EXPERIMENTAL INVESTIGATION OF MECHANICAL PROPERTIES OF ACRYLIC, SIC, AND BORON FIBER COMPOSITES FABRICATED BY HAND LAY-UP TECHNIQUE

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ABSTRACT

Composite materials have gained significant attention in modern engineering applications due to their high strength-to-weight ratio, durability, and versatility. Synthetic fiber-reinforced polymer composites, particularly those reinforced with Acrylic fiber, Boron fiber, and Silicon Carbide (SiC) fiber, exhibit superior mechanical properties and are widely used in aerospace, automotive, marine, defense, and structural applications. The present study focuses on the fabrication and mechanical characterization of epoxy-based hybrid composites reinforced with different combinations of Boron fiber, Acrylic fiber, and SiC fiber with 10 g of Zinc Oxide (ZnO) powder as a secondary reinforcement.

Seven composite variations were prepared using the hand lay-up fabrication technique, including Boron + ZnO, Acrylic fiber + ZnO, SiC fiber + ZnO, Boron + Acrylic fiber + ZnO, SiC fiber + Boron + ZnO, Acrylic fiber + SiC fiber + ZnO, and Boron + Acrylic fiber + SiC fiber + ZnO. The composite specimens were fabricated according to ASTM standards and cut into required dimensions for mechanical evaluation. The mechanical performance of the composites was investigated through tensile testing, flexural testing, impact testing, and hardness testing. In addition, Scanning Electron Microscopy (SEM) analysis was conducted to study the surface morphology, fiber–matrix interaction, and dispersion of ZnO particles within the composite structure.

The experimental results indicate that hybrid fiber composites exhibit improved mechanical properties compared to single-fiber composites due to better stress transfer and reinforcement synergy. SEM observations revealed effective dispersion of ZnO particles and enhanced interfacial bonding between fibers and the epoxy matrix. The developed hybrid composites demonstrated promising mechanical performance, making them suitable for lightweight structural and engineering applications requiring high strength and reliability.

Keywords: *Acrylic, Boron, Silicon Carbide, Zinc Oxide powder, Tensile, Flexural, Impact, Hardness tests.*

1.1 INTRODUCTION

A fiber is a slender, thread-like material with a length far greater than its diameter. It serves as the fundamental element in textiles, ropes, brushes, and composite materials. Fibers can be spun into yarns, woven into fabrics, or used as reinforcements in composites. Any material that can be drawn into fine filaments and possesses high strength, flexibility, and durability qualifies as a fiber.

Composite materials possess properties such as high fatigue life, wear and heat resistance, low weight, and excellent strength-to-weight ratio. They are durable, corrosion-resistant, and can be easily molded into complex shapes. Their renewable and biodegradable nature adds environmental value. Due to their strength, resilience, and design flexibility, composites are widely used in surface transportation and other engineering applications.

1.1.1ADVANTAGES OF COMPOSITES

Composite materials combine the strengths of different substances to create stronger, lighter, and more durable structures. For example, in mud and straw bricks, straw reinforces the mud, improving its ability to withstand compression. The individual materials in a composite retain their distinct properties while working together to deliver improved overall performance.

1.1.2 APPLICATIONS OF COMPOSITE

Composite materials used in construction and engineering are made by combining two or more distinct materials that remain separate within the structure. A common example is concrete, where cement binds gravel, and steel rebar often provides additional reinforcement, forming a strong multi-phase composite.

Figure 1.4 Applications of composite

The commercial use of composite materials is expanding rapidly, especially in the transportation industry, which now surpasses aerospace in demand. Advances in polymer resins and high-performance fibers like glass, carbon, and aramid have lowered costs and broadened applications. Today, composites are used in fuel cylinders, wind turbine blades, protective armor, and industrial components. In many cases, replacing metals with composites provides significant weight and cost savings.

2 LITERATURE REVIEW

Several researchers have investigated the fabrication, characterization, and mechanical performance of fiber-reinforced composite materials using different reinforcement and matrix combinations.

Rohith S., Yashwanth N., and Rathnakar G. investigated the mechanical behavior of epoxy-based hybrid composites reinforced with jute fibers and boron carbide particles. Boron carbide, known for its exceptional hardness and wear resistance, significantly improves the structural strength of polymer composites. Their findings indicate that hybrid composites containing jute fiber and boron carbide exhibit improved mechanical performance, making them suitable for aerospace, automotive, marine, and ballistic protection applications.

Abhilash Gowda T.H., Madhusudhan T., and Bhanuprakash N. studied the tensile and flexural behavior of polymer composites reinforced with various natural fibers and filler materials. The researchers fabricated composite specimens using fibers such as jute, hemp, coir, sisal, bamboo, and banana, combined with fillers including silicon carbide, tungsten carbide, fly ash, rubber particles, eggshell powder, and rice husk. The experimental results demonstrated that the type of reinforcement and filler significantly influences the mechanical strength and stiffness of the composite materials.

Kommineni Madhu and Pavan Kumar focused on the development of lightweight reinforced polymer composites using natural fibers as reinforcement materials. Their research emphasized the use of jute fiber due to its low cost, high strength, and easy availability. The study examined the mechanical performance of epoxy composites reinforced with jute and basalt fibers, evaluating properties such as hardness, tensile strength, and resistance to mechanical stress.

