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Development And Performance Evaluation Of Fly Ash–Polymer Composites For Sustainable Applications

Dr. Rahul D. Shelke 1, Kulkarni Naineesh Arun 2

Principal, Associate Professor, EESGOI, Chhatrapati Sambhajinagar 1,

ME Student, Department of Mechanical Engineering, EESGOI, Chhatrapati Sambhajinagar 2

Abstract

The generation of large volumes of fly ash from coal-fired thermal power plants poses serious environmental, land-use, and waste-management challenges. This research investigates the development of sustainable fly ash–polymer composites using cold-setting resin as a binding matrix, with the objective of transforming an industrial waste into a value-added construction material. Composite samples were prepared with three fly ash contents (75%, 80%, and 85 wt.%) using a powder-metallurgy-based compaction approach. Selected samples underwent hydrothermal curing at 110–180°C to study hydration-induced structural changes. A comprehensive characterization was performed, including hardness, compressive strength, density, water absorption, thermal conductivity, wear behaviour, and microstructural analysis using SEM, XRD, and FTIR.

The results reveal that increasing fly ash content significantly enhances hardness (32.93–47.37 HV) and compressive strength (6.50–11.28 MPa). Hydrothermal curing promoted the formation of calcium silicate hydrate (CSH) and calcium aluminate silicate hydrate (CASH) phases, improving hardness and reducing wear. Thermal conductivity declined with higher fly ash content, exhibiting excellent insulation potential (minimum 0.055 W/m·K). Microstructural studies confirmed densification, improved bonding, and hydration gel formation. The findings demonstrate that high-volume fly ash polymer composites are strong, lightweight, thermally insulating, and suitable for green construction applications.

Keywords: Fly ash; Polymer composites; Cold-setting resin; Hydrothermal curing; Compressive strength; Microhardness; Wear behaviour; Thermal conductivity; SEM; XRD; FTIR; Sustainable building materials.

1. Introduction

Coal-based thermal power plants remain a major source of energy in developing countries such as India, producing millions of tonnes of fly ash annually. In the absence of efficient utilization mechanisms, fly ash is often disposed of in landfills or ash ponds, creating severe environmental challenges including air pollution, groundwater contamination, land degradation, and health hazards. At the same time, the construction industry faces pressure to reduce its environmental footprint, conserve natural resources, and adopt sustainable materials.

Fly ash, a siliceous and aluminous by-product, exhibits favourable pozzolanic activity, spherical morphology, low density, and thermal insulation characteristics. These properties make it a strong candidate for the development of building materials such as bricks, blocks, tiles, and composite units. Traditional applications of fly ash include blended cements, road embankments, soil stabilisation, and geopolymers.

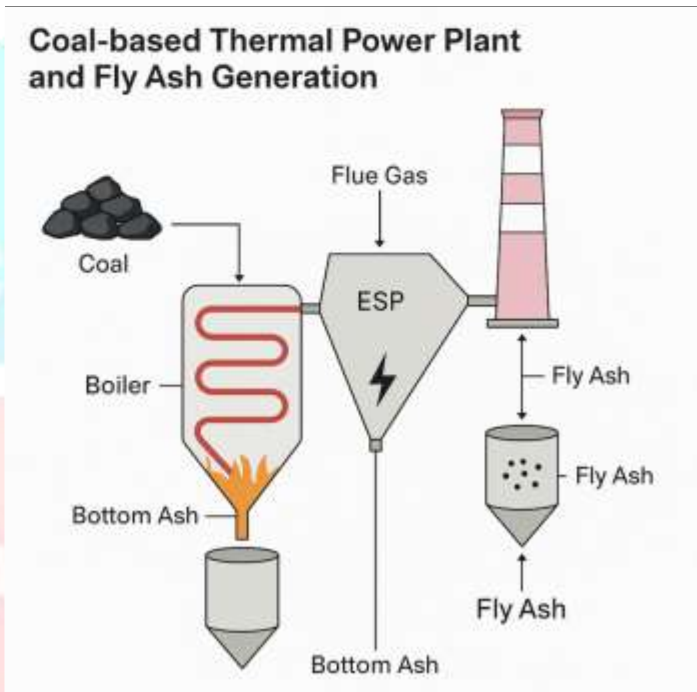


Figure 1.1 — Fly Ash Generation in Thermal Power Plant

However, the potential of **polymer-bound fly ash composites** remains relatively unexplored. Cold-setting resins offer significant advantages over cementitious binders, including room-temperature curing, dimensional stability, chemical resistance, and reduced energy consumption. When combined with fly ash, they form lightweight yet durable composites suitable for construction.

