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FABRICATION AND TESTING OF HYBRID COMPOSITES REINFORCED WITH BASALT FLAX AND ARAMID FIBRES

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Abstract : Hybrid fibre-reinforced polymer composites have attracted significant interest due to their potential to combine the advantages of natural and synthetic fibres within a single material system. In this study, hybrid composites reinforced with basalt, flax, and aramid fibres were fabricated and experimentally evaluated to investigate their mechanical performance. The composites were manufactured using a controlled fabrication process to ensure uniform fibre distribution and proper matrix impregnation. Different stacking sequences and fibre combinations were employed to assess the synergistic effect of hybridization. Mechanical characterization was carried out through tensile, flexural, impact, and hardness tests in accordance with relevant ASTM standards. The results indicate that the incorporation of basalt and aramid fibres significantly enhances strength and impact resistance, while flax fibres contribute to reduced weight and improved sustainability. Hybrid configurations demonstrated superior mechanical performance compared to single-fibre composites, highlighting the beneficial interaction between natural and high-performance fibres. The study demonstrates that basalt–flax–aramid hybrid composites offer a promising balance between mechanical efficiency, cost, and environmental considerations, making them suitable for applications in automotive, aerospace, and structural components

Index Terms **-** Hybrid fibre-reinforced polymer composites, basalt fibre, flax fibre, aramid fibre, mechanical properties, stacking sequence, hybridization, ASTM testing.

I. INTRODUCTION

Fiber-Reinforced Polymer (FRP) composites have become essential in modern materials engineering due to their high specific strength, stiffness-to-weight ratio, corrosion resistance, and design flexibility. These advantages have driven their widespread use in automotive, aerospace, marine, and renewable energy applications, particularly as industries seek weight reduction and lower emissions. Traditionally, synthetic fibers such as glass, carbon, and aramid have dominated FRPs; however, their energy-intensive production, reliance on non-renewable resources, and poor recyclability have raised serious environmental concerns.

These challenges have accelerated interest in green composites, especially Natural Fiber Reinforced Polymers (NFRPs). Among natural fibers, flax (Linum usitatissimum) has gained prominence due to its renewability, low density, high cellulose content, good tensile properties, and excellent vibration and acoustic damping. Despite these benefits, flax composites suffer from moisture absorption, poor Fiber–matrix adhesion, property variability, and limited impact resistance, restricting their use in primary structural applications.

Hybridization offers an effective solution by combining different fibers to exploit synergistic effects. Basalt and aramid fibers are particularly suitable for reinforcing flax-based composites. Basalt Fiber provides high stiffness, thermal stability, chemical resistance, and environmental compatibility, while aramid fibers contribute exceptional toughness and impact resistance. In a tri-hybrid system, basalt enhances structural rigidity, aramid improves impact and wear resistance, and flax reduces weight and enhances damping. Proper stacking sequence, with synthetic fibers on the outer layers, further protects the natural fiber core and improves durability.

Matrix modification also plays a crucial role in performance. The incorporation of particulate fillers such as bio-silica into epoxy matrices enhances stiffness, interfacial bonding, and crack resistance through crack-pinning mechanisms. Although binary hybrid composites have been widely studied, research on aramid–basalt–flax tri-hybrid systems, particularly with filler-modified matrices, remains limited.

Therefore, this work focuses on the fabrication and mechanical characterization of aramid–basalt–flax hybrid epoxy composites produced via hand lay-up followed by compression moulding. Tensile, flexural, impact, and hardness tests conducted according to ASTM standards are used to evaluate their mechanical performance. The study aims to demonstrate the potential of these tri-hybrid composites as sustainable, cost-effective, and high-performance materials for future structural applications.