Arnav, Ankit Kumar Yadav, Saddaf Kamran Ali, S. M. Uruf Negami, Rahul Malik, and Vishal Sharma investigated aluminum matrix composites reinforced with boron carbide and silicon carbide particles. The composites were fabricated using the stir casting technique, and the mechanical properties were evaluated experimentally. The results showed that the addition of ceramic reinforcements significantly improved the hardness and tensile strength of AA2024 aluminum alloy.

Larissa Wahl and co-researchers explored the fabrication of boron carbide–based composites using binder jetting additive manufacturing followed by liquid silicon infiltration to produce reaction-bonded boron carbide structures. The printed components were further compacted through static pressing to achieve improved microstructural uniformity and density while preserving complex geometries. The study also examined the influence of binder content on residual silicon levels within the composite.

Mohammad Giyahudeen and colleagues analysed the tensile behavior of glass fiber reinforced polymer composites containing silicon carbide reinforcement. Single lap joints were fabricated using unidirectional and bidirectional GFRP laminates, and their mechanical performance was evaluated through experimental testing, numerical modeling, and finite element analysis using ANSYS. The study provided valuable insights into joint performance and structural reliability.

M. K. N. Sateesh and J. Srikanth investigated hybrid composite laminates reinforced with carbon fiber, Kevlar fiber, and E-glass fiber using epoxy resin as the matrix material. The composites were fabricated through the hand lay-up technique and reinforced with graphite particles. Mechanical tests including tensile, flexural, impact, and hardness evaluations were conducted according to ASTM standards to assess the structural performance of the composites.

Manohar and Javeed Shaik studied lightweight polymer composites reinforced with glass fibers and carbon fibers. Their research highlighted the advantages of Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP) composites in engineering applications. The study emphasized that the mechanical properties of composites can be tailored through appropriate selection of fiber type, orientation, and fabrication method.

Muzeer Saiyed, L. Sushma, and M. Natesan investigated carbon fiber reinforced epoxy composites fabricated through the hand lay-up method. Laminates were prepared with different stacking configurations including symmetric, cross-ply, and angle-ply orientations. Mechanical testing such as tensile and bending tests were conducted to analyze stress, strain, displacement, and Young's modulus for different fiber orientations.

Girish C. Mekalke and S. R. Basavaraddi examined the effect of fabrication techniques on the mechanical and fire behavior of epoxy-based hybrid composites. The composites were produced using hand lay-up, vacuum bagging, and resin infusion processes. The results indicated that composites fabricated through vacuum bagging exhibited significantly lower smoke emission and improved fire resistance compared to those produced by hand lay-up methods.

Ramakishore and Manikanta Alluri conducted a comprehensive review on the low-velocity impact behavior of fabric reinforced polymer composites. The study summarized various research findings related to impact resistance in composites reinforced with glass, carbon, Kevlar, and hybrid fiber systems. The authors also discussed failure mechanisms, fabrication techniques, and testing standards associated with impact performance.

Raviraja Atmakuri and Ashok Kumar Reddy developed hybrid polymer composites reinforced with carbon, glass, and Kevlar fibers to improve flexural and impact performance. Their research focused on the influence of different stacking sequences on the mechanical behavior of hybrid composites, highlighting the synergistic effects achieved through multi-fiber reinforcement systems.

3 MATERIALS USED

3.1. ACRYLIC FIBER

Acrylic fiber is a synthetic material made mainly from polyacrylonitrile (PAN), designed as a lightweight, soft, and warm alternative to wool. Produced through wet or dry spinning, it forms long, continuous filaments. Acrylic fibers are durable, resisting sunlight, chemicals, and moths, and are widely used in knitwear, carpets, upholstery, and outdoor fabrics due to their colorfastness and ease of maintenance. However, they absorb little moisture and have limited heat resistance, restricting their use in high-temperature applications.

Figure 3.1 Acrylic fiber

3.2. SILICON CARBIDE (SIC) FIBER

Silicon Carbide fibers are inorganic ceramic fibers made from silicon and carbon atoms. These fibers are produced through pyrolysis of polymer precursors, such as polycarbosilane. SiC fibers are extremely strong, stiff, and thermally stable, maintaining their mechanical integrity at temperatures exceeding 1500°C. They are primarily used in aerospace, nuclear, and turbine components, especially as reinforcement in metal and ceramic matrix composites. SiC fibers exhibit excellent oxidation resistance, corrosion resistance, and dimensional stability, making them suitable for harsh environments where metals would fail.

Figure 3.2 Silicon Carbide fiber

3.3. BORON FIBER

Boron fiber is an inorganic high-strength fiber produced by chemical vapor deposition (CVD) of boron on a tungsten filament core. It is extremely stiff and strong, though brittle and costly. The fiber's surface has an amorphous boron coating that contributes to its high compressive and tensile strength. Boron fibers are used in aerospace structures, sporting goods, and high-performance composites where stiffness and dimensional stability are critical. They are often embedded in epoxy or aluminum matrices to create lightweight, high-strength composites.

Figure 3.3 Boron fiber

3.4. EPOXY LY556

In the hand lay-up process, Araldite LY 556 epoxy resin is commonly used as the matrix material to bind and reinforce fibers such as glass, carbon, or natural fibers. The resin serves as the continuous phase that transfers loads between the fibers and provides structural integrity to the composite. Before beginning, the LY 556 resin is mixed with a suitable hardener (such as HY 951 or HY 951K) in a specific ratio, typically by weight. This mixture initiates a chemical reaction that allows the resin to cure and harden over time, forming a strong and rigid composite structure.