Hydrothermal curing further enhances microstructural evolution by forming cementitious hydration phases such as CSH and CASH, improving mechanical integrity. Despite these advantages, systematic studies addressing the influence of fly ash proportion, compaction, polymer content, hydrothermal treatment, and performance correlations are limited.

This research aims to fill this gap by developing and characterizing resin-bound fly ash composites with varying fly ash proportions and evaluating their engineering properties, microstructure, and application potential.

2. Literature Review

Malhotra and Mehta (1996) in their seminal work on high-volume fly ash concrete highlighted the potential of fly ash as a sustainable construction material capable of reducing cement consumption while maintaining adequate mechanical strength. Their findings established fly ash as a viable substitute in building materials, particularly for improving durability and long-term performance.

Kayali (2004) investigated fly ash bricks and reported that fly ash–based masonry units exhibit superior compressive strength and lower density compared to conventional clay bricks. The study emphasized that spherical fly ash particles enhance packing density and reduce water demand, leading to improved structural performance.

Siddique (2008) provided a comprehensive review of fly ash utilization in concrete and construction materials, noting that fly ash improves workability, reduces permeability, and enhances resistance to chemical attack. The author emphasized the environmental benefits of fly ash utilization in reducing landfill disposal and greenhouse gas emissions.

McCarthy and Dhir (2005) studied the effect of curing conditions on fly ash–based products and observed that elevated-temperature and hydrothermal curing significantly improve strength due to the formation of calcium silicate hydrate (CSH) and calcium aluminate silicate hydrate (CASH) phases. Their work highlighted the importance of curing regime in controlling microstructural development.

Huang et al. (2010) investigated the microstructural evolution of fly ash systems using SEM and XRD and confirmed that amorphous aluminosilicates in Class F fly ash actively participate in pozzolanic reactions, leading to densification of the matrix and improved mechanical properties.

Davidovits (2011) explored geopolymer binders derived from fly ash and demonstrated that alkali-activated aluminosilicates can achieve high compressive strength. However, the study also reported sensitivity of geopolymer systems to activator concentration and curing conditions, which may limit large-scale industrial adoption.

Rai, Prasad, and Kumar (2012) examined the thermal behavior of fly ash bricks and found that the presence of cenospheres significantly reduces thermal conductivity, making fly ash products suitable for insulation applications in energy-efficient buildings.

Zhang et al. (2015) analyzed the wear and friction behavior of fly ash–reinforced composites and concluded that increased fly ash content enhances hardness and wear resistance due to the ceramic nature of ash particles, reducing material loss during abrasive sliding.

Kumar and Singh (2017) studied polymer-bound fly ash composites and reported improved dimensional stability, chemical resistance, and ease of processing compared to cementitious systems. However, their work primarily focused on mechanical properties and did not extensively address tribological or thermal behavior.

Suresh et al. (2020) emphasized the need for integrated studies combining mechanical, thermal, and microstructural analyses to fully understand fly ash–based composite performance. They highlighted that limited literature exists on cold-setting polymer–fly ash systems subjected to hydrothermal curing.

3. Materials and Methods

3.1 Materials

Fly Ash

Fly ash was collected from the electrostatic precipitators of a captive thermal power plant (CPP-II). It predominantly contained silica, alumina, and iron oxide, classifying it as **ASTM Class F fly ash**. The ash was dried at 110–160°C for 24 hours to eliminate moisture and stored in sealed containers.

Cold-Setting Resin

Commercial cold-setting resin and liquid hardener supplied by Geosyn Pvt. Ltd., Kolkata, were used. The resin provides crosslinking at ambient temperature, forming a rigid polymer network capable of binding fly ash particles.

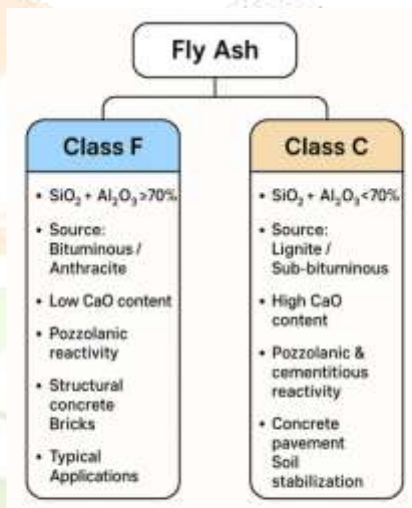


Figure 3.1 — Classification of Fly Ash (ASTM / IS Standards)

3.2 Composite Preparation

3.2.1 Powder Mixing

Three compositions were prepared:

- 75% fly ash + 25% resin powder
- 80% fly ash + 20% resin powder
- 85% fly ash + 15% resin powder

The powders were mixed for 5 hours in airtight vessels using steel balls and a mechanical vibrator to ensure homogeneous distribution.

