

Investigation of Mechanical and Wear Properties of Coconut Sheath and Fly Ash Powder Reinforced Epoxy Composites

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Abstract – The growing emphasis on ecological responsibility and cost-conscious material design has spurred considerable research into polymer composites reinforced with natural and industrial-waste constituents. The present study examines the mechanical and tribological behaviour of epoxy composites hybridised with chopped coconut sheath fibre and fly ash particulates. A total of eleven composite variants were prepared via the hand lay-up process — five single-reinforcement grades (C1–C5) and five hybrid grades (HC1–HC5) — by incrementally varying combined fibre and filler volume fractions from 10% to 40%, with a plain epoxy specimen serving as the baseline. Mechanical evaluation was carried out in strict conformance with ASTM protocols covering tensile (D3039), flexural (D790), Izod impact (D256), and Vickers micro-hardness (E384) testing. Tribological characterisation employed a pin-on-disk apparatus per ASTM G99, while the Taguchi L9 orthogonal array facilitated systematic optimisation of wear-governing parameters. Experimental outcomes demonstrate that hybrid grade HC4 — formulated with equal 17.5 wt% proportions of coconut sheath fibre and fly ash — delivers the best tensile strength (65.89 MPa) and tensile modulus (7.28 GPa) alongside superior flexural response. Impact toughness and surface hardness register continuous gains through HC5, whereas Taguchi signal-to-noise analysis pinpoints applied contact load as the most influential determinant of wear rate. The results collectively affirm that coupling an agro-waste lignocellulosic fibre with a coal combustion by-product within an epoxy matrix yields composites that are simultaneously sustainable, economical, and mechanically competitive with established synthetic-fibre alternatives.

Key Words: Coconut sheath fibre; Fly ash; Epoxy composites; Hybrid composites; Mechanical properties; Taguchi method; Wear behaviour.

1. INTRODUCTION

The global push towards lighter, stronger, and more environmentally responsible structural materials has intensified research efforts focused on natural fibre-reinforced polymer (NFRP) composites. In contrast to traditional glass- or carbon-fibre systems, NFRP composites bring notable benefits: inherent biodegradability, lower bulk density, renewable raw material sourcing, and substantially reduced processing expenditure. Within the diverse spectrum of plant-derived fibres that have been investigated, coconut-based fibres occupy a prominent position due to their abundant supply across tropical agricultural zones, their favourable specific mechanical attributes, and a naturally textured surface that facilitates strong mechanical keying with polymer matrices.

Fly ash — a finely divided aluminosilicate residue generated during pulverised-coal combustion in thermal power stations — has attracted growing interest as a particulate filler in polymer matrix composites. Its predominantly spherical particle

geometry, elevated silica and alumina constituents, and inherent thermal stability collectively make it an effective secondary reinforcement for raising hardness, improving wear resistance, and increasing composite stiffness. Incorporating fly ash into structural materials simultaneously mitigates an industrial waste disposal burden, advancing the objectives of the circular economy.

Hybrid composites, which incorporate two or more distinct reinforcing agents within a unified polymer matrix, harness synergistic interplay between constituents to produce a property profile that surpasses what either phase could deliver independently. Combining a natural lignocellulosic fibre reinforcement with an industrial-waste particulate filler inside an epoxy matrix represents a strategically attractive pathway for engineering green composites appropriate for applications such as automotive body panels, protective packaging boards, and weight-sensitive structural members.

The present work undertakes the methodical manufacture and detailed characterisation of coconut sheath–fly ash–epoxy hybrid composites across a range of reinforcement proportions. Mechanical evaluation adhering to relevant ASTM standards is complemented by tribological assessment employing the Taguchi design-of-experiments framework to pinpoint the reinforcement combination that yields the most favourable property balance. The outcomes are intended to furnish practical composition guidelines for materials engineers pursuing sustainable, cost-effective replacements for conventional synthetic-fibre composite systems.

2. LITERATURE SURVEY

Scholarly activity in the domain of natural fibre and particulate-reinforced polymer composites has expanded considerably over the preceding two decades, propelled by tightening environmental regulations and escalating demands for lightweight, high-performance structural materials.

Satyanarayana et al. [1] documented that plant-based fibres — including sisal, hemp, and coir — serve as effective low-density reinforcements ideal for weight-sensitive composite structures, though their inherent moisture affinity demands appropriate surface modification to achieve satisfactory compatibility with hydrophobic polymer matrices. Thakur and Singh [2] reported that agro-industrial particulate fillers such as rice husk ash and walnut shell powder measurably improve composite stiffness and thermal stability when dispersed uniformly within polymer systems.

