



Journal of Materials and Engineering Structures

Research Paper

Novel Glass Fiber Composites Reinforced with Date Seed-Derived Carbon for High-Performance Submarine Hulls

Sani Mohammed Adams ^{a,c}, Victor Sunday Aigbodion ^{a,b,c}, Adaeze Chisomaga Nduanya ^a, Ekele Dinneya-Onuoha ^{d,e,*}

^aDepartment of Metallurgical and Materials Engineering, University of Nigeria, Nsukka, Ihe Nsukka, Enugu-State 410105, Nigeria

^bFaculty of Engineering and the Built Environment, University of Johannesburg, P. O. Box 534, Auckland Park, South Africa

^cAfrica Centre of Excellence, ACESPED University of Nigeria, Nsukka, Ihe Nsukka, Enugu-State 410105, Nigeria

^dDepartment of Pure and Industrial Chemistry, University of Nigeria, Nsukka, Ihe Nsukka, Enugu-State 410105, Nigeria

^eDepartment of Chemical Engineering, Tennessee Technological University, William L Jones Dr, Cookeville, TN 38505, USA

ARTICLE INFO

Article history :

Received : 21 March 2025

Revised : 30 September 2025

Accepted : 2nd November 2025

Keywords:

Date seeds

bio-based carbon

glass fiber composites

submarine hulls

microstructural analysis

ABSTRACT

This study examines glass fiber-reinforced polyester composites enhanced with carbon derived from date seeds as potential materials for submarine hull construction. Mechanical, physical, and microstructural properties were evaluated through tensile, flexural, compression, impact, density, and water absorption tests. Composites containing 0.5–2.0 wt% carbon were fabricated and assessed under varied loading and environmental conditions. Results show that the 0.5% carbon composite achieved the highest impact toughness (0.137 J) and flexural modulus (95,639.879 MPa), indicating superior resistance to dynamic and bending stresses. The 2.0% carbon composite recorded the greatest tensile strength (4,844.308 MPa) but lower flexibility, whereas the 1.0% carbon composite displayed the lowest density (0.97 g/cm³), enhancing buoyancy for marine use. All samples exhibited 0% water absorption, confirming excellent moisture resistance. SEM–EDS analysis revealed uniform reinforcement dispersion and strong interfacial bonding, particularly in the 0.5% hybrid composite. Overall, the findings highlight date seed-derived carbon as a sustainable reinforcement capable of improving the strength-to-weight ratio of glass fiber composites. It offers a lightweight, corrosion-resistant alternative to conventional metals for submarine structures, warranting further optimization and field testing for marine deployment.

1 Introduction

Beneath the ocean's depths, where immense hydrostatic pressures and corrosive forces prevail, submarines serve as critical assets for naval defense, deep-sea exploration, and underwater research [1]. The structural integrity of these vessels

* Corresponding author.

E-mail address: ekele.onuoha@unn.edu.ng

depends on materials that can endure extreme conditions while maintaining mechanical strength, resilience, and durability. Historically, high-strength metals such as steel and titanium have been the primary choices for submarine hull construction due to their robustness and load-bearing capabilities [2 – 3]. However, these materials present significant challenges, including excessive weight that hinders maneuverability and fuel efficiency, susceptibility to corrosion despite protective coatings, and the high costs associated with fabrication and maintenance [4 – 5]. Additionally, the magnetic signature of metallic hulls increases the risk of detection [6], further emphasizing the need for alternative materials that enhance operational stealth and efficiency.

Submarine hulls are subject to some of the most demanding service environments in engineering, requiring materials that combine mechanical robustness with long-term durability in corrosive and high-pressure conditions [1]. Hull structures must not only sustain the immense hydrostatic pressures encountered at operational depths but also exhibit sufficient fracture toughness and fatigue resistance to survive repeated pressurization cycles without catastrophic crack propagation [7]. In addition to strength and toughness, adequate flexural and compressive stiffness is essential to maintain shape stability under distributed loads and prevent buckling failures [4]. Equally critical is the balance between structural integrity and buoyancy; materials must provide a high strength-to-weight ratio to minimize displacement, reduce fuel consumption, and improve maneuverability relative to heavy metallic hulls [5].