Fig. 3.2 Experimental Procedure Flowchart and Micro Indentation Hardness Tester (Leco LM-248AT)

3.2.2 Powder Compaction

A stainless-steel die (15 mm diameter) was cleaned and lubricated. About 5 g of powder mix was compacted at **6 tons** on a hydraulic press. Green compacts were allowed to rest for 24 hours, after which the liquid hardener was applied dropwise for polymerization.

3.2.3 Hydrothermal Treatment

Selected samples were immersed in water and cured at 110–180°C for 48 hours. This procedure promotes hydration reactions leading to CSH and CASH formation.

3.3 Characterization Techniques

Mechanical Testing

- **Microhardness:** Measured using a Vickers indenter at 20 gf load and 15 sec dwell.
- **Compressive Strength:** Measured on INSTRON 1196 UTM at 1 mm/min loading rate.

Tribological Testing

A ball-on-plate wear tester (TR-208-M1) was used with a 4 mm diamond indenter under 10 N and 20 N loads for 600 seconds.

Thermal Conductivity

Measured using KD2 Pro Transient Hot Wire Analyzer.

Physical Testing

- Water absorption (ASTM C642)
- Dry and wet density (geometrical method)

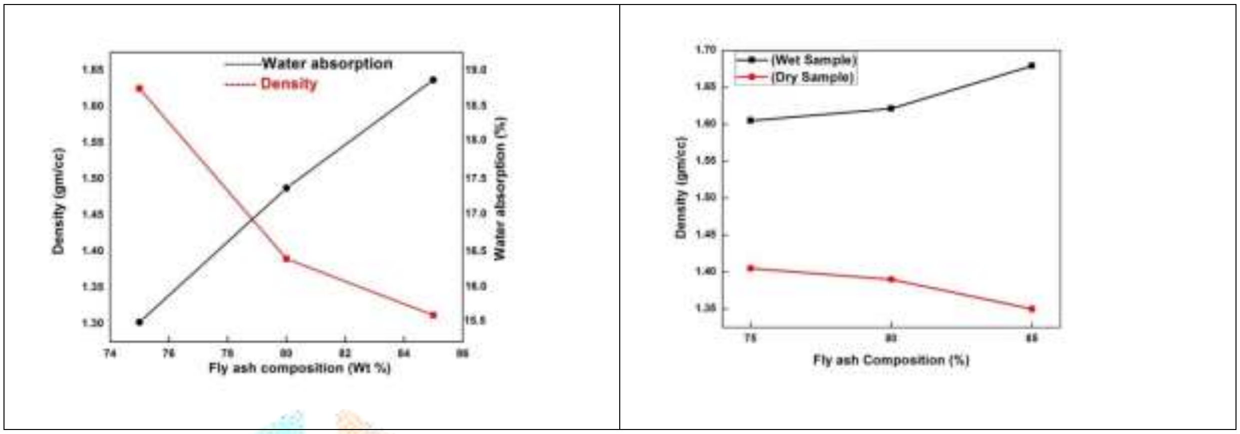
Microstructural Analysis

- **SEM:** Morphology, porosity, wear mechanisms
- **XRD:** Identification of mineral phases
- **FTIR:** Detection of bonding groups and hydration products