Figure 3.4 Araldite LY 556 epoxy resin

The process begins by preparing the mould surface with a release agent to prevent sticking. Layers of fiber reinforcement (e.g., glass fiber mats or woven roving) are then placed on the mould, and the mixed LY 556 epoxy resin is applied evenly using brushes or rollers. The resin impregnates the fibers, ensuring complete wetting and removal of air bubbles, which is essential for achieving a void-free laminate. Several layers are built up in this way until the desired thickness is reached. Care must be taken to control the amount of resin applied too little can cause dry spots, while too much increases weight and reduces mechanical strength.

Once all layers are in place, the composite is left to cure at room temperature or under mild heating, depending on the hardener used. During curing, the epoxy resin cross-links and solidifies, forming a rigid and durable composite material. After full curing, the laminate is removed from the mould and trimmed to the required dimensions. The resulting epoxy–fiber composite exhibits excellent strength, stiffness, and resistance to chemicals and environmental degradation, making it suitable for structural applications in automotive, marine, and aerospace industries.

3.5. HARDENER HY951

In the hand lay-up process, Araldite HY 951 acts as the hardener (curing agent) for the epoxy resin LY 556. It is typically a low-viscosity aliphatic or aromatic amine hardener that reacts chemically with the epoxy groups in LY 556 to form a cross-linked, thermoset network. Before application, the resin and hardener are measured accurately usually in a mixing ratio of 100 parts of LY 556 to 10 parts of HY 951 by weight. This precise proportion is critical; too much or too little hardener can weaken the final composite or prevent complete curing. The two components are mixed thoroughly until a uniform blend is achieved, ensuring the chemical reaction proceeds evenly throughout the resin.

Figure 3.5 Hardener HY951

3.6. ZINC OXIDE POWDER

When incorporating Zinc Oxide Powder into a hand-lay-up composite process, the powder is first dispersed in the liquid resin matrix (for example an epoxy resin) before the fiber reinforcement is laid. For instance, researchers added ZnO nanoparticles into an epoxy resin and manually layered carbon fibers using the hand-lay-up technique. The role of the ZnO is to act as a filler or nanofiller, modifying the matrix behavior: it can enhance properties such as impact resistance, thermal stability or interfacial bonding with fibers when well dispersed.

After mixing the ZnO into the resin and hardener mix, the fiber mat is placed onto the mould and the ZnO-modified resin is applied over the reinforcement layers. The lay-up proceeds layer by layer until the required thickness is achieved, ensuring that the resin fully wets the fibers and the ZnO particles are uniformly distributed so that voids and agglomeration are minimized. For example, a study found that when ZnO was used in a synthetic composite via hand lay-up, it influenced flexural strength depending on loading and dispersion.

Figure 3.6 Zinc Oxide Powder

4 HAND LAYUP FABRICATION PROCESS AND TESTINGS

4.1 HAND LAYUP FABRICATION PROCESS

The hand lay-up process is one of the simplest and most commonly used methods for fabricating fiber-reinforced polymer composites. In this process, fibers such as glass, carbon, or natural fibers are manually placed in layers over a mould surface that has been coated with a release agent to prevent sticking. A thin layer of resin (such as epoxy LY 556) mixed with a suitable hardener (like HY 951) is applied to the mould to form the first layer. This resin acts as the matrix, binding the fibers together and transferring loads within the composite.

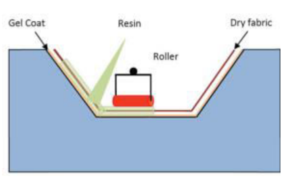


Figure 4.1 Hand lay-up process

Once the first layer of resin is applied, fiberglass mats or woven fabric are laid on top, and more resin is brushed or rolled over them to ensure complete wetting of the fibers. This step is repeated several times, alternating layers of fiber and resin, until the desired thickness of the composite laminate is achieved. During this process, rollers or brushes are used to remove air bubbles and ensure uniform resin distribution, which helps improve the mechanical strength and finish of the composite. The key is to achieve full impregnation of the fibers without trapping air voids.

After the lay-up is complete, the laminate is left to cure either at room temperature or under mild heating, depending on the resin–hardener system used. Curing allows the resin to harden through a chemical reaction, forming a rigid, durable composite structure. Once fully cured, the composite is carefully removed from the mould, trimmed, and finished as required. The hand lay-up process is widely used because it is low-cost, simple to perform, and suitable for producing large or complex parts such as boat hulls, vehicle panels, and wind turbine blades.

4.2 STEP BY STEP PROCESS

1. **Mold preparation:** The mold is cleaned and coated with a release agent to prevent the part from sticking. A gel coat is often applied to the mold first to form the outer surface of the finished part.