Beyond these mechanical considerations, environmental resistance and stealth performance play pivotal roles in submarine material selection. Conventional steels are prone to seawater corrosion and require costly maintenance, whereas advanced composites and polymers offer intrinsic hydrophobicity and improved durability [2]. Materials must also absorb or dampen acoustic, magnetic, and thermal signatures to ensure operational stealth; fiber-reinforced polymers, for example, exhibit inherently low magnetic permeability and favorable sound-dampening properties [8]. Furthermore, practical engineering considerations such as manufacturability, scalability, and repairability remain central to hull design, since submarine construction demands cost-effective fabrication processes that allow integration of stiffeners, joints, and potential field retrofitting [9]. Taken together, these stringent requirements underscore the limitations of traditional metallic solutions and highlight the need for innovative, lightweight, corrosion-resistant, and mechanically balanced materials that can address the diverse demands of submarine operations [10].

The development of polymer composite materials has introduced a promising alternative, offering a superior strength-to-weight ratio, enhanced corrosion resistance, and greater design flexibility [8, 9, 11]. Fiber-reinforced polymer (FRP) composites, in particular, have gained widespread adoption across aerospace, automotive, and marine industries due to their exceptional mechanical performance [12 – 13]. The increasing demand for sustainable, lightweight, and cost-effective solutions has also spurred interest in bio-based reinforcements, leading to the exploration of hybrid composites. This shift is especially relevant because submarine materials must withstand extreme external pressures while ensuring long-term structural reliability. Traditional steels such as HY-80 and HY-100, though known for their toughness and weldability, remain constrained by their density, corrosion susceptibility, and high production costs [14]. Consequently, researchers are investigating innovative composite materials that combine the advantages of synthetic and natural reinforcements, paving the way for more efficient, resilient, and sustainable submarine hull designs.

Extensive research has demonstrated that fiber-reinforced polymer (FRP) composites can achieve strength levels comparable to or exceeding those of metals while offering substantial weight reductions, thereby improving propulsion efficiency and reducing energy demands. According to El Hawary et al [15], the FIBRESHIP project showcased that replacing steel with FRPs in large vessel hulls resulted in up to a 30% reduction in weight, leading to lower fuel consumption and emissions while preserving structural integrity. Unlike metals, polymer matrices exhibit inherent corrosion resistance, prolonging service life in marine environments. Supporting this, Choudhari et al [16] conducted an extensive review of FRP composites exposed to seawater aging and found that advanced resin systems effectively mitigate moisture absorption, ensuring the retention of mechanical properties over extended periods.

A key advantage of FRPs lies in their ability to be engineered for specific performance requirements through precise control of fiber orientation and resin composition, enabling optimized mechanical behavior [17]. Studies have consistently demonstrated that CFRPs exhibit high tensile strength, and fatigue resistance, making them ideal for withstanding the extreme pressures of underwater environments [12, 18 – 19]. Beyond their mechanical advantages, FRPs contribute significantly to stealth capabilities. Their reduced magnetic signature enhances operational security, making them particularly well-suited for submarine applications. According to Rubino et al [12], carbon fibers not only provide high strength-to-weight benefits but also offer electromagnetic shielding, reducing the risk of magnetic detection. Additionally, they exhibit lower thermal

conductivity and superior acoustic insulation, which further enhance stealth performance [20 – 21]. Moreover, Kappenthuler and Seeger [18] noted that these materials minimize heat transfer and possess intrinsic sound-dampening properties, effectively lowering acoustic signatures and improving a submarine's ability to evade detection. Despite these advantages, CFRPs face notable challenges, including brittle failure modes, high manufacturing costs, and susceptibility to matrix cracking under extreme loads [22 – 24]. The energy-intensive production of carbon fiber also raises environmental concerns [25]. Additionally, while recent advancements in CFRP manufacturing have led to the development of hierarchical composites with superior mechanical performance, impact resistance remains a concern [26 – 27]. In order to deal with the issue, aramid fibers such as Kevlar have been explored as alternative reinforcements due to their excellent toughness and lightweight properties [28 – 30]. Kevlar composites have been utilized in military vehicle armor, ballistic protection systems, and marine hulls [31 – 32]; however, they suffer from UV degradation, moisture absorption, and reduced compressive strength, limiting their long-term effectiveness in submerged applications [33 – 35]. These limitations have driven ongoing research into cost-effective and sustainable reinforcement solutions that balance performance, durability, and economic feasibility. The continuous evolution of composite technology, particularly in addressing the challenges of impact resistance, affordability, and environmental sustainability, will be crucial in shaping the future of FRPs for submarine and other advanced marine applications.

