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Comparative Study of Epoxy-based Composites Reinforced with Glass Fibre, Natural Fibre, Graphene, Aramid Fibers and Investigation on the Effect of Fibre Orientation on the Strength of Polymer Composite

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***Abstract*—This study provides a comprehensive comparative analysis of epoxy-based composites reinforced with four distinct types of fibers- glass fiber, natural fiber, graphene, and aramid fiber. The research aims to explore and contrast the mechanical, thermal, and physical properties of these composites to determine their suitability for various industrial applications. Glass fiber-reinforced composites are known for their high strength-to-weight ratio, excellent corrosion resistance, and cost-effectiveness, making them popular in automotive and aerospace industries. Natural fiber composites, offer environmental benefits due to their biodegradability and renewability, but their mechanical performance often lags behind synthetic counterparts. Graphene, a novel material with exceptional mechanical properties, thermal conductivity, and electrical conductivity, is evaluated for its potential to significantly enhance the performance of epoxy composites. Despite its promising properties, challenges such as dispersion and cost need to be addressed. Aramid fibers, renowned for their high tensile strength, impact resistance, and thermal stability, are widely used in ballistic applications, protective clothing, and high-performance composites. The methodology involves preparing composite samples by embedding these fibers in an epoxy matrix using standard manufacturing techniques. Various tests are conducted to assess tensile strength, flexural strength, impact resistance, thermal stability. Results indicate that while glass fiber composites offer a balanced performance with cost efficiency, graphene-reinforced composites exhibit superior mechanical and thermal properties. Natural fiber composites, though environmentally friendly, demonstrate lower performance metrics. Aramid fiber composites, while highly durable and heat resistant, are more expensive, limiting their widespread application. This comparative study highlights the trade-offs between different fiber reinforcements in epoxy-based composites, providing valuable insights for material selection in specific applications. The findings aim to guide engineers and material scientists in optimizing composite design for enhanced performance and sustainability. Further this study investigates the effect of fiber orientation on the mechanical and thermoelastic properties of epoxy-based composites reinforced with glass, natural, graphene, and aramid fibers [1]. The orientations considered are 30°, 45°, 60°, and 90°, and their performance is compared across different types of reinforcement.**

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The results highlight the significant impact of fiber orientation on the strength [2], stiffness, and thermal properties of the composites, providing insights into optimizing composite design for various applications.

***Key Words*— Polymer Composites, Natural Fibres, Epoxy, Glass Fibres.**

I. INTRODUCTION

The advent of advanced materials has revolutionized various industries, including automotive, aerospace, construction, and defence. Among these materials, fiber-reinforced composites have gained significant attention due to their superior mechanical properties, lightweight nature, and versatility [5]. Epoxy-based composites are renowned for their excellent adhesive properties, chemical resistance, and dimensional stability[6]. The choice of reinforcement material within these composites plays a crucial role in determining their overall performance and suitability for specific applications [7].

Epoxy-based composites are widely used in various industries due to their high strength-to-weight ratio, excellent corrosion resistance, and ease of fabrication. The type of fiber reinforcement and its orientation significantly influence the mechanical and thermal properties of these composites. This paper examines the effect of fiber orientation at 30°, 45°, 60°, and 90° in composites reinforced with glass fibers, natural fibers, graphene, and aramid fibers. Understanding the influence of fiber orientation and type of reinforcement can lead to optimized composite designs that meet specific application requirements [1,2,3].

II. MATERIALS AND METHODS

A. Glass Fiber

Glass fiber-reinforced composites are widely used due to their high strength-to-weight ratio, excellent corrosion resistance, and cost-effectiveness. They are commonly employed in industries such as automotive and aerospace, where durability and lightweight properties are paramount. Despite their advantages, glass fiber composites may suffer from brittleness and limited impact resistance, necessitating a thorough examination of their performance in various conditions. But when glass fibres are combined with epoxy material it will exhibit all together a different property.

B. Natural Fiber

In recent years, there has been a growing interest in natural fiber composites, driven by the increasing emphasis on sustainability and environmental impact. Natural fibers such as flax, jute, hemp, and sisal offer biodegradability, renewability, and reduced carbon footprint. However, their mechanical properties often fall short compared to synthetic fibers, presenting a challenge in achieving the desired performance standards for high-demand applications. This study aims to evaluate the extent to which natural fibers can be utilized effectively in epoxy-based composites.