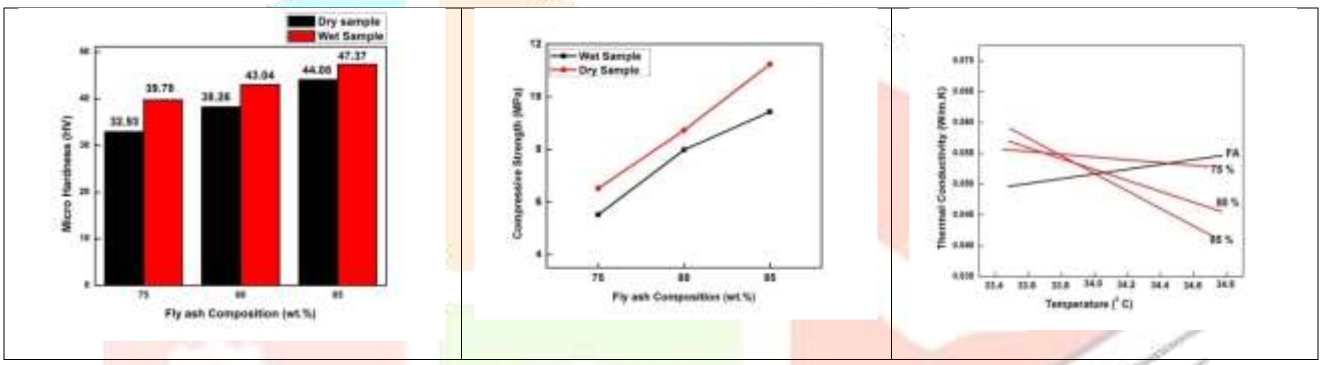
4. Results and Discussion

4.1 Chemical Properties

The fly ash exhibited high SiO_2 and Al_2O_3 with low CaO, confirming Class F characteristics. These oxides promote pozzolanic reactions essential for forming CSH and CASH during hydrothermal curing.



Graph 4.1 Particle Size Distribution at Various Magnifications



Graph 4.2 Morphology of Fly Ash Compacts (Different Mix Compositions)

4.2 Water Absorption and Density

Water absorption increased with higher fly ash content (15.55% → 19.09%) due to reduced resin availability and higher porosity. Dry density decreased (1.40 → 1.35 g/cm³), consistent with the lightweight nature of fly ash. After hydrothermal curing, wet density increased significantly due to hydration gel formation.

4.3 Mechanical Properties

4.3.1 Hardness

Hardness increased with fly ash content:

- 32.93 HV (75% FA) → 44.08 HV (85% FA) dry
- 47.37 HV after water treatment

Reasons:

- Ceramic hardness of quartz and mullite
- Hydration gel formation densifying the matrix

4.3.2 Compressive Strength

Strength values increased:

- 6.5 MPa → 11.28 MPa (dry)
- Slight reduction after water curing due to microcracks caused by vapor pressure

However, water-treated samples showed improved hardness and stability.

4.4 Thermal Conductivity

Thermal conductivity decreased with increasing fly ash:

- Minimum observed: **0.055 W/m·K**

This indicates excellent insulation performance due to hollow cenospheres and porous microstructure.

4.5 Tribological Behavior

Wear depth reduced with higher fly ash percentage, attributed to increased hardness and ceramic particle reinforcement. Coefficient of friction ranged from 1.1 to 1.4. SEM of wear tracks showed micro-cutting, ploughing, and occasional brittle fracture.

4.6 Microstructural Analysis

SEM

- Spherical particles aid packing
- Hydration gels fill pores
- Water-treated samples show microcracks but exhibit increased hardness

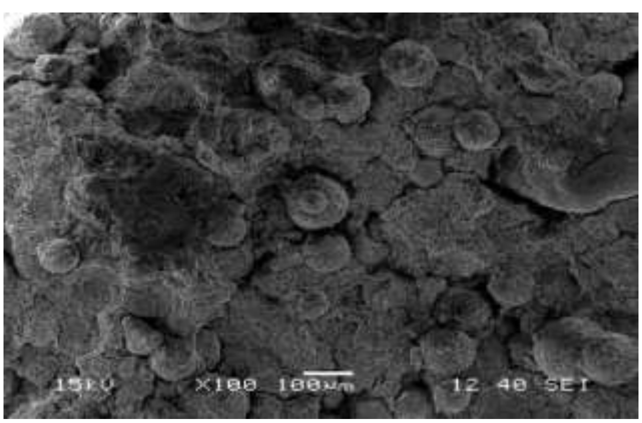
XRD

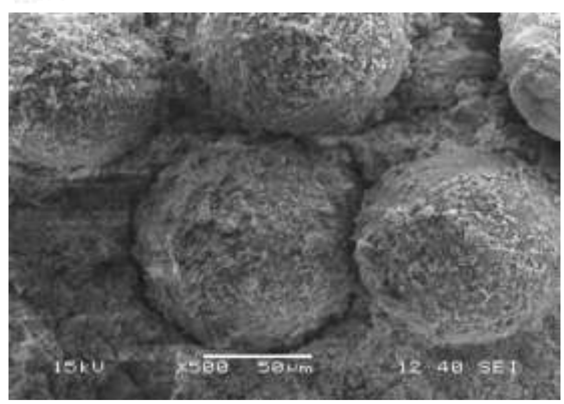
- Quartz and mullite dominate in untreated samples
- New peaks corresponding to CSH and CASH appear after hydrothermal curing

FTIR

- Si–O–Si and Al–O–Si vibrations confirm aluminosilicate network
- O–H stretching indicates hydration

These results validate the formation of binder phases that enhance material performance.





