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Mechanical, Thermal And Tribological Performance Evaluation Of Fly Ash Reinforced Polymer Composites

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Abstract

The large-scale generation of fly ash from coal-based thermal power plants presents serious environmental and land-use challenges. The present study investigates the development of fly ash reinforced polymer composites aimed at converting industrial waste into value-added engineering materials. Composite specimens were fabricated using a compaction-based technique followed by room-temperature curing, with fly ash content varied at 75 wt.%, 80 wt.%, and 85 wt.%. Mechanical properties were evaluated through hardness and compressive strength tests, while tribological performance was assessed under dry sliding conditions. Thermal conductivity measurements were conducted to examine insulation capability, and microstructural analysis was performed using scanning electron microscopy.

The results demonstrate that hardness and wear resistance increase consistently with increasing fly ash content due to the ceramic nature of fly ash particles and improved load-sharing mechanisms. Compressive strength exhibited an optimum value at intermediate fly ash content, indicating a balance between reinforcement loading and matrix continuity. Thermal conductivity decreased significantly with higher fly ash content owing to hollow cenospheres, increased porosity, and interfacial thermal resistance. Microstructural observations confirmed uniform particle dispersion and effective interfacial bonding at optimum compositions. The study establishes a clear structure–property relationship and highlights the potential of fly ash reinforced polymer composites for structural, tribological, and thermal insulation applications.

Keywords: Fly ash, Polymer composites, Mechanical properties, Tribological behavior, Thermal conductivity, Sustainable materials

1. Introduction

Coal-based thermal power plants remain a major source of energy in developing countries, resulting in the generation of enormous quantities of fly ash. Disposal of fly ash poses environmental challenges such as land degradation, air pollution, and groundwater contamination. Simultaneously, the construction and mechanical engineering sectors face increasing pressure to adopt sustainable materials with reduced environmental impact.

Fly ash is rich in silica and alumina and exhibits spherical morphology, low density, and thermal insulation characteristics. These properties make it a promising reinforcement material for polymer composites. Polymer-based composites offer advantages such as low weight, ease of processing, and corrosion resistance. When combined with fly ash, they form composites that are economical, sustainable, and suitable for engineering applications.

Despite these advantages, systematic studies evaluating the combined mechanical, thermal, and tribological performance of fly ash reinforced polymer composites remain limited. The present research addresses this gap by developing and experimentally evaluating fly ash reinforced polymer composites using a compaction-based processing route.

Figure 1.1. Fly ash generation and typical spherical morphology

2. Materials and Experimental Methodology

Fly ash used in the present study was collected from electrostatic precipitators of a coal-based thermal power plant. The ash was oven-dried to remove moisture prior to composite fabrication. A cold-setting polymer resin with a compatible hardener was used as the matrix material.

Composite specimens were prepared with three different compositions, namely 75 wt.% fly ash + 25 wt.% polymer, 80 wt.% fly ash + 20 wt.% polymer, and 85 wt.% fly ash + 15 wt.% polymer. The constituents were mechanically mixed to ensure uniform dispersion and then compacted using a hydraulic press. The compacted specimens were cured at room temperature to achieve complete polymerization.

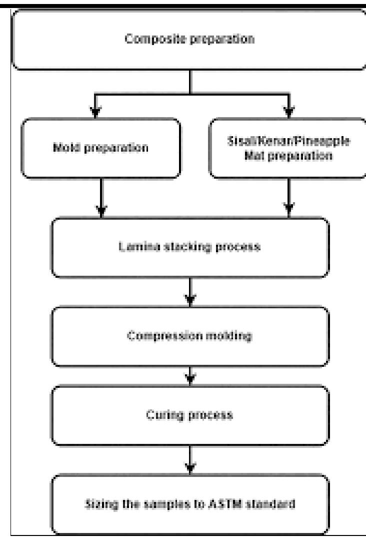


Figure 2.2. Composite fabrication and experimental methodology

3. Literature Review

Fly ash has been widely investigated as a reinforcement material in polymer composites due to its ceramic nature, low density, and environmental benefits. Kayali and Haque reported that the incorporation of fly ash into polymer matrices improves hardness and compressive strength by restricting matrix deformation and enhancing load-bearing capability. Their work highlighted the role of spherical fly ash particles in improving packing density and stress distribution within composites.