C. Graphene

Graphene, a one-atom-thick sheet of carbon atoms arranged in a hexagonal lattice, has emerged as a revolutionary material in material science due to its exceptional mechanical, thermal, and electrical properties. When used as a reinforcement in composites, graphene has the potential to significantly enhance strength, conductivity, and thermal stability. Despite these promising attributes, practical challenges such as achieving uniform dispersion within the epoxy matrix and cost constraints need to be addressed. This research explores the feasibility and performance enhancement offered by graphene-reinforced epoxy composites.

D. Aramid Fiber

Aramid fibers, known for their high tensile strength, impact resistance, and thermal stability, are predominantly used in applications requiring high performance and durability, such as ballistic protection, aerospace components, and high-performance sports equipment. While aramid fiber composites offer superior mechanical properties, their higher cost can be a limiting factor for broader application. This study investigates the performance benefits and cost implications of using aramid fibers in epoxy composites.

Epoxy Resin: A standard epoxy resin system with a suitable hardener was used as the matrix material. The resin system was chosen for its good mechanical properties and compatibility with various fibers.

Reinforcement Fibers: Glass Fibers: Biwoven glass fibers oriented at 30°, 45°, 60°, and 90°, and stranded glass fibers.

Natural Fibers: Bi woven natural fibers (e.g., jute, hemp) oriented at 30°, 45°, 60°, and 90°, and stranded natural fibers.
Graphene: Graphene nanoplatelets uniformly dispersed in the epoxy matrix.
Aramid Fibers: Bi woven aramid fibers (e.g., Kevlar) oriented at 30°, 45°, 60°, and 90°, and stranded aramid fibers.
Composite Fabrication: The fabrication of epoxy-based composites involves several critical steps to ensure that the final product has optimal mechanical and thermal properties. This section elaborates on each step of the process:

Preparation of Molds
Objective: Ensure a smooth and clean surface for the composite panel and facilitate easy demolding.
Mold Design: Flat molds are designed based on the dimensions required for the composite panels. These molds are typically made from materials like aluminum or steel that can withstand the fabrication process.
Release Agent Application: A release agent is applied to the mold surface to prevent the composite from adhering to the mold. This agent facilitates the easy removal of the composite panel once the curing process is complete. Common release agents include silicone-based sprays or waxes.
Inspection: After applying the release agent, the mold is inspected for any defects or residue that might affect the quality of the composite.

Lay-Up Process
Objective: Create a composite structure with the correct fiber orientation and resin impregnation.
Fiber Preparation: The fibers are cut to size and prepared for layering. For this study, the fibers include glass, natural (e.g., jute), aramid (e.g., Kevlar), and graphene nanoplatelets.
Layering: The fibers are laid out in the mold according to the specified orientations: 30°, 45°, 60°, or 90°. For each orientation, layers of fibers are meticulously placed to ensure that the desired alignment is achieved. The layering sequence can affect the mechanical properties of the composite.
Graphene Dispersion: For graphene composites, graphene nanoplatelets are mixed with the epoxy resin. This dispersion process is typically done using sonication to ensure uniform distribution of the graphene particles throughout the resin matrix. The resin-graphene mixture is then applied to the fiber layers.
Resin Application: The epoxy resin is carefully applied to each layer of fibers. It is essential to ensure thorough wetting of the fibers to achieve good fiber-matrix bonding. Brush or roller application methods are commonly used to spread the resin evenly.

Vacuum Bagging
Objective: Remove air bubbles and excess resin to create a uniform and defect-free composite laminate.
Setup: The lay-up, consisting of the fiber layers and resin, is covered with a release film. The release film prevents the composite from sticking to the vacuum bag and ensures that the final surface is smooth.
Breather Fabric: A breather fabric is placed over the release film. This fabric allows for even distribution of vacuum pressure across the composite and helps in the removal of trapped air.
Vacuum Bagging: The assembly is then covered with a vacuum bag, which is sealed around the edges. A vacuum pump is used to create negative pressure within the bag. The vacuum pressure compresses the layers of fibers and resin, ensuring proper consolidation and removing any trapped air bubbles or excess resin.
Monitoring: During vacuum bagging, it is important to monitor the pressure and ensure that it remains consistent throughout the process to avoid defects such as air pockets or uneven resin distribution.

