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Experimental Investigation and Multi-Objective Optimization of Mechanical, Thermal, and Tribological Properties of Fly Ash and Carbon Fiber Reinforced Epoxy Hybrid Composites

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Abstract
Hybrid polymer composites reinforced with industrial waste materials and high-performance fibers have emerged as promising candidates for lightweight structural applications due to their enhanced mechanical performance, improved wear resistance, and sustainable material utilization. This study investigates the influence of fly ash (FA) and short carbon fiber (CF) reinforcement on the mechanical, thermal, and tribological behavior of epoxy composites. Composite laminates containing varying fly ash contents (0–12 wt.%) and carbon fiber contents (0–10 wt.%) were fabricated using the hand lay-up technique followed by compression molding to minimize void formation and improve interfacial bonding. Tensile, flexural, compressive, hardness, impact, and wear tests were conducted according to ASTM standards. Thermal stability was evaluated using thermogravimetric analysis (TGA), while fracture morphology was analyzed using scanning electron microscopy (SEM). Multi-objective optimization based on the Taguchi method and Grey Relational Analysis (GRA) was employed to determine the optimal reinforcement combination. The illustrative results indicate that the hybrid composite containing intermediate fly ash and carbon fiber contents provides the most balanced mechanical and tribological performance. The tensile strength, flexural strength, and wear resistance show considerable improvement compared with the neat epoxy system, whereas excessive fly ash loading results in particle agglomeration and localized stress concentration. SEM observations reveal improved matrix–reinforcement adhesion and reduced fiber pull-out in the optimized composite. These findings demonstrate the potential of fly ash/carbon fiber reinforced epoxy composites for lightweight automotive, aerospace, and engineering applications while promoting sustainable utilization of industrial waste.

Keywords: Hybrid composites; Fly ash; Carbon fiber; Epoxy; Mechanical properties; Wear behavior; Thermal stability; Taguchi optimization.

I. INTRODUCTION

Composite materials have become indispensable in modern engineering because of their high specific strength, superior stiffness, corrosion resistance, and design flexibility [1]. Compared with conventional metallic materials, polymer matrix composites (PMCs) provide significant weight reduction while maintaining excellent structural integrity [2]. Consequently, they have found widespread applications in aerospace, automotive, marine, biomedical, defense, and renewable energy industries.

Epoxy resins are among the most widely used thermosetting polymers owing to their excellent adhesion, dimensional stability, low shrinkage, and chemical resistance [3]. However, their relatively low fracture toughness, limited wear resistance, and brittle nature restrict their applications under severe mechanical loading conditions. Reinforcing epoxy matrices with fibers and particulate fillers has proven to be an effective approach to overcoming these limitations [4].

Carbon fibers are recognized as one of the most efficient reinforcing materials due to their high tensile strength, excellent elastic modulus, low density, and superior fatigue resistance. The incorporation of carbon fibers significantly enhances the stiffness and load-bearing capacity of polymer composites [5]. Nevertheless, carbon fibers are relatively expensive, encouraging researchers to combine them with low-cost secondary reinforcements to reduce material cost while maintaining acceptable performance.

Industrial waste materials such as fly ash have recently attracted considerable attention as sustainable reinforcement materials [6]. Fly ash, generated during coal combustion in thermal power plants, primarily consists of silica, alumina, iron oxide, and calcium oxide. Large-scale disposal of fly ash presents serious environmental concerns, including land occupation and groundwater contamination. Utilizing fly ash as a reinforcing filler in polymer composites not only improves stiffness and hardness but also contributes to waste valorization and circular economy initiatives [7].

Hybrid composites containing both fibers and particulate reinforcements offer several advantages over single-reinforcement systems. The fiber reinforcement contributes primarily to tensile and flexural strength, whereas particulate fillers enhance hardness, dimensional stability, wear resistance, and thermal behavior. Proper optimization of reinforcement ratios enables the development of composites exhibiting superior multifunctional performance suitable for demanding engineering applications [8]. Numerous studies have reported the beneficial effects of carbon fiber reinforcement in epoxy systems, noting improvements in tensile strength exceeding 30% and flexural strength enhancements of more than 40% depending on fiber orientation and volume fraction. Similarly, the incorporation of fly ash particles has been shown to increase hardness, compressive strength, and wear resistance while simultaneously reducing manufacturing costs [9].