2. **First reinforcement layer:** The first layer of reinforcement material, such as a woven fabric or chopped strand mat, is placed in the mold.
3. **Resin application:** A resin-catalyst mixture is applied to the reinforcement, either by pouring or brushing.
4. **Resin impregnation:** The resin is thoroughly worked into the reinforcement using a brush or roller to ensure the material is fully saturated and to eliminate trapped air bubbles.
5. **Building subsequent layers:** Additional layers of reinforcement and resin are applied until the desired thickness is reached. Each layer is consolidated with a roller to remove air and ensure proper adhesion to the layer below.
6. **Curing:** The laminate is allowed to cure. This can happen at room temperature, or the part can be placed in an oven for a specific curing temperature, depending on the resin system used.
7. **Demolding:** Once the composite is fully cured, it is carefully removed from the mold.

4.3 SPECIMEN COMPOSITIONS

Following specimen was fabricated by hand layup technique.

Following specimen was fabricated by hand layup technique.

- Boron fiber+10grms Zinc Oxide Powder
- Acrylic Fiber+10grms Zinc Oxide Powder
- SiC Fiber+10grms Zinc Oxide Powder
- Boron fiber + Acrylic Fiber+10grms Zinc Oxide Powder
- SiC Fiber + Boron fiber+10grms Zinc Oxide Powder
- Acrylic Fiber+ SiC Fiber +10grms Zinc Oxide Powder
- Boron fiber + Acrylic Fiber+ SiC Fiber +10grms Zinc Oxide Powder

4.4 TENSILE TESTING OF COMPOSITES

The tensile testing of composite materials using a tensometer is generally conducted in accordance with the ASTM D3039/D3039M standard, which specifies procedures for polymer matrix composites. The test begins with the preparation of a rectangular flat specimen, commonly referred to as a coupon, with end tabs bonded to both ends to facilitate proper gripping and to prevent premature failure at the clamps. The specimen is carefully mounted between the grips of the testing machine, ensuring accurate axial alignment so that the applied force acts purely in tension, minimizing any bending or shear effects. To measure deformation accurately, an extensometer or strain gauge is attached along the gauge length of the specimen. The test is carried out under a controlled crosshead speed, typically around 2 mm/min for most composite laminates, ensuring a consistent and uniform loading rate throughout the test.

Figure 4.4 Tensometer experimental setup Specifications

During the tensile test, the testing machine continuously records the applied load and the corresponding extension or strain of the specimen until failure occurs. The collected data is then used to generate a stress–strain curve, from which several important mechanical properties can be determined. These include the ultimate tensile strength (the highest stress the material can withstand), the tensile modulus (the slope of the linear elastic region, representing stiffness), and the strain at break (the total elongation before fracture). In some cases, parameters such as Poisson's ratio or transition strain may also be derived. To ensure accurate and consistent results, careful specimen preparation—including maintaining parallel edges, proper tabbing, and precise alignment—is essential. Additionally, preventing grip-induced failures is crucial for obtaining reliable and representative tensile data for composite materials.

4.5 FLEXURAL TESTING OF COMPOSITES

In flexural testing, a composite specimen—usually a rectangular bar fabricated from fiber-reinforced laminates—is positioned on two or more supports depending on the testing configuration. In the three-point bending method, the specimen rests on two supports while a single load is applied at the midpoint; in the four-point bending method, the load is distributed at two points between the supports. As the load increases, the specimen bends until fracture occurs. During this process, the upper surface of the specimen (under the applied load) is subjected to compressive stress, while the lower surface experiences tensile stress, and shear stresses develop in the intermediate region. Standard testing procedures such as ASTM D790 (three-point bending) and ASTM D6272 or ASTM D7264 (four-point bending) define the specimen dimensions, span-to-depth ratio, loading rate, and methods for measuring deflection. The resulting load–deflection curve is used to determine both the flexural strength (maximum stress sustained at the outermost fiber before failure) and the flexural modulus (a measure of stiffness under bending).

Figure 4.5 **Electronic tensometer for tensile & flexural testing**

4.6 IMPACT TESTING OF COMPOSITES

The impact strength of the fabricated fiber-reinforced composite specimens was evaluated in accordance with the ASTM D256-97 standard test procedure. This standard outlines the method for determining the impact resistance of unidirectional composite materials. The test specimens were prepared with dimensions of 63.5 mm in length, 12.36 mm in width, and 6 mm in thickness. A V-notch was precisely machined at the center of each specimen, forming an included angle of 45°, and oriented perpendicular (90°) to the specimen axis. The notch depth was maintained at 2 mm to ensure uniformity across all samples. The specimens were then tested using a pendulum-type impact testing machine, which recorded the energy absorbed during fracture. This standardized setup ensures accurate and repeatable measurement of the impact behavior of the composite materials.

Figure 4.6 Impact tester experimental setup Specifications

4.7 HARDNESS TEST

The hardness characteristics of the developed composite specimens were evaluated in accordance with ASTM D785 standards using the Rockwell B hardness test. The specimens were prepared with a diameter of 25 mm and a length of 20 mm to meet the required testing specifications. The fiber configuration and volume fraction play a crucial role in determining the mechanical behavior and hardness of the composites. In this investigation, the fibers were arranged in a unidirectional and continuous manner, corresponding to the full length of the specimen. The hardness performance was analyzed by applying an indentation load perpendicular to both the fiber diameter and fiber length. The influence of fiber loading and post-curing duration on the Rockwell hardness values is illustrated in Figures 3 and 4. It was observed that an increase in fiber content and modulus generally led to improved hardness of the composite, as hardness is directly related to the fiber volume fraction and stiffness (modulus) of the reinforcing material.