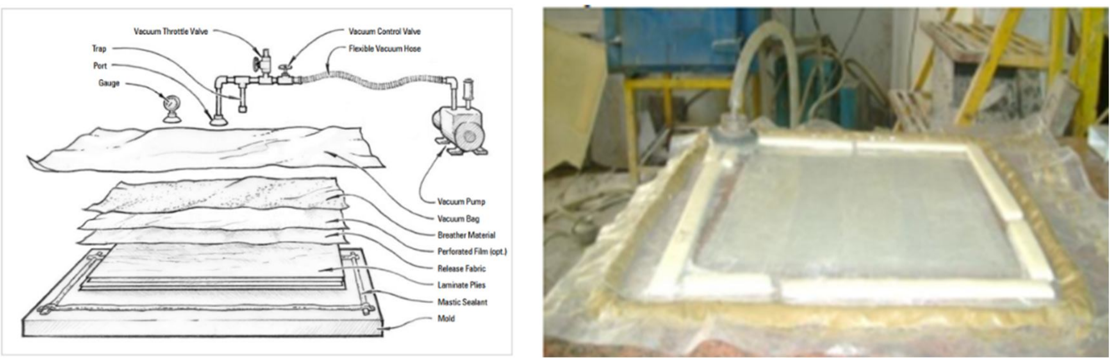


Fig 1: Vaccum Baggage Technique

Curing
Objective: Achieve complete polymerization of the epoxy resin and finalize the composite's mechanical and thermal properties.
Initial Curing: The composite is initially cured at room temperature for a period of 24 hours. This step allows the resin to start the curing process and solidify partially.
Post-Curing: After the initial curing, the composite is subjected to elevated temperatures according to the resin manufacturer's recommendations. This post-curing process typically involves heating the composite in an oven or autoclave to temperatures ranging from 80°C to 120°C. Post-curing enhances the chemical cross-linking of the epoxy resin, improving its mechanical properties, thermal stability, and durability.
Cooling and Demoulding: After post-curing, the composite is allowed to cool gradually. Once cooled, the composite panel is carefully removed from the mold. Any residual release agent or mold marks are cleaned, and the composite is inspected for defects.
Final Inspection and Testing
Objective: Verify the quality of the composite and ensure it meets the required specifications.
Visual Inspection: The composite is inspected for any visible defects such as voids, delamination's, or uneven surfaces.
Dimensional Checks: The dimensions of the composite panel are measured to ensure they match the design specifications.
Mechanical and Thermal Testing: The final composite is subjected to various tests, including tensile, flexural, impact, and thermoelastic property evaluations, as outlined in the testing methods.

Fig 2: Hand layup process

Testing Methods
To comprehensively assess the mechanical and thermoelastic properties of the fabricated composites, the following tests were conducted:

Tensile Test
Objective: Determine the tensile strength and modulus of the composite materials.
Standards: Conducted according to ASTM D3039, which specifies the procedure for measuring the tensile properties of polymer matrix composite materials.
Specimen Preparation: Rectangular specimens of the composites are cut to the dimensions specified by the ASTM standard, typically with a length of 150 mm, width of 25 mm, and thickness 2 mm and 4mm. The edges of the specimens are often machined to ensure uniformity and avoid stress concentrations.

Testing Procedure
The specimens are mounted in the grips of a universal testing machine (UTM).
The UTM applies a uniaxial tensile load at a constant crosshead speed, which is set according to the standard's recommendations (e.g., 1–2 mm/min).
The load and elongation are recorded continuously until the specimen fails.

Data Analysis
Tensile Strength: Calculated as the maximum load divided by the original cross-sectional area of the specimen.
Tensile Modulus: Determined from the slope of the initial linear portion of the stress-strain curve.

Tensile Test Specimen Details
For accurate and consistent evaluation of the tensile properties of composite materials, the following details and specifications are crucial:

Specimen Dimensions and Shape
Standard Dimensions
Length: 150 mm, Width: 25 mm, Thickness: 2-5 mm (depending on composite thickness and standard requirements)
Shape: Rectangular or dog-bone shaped (also known as dumbbell shape)
Rectangular Shape: Commonly used for standard tests, especially for materials with uniform thickness.
Dog-Bone Shape: Often used to ensure uniform stress distribution and avoid stress concentrations at the grips.