Table 1.1

Fiber	Density (g/cm^3)	Tensile Strength (MPa)	E-Modulus (GPa)	Elongation at Break (%)
Bast fiber				
Flax	1.5	345–1100	27.6	0.2–3.2
Hemp	1.48	690	30–70	1.6–4
Jute	1.3–1.45	393–773	10.0–30.0	1.2–1.8
Kenaf	-	930	22.0–60.0	1.6
Leaf fiber				
Sisal	1.5	468–640	9.4–22.0	3.0–7.0
Curaua	1.4	500–1150	9–11.8	3.7–7.5
Pineapple	1.5	413–1627	34.5–82.5	0.8–1.6
Fruit/Seed fiber				
Cotton	1.5–1.6	287–800	5.5–12.6	7.0–8.0
Coir	1.2	131–175	4.0–6.0	15.0–40
Oil palm	0.7–1.55	248	3.2	25.0
Synthetic fiber				
Aramid	1.4	3000–3150	63.0–67.0	3.3–3.7
Carbon	1.7	4000	230–240	1.4–1.8
E-glass	2.5	2000–3500	70.0	2.5
S-glass	2.5	4570	86.0	2.8

The above table 1.1 a comparative overview from Mohsen Bahrami et.al (18), the physical and mechanical properties of natural and synthetic fibers commonly used as reinforcements in composite materials. Natural fibers such as bast, leaf, and fruit/seed fibers exhibit low density, moderate tensile strength, and variable stiffness, making them lightweight, eco-friendly, and suitable for non-structural to semi-structural applications. In contrast, synthetic fibers such as aramid, carbon, and glass fibers demonstrate significantly higher tensile strength and elastic modulus, offering superior load-bearing capability and stiffness for high-performance applications[17]. The comparison highlights the trade-off between sustainability and mechanical performance and emphasizes the relevance of hybrid composites, where natural fibers are combined with synthetic fibers to achieve a balanced combination of strength, weight reduction, cost efficiency, and environmental benefits.

1.1 Hybridization configuration

Because no single Fiber type can give all mechanical and economic properties, engineers often employ hybridization techniques, i.e. combining two or more fibers within the same composite to optimize performance. Hybridization allows designers to balance stiffness, toughness, and cost based on specific application needs. There are three principal hybridization configurations

- **Interply Hybrid** Different fibers are arranged in alternating layers (plies) within a composite laminate. For example, a carbon–aramid hybrid might have carbon Fiber as top layers and aramid Fiber as next layers. This configuration is the easiest to manufacture and allows to control how each layer contributes to the overall mechanical behaviour.

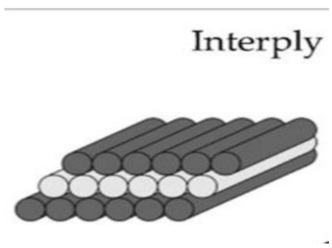

Fig 1.1 interply

- **Intraply Hybrid:**

- **Intraply Hybrid:** Different Fiber types are woven or stitched together within a single ply or fabric. Here, fibers such as carbon and aramid run side by side within the same layer. This design ensures uniform distribution of properties throughout the material and provides better resistance to delamination. However, it is more complex to produce than interply hybrids.

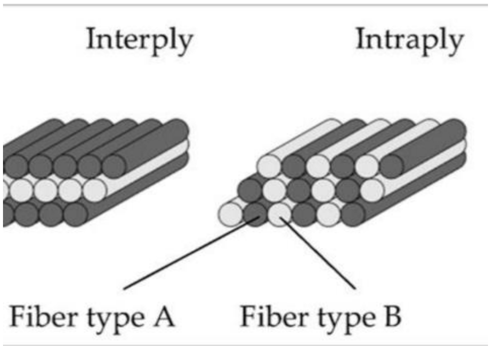

Fig 1.2 intraply

- **Intrayarn Hybrid:** This is the most advanced technique, where different fibers are combined within a single yarn or two before weaving. This method provides homogeneous micro-level blending, giving a material that behaves as a unified hybrid system. It delivers exceptional balance in mechanical performance but is also the most expensive and difficult to manufacture.

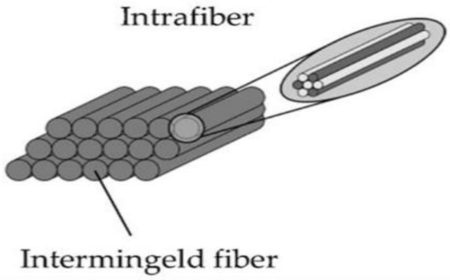

Fig 1.3 intrayarn

Each approach balances stiffness, toughness, and cost. For example, an interply carbon-aramid laminate provides high stiffness on carbon layers and impact protection on aramid layers.