Figure 4.7 Hardness testing machine

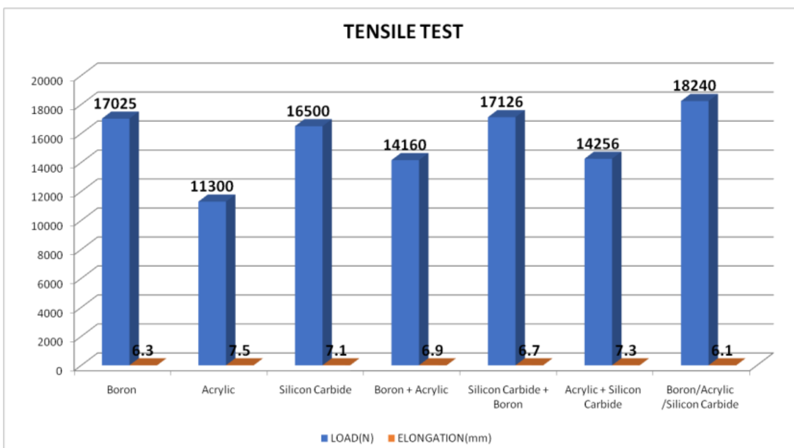
5 RESULTS AND DISCUSSION

5.1 MECHANICAL CHARACTERISTICS OF COMPOSITES

The composite specimens consisting of Boron Fiber with 10 g of Zinc Oxide powder, Acrylic Fiber with 10 g of Zinc Oxide powder, Silicon Carbide Fiber with 10 g of Graphite powder, Boron Fiber/Acrylic Fiber with 10 g of Zinc Oxide powder, Silicon Carbide Fiber/Boron Fiber with 10 g of Zinc Oxide powder, Silicon Carbide Fiber/Acrylic Fiber with 10 g of Zinc Oxide powder, and Silicon Carbide Fiber/Acrylic Fiber/Boron Fiber with 10 g of Zinc Oxide powder were fabricated using the hand lay-up technique as part of this investigation. The experimental results and corresponding properties of these composites are presented in the table below, with each specimen tested individually for mechanical performance evaluation. The fabrication process and the testing procedures adopted for these composites have been discussed in detail in the preceding chapter. The mechanical behavior of synthetic fiber-reinforced composites is greatly influenced by several factors such as the chemical composition, structural configuration, type of fiber used, and filler material, as well as environmental and atmospheric conditions during fabrication. These factors collectively determine the overall strength, stiffness, and durability of the developed composites.

5.2 TENSILE STRENGTH

The fabrication and testing of composite specimens to evaluate their tensile properties were successfully completed in this research work. All the samples were prepared using the hand lay-up technique, with epoxy resin as the matrix material and various combinations of fibers and fillers incorporated for performance comparison. The investigated compositions include Boron Fiber with 10 g of Zinc Oxide powder, Acrylic Fiber with 10 g of Zinc Oxide powder, Silicon Carbide Fiber with 10 g of Graphite powder, Boron Fiber/Acrylic Fiber with 10 g of Zinc Oxide powder, Silicon Carbide Fiber/Boron Fiber with 10 g of Zinc Oxide powder, Silicon Carbide Fiber/Acrylic Fiber with 10 g of Zinc Oxide powder, and Silicon Carbide Fiber/Acrylic Fiber/Boron Fiber with 10 g of Zinc Oxide powder. Each specimen was subjected to tensile testing to determine its ultimate load-bearing capacity and deformation behavior under applied stress.

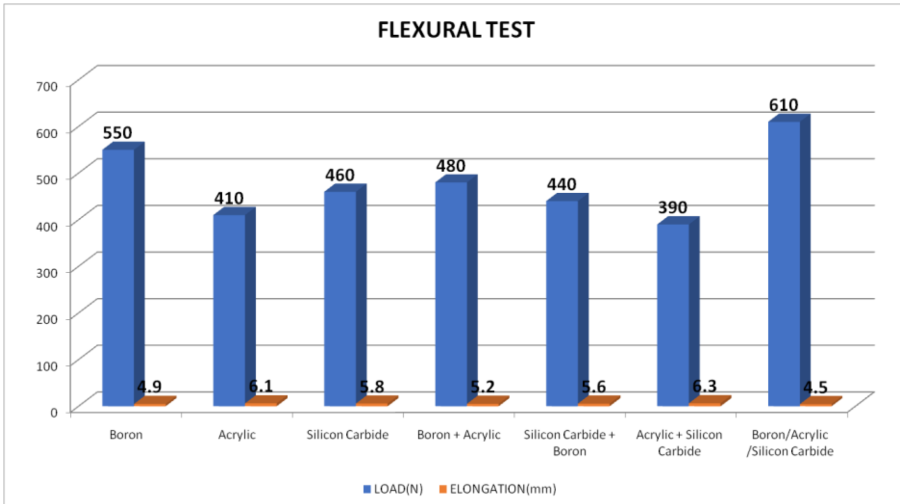


Graph 1 tensile test result graph

After the successful completion of tensile testing, it was observed that the Boron/Acrylic/Silicon Carbide composite reinforced with 10 grams of Zinc Oxide powder exhibited the highest tensile performance among all the tested specimens. This composite achieved a maximum tensile load of 18,240 N with a minimum deformation of 6.1 mm, indicating superior strength and rigidity. The results clearly demonstrate that the hybrid reinforcement of Boron, Acrylic, and Silicon Carbide fibers with Zinc Oxide significantly enhances the load-carrying capacity of the composite compared to the other material combinations.