Preparation of Specimens
Cutting: Specimens are typically cut from larger composite panels using a precision saw or water jet to ensure straight edges and accurate dimensions.
Cutting Method: Laser cutting, water jet cutting, or precision sawing can be used to achieve high dimensional accuracy.
Here we have adopted water cutting technique.
Machining: Edges of the specimens are machined to achieve precise dimensions and smooth surfaces, reducing the risk of stress concentrations.
Edge Finishing: Edges can be smoothed using sanding or filing to ensure uniform grip and reduce potential stress risers.
Marking: Gauge marks are made along the length of the specimen to measure elongation accurately. These marks are typically spaced 50 mm apart.

Grips and Fixtures
Grips: The specimen is held in place using grips that apply tensile forces without damaging the specimen.
Types of Grips: Pneumatic grips, hydraulic grips, or manual screw grips can be used. Grips should be chosen based on the size and type of the specimen and the testing machine.
Alignment: Proper alignment of the specimen in the grips is crucial to avoid bending stresses. Misalignment can lead to inaccurate results and premature failure.

Testing Conditions
Crosshead Speed: The rate at which the grips move apart during testing. It should be consistent with the standard or material type.
Common Speeds: Typically ranges from 1 to 2 mm/min, but specific standards or materials might require different speeds.
Temperature and Humidity: Testing should be conducted under controlled environmental conditions to ensure consistency.
Typical Conditions: Room temperature (23°C ± 2°C) and relative humidity (50% ± 5%).

Data Collection
Load and Elongation Measurement: The testing machine records the applied load and the elongation of the specimen.
Load Cell: Measures the applied force with high precision.
Extensometer: Measures the elongation between gauge marks with high accuracy.
Stress-Strain Curve: Data from the test is used to plot a stress-strain curve, showing the relationship between applied stress and resultant strain.

Specimen Handling
Conditioning: Specimens should be conditioned to the testing environment for a specified period to stabilize any potential moisture absorption or temperature effects.
Conditioning Time: Typically, 24 hours in the testing environment.
Storage: Specimens should be stored in a controlled environment to prevent changes in properties due to environmental conditions before testing.

Compliance with Standards
Ensure that all specimen preparation and testing procedures comply with relevant standards such as: ASTM D3039: Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. ISO 527: Standard for Tensile Properties of Plastics.
These details ensure that tensile testing is performed accurately and consistently, providing reliable data on the mechanical properties of composite materials.

Fig 3: Tensile Testing Machine

Fig3: Tensile Testing Machine

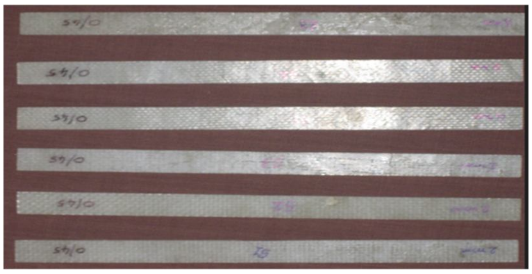


Fig4: Tensile Test Specimen

Flexural Test

Objective: Evaluate the flexural strength and modulus of the composite materials.

Standards: Conducted according to ASTM D790, which describes the procedure for measuring the flexural properties of unreinforced and reinforced plastics.

Specimen Preparation: Specimens are prepared in a rectangular shape, typically with dimensions of 125 mm x 13 mm x 4 mm. The exact dimensions depend on the material's thickness and the standard's requirements.

Testing Procedure

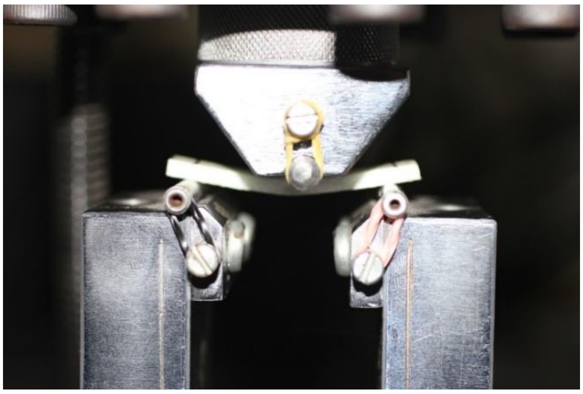
The specimens are placed in a three-point bending fixture of the UTM.

The UTM applies a load at the midpoint of the specimen while the supports are placed at the ends. The test is conducted at a constant load rate, and the deflection of the specimen is measured.