Several studies have focused on the mechanical performance of fly ash reinforced polymer composites. Kumar et al. observed an increase in hardness and stiffness with increasing fly ash content, while noting that excessive filler loading may lead to porosity and reduced strength. Patel and Singh emphasized the importance of particle size and distribution, reporting that finer fly ash particles provide improved interfacial bonding and enhanced compressive strength.

Tribological behavior of fly ash filled polymer composites has also received significant attention. Reddy and Gourav reported reduced wear rates with increasing fly ash content due to increased surface hardness and resistance to micro-cutting. Sidhu et al. demonstrated that fly ash particles act as load-supporting elements during sliding, thereby reducing material removal and improving wear resistance under dry sliding conditions.

Thermal properties of fly ash reinforced composites have been investigated to evaluate their insulation potential. Zhao et al. reported a significant reduction in thermal conductivity with increasing fly ash cenosphere content, attributing this behavior to the presence of hollow particles and disrupted heat conduction paths. Pan et al. confirmed that fly ash based composites exhibit improved thermal insulation while maintaining adequate mechanical strength.

Microstructural studies have established a strong correlation between particle dispersion and composite performance. Fernandez-Jimenez and Palomo reported that uniform dispersion of fly ash particles enhances interfacial bonding and mechanical stability. Liu et al. further confirmed that improved microstructural homogeneity leads to enhanced hardness and wear resistance.

Although extensive research has been conducted on individual mechanical, thermal, and tribological properties of fly ash reinforced polymer composites, limited studies have addressed the combined evaluation of these properties under identical processing conditions. The present study aims to bridge this gap by systematically investigating the mechanical, thermal, and tribological performance of fly ash reinforced polymer composites fabricated using a compaction-based technique.

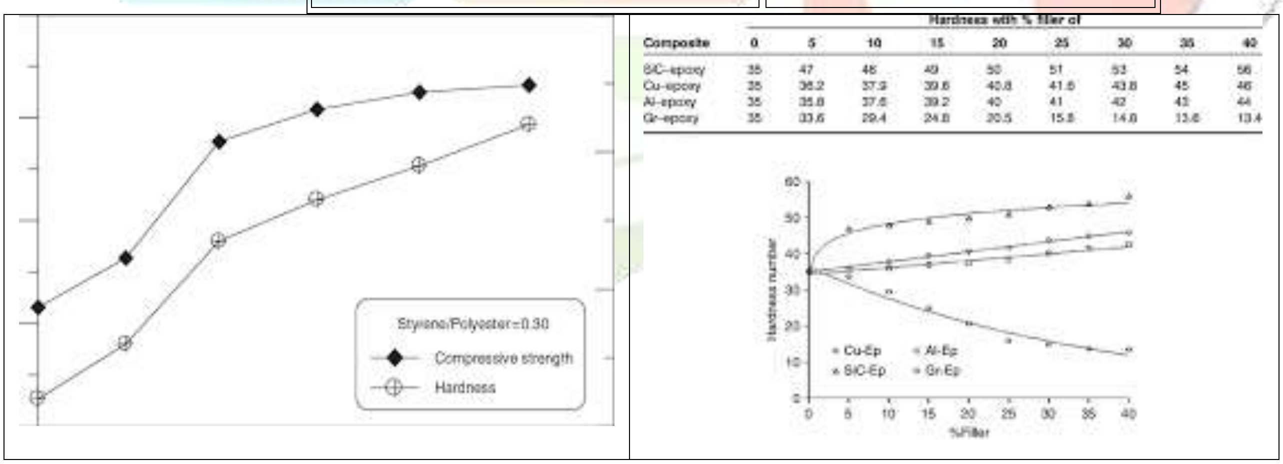
4. Results and Discussion

4.1 Hardness

Hardness increased with increasing fly ash content due to the presence of hard ceramic phases such as quartz and mullite. Higher fly ash content restricts polymer matrix deformation under indentation, resulting in improved surface hardness.