1.2 Sandwich Hybrid Composite Concept

A sandwich hybrid composite is an extension of the hybrid laminate concept, where strong outer skins are separated by a lightweight core[16].

This structure offers several advantages:

- High flexural stiffness: The separation of outer layers by a lightweight core increases the laminate's moment of inertia, improving resistance to bending.
- Energy absorption: Outer layers resist tensile and compressive forces, while the core dissipates impact energy.
- Vibration damping and noise reduction: Flax core mitigates vibrations and reduces acoustic transmission.
- Lightweight and sustainable: Combines natural and synthetic fibers for eco-friendly, high-performance laminates.

Hybrid and sandwich hybrid composites fabricated from aramid, basalt, and flax fibers in an epoxy–bio-silica matrix provide a balanced combination of strength, stiffness, lightweight behavior, impact resistance, thermal stability, and sustainability.

II. MATERIALS AND METHODS

The selection of constituent materials for this study was governed by a rigorous design philosophy aimed at addressing the specific limitations of mono-material composites. The primary objective was to engineer a hybrid composite system that synergizes the distinct advantages of mineral, natural, and synthetic reinforcements. This "multi-scale" approach necessitates a deep understanding of the individual physical, mechanical, and chemical characteristics of each fiber type, as well as their interaction with the polymer matrix. The following subsections detail the properties and scientific rationale for the selection of Basalt, Flax, and Aramid fibers, along with the epoxy matrix system.

Reinforcement Fibers

i. Basalt Fibre

Basalt fiber serves as the primary structural reinforcement in this hybrid system, bridging the performance gap between cost-effective E-glass and high-cost Carbon fibers.

- **Origin and Manufacturing:** Basalt fibers[32] are extruded from naturally occurring volcanic rocks, specifically plagioclase, pyroxene, and olivine. The manufacturing process involves melting the crushed rock at temperatures ranging from 1400°C to 1500°C and extruding it through platinum-rhodium bushings to form continuous filaments. Crucially, this is a single-stage process that requires no secondary chemical additives or complex precursors, distinct from the multi-step production of glass or carbon fibers. This imparts a lower embodied energy and a reduced environmental footprint, aligning with the sustainability goals of this research[35].

- **Chemical and Mechanical Profile:** Chemically, basalt is rich in silica and alumina which contributes to its exceptional chemical stability. It exhibits superior resistance to alkaline and acidic environments compared to E-glass, a critical factor for ensuring long-term durability in corrosive service conditions[26]. Mechanically, the basalt fibers selected for this study possess a tensile modulus of approximately 89 GPa and a tensile strength of 2800 MPa. These values provide the necessary stiffness to the composite laminate.

- **Textile Architecture:** In this work, basalt fibers were utilized in a bidirectional plain-weave fabric form. The plain-weave architecture was selected because the interlacing of warp and weft yarns provides a high degree of fabric stability, minimizing distortion during the manual lay-up process. Furthermore, the crimp inherent in the weaves contribute to through-thickness reinforcement, potentially improving interlaminar fracture toughness.

Fig 2.1 Basalt

ii. Flax Fibre

To address the "green" mandate of modern materials engineering, Flax (*Linum usitatissimum*) was chosen as the natural fiber constituent.

- **Morphology and Microstructure:** Flax[34] is a bast fiber derived from the stem of the plant. Its microstructure is hierarchical, consisting of elementary fibers glued together by pectin. The cell walls are composed of highly crystalline cellulose microfibrils aligned at a low angle (approximately 10°) relative to the fiber axis. This low microfibril angle (MFA) is responsible for the high axial stiffness of flax compared to other plant fibers like jute or coir.

- **The "Lumen" Effect:** A unique morphological feature of flax is the presence of a central hollow channel, known as the lumen. This porous structure significantly reduces the bulk density of the fiber (approximately 1.4–1.5 g/cm³), allowing for the fabrication of lightweight composites. More importantly, the lumen and the amorphous regions within the cell wall act as frictional elements that dissipate energy under dynamic loading. This imparts superior vibration damping and acoustic absorption properties to the hybrid composite, a functional requirement for automotive interior components that purely synthetic composites often fail to meet.