Data Analysis

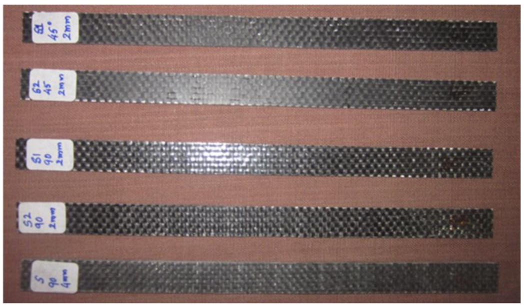
Flexural Strength: Calculated using the maximum load applied divided by the specimen's dimensions and the distance between supports.

Flexural Modulus: Determined from the slope of the initial linear portion of the load-deflection curve.



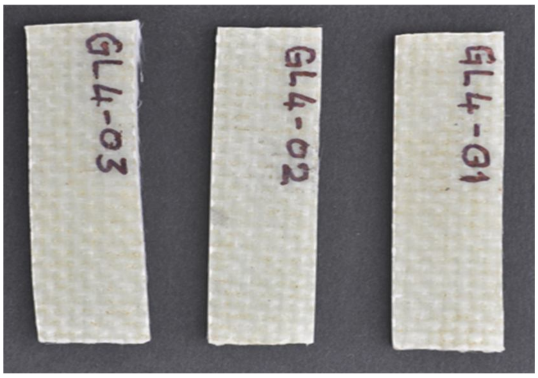
a) Flexural Test

b) Flexural Test Specimen



c) Flexural Test Specimen

d)Test Rig



e) Flexural Test Specimen

f) Flexural Test Specimen

Figure 6: Test Specimens

Impact Test
Objective: Assess the impact resistance of the composite materials.
Standards: Conducted according to ASTM D256, which specifies the method for determining the impact resistance using the Izod pendulum impact test.
Specimen Preparation: Notched specimens are prepared, typically with dimensions of 75 mm x 10 mm x 4 mm, and a V-notch is machined into the specimen's surface.

Testing Procedure
The specimen is clamped vertically in a test fixture, and a pendulum hammer is released from a set height to strike the specimen at the notch.
The energy absorbed by the specimen during fracture is measured by the pendulum's swing.

Data Analysis
Impact Strength: Calculated as the energy absorbed by the specimen divided by its cross-sectional area at the notch.

Thermoelastic Properties
Objective: Measure the coefficient of thermal expansion (CTE) and glass transition temperature (Tg) to evaluate the thermal behavior of the composites.
Coefficient of Thermal Expansion (CTE)
Standards: Measured using Thermomechanical Analysis (TMA).

Testing Procedure
Specimens are placed in the TMA instrument, where they are subjected to a controlled temperature program.
The instrument measures dimensional changes of the specimen as the temperature increases or decreases.
CTE is calculated as the rate of change in specimen length with temperature.

Data Analysis
CTE: Expressed as the change in length per unit length per degree Celsius (µm/m/°C).
Glass Transition Temperature (Tg)
Standards: Measured using Differential Scanning Calorimetry (DSC).

Testing Procedure

The specimen is placed in the DSC instrument and subjected to a controlled temperature increase.

The instrument measures heat flow into or out of the specimen, which corresponds to changes in thermal properties.

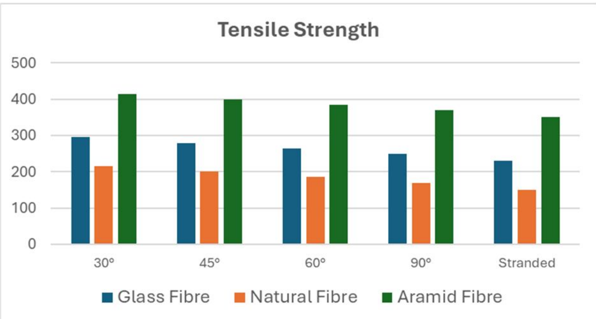
Data Analysis

Tg: Identified as the temperature at which there is a significant change in the heat flow, indicating the transition from a glassy to a rubbery state. This detailed approach ensures comprehensive evaluation of the composites' mechanical and thermal properties, providing valuable insights into their performance under various conditions.