5.3 FLEXURAL STRENGTH

The fabrication and testing of composite specimens to determine their flexural properties were successfully completed in this study. All samples were prepared using the hand lay-up technique, with epoxy resin as the binding matrix and various fiber–filler combinations incorporated to evaluate performance differences. The compositions investigated include Boron Fiber with 10 g of Zinc Oxide powder, Acrylic Fiber with 10 g of Zinc Oxide powder, Silicon Carbide Fiber with 10 g of Graphite powder, Boron Fiber/Acrylic Fiber with 10 g of Zinc Oxide powder, Silicon Carbide Fiber/Boron Fiber with 10 g of Zinc Oxide powder, Silicon Carbide Fiber/Acrylic Fiber with 10 g of Zinc Oxide powder, and Silicon Carbide Fiber/Acrylic Fiber/Boron Fiber with 10 g of Zinc Oxide powder. Each specimen was subjected to flexural testing to assess its bending strength and deformation behavior.

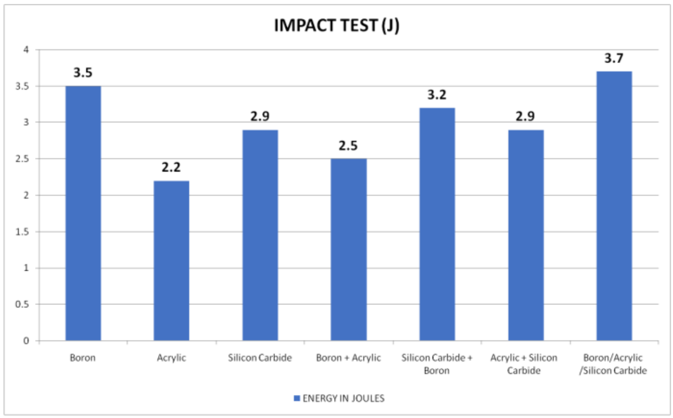


Graph 2 Flexural test result graph

Based on the flexural strength analysis, it is concluded that the Boron/Acrylic/Silicon Carbide composite reinforced with 10 grams of Zinc Oxide powder exhibited the highest flexural strength among all tested specimens. This composite achieved a maximum flexural load of 610 N with a minimum deflection of 4.5 mm, indicating superior stiffness and load-bearing capability. The results, as illustrated in the corresponding graph, clearly demonstrate that the combination of Boron, Acrylic, and Silicon Carbide fibers with Zinc Oxide reinforcement provides enhanced structural rigidity and resistance to bending when compared to the other composite formulations.

5.4 IMPACT STRENGTH

The fabrication and testing of composite specimens to evaluate their impact properties were successfully carried out in this project. All specimens were prepared using the hand lay-up technique, with epoxy resin as the matrix material and different fiber–filler combinations. The investigated compositions include Boron Fiber with 10 grams of Zinc Oxide powder, Acrylic Fiber with 10 grams of Zinc Oxide powder, Silicon Carbide Fiber with 10 grams of Graphite powder, Boron Fiber/Acrylic Fiber with 10 grams of Zinc Oxide powder, Silicon Carbide Fiber/Boron Fiber with 10 grams of Zinc Oxide powder, Silicon Carbide Fiber/Acrylic Fiber with 10 grams of Zinc Oxide powder, and Silicon Carbide Fiber/Acrylic Fiber/Boron Fiber with 10 grams of Zinc Oxide powder. The experimental evaluation of impact strength demonstrated that the composites exhibited varying levels of energy absorption depending on the fiber and filler combination. The successful fabrication and testing confirm the effectiveness of the adopted manufacturing process and the potential of these hybrid composites for enhanced impact resistance applications.

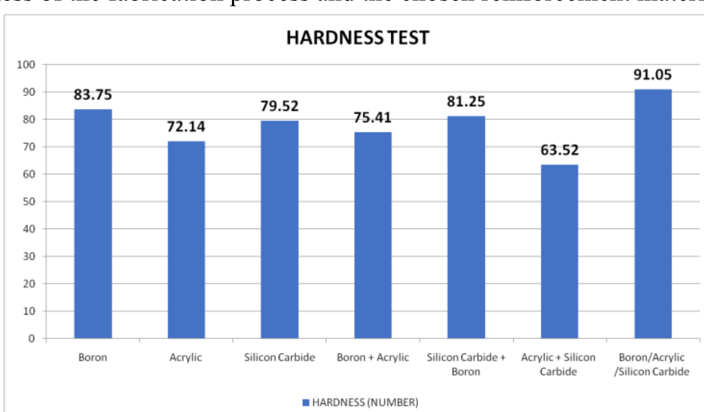


Graph 3 Impact strength result graph

After compact impact test finally concluded the Boron / Acrylic / Silicon Carbide with 10 grams of zinc oxide powder possess high impact strength of 3.7 Joules compared to remaining compositions as shown graph.