- **Justification for Hybridization:** Despite these advantages, flax is inherently hydrophilic due to the abundance of hydroxyl (-OH) groups on the cellulose backbone. This leads to moisture absorption and potential swelling. By hybridizing flax with hydrophobic Basalt and Aramid layers, the flax core is effectively shielded from environmental exposure, mitigating its primary weakness.

Fig 2.2 Flax

iii. Aramid Fibre

To install high-strain-rate damage tolerance and fracture toughness into the composite, Aramid (aromatic polyamide) fibers were integrated selectively.

- **Molecular Structure:** The aramid fibers[31] used (commercial grade Kevlar-49 type) are characterized by rigid polymer chains containing aromatic rings linked by amide groups. These chains are highly oriented along the fiber axis and are held together by strong transverse hydrogen bonds. This molecular alignment results in extremely high tensile strength and a high modulus of elasticity.

- **Failure Mechanism and Impact Resistance:** Unlike glass or carbon fibers, which are brittle and fail catastrophically under impact, aramid fibers exhibit a unique ductile-like failure mode involving fibrillation. Upon impact, the fibre splits into smaller fibrils, a process that consumes a vast amount of kinetic energy. This energy absorption capability makes aramid the industry standard for ballistic protection and containment structures[6][7].

- **Strategic Placement:** Due to the high cost of aramid fibres relative to basalt and flax, they were not used for the entire bulk of the laminate. Instead, they were employed as "skin" layers. According to sandwich beam theory, the outer layers of a composite experience the highest tensile and compressive stresses during bending. Positioning the tough aramid fibres on the exterior maximizes the flexural strength and impact resistance of the laminate while maintaining economic feasibility.

Fig 2.3 Aramid

iv. Matrix Material

The mechanical integrity of any fibre-reinforced polymer (FRP) is fundamentally dependent on the matrix, which serves to bind the fibres, transfer stress via interfacial shear, and protect the reinforcement from abrasion and environmental degradation.

- **Epoxy Resin System:** A thermosetting epoxy resin[33] system was selected as the continuous phase. Specifically, a Di glycidyl Ether of Bisphenol-A (DGEBA) based resin (LY556). Epoxy was preferred over polyester or vinyl ester resins due to its superior adhesive properties, which are critical for ensuring compatibility between the diverse surface chemistries of the hydrophilic flax and hydrophobic basalt/aramid fibres. Furthermore, epoxy exhibits low volumetric shrinkage during curing (typically < 2%), which minimizes residual internal stresses that could otherwise lead to warping or pre-mature micro-cracking.

Fig 2.4 Epoxy resin

- **Hardener and Stoichiometry:** The resin was combined with a compatible amine-based hardener (HY951) acting as the curing agent. The mixing ratio was strictly controlled in accordance with the manufacturer's stoichiometric recommendations. Precise metering is vital; an excess of resin can lead to plasticization and reduced modulus, while an excess of hardener can cause brittleness.

Fig 2.5 Hardner

III. FABRICATION OF HYBRID COMPOSITE LAMINATES

The fabrication process employed in this study was the Hand Lay-up technique. While labor-intensive, this contact molding method allows for precise control over the stacking sequence and fibre orientation, making it ideal for laboratory-scale experimental validation of novel hybrid architectures.

Mold Preparation

A flat, rigid metallic mold (mild steel plate) of dimensions 300 mm x 300 mm was employed. The surface preparation is a critical first step to ensure surface quality and ease of demolding.