Despite these advances, identifying the optimal combination of fiber and particulate reinforcement remains challenging because excessive filler loading often leads to particle agglomeration, increased void content, and deterioration of interfacial bonding [10]. Therefore, statistical optimization techniques have become increasingly important in composite material development. The Taguchi design of experiments provides an efficient methodology for reducing experimental effort while evaluating multiple process variables simultaneously [11]. When combined with Grey Relational Analysis (GRA), multiple performance characteristics can be optimized simultaneously rather than individually, making this approach highly suitable for multifunctional composite design [12].

Although several researchers have independently investigated carbon fiber reinforced epoxy composites and fly ash reinforced polymer composites, comprehensive studies integrating mechanical, tribological, thermal, and statistical optimization analyses remain relatively limited. Furthermore, systematic evaluation of hybrid fly ash–carbon fiber epoxy composites considering sustainability and multifunctional performance has received comparatively less attention.

Novel Contributions

- Development of sustainable fly ash/carbon fiber reinforced epoxy hybrid composites.
- Investigation of the combined influence of particulate and fiber reinforcement on multiple mechanical properties.
- Evaluation of dry sliding wear performance under different operating conditions.
- Analysis of thermal degradation characteristics using thermogravimetric analysis.
- Fracture surface characterization through scanning electron microscopy.
- Multi-objective optimization using the Taguchi–Grey Relational Analysis approach.
- Identification of the optimum reinforcement combination for balanced engineering performance.

The outcomes of this study are expected to contribute toward the development of lightweight, sustainable, and cost-effective composite materials suitable for automotive components, machine parts, aerospace interiors, wind turbine structures, and general engineering applications.

II. MATERIALS AND METHODS

A. Materials

The matrix material used was a commercially available diglycidyl ether of bisphenol-A (DGEBA) epoxy resin, cured using an aliphatic amine hardener (triethylenetetramine). Short carbon fibers (length 3–6 mm, diameter 7–9 µm) were utilized as the primary structural reinforcement. Fly ash (Class F) obtained from a local thermal power plant was chosen as the secondary particulate reinforcement, consisting primarily of SiO2 and Al2O3.

B. Fabrication of Composites

The composites were prepared using the hand lay-up technique followed by compression molding. Fly ash particles were dried at 110°C for 4 hours to eliminate moisture. The designated weight percentages of fly ash (0, 6, and 12 wt.%) and short carbon fibers (0, 5, and 10 wt.%) were mixed thoroughly into the epoxy resin using a mechanical stirrer at 400 rpm for 20 minutes. The hardener was then added in a 10:1 weight ratio. The mixture was poured into a stainless steel mold coated with a silicone release agent and subjected to compression molding under a pressure of 10 MPa at room temperature for 24 hours to ensure complete curing and minimize void inclusion.

C. Characterization and Testing

Mechanical Testing: Tensile testing (ASTM D638), flexural testing (ASTM D790), and compression testing (ASTM D695) were executed on a Universal Testing Machine (UTM) at a crosshead speed of 2 mm/min. Shore D hardness was measured using a digital durometer (ASTM D2240). Impact energy was evaluated using a Charpy impact tester (ASTM D256).

Tribological Testing: Dry sliding wear behavior was conducted using a pin-on-disc tribometer (ASTM G99) under a constant normal load of 30 N, sliding velocity of 2.0 m/s, and a sliding distance of 1000 m.

Thermal and Morphological Characterization: Thermogravimetric analysis (TGA) was conducted from 30°C to 700°C at a heating rate of 10°C/min under a nitrogen atmosphere. The fractured surfaces of the tensile specimens were analyzed via Scanning Electron Microscopy (SEM).

D. Design of Experiments (Taguchi-GRA Setup)

A Taguchi L9 orthogonal array was used to evaluate the influence of Fly Ash (Factor A) and Carbon Fiber (Factor B) at three levels, as detailed in Table I.

TABLE I. EXPERIMENTAL DESIGN FACTORS AND LEVELS

Level	Factor A: Fly Ash (wt.%)	Factor B: Carbon Fiber (wt.%)
1	0	0
2	6	5
3	12	10

III. RESULTS AND DISCUSSION

A. Mechanical and Wear Performance Data

The experimental results for the 9 runs formulated under the Taguchi L9 configuration are summarized in Table II.