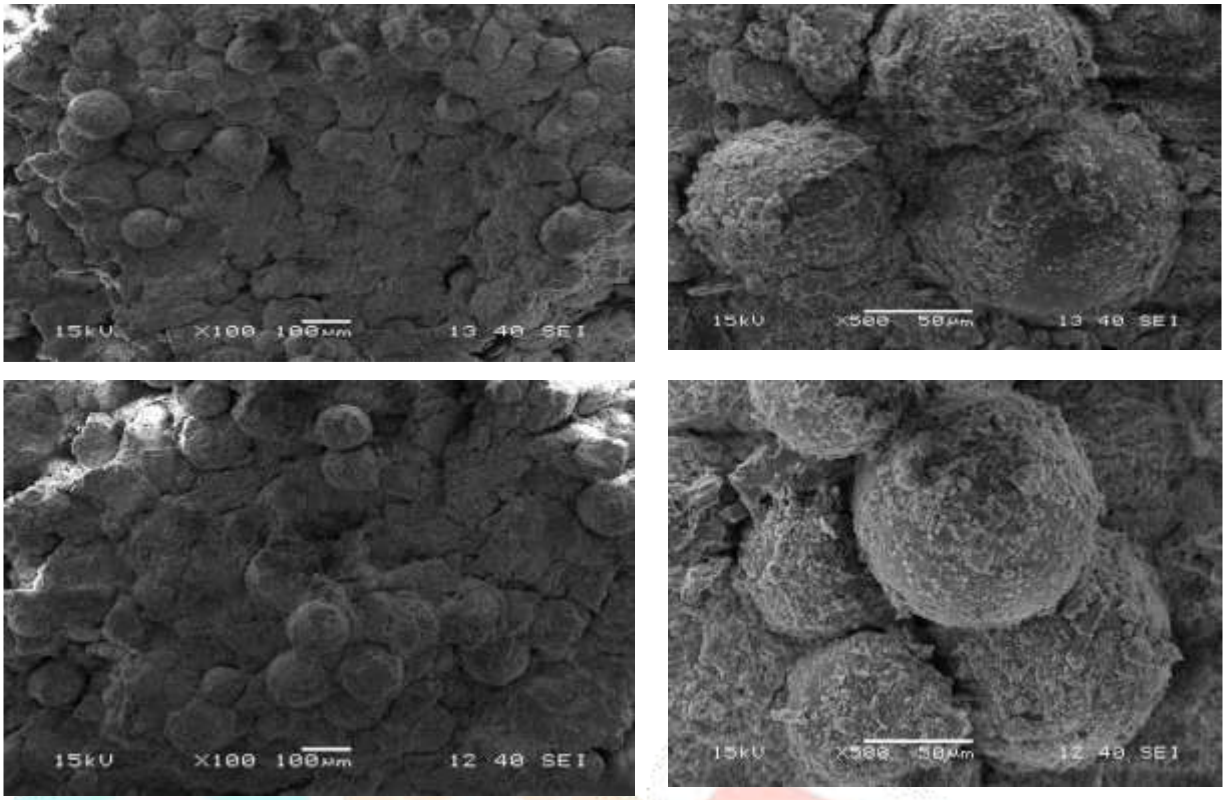


Fig.4.2 Morphology of Fly ash compacts with different composition and at different magnifications

5. Conclusions

1. High-volume fly ash polymer composites can be successfully fabricated using powder compaction and cold-setting resins.
2. Mechanical properties improved significantly with higher fly ash content and hydrothermal curing.
3. Thermal conductivity decreased, proving the suitability of the composites as insulating construction materials.
4. Wear resistance and hardness increased due to the presence of ceramic phases and hydration gels.
5. The best-performing composition was **85% fly ash + 15% resin**, offering the optimal balance between strength, cost, sustainability, and insulation.

These composites demonstrate strong potential as eco-friendly substitutes for clay bricks, tiles, and lightweight structural materials.

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