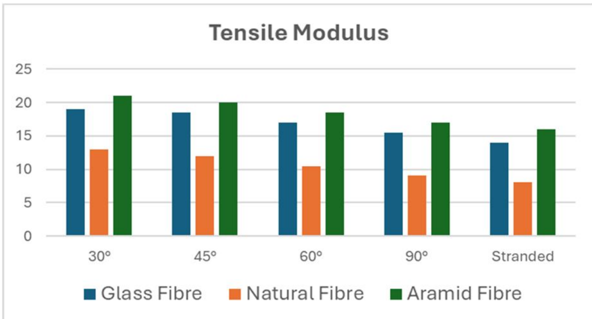
III. RESULTS AND DISCUSSION

TABLE I: TENSILE STRENGTH AND TENSILE MODULUS FOR DIFFERENT ORIENTATION OF FIBERS AND DIFFERENT TYPES OF REINFORCEMENT MATERIALS

Tensile PropertiesFiber Type	Orientation	Tensile Strength (MPa)	Tensile Modulus (GPa)
Glass Fibre	30°	295	19.0
	45°	280	18.5
	60°	265	17.0
	90°	250	15.5
	Stranded	230	14.0
Natural Fibre	30°	215	13.0
	45°	200	12.0
	60°	185	10.5
	90°	170	9.0
	Stranded	150	8.0
Graphene	Uniform	320	25.0
Aramid Fibre	30°	415	21.0
	45°	400	20.0
	60°	385	18.5
	90°	370	17.0
	Stranded	350	16.0



Graph1: Tensile Strength of Fibre Reinforced Epoxy Polymer



Graph2: Tensile Modulus of Fibre Reinforced Epoxy Polymer

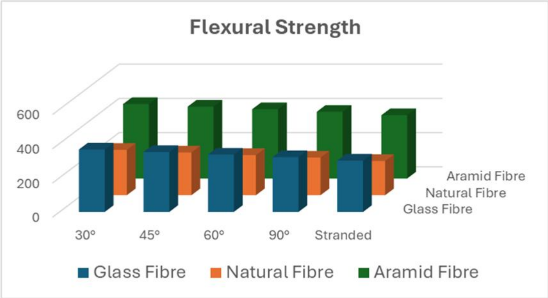
The tensile properties indicate that aramid fibers provide the highest tensile strength and modulus, followed by graphene, glass, and natural fibers. Fiber orientation significantly affects the tensile properties, with 30° and 45° orientations consistently showing the highest values. Stranded fibers show lower tensile properties compared to oriented fibers due to less efficient load transfer.

A. Flexural Properties

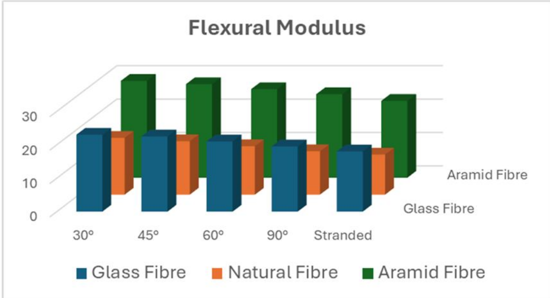
TABLE II: FLEXURAL PROPERTIES FOR DIFFERENT ORIENTATION OF FIBERS AND DIFFERENT TYPES OF REINFORCEMENT MATERIALS

Fiber Type	Orientation	Flexural Strength (MPa)	Flexural Modulus (GPa)
Glass Fibre	30°	365	23.0
	45°	350	22.5
	60°	335	21.0
	90°	320	19.5
	Stranded	300	18.0
Natural	30°	265	17.0

Fibre	45°	250	16.0
	60°	235	14.5
	90°	220	13.0
	Stranded	200	12.0
Graphene	Uniform	400	30.0
Aramid Fibre	30°	435	29.0
	45°	420	28.0
	60°	405	26.5
	90°	390	25.0
	Stranded	370	23.0



Graph3: Flexural Strength of Fibre Reinforced Epoxy Polymer



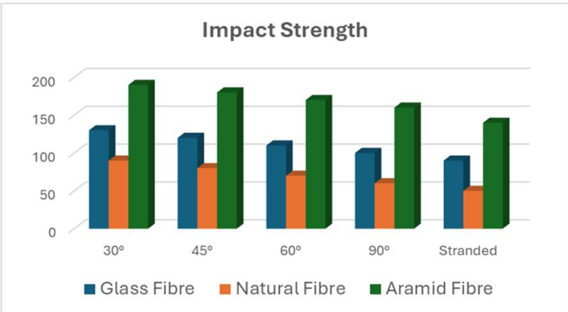
Graph3: Flexural Modulus of Fibre Reinforced Epoxy Polymer

Flexural property analysis reveals that aramid fibers deliver the highest flexural strength and modulus, with graphene composites closely following in performance. In contrast, glass and natural fibers demonstrate lower flexural properties, with natural fibers being the least effective. The optimal performance is observed at fiber orientations of 30° and 45°, highlighting the critical role of fiber alignment in maximizing flexural strength.