- **Cleaning:** The mold surface was thoroughly cleaned with acetone to remove any dust, grease, or oxidation residues that could contaminate the laminate surface.
- **Release Agent Application:** A commercial-grade polyvinyl alcohol (PVA) or wax-based mold release agent was applied in multiple thin coats. This creates a low-surface-energy barrier, preventing the epoxy from chemically bonding to the metal mold.
- **Layering and Impregnation:** The distinct reinforcements—Basalt, Flax, and Aramid—were precision-cut to the mould dimensions. The fabrication followed a symmetric stacking sequence to prevent thermal warping caused by mismatched coefficients of thermal expansion (CTE) during cure.
- **Wetting Out:** The degassed epoxy mixture was poured onto the mold surface for the first layer. The reinforcement fabric was laid down, and resin was distributed using a serrated steel roller. The rolling action is physically necessary to apply shear pressure, forcing the viscous resin into the fibre tows (bundles) and displacing entrapped air. This ensures thorough "wetting out" of individual filaments, which is essential for load transfer.
- **Stacking:** Subsequent layers were added wet-on-wet. Special care was taken with the flax layers, as natural fibres have a higher resin uptake due to their porous structure. The amount of resin applied was carefully monitored to aim for a consistent fibre volume fraction across specimens.
- **Consolidation and Curing:** Once the stacking was complete, a peel ply was placed on the top surface to provide a textured finish, followed by a release film. A flat caul plate was placed on top of the assembly.
- **Compression:** Dead weights were applied to the caul plate to generate a uniform compressive pressure. This pressure serves two thermodynamic functions: it squeezes out excess resin to optimize the fibre-to-resin ratio, and it helps mobilize and evacuate any remaining volatile gases or air pockets.
- **Cure Cycle:** The laminates were allowed to cure at room temperature for 24 hours. Following the initial cure, a post-curing cycle was implemented in a hot air oven. Post-curing increases the cross-link density of the polymer network, thereby enhancing the glass transition temperature and stabilizing the mechanical properties of the matrix.

IV. MECHANICAL TESTING

To comprehensively evaluate the synergistic effects of the tri-hybrid system, a suite of mechanical tests was conducted. Each test was chosen to isolate specific failure modes and material responses.

1. Tensile Testing

Tensile properties were evaluated in accordance with ASTM D3039 ("Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials").

- **Setup:** Rectangular specimens is mounted in the wedge grips of a servo-hydraulic Universal Testing Machine (UTM). To prevent slippage or crushing of the specimen ends within the grips, aluminum tabs were bonded to the grip sections of the specimens.

- **Procedure:** The test was conducted under displacement control at a constant crosshead speed (typically 2 mm/min). This quasi-static loading rate ensures that strain rate effects do not influence the results.

- **Data Analysis:** An extensometer or strain gauge was used to measure strain. The stress-strain curve generated allows for the calculation of Ultimate Tensile Strength (UTS), Tensile Modulus (Young's Modulus), and elongation at break. The failure mode (fibre pull-out, brittle fracture, or delamination) was recorded to assess the quality of interfacial bonding.

2. Flexural Testing

Flexural strength and modulus were determined using the three-point bending method per ASTM D790.

- **Theory:** Flexural testing is critical for hybrid laminates because it subjects the material to a complex stress state: compressive stress on the top surface, tensile stress on the bottom surface, and interlaminar shear stress at the neutral axis.

- **Setup:** The specimen was placed on two support cylinders, and load was applied via a loading nose at the center of the span. The span-to-depth ratio was maintained (typically 16:1) to ensure that failure occurs due to bending rather than shear.

- **Relevance:** This test specifically validates the "sandwich" design logic. A high flexural strength indicates that the outer Aramid/Basalt skins effectively bearing the tensile and compressive loads, shielding the Flax core.

3. Impact Testing

The dynamic toughness of the composites was assessed using a pendulum impact tester according to ASTM D256 (Izod or Charpy configuration).

- **Procedure:** A notched or un-notched specimen is clamped in the fixture and struck by a heavy pendulum hammer released from a known height. The potential energy lost by the pendulum breaking the specimen is recorded as the absorbed impact energy.

- **Mechanism:** This test serves as the primary indicator of the "Aramid Effect." While pure epoxy or glass/epoxy composites tend to be brittle, the presence of Aramid fibres is expected to significantly increase the energy absorption values due to the fibrillation mechanism and the high strain-to-failure of the aramid skins. The test provides a quantitative measure of the material's ability to resist sudden shocks and prevent catastrophic shattering.