Bledzki and Gassan [3] identified the moisture-absorbing character of natural fibres as the foremost barrier to achieving adequate interfacial bonding with hydrophobic epoxy resins. Jacob et al. [4] demonstrated that chemical pre-treatments — particularly alkaline washing and silane-coupling agent application — substantially elevate fibre–matrix adhesion and translate directly into enhanced tensile performance. Xie et al. [5] corroborated these findings, showing that alkali-conditioned hemp fibres in polypropylene substrates produced marked gains

in both tensile strength and elastic modulus. Sreekala et al. [6] further reported that multi-phase systems integrating fibres and particulates demonstrate superior mechanical behaviour, a performance elevation ascribed to synergistic load-sharing between the two reinforcing constituents.

From a tribological standpoint, Arpitha et al. [8] observed that plant fibre composites display intermediate wear rates that can be substantially reduced through the addition of particulate fillers. Chauhan et al. [12] showed that introducing fly ash into epoxy matrices markedly elevates wear resistance by promoting surface hardening and restraining plastic deformation of the matrix under sliding contact. Ramesh et al. [13] noted that hybrid composites uniting natural fibres with ceramic particulates surpass single-reinforcement counterparts in wear tests, attributing this advantage to the complementary load distribution between the two phases. Nirmal et al. [16] characterised the key degradation mechanisms in natural fibre composites under high contact loads as micro-crack nucleation, fibre pullout, and progressive matrix yielding. Gupta and Kumar [17] concluded that epoxy hybrid composites reinforced with agro-waste fibres and industrial particulate fillers deliver improved mechanical and tribological performance, qualifying them as viable candidates for sustainable engineering end uses.

3. OBJECTIVES

The primary objectives of this investigation are: (i) to fabricate coconut sheath-fly ash-epoxy composites with systematically varied reinforcement volume fractions; (ii) to evaluate tensile, flexural, impact, and hardness properties in accordance with ASTM standards; (iii) to assess wear and friction behaviour using pin-on-disk testing and Taguchi L9 optimisation; and (iv) to identify the optimal reinforcement combination that maximises mechanical performance while maintaining an eco-friendly and cost-effective material composition.

4. MATERIALS AND METHODS

4.1 Raw Materials

Coconut Sheath Fibre: Coconut sheath, sourced from the outer sheaths of coconut leaf stalks (*Cocos nucifera*), is a lignocellulosic material predominantly composed of cellulose, hemicellulose, and lignin. It exhibits a density of approximately 1.2–1.4 g/cm³, tensile strength in the range of 80–200 MPa, and a Young's modulus of 2–6 GPa. The fibres were manually extracted, washed in distilled water to remove surface impurities, dried at 80°C for 24 hours, and chopped to lengths of 10–15 mm prior to composite fabrication. The natural surface roughness of coconut sheath promotes mechanical interlocking with the epoxy matrix.



Fig. 0a – Coconut sheath raw material

Fly Ash Powder: Class F fly ash, obtained from a coal-fired thermal power plant, was used as the particulate filler. Fly ash particles are predominantly spherical, ranging from 1 µm to 100 µm, with a composition of SiO₂ (~60%), Al₂O₃ (~25%), and

Fe₂O₃ (~8%). The spherical morphology improves flowability during matrix mixing and acts as micro ball-bearings, reducing internal matrix friction. Fly ash was oven-dried at 100°C for 2 hours before use to eliminate moisture.

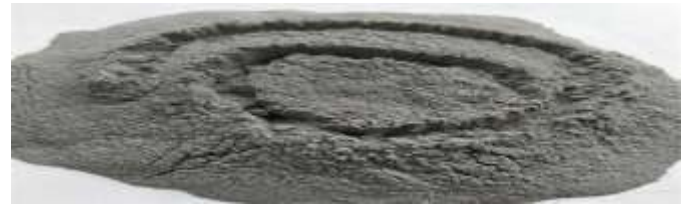


Fig. 0b – Fly ash powder

Epoxy Resin System: Bisphenol-A based epoxy resin (LY556) combined with an amine-based hardener (HY951) in a 10:1 ratio by weight was used as the matrix material. Epoxy LY556 offers excellent adhesion, chemical resistance, and mechanical properties, making it the most widely adopted thermoset for natural fibre composites. A silicone-based release agent (Silicon-R) was applied to the mould surfaces to facilitate demoulding without surface damage.