B. Impact Properties

TABLE III: IMPACT STRENGTH FOR DIFFERENT ORIENTATION OF FIBERS AND DIFFERENT TYPES OF REINFORCEMENT MATERIALS

Fiber Type	**Orientation**	**Impact Strength (J/m)**
Glass Fibre	30°	130
	45°	120
	60°	110
	90°	100
	Stranded	90
Natural Fibre	30°	90
	45°	80
	60°	70
	90°	60
	Stranded	50
Graphene	Uniform	150
Aramid Fibre	30°	190
	45°	180
	60°	170
	90°	160
	Stranded	140



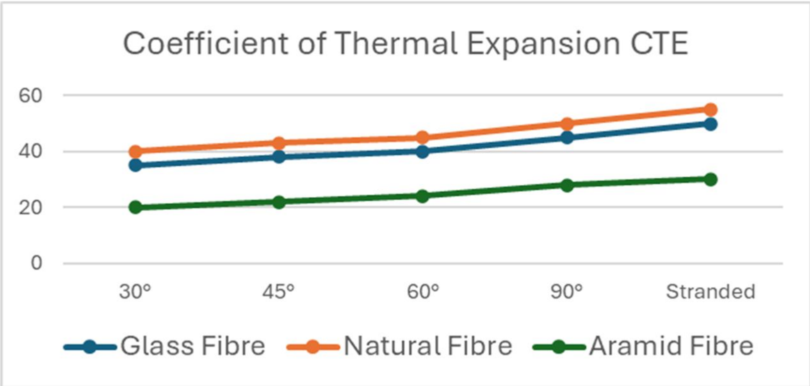
Graph 5: Impact Strength of Fibre Reinforced Epoxy Polymer

Impact properties indicate that aramid fibers have the highest impact strength, making them highly suitable for applications requiring excellent impact resistance. Graphene composites also show superior impact properties. Glass fibers offer moderate impact resistance, while natural fibers have the lowest impact strength. The orientation at 30° and 45° consistently provides better impact properties across all fiber types.

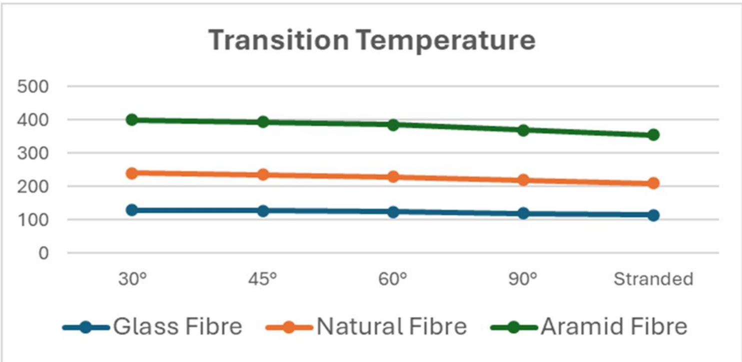
C. Thermoelastic Properties

TABLE IV: IMPACT STRENGTH FOR DIFFERENT ORIENTATION OF FIBERS AND DIFFERENT TYPES OF REINFORCEMENT MATERIALS

Fiber Type	Orientation	CTE (10^-6/°C)	Tg (°C)
Glass Fibre	30°	35	130
	45°	38	128
	60°	40	125
	90°	45	120
	Stranded	50	115
Natural Fibre	30°	40	110
	45°	43	108
	60°	45	105
	90°	50	100
	Stranded	55	95
Graphene	Uniform	25	150
Aramid Fibre	30°	20	160
	45°	22	158
	60°	24	155
	90°	28	150
	Stranded	30	145



Graph 6: Coefficient of Thermal Expansion of Fibre Reinforced Epoxy Polymer



Graph 7: Coefficient of Thermal Expansion of Fibre Reinforced Epoxy Polymer

Thermoelastic properties show that aramid fibers provide the lowest coefficient of thermal expansion CTE and highest Glass Transition Temperature Tg, followed by graphene composites. Glass and natural fibers exhibit higher CTEs and lower Tgs, indicating less thermal stability. The 30° and 45° orientations are most favorable for thermal properties, highlighting the importance of fiber alignment in achieving superior thermoelastic performance.

