7. Data analysis and comparison across mixes.

Table1: Mix Composition

Mix	OPC (%)	FA (%)	GGBS (%)	MK (%)
M0	100	0	0	0
M1	70	20	0	10

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Mix	OPC (%)	FA (%)	GGBS (%)	MK (%)
M2	70	0	20	10
M3	60	15	15	10

4. RESULTS AND DISCUSSION

This section evaluates the performance of four concrete mixes (M0–M3) under mechanical and durability tests. M3 incorporates a hybrid ternary blend of 15% Fly Ash, 15% GGBS, and 10% Metakaolin.

Table2: Compressive Strength

Mix	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)	90 Days (MPa)
M0	42.3	61.5	63.0	63.5
M1	40.2	62.8	66.1	68.0
M2	41.0	63.5	68.5	71.3
M3	44.5	66.7	72.4	75.1

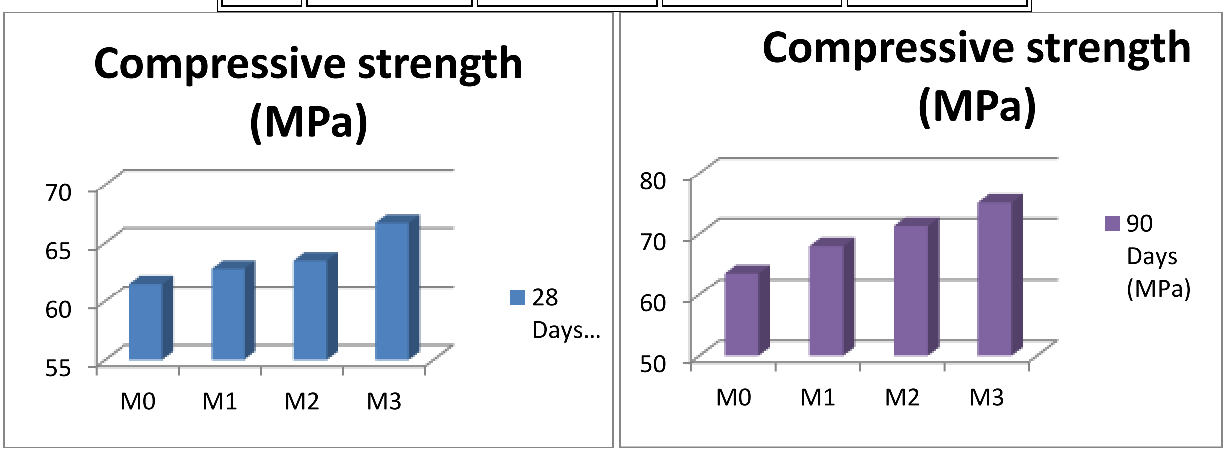

Fig4.1 Compressive strength of Concrete

4.1. Interpretation:

- The control mix (M0) achieved 61.5 MPa at 28 days, but its strength gain beyond this was marginal.
- Mixes M1 and M2, with binary blends of FA/MK and GGBS/MK respectively, showed better long-term strength development.
- **M3 performed best**, reaching **75.1 MPa at 90 days**, due to the **synergistic pozzolanic reaction** among FA, GGBS, and MK which densifies the microstructure and promotes secondary C–S–H formation.

Table3: Chloride Penetration (RCPT Test)

Mix	Charge Passed (Coulombs)	Chloride Permeability Rating
M0	3050	Moderate
M1	2150	Low
M2	1650	Low
M3	950	Very Low

4.2. Interpretation:

- The RCPT results show a significant **68.8% reduction in charge passed for M3** compared to M0.

- M3's very low permeability is attributed to the **pore refinement** and reduced connectivity in the hydrated matrix.
- The inclusion of metakaolin and GGBS decreases calcium hydroxide and unreacted phases, further improving resistance to chloride ingress.

Table:4 Acid Resistance (5% H_2SO_4 Exposure for 28 Days)

Mix	Mass Loss (%)
M0	8.1%
M1	5.3%
M2	4.9%
M3	3.4%

4.3. Interpretation:

- Control mix M0 suffered **8.1% mass loss**, indicating significant deterioration.
- The hybrid blend M3 showed the **lowest mass loss (3.4%)**, due to its refined matrix and low calcium hydroxide content.
- Pozzolanic reactions reduce the availability of lime (which reacts with acids), improving acid resistance.

Table: Sulfate Resistance (5% Na_2SO_4 for 90 Days)

Mix	Linear Expansion (%)
M0	0.085
M1	0.051
M2	0.048
M3	0.030

4.4. Interpretation:

- Sulfate attack often causes expansion due to ettringite formation.
- **M3 exhibited the lowest expansion**, demonstrating its suitability in sulfate-rich environments.
- The reduced permeability and stabilized C–S–H gel in ternary blended concrete minimize internal stress development.

4.5 Water Absorption and Sorptivity

Mix	Water Absorption (%)	Sorptivity (mm/min^0.5)
M0	4.2	0.134
M1	3.1	0.095
M2	2.8	0.088
M3	2.1	0.066

Interpretation:

- Lower sorptivity and water absorption in M3 indicate **improved pore structure** and water-tightness.
- These parameters directly correlate with **service life prediction** in structures exposed to wetting/drying or freeze–thaw cycles.

4.6 Microstructural Observations (SEM & XRD)

- **SEM analysis** of M3 shows a **densely packed matrix** with reduced voids and crystalline phases, confirming enhanced hydration.

- **XRD patterns** revealed a **decrease in portlandite peaks** and **increase in amorphous C–S–H**, indicating active pozzolanic reaction.
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Conclusion from Microstructure:
The ternary system forms a **low-porosity, high-C–S–H content matrix**, which supports the superior mechanical and durability behavior observed.

4. CONCLUSION

- A ternary blend of **15% FA + 15% GGBS + 10% MK** significantly improved both strength and durability.
- M3 exhibited **highest compressive strength (75.1 MPa at 90 days)** and **lowest chloride permeability (950 Coulombs)**.
- Durability under acid and sulfate attack was considerably enhanced due to the **synergistic action of SCMs**, especially Metakaolin's filler and reactivity effects.
- This ternary blended HPC is highly suitable for **coastal, industrial, and chemically aggressive environments**.

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