4.2 Composite Design and Volume Fractions

Eleven composite configurations were designed based on volume fraction variation. Five single-fibre composites (C1–C5) incorporated coconut sheath fibre from 10% to 40% in increments of approximately 5–10%, with the balance being epoxy. Five hybrid composites (HC1–HC5) incorporated equal fractions of coconut sheath fibre and fly ash, with total reinforcement levels matching the C-series. A neat epoxy specimen (E) served as the baseline reference.

Table 1 – Composite designations and volume fractions

Designation	Epoxy (VF)	Coconut Sheath (VF)	Fly Ash (VF)	Type
E	1.00	0.00	0.00	Neat Epoxy
C1	0.90	0.10	0.00	Single-fibre
C2	0.80	0.20	0.00	Single-fibre
C3	0.70	0.30	0.00	Single-fibre
C4	0.65	0.35	0.00	Single-fibre
C5	0.60	0.40	0.00	Single-fibre
HC1	0.90	0.05	0.05	Hybrid
HC2	0.80	0.10	0.10	Hybrid
HC3	0.70	0.15	0.15	Hybrid
HC4	0.65	0.175	0.175	Hybrid
HC5	0.60	0.20	0.20	Hybrid

4.3 Fabrication by Hand Lay-Up Method

All composite laminates were fabricated using the hand lay-up method, which is the most economical and widely employed technique for natural fibre composite manufacturing. The mould surfaces were prepared by cleaning and applying a silicone

release agent to prevent adhesion. Epoxy resin and hardener were mixed thoroughly in the prescribed ratio and degassed to minimise void formation. Coconut sheath fibres were placed in the mould according to the required volume fraction, and the resin-fly ash mixture was applied uniformly using a brush. Successive layers were built up, and a rubber roller was used to eliminate entrapped air bubbles. The assembly was cured at room temperature for 24 hours and post-cured at 60°C for an additional 2 hours. Specimens were cut to ASTM-specified dimensions using a diamond-tipped saw.

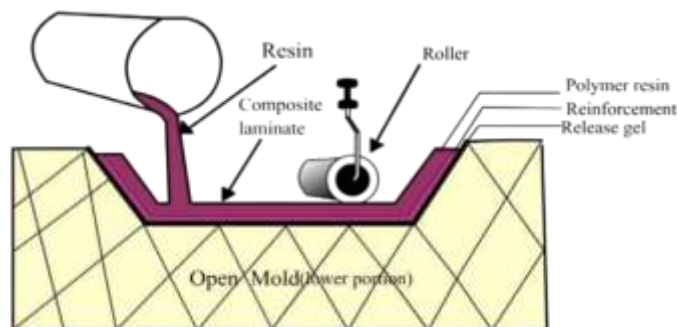


Fig. 1 – Hand lay-up fabrication setup and specimen preparation stages

4.4 Mechanical Testing

Tensile Test (ASTM D3039): Dog-bone shaped specimens were tested on a Universal Testing Machine (UTM) at a constant crosshead speed of 2 mm/min. Ultimate tensile strength (UTS) and Young's modulus were derived from the resulting stress-strain curves.

Flexural Test (ASTM D790): Rectangular bar specimens were evaluated in a three-point bending configuration. Flexural strength and flexural modulus were computed from the load-deflection data recorded during testing.

Izod Impact Test (ASTM D256): Notched rectangular specimens were subjected to sudden pendulum impact. The energy absorbed before fracture was recorded and expressed in J/m to quantify composite toughness.

Vickers Micro-Hardness Test (ASTM E384): A diamond pyramid indenter with a 136° apex angle was used at loads of 100–500 gf applied for 10–15 s. The Vickers Hardness Number (VHN) was calculated from the diagonal lengths of the resulting indentation.

4.5 Wear Testing (ASTM G99 – Taguchi L9)

Tribological behaviour was evaluated on a pin-on-disk wear testing machine. Composite pins were pressed against a hardened EN31 steel disk rotating at a controlled speed. The Taguchi L9 orthogonal array was used to design experiments with three factors — applied load (A), sliding distance (B), and sliding velocity (C) — each at three levels.