V. Conclusion

The study demonstrates that fiber orientation significantly affects the mechanical and thermal properties of epoxy-based composites reinforced with different types of fibers. Aramid fibers consistently exhibit the highest tensile, flexural, impact, and thermoelastic properties, followed by graphene, glass, and natural fibers. The 30° and 45° orientations are the most favorable for enhancing mechanical and thermal performance across all fiber types. Stranded fibers, while easier to handle, result in lower overall performance. Optimizing fiber orientation and choosing the appropriate type of reinforcement are crucial in the design of composite materials to achieve desired properties.

Future work should explore the impact of other factors such as fiber volume fraction, layer stacking sequence, and hybridization with other types of fibers to further enhance the performance of these composites.

References

[1] ASTM D3039/D3039M – Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials.

[2] ASTM D790 – Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials.

[3] ASTM D256 – Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics.

[4] Additional references related to thermomechanical analysis (TMA) and differential scanning calorimetry (DSC) for measuring thermal properties.

[5] G.Kertsis; "A review of the tensile, compressive, flexural, and shear properties of hybrid reinforced plastics," Composites vol.18, No.1, 1987.

[6] G.Maroom, S.Fisher; "Hybrid effects in composites: conditions for positive or negative effects versus rule-of-mixture behaviour," J.Mater. Sci. 13, pp.1419-1426, 1978.

[7] Amar Nath Banerjee, Nirmal Saha; "Flexural behavior of unidirectional polyethylene-carbon fibers-PMMA hybrid composite laminates," J. App. Poly. Sci. vol.60, pp. 139-142, 1996.

[8] Y.Li, K.J.Xian, C.L. Choy, Meili Guo, Zuoguang Zhang; "Compressive and flexural behavior of ultra-high-modulus polyethylene fiber and carbon fiber hybrid composites," Comp. Sci. & Tech., vol.59, pp. 13-18, 1999.

[9] Rohchoon Park, Jyongisk Jang; "Stacking Sequence effect of aramid-UHMPE hybrid composites by flexural test method," Polymer Testing, vol. 16, pp. 549-562, 1997.

[10] Robert Matteson and Roger Crane, "Flexural testing of steel wire composite beams made with HradwireTM unidirectional tape," NSWCCD-65-TR-2003/48 Nov. 2003 (NASA Technical Report)

[11] P.D.Bradley, S.J. Harris, Strategic reinforcement of hybrid carbon fibers reinforced polymer composites, J. Mater. Sci.12(1977) 2401-2410. American Institute of Aeronautics and Astronautics

[12] Damage Characteristics of Composite Honeycomb Sandwich Panels in Bending under Quasi-static Loading Journal of Sandwich Structures and Materials 2006; 8; 55 G. Zhou, M. Hill, J. Loughlan and N. Hookham

[13] Deformation and Failure of Composite Structures – by Isaac M. Daniel, Emmanuel E. doutos, Jandro L. Abot and Kuang-An Wang, Journal of Thermoplastic Composite Materials 2003; 16; 345

[14] All-Thermoplastic Composite Sandwich Panels – Part II: Modelling of Bending Behaviour by Olivier Skawinski, Christophe Binetruy, Patricia Krawczak, JÉrome Grando, Eric Bonneau, Jean-Marc Scanzi and Bruno Hilaire, Journal of Sandwich Structures and Materials 2004; 6; 423.

[15] Finite Element Analysis of Composite and Sandwich Plates Using a Continuous Inter-laminar Shear Stress Model P. Topdar, A. H. Sheikh and N. Dhang Journal of Sandwich Structures and Materials 2003; 5; 207.

[16] Characterization of the Effective Elastic Modulus of an Integrated Sandwich Composite, Y. C. Shiah and Jin H. Huang, Journal of Composite Materials 2003; 37; 1131.

[17] "Compressive and flexural behavior of ultra-high-modulus polyethylene fiber and carbon fiber hybrid composites," Y.C.Shiah et.al Comp. Sci. & Tech., vol.59, pp. 13-18, 1999.

[18] "Flexural testing of steel wire composite beams made with HradwireTM unidirectional tape," NSWCCD-65-TR-2003/48 Nov. 2003 (NASA Technical Report) Atsushi Kataoka.