4. Hardness Testing

Surface hardness was measured using a Shore D Durometer in accordance with ASTM D2240.

- **Procedure:** The durometer indentor is pressed vertically into the composite surface with a specific force. The resistance of the material to indentation is indicated on a scale from 0 to 100.

- **Significance:** While often overlooked, hardness testing provides valuable insight into the degree of cure of the epoxy matrix and the surface density of the laminate. It serves as a quality control check; low hardness values may indicate incomplete curing or high void content near the surface. Multiple readings (minimum of 5) were taken at random locations on each specimen to ensure statistical reliability.

V. THE HYBRID EFFECT

The results indicate a "positive hybrid effect," where the experimental tensile strength exceeded the theoretical values predicted by the Rule of Mixtures. This synergy is likely due to the "barrier effect" of hybrid architecture. In a pure flax laminate, failure is often initiated by defects inherent to natural fibres (such as kinks or micro-voids in the cell wall). In the hybrid configuration, the outer layers of Aramid and Basalt act as a high-strength shield, preventing surface micro-cracks from propagating into the weaker flax core. Furthermore, the presence of bio-silica filler in the matrix has likely enhanced the interfacial load transfer. The silica particles act as rigid anchors at the fibre-matrix interface, reducing the stress concentration at the fibre ends and preventing premature debonding.

- **Stress-Strain Behaviour** The stress-strain curves for the hybrid composites typically displayed a bi-linear response. The initial linear region corresponds to the elastic deformation of both fibres and matrix. As the load increased, a "knee" point was observed, marking the onset of micro-cracking in the brittle epoxy matrix and the yielding of the weaker flax fibres. However, unlike the flax-only specimens which failed shortly after this point, the hybrid specimens continued to carry load due to the superior tenacity of the Aramid skins, demonstrating a pseudo-ductile failure mode that is highly desirable for safety-critical applications.

- **Flexural Properties** Flexural testing serves as a critical evaluation for laminated composites, as it subjects the material to a complex stress state combining compression (top face), tension (bottom face), and interlaminar shear (mid-plane). The data clearly demonstrates the dominance of the stacking sequence in determining flexural performance.
- **Moment of Inertia:** In bending, the normal stress varies linearly from zero at the neutral axis to a maximum at the outer surfaces. By positioning the strongest and stiffest fibres (Aramid and Basalt) at the extreme distances from the neutral axis, the Flexural Rigidity of the section is maximized. The outer Aramid layers effectively acted as the "flanges" of an I-beam, bearing the peak tensile and compressive loads.

- **Core Functionality:** The flax fibres, positioned at the neutral axis (the core), experienced minimal normal stress. Their primary role was to maintain the spacing between the stiff outer skins and to transmit shear loads. This efficient distribution of material ensures that the high-cost, high-performance fibres are utilized where the stresses are highest, validating the design logic of the hybrid.

- **Failure Mode in Bending:** The non-hybrid flax laminates failed largely due to tensile rupture on the bottom face at relatively low loads. In contrast, the hybrid specimens exhibited a more complex failure progression. Initial failure was often observed as compressive buckling of the Aramid fibres on the top surface (kinking), followed by delamination at the Basalt/Flax interface. However, the specimen retained significant residual load-carrying capacity, avoiding the sudden, brittle fracture typical of glass/epoxy composites.

- **Impact Strength:** Perhaps the most significant performance leap was observed in the impact testing results. The ability of a material to absorb sudden dynamic energy is a function of its toughness, and the inclusion of Aramid fibres proved transformative in this regard.

- **Energy Absorption Mechanisms:** The hybrid composites demonstrated substantially higher impact energy absorption (toughness) compared to the flax-only samples. This improvement is driven by the specific energy dissipation mechanisms of the constituent fibres.

- **Aramid Fibrillation:** Upon impact, Aramid fibres do not snap cleanly; they undergo fibrillation, splitting into thousands of microscopic fibrils. This process creates a massive increase in surface area and consumes a vast amount of kinetic energy through plastic work.

- **Crack Pinning and Deviation:** The high-modulus Basalt fibres acted as obstacles to the propagating crack front. When a crack encounters a basalt fibre, it is forced to bow or deflect around it, increasing the total crack path length and the energy required to drive failure.