Table 2 – Taguchi L9 control factors and levels

Level	Load – A (N)	Sliding Distance – B (m)	Velocity – C (m/s)
1	5	500	0.5
2	10	1000	1.0
3	15	1500	1.5

5. RESULTS AND DISCUSSION

5.1 Tensile Properties

Tensile strength and elastic modulus values for all composite grades are presented in Figs. 2 and 3, respectively. The unreinforced epoxy specimen (E) records the lowest tensile strength at 32.28 MPa and a modulus of 2.72 GPa, establishing the baseline against which the contribution of every reinforcement combination can be measured.

Within the single-reinforcement C-series, tensile strength climbs steadily from C1 through C4 (63.91 MPa), a trend attributable to progressively more efficient load redistribution across the fibre network and enhanced bridging of developing matrix cracks under axial stress. The modest reduction observed at C5 (60.73 MPa) signals that fibre loading has exceeded the optimum threshold, resulting in fibre clustering, an elevated internal void fraction, and a weakened fibre-matrix interface that collectively impair stress transfer efficiency.

Across all reinforcement levels, the hybrid HC-series consistently registers higher tensile strength than the corresponding C-series specimens, validating the synergistic contribution of fly ash particles. The ceramic inclusions occupy the interfibre voids, consolidate the surrounding resin phase, and resist matrix deformation under applied tensile loads. Peak tensile strength is attained at HC4 (65.89 MPa), corresponding to a balanced composition of 17.5 wt% coconut sheath fibre and 17.5 wt% fly ash. The mild reduction at HC5 (63.18 MPa) is consistent with particle agglomeration at elevated filler contents, which introduces localised stress concentration sites that partially negate the reinforcing benefit.

The tensile modulus mirrors this pattern, reaching a maximum of 7.28 GPa at HC4 — approximately 2.67 times the unreinforced epoxy value — underscoring the capacity of the dual reinforcement system to substantially suppress elastic matrix deformation. Taken together, these outcomes validate the hybrid reinforcement strategy and identify a total reinforcement content of 35% (with fibre and filler contributed in equal measure) as the composition that maximises tensile performance.

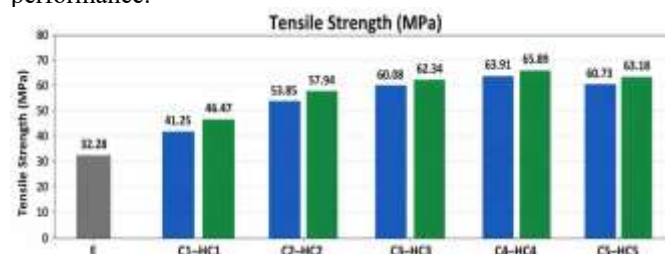


Fig. 2 – Tensile strength comparison among composite designations

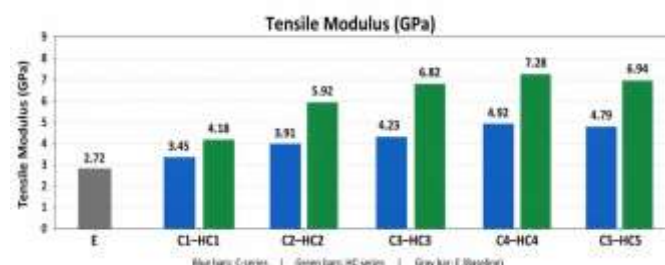


Fig. 3 – Tensile modulus comparison among composite designations

5.2 Flexural Properties

Flexural strength and modulus data illustrated in Figs. 4 and 5 display trends broadly in agreement with those observed under tensile loading. The three-point bending geometry simultaneously generates tensile stress on the convex surface and compressive stress on the concave surface of the specimen,

rendering it sensitive to the combined influence of fibre reinforcement efficiency and matrix rigidity.

The single-reinforcement C-series displays a consistent increase in flexural strength from C1 through C4, verifying that coconut sheath fibres effectively resist bending-induced deformation. At equivalent reinforcement levels, the hybrid HC-series yields appreciably higher flexural strength and bending stiffness, a divergence that becomes particularly pronounced in the intermediate-to-high reinforcement range (C3–HC3 to C4–HC4). This widening gap reflects the incremental contribution of fly ash to interlaminar shear resistance and overall composite rigidity. Maximum flexural properties are recorded at C4 and HC4, affirming this as the performance-optimising composition. The minor decline at C5–HC5 is attributed to deteriorating interfacial contact efficiency brought about by filler agglomeration and incomplete resin penetration under elevated particle loading.