Table 4.1. Vickers hardness of fly ash reinforced polymer composites

Fly Ash Content (wt.%)	Hardness (HV)
75	42
80	51
85	58



Composite	0	5	10	15	20	25	30	35	40
SiC–epoxy	35	47	48	49	50	51	53	54	56
Cu–epoxy	35	36.2	37.9	39.6	40.8	41.6	43.8	45	46
Al–epoxy	35	35.8	37.6	39.2	40	41	42	43	44
Gr–epoxy	35	33.6	29.4	24.8	20.5	15.8	14.8	13.6	13.4

Figure 4.1. Variation of hardness with fly ash content

4.2 Compressive Strength

Compressive strength increased with fly ash content up to 80 wt.% and slightly decreased at 85 wt.%. The initial increase is attributed to improved load transfer and particle packing, while the reduction at higher fly ash content is due to insufficient polymer matrix to bind particles effectively.

Table 4.2. Compressive strength of composites

Fly Ash Content (wt.%)	Compressive Strength (MPa)
75	7.8
80	9.6
85	8.9

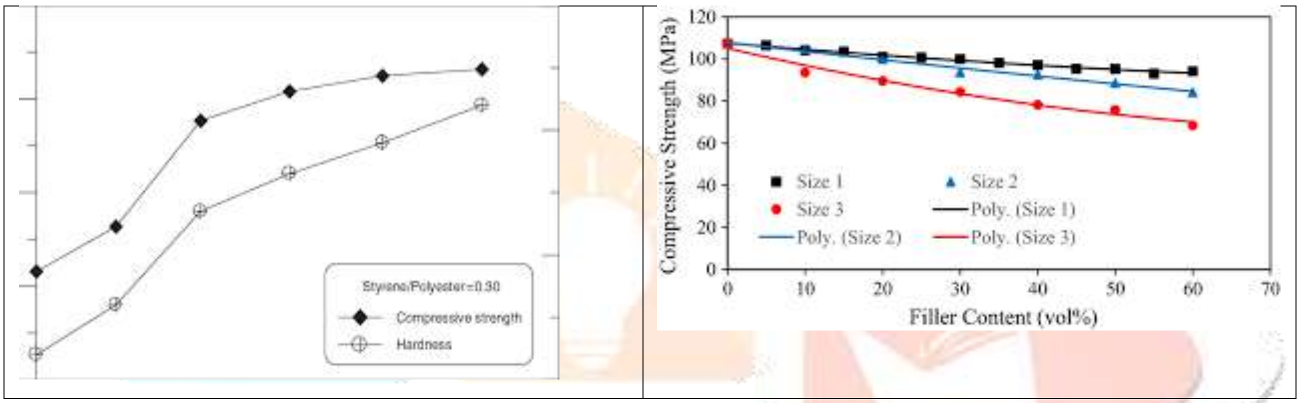


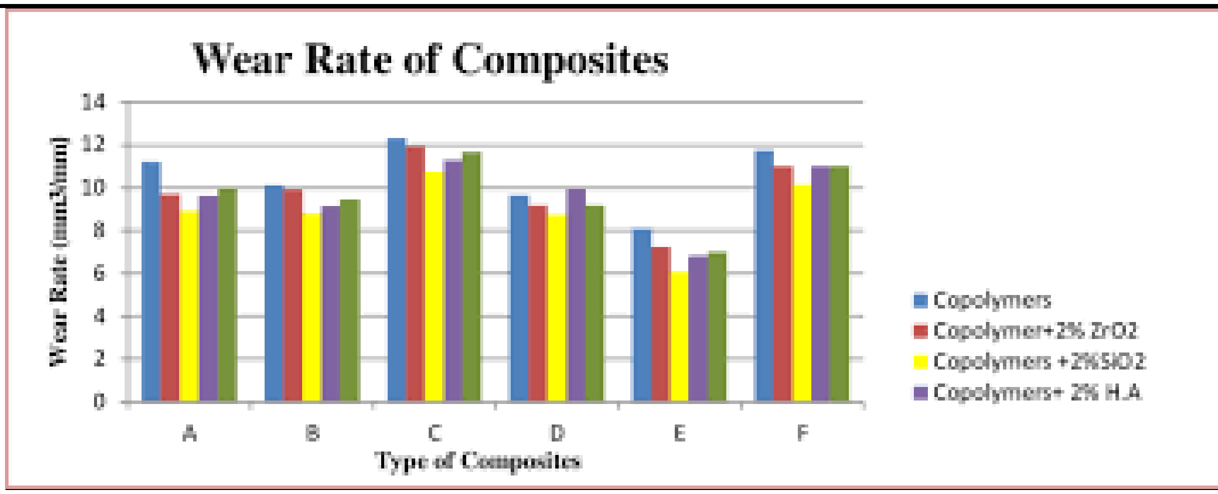
Figure 4.2. Compressive strength variation with fly ash content

4.3 Tribological Behavior

Wear rate decreased with increasing fly ash content due to enhanced surface hardness and reduced adhesive wear. Fly ash particles act as load-bearing elements during sliding, reducing material removal.

Table 4.3. Wear rate of composites

Fly Ash Content (wt.%)	Wear Rate ($\times 10^{-4}$ mm^3/N·m)
75	5.2
80	3.8
85	3.1



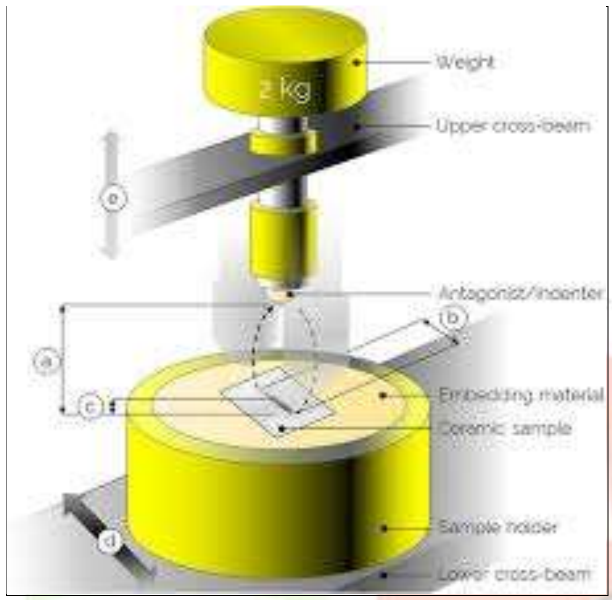


Figure 4.3. Wear rate variation with fly ash content

4.4 Thermal Conductivity

Thermal conductivity decreased with increasing fly ash content due to hollow cenospheres, entrapped air, and interfacial thermal resistance. This behavior indicates excellent insulation performance.