- **Matrix Toughening:** The bio-silica modified matrix also contributed to impact resistance. The hard silica particles induce a mechanism known as "crack pinning," where the crack front is impeded by the particles, requiring higher stress to bypass them

VI. EFFECT OF HYBRIDIZATION

The hybrid composites yielded consistently higher Shore D values compared to the pure flax laminates. Natural fibres like flax are composed of cellulose, hemicellulose, and pectin, which are relatively soft and compliant. In contrast, Basalt is a mineral (rock-based) fibre with high inherent hardness, and Aramid is a high-density crystalline polymer. The presence of these harder phases near the surface directly reinforces the matrix against indentation.

The hardness values also serve as a proxy for fabrication quality. The uniformly high hardness values across the hybrid specimens suggest a low void content and a high degree of cure. It indicates that the hand lay-up and compression molding process successfully consolidated the laminate, minimizing surface porosity. A porous surface would have yielded lower and more variable hardness readings.

- **Morphological and Failure Analysis:** To fully understand the micromechanical origins of the observed properties, the fractured surfaces were analysed. This fractography provides the physical evidence supporting the mechanical data
  .

- **Fibre-Matrix Interface**: In the flax-dominated regions, failure was often characterized by fibre pull-out. This phenomenon occurs when the fibre debonds from the matrix before the fibre itself breaks, indicating a sub-optimal interface due to the chemical incompatibility between the hydrophilic flax and hydrophobic epoxy. However, in the hybrid regions (Basalt/Epoxy and Aramid/Epoxy), the failure mode shifted towards fibre fracture. This indicates a strong interfacial bond; the stress transfer was efficient enough to load the fibres to their breaking point. The bio-silica filler likely played a role here by increasing the friction and mechanical interlocking at the interface.

- **Delamination and Matrix Cracking**: Examination of the flexural failure surfaces revealed delamination primarily at the interface between the stiff Basalt layers and the compliant Flax core. This is a common issue in hybrids due to the mismatch in stiffness (modulus mismatch) between adjacent plies, which generates high interlaminar shear stresses. However, the presence of the bio-silica filler appeared to roughen the matrix texture, potentially providing resistance to this delamination growth. On the compressive side of the flexural specimens, characteristic "kink bands" were observed in the Aramid fibres. Unlike carbon fibres which shatter under compression, Aramid fibres yield plastically by buckling locally. While this limits the ultimate compressive strength, it prevents the sudden, explosive failure seen in carbon composites, contributing to the "graceful failure" mode observed in this study.

VII. CONCLUSION

The present study successfully demonstrated the fabrication and mechanical characterization of hybrid fibre-reinforced polymer composites incorporating basalt, flax, and aramid fibres. The experimental evaluation confirmed that hybridization is an effective approach to overcoming the inherent limitations of natural fibre composites while retaining their sustainability advantages.

Mechanical testing results revealed that the hybrid composites exhibited significant improvements in tensile, flexural, impact, and hardness properties compared to flax-only composites. The inclusion of basalt fibres enhanced stiffness and load-bearing capacity, while aramid fibres contributed to superior toughness and impact resistance. Flax fibres played an important role in reducing the overall weight and environmental impact of the composites. The synergistic interaction among the three fibre types resulted in balanced and optimized mechanical performance.

The study also highlighted the critical influence of stacking sequence on composite behavior. Laminates with high-strength fibres placed in the outer layers showed improved resistance to tensile and flexural loads, while flax fibres positioned in the core contributed to energy absorption and weight reduction. The observed failure mechanisms indicated improved damage tolerance and delayed catastrophic failure in hybrid composites.

Overall, basalt–flax–aramid hybrid composites offer a promising combination of mechanical efficiency, sustainability, and cost-effectiveness. These materials have strong potential for use in automotive, aerospace, marine, and structural applications where lightweight and high-performance materials are required. Future work may focus on optimizing fibre volume fractions, investigating long-term durability, and performing microstructural analysis to further enhance the performance and application scope of these hybrid composite systems.

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