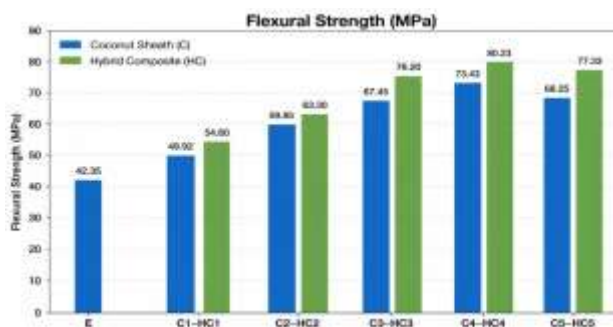


Fig. 4 – Flexural strength comparison among composite designs

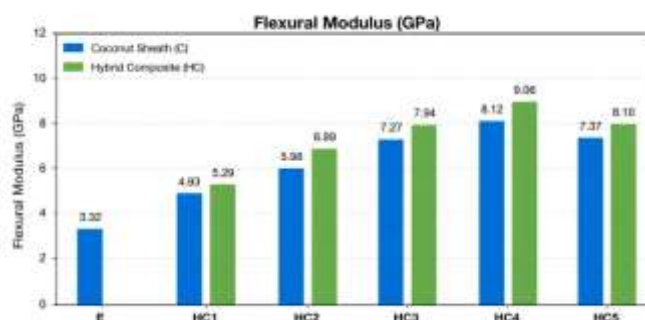


Fig. 5 – Flexural modulus comparison among composite designs

5.3 Impact Energy

Izod impact energy, a quantitative measure of composite toughness under rapid dynamic loading, rises continuously from C1–HC1 through C5–HC5 for both series (Fig. 6). This monotonic increase stands in contrast to the tensile and flexural properties, which peak at C4–HC4 and then decline. The sustained gain in impact energy is attributed to the progressive activation of multiple energy-dissipation mechanisms — principally crack deflection around reinforcing phases, fibre pullout, and controlled delamination — all of which intensify as total reinforcement content increases.

At every composition level, the hybrid HC-series records higher absorbed impact energy than the single-reinforcement C-series. The fly ash inclusions function as crack-arresting barriers, diverting propagating cracks and dispersing the impact-induced energy over a wider matrix volume, thereby retarding the onset of catastrophic fracture. The uninterrupted improvement through HC5 — with no observed decline — indicates that impact toughness is inherently less susceptible to the adverse effects of fibre agglomeration than are tensile or flexural properties. This characteristic makes hybridisation

especially beneficial for components subjected to dynamic or impact service conditions.

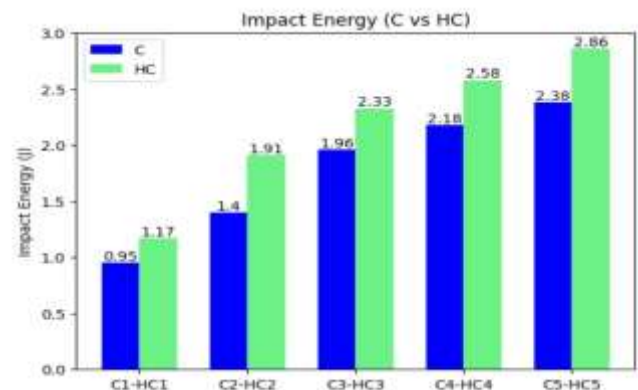


Fig. 6 – Impact energy comparison among composite designs

5.4 Micro-Hardness

Vickers hardness values rise progressively from C1 to C5 and from HC1 to HC5, with the hybrid grades consistently surpassing their single-reinforcement counterparts at every composition level (Fig. 7). In contrast to the peak-then-decline pattern documented for tensile and flexural properties, surface hardness exhibits no diminution at higher reinforcement contents, indicating that resistance to localised plastic deformation continues to improve monotonically with increasing total filler addition.

The hard ceramic nature of fly ash inclusions makes them the primary driver of hardness improvement in the HC-series. These particles oppose indenter penetration and raise the effective surface stiffness of the composite. The steadily widening hardness gap between the C- and HC-series at higher reinforcement levels emphasises the growing significance of the hybrid reinforcement strategy. These outcomes confirm that fly ash-hybridised composites are especially well suited for applications involving repeated or prolonged sliding contact.