5.5 HARDNESS NUMBER:

The Brinell hardness evaluation of the fabricated natural composite specimens was successfully carried out in this project. Each specimen was prepared using the hand lay-up technique, with epoxy resin as the matrix material and different fiber–filler combinations. The compositions include Boron Fiber with 10 grams of Zinc Oxide powder, Acrylic Fiber with 10 grams of Zinc Oxide powder, Silicon Carbide Fiber with 10 grams of Graphite powder, Boron Fiber/Acrylic Fiber with 10 grams of Zinc Oxide powder, Silicon Carbide Fiber/Boron Fiber with 10 grams of Zinc Oxide powder, Silicon Carbide Fiber/Acrylic Fiber with 10 grams of Zinc Oxide powder, and Silicon Carbide Fiber/Acrylic Fiber/Boron Fiber with 10 grams of Zinc Oxide powder. The hardness results demonstrated notable variations among the composites, reflecting the influence of fiber type and filler combination on surface resistance. The experimental findings confirmed that the prepared composites exhibited promising hardness characteristics, validating the effectiveness of the fabrication process and the chosen reinforcement materials.



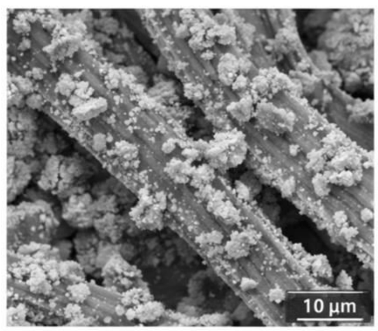
Graph 4 Hardness number result graph

The graph illustrating the variation of Brinell hardness with respect to the experiment number depicts the hardness performance of different composite specimens. It is observed from the figure that the Brinell hardness values vary depending on the fiber and filler composition used. Among all the tested specimens, the composite consisting of **Boron, Acrylic, and Silicon Carbide fibers reinforced with 10 grams of Zinc Oxide powder** exhibited the **highest Brinell hardness value of 91.05**. This indicates that the combined reinforcement of these fibers with Zinc Oxide significantly enhances the surface hardness of the composite when compared to the other compositions.

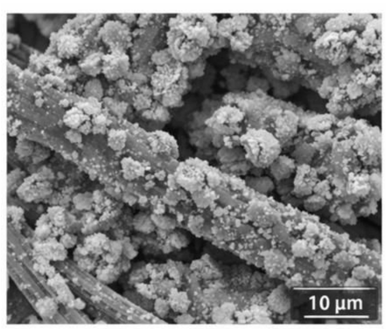
5.6 SCANNING ELECTRON MICROSCOPY (SEM) ANALYSIS

Scanning Electron Microscopy (SEM) was used to investigate the surface morphology and dispersion of zinc oxide (ZnO) particles within different fiber-reinforced mixtures. The SEM micrographs (scale bar: 2 µm) reveal the interaction between ZnO powder and reinforcing materials such as boron fiber, acrylic fiber, and silicon carbide (SiC) fiber. In the sample containing boron fiber with 10 g ZnO, significant agglomeration of ZnO particles is observed, forming irregular clusters around the boron structures. In contrast, the acrylic fiber + ZnO sample shows ZnO particles adhering along the cylindrical surfaces of the fibers, indicating improved particle distribution due to the larger surface area provided by the fibers. The SiC fiber + ZnO micrograph demonstrates relatively uniform deposition of ZnO particles on the rigid fiber surfaces, suggesting stronger interfacial interaction and better dispersion compared to boron alone.

For hybrid compositions, the boron fiber + acrylic fiber + ZnO sample exhibits ZnO particles attached to both boron particles and acrylic fibers, resulting in a partially improved distribution. Similarly, the SiC fiber + boron fiber + ZnO mixture shows ZnO particles coating the SiC fibers while also surrounding the boron clusters, indicating enhanced particle anchoring due to the presence of fibrous reinforcement. The acrylic fiber + SiC fiber + ZnO system presents a more interconnected fiber network with ZnO particles distributed along the fiber surfaces, reducing particle agglomeration. Overall, the SEM observations suggest that the presence of fiber reinforcements, particularly SiC and acrylic fibers, significantly improves the dispersion of ZnO particles and promotes better interfacial bonding within the composite structure.



SiC Fiber + 10g ZnO Powder



SiC Fiber + Boron + 10g ZnO Powder

6 CONCLUSIONS & FUTURE SCOPE

6.1 CONCLUSION

The present investigation was carried out with the objective of exploring the mechanical properties of different hybrid fiber-reinforced composites by incorporating various fiber and filler combinations. The composites were prepared using the hand lay-up technique, with epoxy resin serving as the matrix material. The study involved seven distinct compositions: Boron Fiber with 10 grams of Zinc Oxide powder, Acrylic Fiber with 10 grams of Zinc Oxide powder, Silicon Carbide Fiber with 10 grams of Graphite powder, Boron Fiber/Acrylic Fiber with 10 grams of Zinc Oxide powder, Silicon Carbide Fiber/Boron Fiber with 10 grams of Zinc Oxide powder, Silicon Carbide Fiber/Acrylic Fiber with 10 grams of Zinc Oxide powder, and Silicon Carbide Fiber/Acrylic Fiber/Boron Fiber with 10 grams of Zinc Oxide powder. Mechanical tests such as tensile, flexural, impact, and hardness tests were conducted to evaluate the performance of each composite. Among all the specimens, the combination of Silicon Carbide Fiber, Acrylic Fiber, and Boron Fiber reinforced with 10 grams of Zinc Oxide powder exhibited the best overall results. This hybrid composite showed superior tensile strength, impact resistance, hardness, and flexural strength when compared to the other combinations. Therefore, it can be concluded that the Boron/Acrylic/Silicon Carbide composite with Zinc Oxide reinforcement possesses excellent mechanical properties and can be considered the most effective composition among the tested specimens.