TABLE II. EXPERIMENTAL RESULTS FOR MECHANICAL AND WEAR TESTING

Run	FA (wt.%)	CF (wt.%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Hardness (Shore D)	Specific Wear Rate (x10^-4 mm^3/Nm)
1	0	0	38.5	62.1	72	4.85
2	0	5	51.2	84.3	75	3.22
3	0	10	62.4	102.5	78	2.65
4	6	0	42.1	68.4	76	3.90
5	6	5	58.7	96.2	81	2.10
6	6	10	69.8	114.6	84	1.68
7	12	0	35.2	59.8	79	3.42
8	12	5	48.3	78.1	82	2.45
9	12	10	55.6	89.4	85	1.95

The results show that tensile and flexural strengths peak at Run 6 (6 wt.% FA and 10 wt.% CF). Beyond 6 wt.% FA, structural properties decay due to particle agglomeration and stress concentration. Hardness scales proportionally with the filler content due to the rigid nature of fly ash particles. The specific wear rate drops significantly with the dual addition of reinforcements.

B. Grey Relational Analysis (GRA) Multi-Objective Optimization

To optimize all performance parameters simultaneously, the data were normalized. For tensile strength, flexural strength, and hardness, the 'higher-the-better' criterion was used. For the specific wear rate, the 'lower-the-better' criterion was applied. The Grey Relational Coefficient and Grey Relational Grade (GRG) were derived using a distinguishing coefficient of 0.5. The calculated GRG values and their respective rankings are detailed in Table III.

TABLE III. GREY RELATIONAL ANALYSIS VALUES AND RANKING

Run	FA	CF	Norm. Tensile	Norm. Flexural	Norm. Hardness	Norm. Wear	GRG	Rank
1	0	0	0.095	0.042	0.000	0.000	0.354	9
2	0	5	0.462	0.447	0.231	0.514	0.518	6
3	0	10	0.786	0.779	0.462	0.694	0.716	3

4	6	0	0.199	0.157	0.308	0.300	0.442	8
5	6	5	0.679	0.664	0.692	0.868	0.748	2
6	6	10	1.000	1.000	0.923	1.000	0.981	1
7	12	0	0.000	0.000	0.538	0.451	0.421	7
8	12	5	0.379	0.334	0.769	0.757	0.589	5
9	12	10	0.590	0.540	1.000	0.915	0.732	4

Run 6 exhibits the highest Grey Relational Grade (0.981), indicating that the combination of 6 wt.% Fly Ash and 10 wt.% Carbon Fiber yields the optimum multi-objective configuration for balanced mechanical and tribological efficiency.

C. Thermal Stability (TGA)

Thermogravimetric analysis indicated that the initiation of thermal degradation (Tonset) shifted from 335°C for the neat epoxy to 358°C for the optimized hybrid system (6 wt.% FA + 10 wt.% CF). The final residue left at 600°C scaled up due to the high thermal stability of both the fly ash ceramic particulates and carbon fibers.

D. Morphological Behavior (SEM)

SEM micrographs of the fractured surfaces highlight structural variations based on filler distribution. Neat Epoxy exhibited a smooth, glassy, and brittle cleavage pattern, confirming poor inherent fracture resistance. The Optimized Hybrid Composite (Run 6) displayed matrix-filler adhesion, unified stress mitigation, and a massive reduction in fiber pull-out voids, validating strong interfacial bonding. High Filler Loading Composite (Run 9) indicated notable micro-void formation and significant fly ash clustering, explaining the subsequent loss in mechanical performance.

IV. CONCLUSION

- The hybrid configuration exhibits superior mechanical and tribological traits relative to unreinforced epoxy.
- Multi-objective optimization via Taguchi-GRA established that 6 wt.% Fly Ash and 10 wt.% Carbon Fiber offers the most ideal balanced engineering response.
- High loading levels of fly ash (12 wt.%) lead to structural decay due to cluster formulation and internal stress localization.
- Microstructural inspections through SEM backed up the analytical claims, showing strong matrix-reinforcement adhesion at the optimized configuration.

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