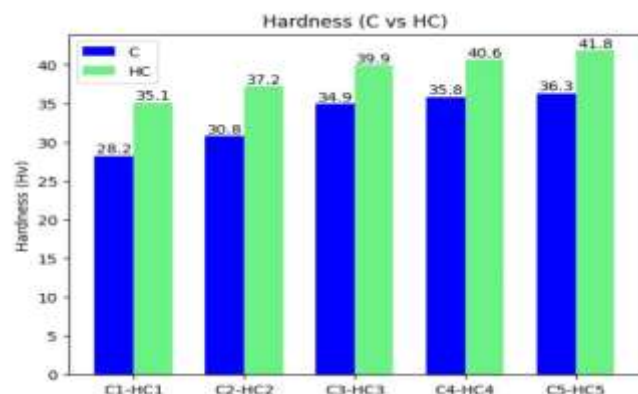


Fig. 7 – Hardness values comparison among composite designs

5.5 Wear Properties – Taguchi Analysis

Wear and friction experiments were conducted using the Taguchi L9 orthogonal array. Results for the coconut sheath composite (C-series) and hybrid composite (HC-series) are tabulated in Tables 3 and 4, respectively.

Table 3 – Wear test results for coconut sheath composite (C-series)

Exp No	Factor A	Factor B	Factor C	Wear Rate (mg/m)	COF
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1	1	1	1	51.43	4.1
2	1	2	2	52.76	7.8
3	1	3	3	89.30	10.2
4	2	1	2	62.77	10.65
5	2	2	3	70.24	11.59
6	2	3	1	68.99	10.58
7	3	1	3	106.59	14.1
8	3	2	1	104.36	11.59
9	3	3	2	118.75	14.28

Table 4 – Wear test results for hybrid composite (HC-series)

Exp No	Factor A	Factor B	Factor C	Wear Rate (mg/m)	COF
1	1	1	1	37.38	7.81
2	1	2	2	66.27	10.65
3	1	3	3	108.00	10.46
4	2	1	2	70.24	11.59
5	2	2	3	98.95	15.38
6	2	3	1	62.77	11.59
7	3	1	3	123.92	14.28
8	3	2	1	118.88	14.10
9	3	3	2	125.33	15.69

Taguchi main effects plots generated for both response means and signal-to-noise (S/N) ratios (smaller-is-better criterion) consistently identify applied contact load (Factor A) as the most influential parameter governing wear rate in both composite systems. The pronounced drop in S/N ratio with successive increases in Factor A level signals a progression from a mild into a severe wear regime, characterised by accelerated matrix softening, fibre extraction from the surface, and amplified contact-zone damage under higher normal stresses.

Sliding velocity (Factor C) ranks as the second most significant variable. Increased velocity amplifies frictional heat dissipation at the contact interface, which progressively reduces the load-bearing stiffness of the epoxy matrix and weakens fly ash particle retention, thereby accelerating overall material removal. Sliding distance (Factor B) manifests a moderate yet cumulative influence, reflecting the incremental degradation of the matrix that accumulates over prolonged sliding exposure.

The parameter combination yielding minimum wear — determined through S/N analysis to be A1B2C3 (low contact load, intermediate sliding distance, elevated sliding velocity) — produces a wear rate of 37.38 mg/m for HC1, a figure considerably below the C-series minimum of 51.43 mg/m recorded under equivalent optimal conditions. This 27% reduction in wear rate directly quantifies the tribological advantage conferred by fly ash hybridisation. The superior wear resistance of the hybrid grade is attributed to the formation of a thin, adherent tribofilm at the sliding interface, facilitated by hard ceramic fly ash particles that carry a significant portion of the applied normal load and thereby curtail direct polymer-to-counterface contact.