6.2 FUTURE SCOPE

The scope for extending the present research work offers several potential directions for further improvement and analysis. In future studies, the fibers can be incorporated in powdered form during the fabrication process, which may enhance the bonding and overall strength of the composite material. Additionally, different types of resin systems can be explored to evaluate variations in mechanical properties such as tensile strength, hardness, and wear resistance. Moreover, the mechanical behavior of the composites can be optimized by experimenting with various processing parameters and alternative fiber–matrix combinations. Such extended investigations would provide a deeper understanding of the influence of material composition and processing conditions on the overall performance of hybrid composites.

REFERENCES

[1]Rohith S., Yashwanth N., Rathnakar G. *et al.*, "Assessment of Mechanical Characteristics of Jute Fiber and Boron Carbide Reinforced Epoxy Hybrid Composites," *International Research Journal of Engineering and Technology (IRJET)*, Vol. 8, Issue 10, 2021.
Available at: https://www.irjet.net/archives/V8/i10/ICRTST-2021/IRJET-V8I1026.pdf

[2]Abhilash Gowda T.H., Madhusudhan T., Bhanuprakash N. *et al.*, "Experimental Study on Tensile and Flexural Behaviour of Polymer Composites Using Various Natural Fibers and Fillers," *IRJET*, Vol. 5, Issue 4, 2018.
Available at: https://www.irjet.net/archives/V5/i4/IRJET-V5I4970.pdf

[3]Kommineni Madhu, T. Pavan Kumar *et al.*, "Fabrication and Evaluation of Mechanical Properties of Reinforced Composite Materials," *IRJET*, Vol. 7, Issue 11, 2020.
Available at: https://www.irjet.net/archives/V7/i11/IRJET-V7I11274.pdf

[4]Arnav, Ankit Kumar Yadav, Sadaf Kamran Ali, S.M. Uruf Negami, Rahul Malik, Vishal Sharma *et al.*, "Influence of B_4C and SiC Reinforcements on the Hardness of AA2024 Alloy," *IRJET*, Vol. 6, Issue 5, 2019.
Available at: https://www.irjet.net/archives/V6/i5/IRJET-V6I5843.pdf

[5] Larissa Wahl, Samuel Schmiedeke, Moritz Knorr, Ines Schneider, Nahum Travitzky *et al.*, "Preparation of Reaction-Bonded Boron Carbide Composites via Binder Jetting 3D Printing," *Materials Proceedings (MDPI)*, Vol.

5, No. 4, 2022.
Available at: https://www.mdpi.com/2571-6131/5/4/82

[6] R. Mohammad Giyahudeen *et al.*, "Fabrication and Structural Analysis of Single Lap Joint Glass Fiber Reinforced Polymer Composites," *IRJET*, Vol. 4, Issue 10, 2017.
Available at: https://www.irjet.net/archives/V4/i10/IRJET-V4I10205.pdf

[7]M.K.N. Sateesh, J. Srikanth *et al.*, "Experimental Investigation of Kevlar, Carbon, and E-Glass Composites with Graphite Additive Using Hand Lay-Up Technique," *IRJAEH*, Vol. 3, Issue 7, 2021.
Available at: file:///C:/Users/Smile/Downloads/IRJAEH-03-07-0461-2505715-3126-3134.pdf

[8] Manohar, Javeed Shaik *et al.*, "Manufacturing Methods and Properties of Carbon/Glass Fiber-Reinforced Polymer Composites," *Frontiers in Materials Science*, 2021.
Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC8588351/

[9] Muzeer Saiyed, L. Sushma, M. Natesan *et al.*, "Evaluation of Mechanical Performance of Carbon-Epoxy Composites Produced by Hand Lay-Up Technique," *Research and Reviews: Journal of Material Sciences*, 2020.
Available at: https://www.rroij.com/open-access/studies-on-mechanical-properties-of-carbon-epoxy-composites-by-hand-layup-process.php?aid=94468

[10] Girish C. Mekalke, S.R. Basavaraddi *et al.*, "Impact of Manufacturing Processes on Mechanical and Burning Properties of Epoxy-Based Hybrid Composites," *Frontiers in Materials*, 2022.
Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC8746176/

[11]Ramakishore, Manikanta Alluri *et al.*, "Review on Low-Velocity Impact Response of Fabric Reinforced Polymer Composites," *Engineered Science Journal*, 2023.
Available at: https://www.espublisher.com/journals/articlehtml/engineered-science/10.30919-es8d670

[12] Raviraja Atmakuri, Ashok Kumar Reddy *et al.*, "Enhanced Flexural and Impact Strength of Kevlar/Carbon/Glass Fiber-Reinforced Hybrid Polymer Composites," *Journal of Composites (MDPI)*, Vol. 6, Issue 9, 2022.
Available at: https://www.mdpi.com/2504-477X/6/9/245