Table 4.4. Thermal conductivity of composites

Fly Ash Content (wt.%)	Thermal Conductivity (W/m·K)
75	0.48
80	0.39
85	0.32

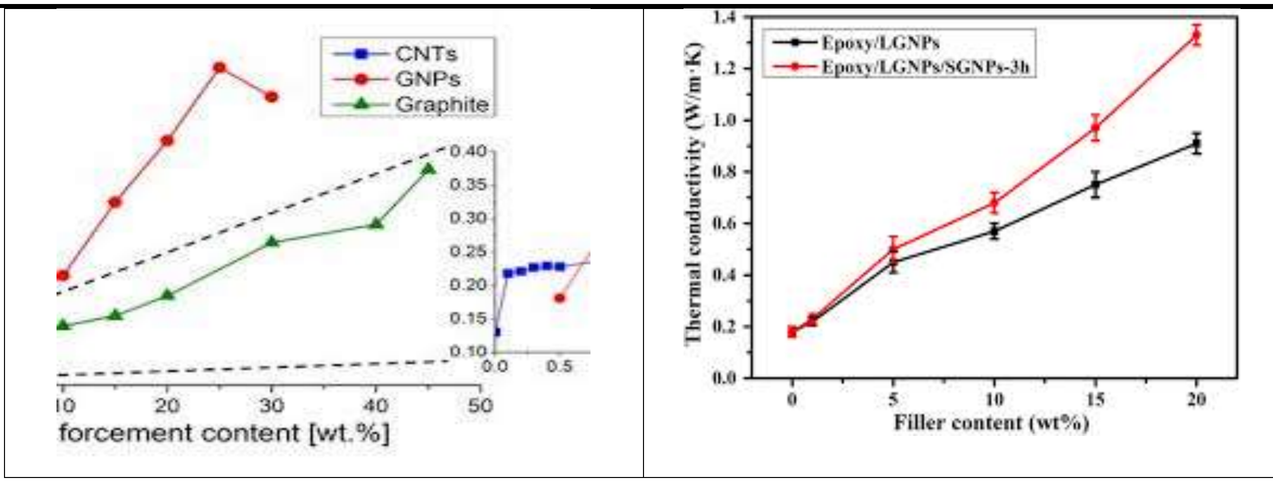


Figure 4.4. Thermal conductivity variation with fly ash content

4.5 Microstructural Analysis

SEM images revealed uniform dispersion of fly ash particles and good interfacial bonding at optimum compositions. At higher fly ash content, minor particle pull-out and voids were observed, correlating with compressive strength results.

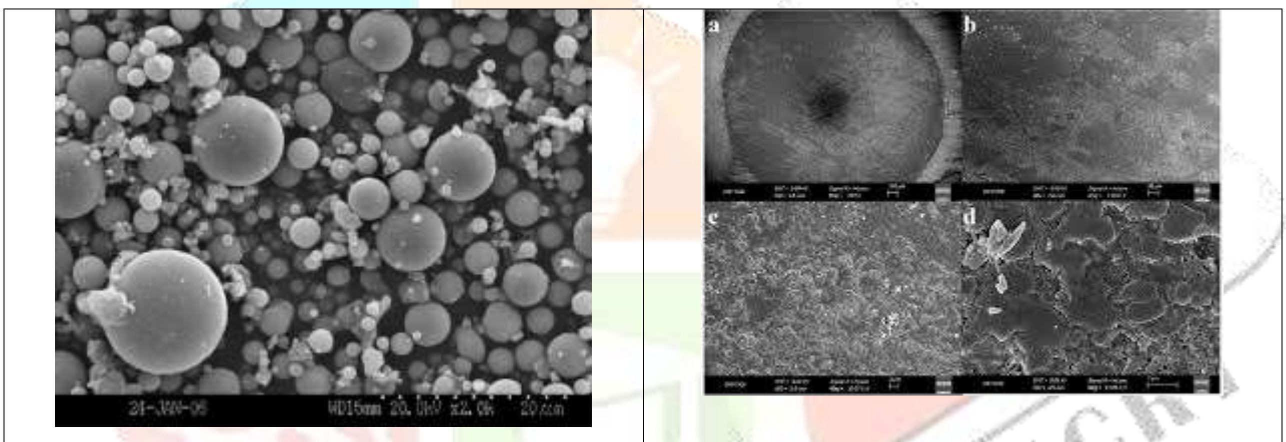


Figure 4.5. SEM micrographs of composite microstructure and worn surfaces

5. Conclusions

Fly ash reinforced polymer composites were successfully fabricated using a compaction-based processing route. Hardness and wear resistance improved significantly with increasing fly ash content, while compressive strength exhibited an optimum value at intermediate reinforcement levels. Thermal conductivity decreased with higher fly ash content, demonstrating excellent insulation capability. Microstructural analysis validated the observed mechanical and tribological trends. The developed composites offer a sustainable, cost-effective solution for structural and insulation applications while promoting effective utilization of industrial waste.

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