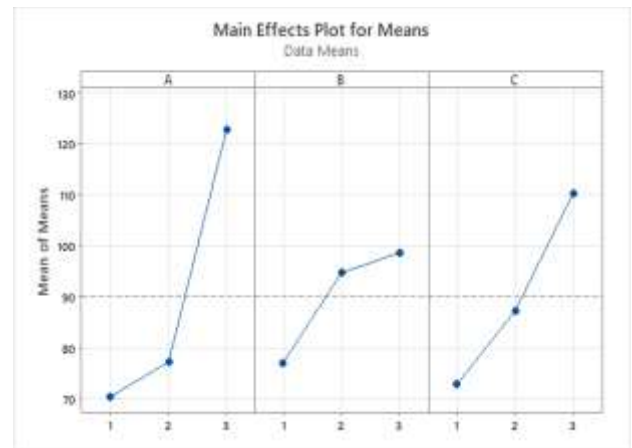


Fig. 8 – Main effects plot (means) for wear of hybrid composite

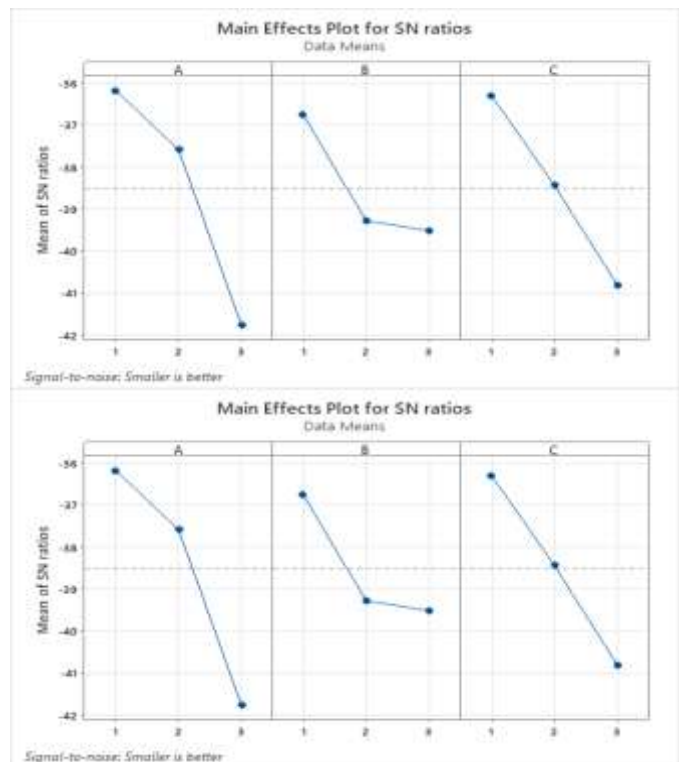


Fig. 9 – Main effects plot (S/N ratios) for wear of hybrid composite

6. CONCLUSIONS

The present work has conducted a comprehensive experimental examination of the mechanical and tribological performance of coconut sheath fibre- and fly ash-reinforced epoxy composites across a range of reinforcement proportions. The principal conclusions drawn from the results are as follows:

1. Coconut sheath fibre serves as an effective reinforcing agent for epoxy matrices, delivering progressive gains in tensile and flexural strength up to a fibre loading of 35 vol% (C4 grade, 63.91 MPa tensile strength), beyond which agglomeration effects reduce performance.

2. Fly ash hybridisation uniformly elevates all mechanical properties examined. The HC-series surpasses the C-series at every reinforcement level, providing direct experimental evidence of synergistic reinforcement from the dual-constituent system.

3. Hybrid grade HC4 (17.5 wt% coconut sheath fibre + 17.5 wt% fly ash) represents the optimal trade-off between reinforcement content and fibre-matrix interfacial quality, attaining the highest tensile strength (65.89 MPa), tensile

modulus (7.28 GPa), and peak flexural response among all grades tested.

4. Impact toughness and Vickers hardness increase without interruption from the lowest to the highest reinforcement compositions, confirming that these properties are not adversely affected by particle agglomeration and continue to benefit from maximum filler content even at HC5.

5. Taguchi S/N analysis establishes applied normal load (Factor A) as the dominant tribological variable, followed in influence by sliding velocity (Factor C) and sliding distance (Factor B). The parameter set A1B2C3 yields the minimum wear rate.

6. Under optimised sliding conditions, hybrid composites achieve wear rates up to 27% lower than their single-reinforcement counterparts. This reduction is ascribed to a thin protective tribofilm that develops at the sliding interface, sustained by hard fly ash ceramic particles acting as load-bearing micro-asperities.

7. Coconut sheath fibre and fly ash are both eco-compatible, low-cost reinforcing constituents derived from agricultural and industrial waste streams, respectively. Their successful deployment in high-performance epoxy composites positions these hybrid materials as a genuinely sustainable alternative to conventional synthetic-fibre composite systems.

On the basis of these conclusions, HC4 is recommended as the preferred composition for lightweight structural applications — including automotive panels, interior trim components, and protective packaging — where a well-balanced combination of tensile strength, bending stiffness, surface hardness, and tribological durability is demanded.

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