Glass fiber-reinforced composites have also been widely used in marine engineering due to their low cost, ease of fabrication, and balanced mechanical properties. Studies indicate that GFRP hulls demonstrate good corrosion resistance, moderate tensile strength, and cost-effectiveness compared to carbon fiber composites [36 – 38]. However, glass fibers are susceptible to moisture absorption, which can weaken the composite over time [39 – 40]. To mitigate this, hybrid reinforcements combining glass fiber with other materials are being explored. With increasing environmental concerns, the incorporation of bio-based reinforcements in composites has become a major research focus [41 – 45]. Date seeds, a byproduct of date fruit processing, offer a renewable and sustainable source of carbon. Studies suggest that date seeds are rich in carbon content, making them suitable for conversion into reinforcement materials through pyrolysis and grinding [46 – 48].

The benefits of using date seed-derived carbon include waste valorization, as utilizing agro-waste materials reduces environmental burdens [49]. It also serves as a renewable reinforcement source, unlike synthetic carbon fibers, which rely on fossil-based resources [50]. Agricultural waste-derived carbon reduces material costs compared to traditional reinforcement additives, making it a cost-efficient alternative. Additionally, it has a lower carbon footprint compared to fossil-derived reinforcements, contributing to eco-friendliness in material engineering. Previous studies have shown that biocarbon additives can enhance composite properties such as improved mechanical strength and toughness, increased thermal stability, reduced water absorption, and better interfacial bonding with polymer matrices. By integrating glass fiber with date seed-derived carbon, this study aims to leverage the benefits of both reinforcements to achieve an optimal balance of strength, flexibility, impact resistance, and environmental sustainability for submarine applications.

This research presents a novel hybrid composite utilizing glass fiber and date seed-derived carbon as reinforcements in a polyester matrix. Unlike conventional composites, this study introduces a bio-based reinforcement from agro-waste to enhance sustainability. It optimizes mechanical properties by varying date seed carbon content and evaluates comprehensive material properties, including tensile strength, flexural behavior, impact resistance, and water absorption. The feasibility for submarine applications is explored, contributing to lightweight, corrosion-resistant, and cost-effective hull materials. This study aims to develop and characterize a glass fiber–date seed carbon reinforced composite and assess its suitability for submarine hull applications. Through experimental validation, this study provides insights into the potential of bio-based reinforcements in marine composites, paving the way for sustainable and high-performance structural materials.

2 Methodology

2.1 Materials

The selection of materials for this study was guided by the need to develop a high-performance composite with superior mechanical strength and lightweight properties, making it suitable for submarine hull applications. The composite system consists of glass fiber reinforcement, carbon derived from date seeds, and a polyester resin matrix, each chosen for its distinct advantages in structural performance and environmental sustainability. The woven glass fiber mats used in this study enhanced load distribution within the composite, improving its tensile and flexural properties. Other materials include

catalysts and activators. To ensure precision in composite preparation, the study utilized a stainless steel mold (15cm by 15cm), which provided dimensional accuracy and surface smoothness during curing. A sieve mesh (150 μ m) was used to standardize the particle size of the date seed-derived carbon, ensuring homogeneous dispersion within the matrix. Various testing equipment, including a universal testing machine, impact testing apparatus, scanning electron microscope (SEM), and hardness testing machine, were employed to evaluate the mechanical and microstructural properties of the composite.

The dates utilized in this research were procured from a rural market in Kano. The polyester resin, catalysts, and activator used in this study were of analytical grade and were procured from a certified supplier in Nsukka, Nigeria.



Fig. 1- Sun-dried date seeds utilized for the study

2.2 Methods

2.2.1 Preparation and Carbonization of Date Seeds

The preparation of date seeds for carbonization began with their collection and preliminary processing to ensure purity and uniformity. The seeds were first separated from the fruit, thoroughly washed to remove residual pulp, and then sun-dried to eliminate surface moisture (see Figure 1). This drying step was essential for preventing unwanted reactions during the carbonization process [51]. Once dried, the seeds were placed in a stainless steel container with a sealed lid to limit oxygen exposure, preventing combustion and facilitating controlled pyrolysis [52].

The carbonization process involved heating the sealed container in a charcoal-fired furnace for one hour and fifteen minutes at high temperatures, allowing the organic material in the date seeds to decompose thermally and convert into carbon [53]. Throughout this phase, a manual blower was used to maintain consistent heating, ensuring uniform carbonization [54]. After cooling to room temperature for approximately forty minutes, the carbonized seeds were carefully removed, ground into a fine powder, and sieved through a 150 μ m mesh to achieve a uniform particle size. This finely processed date seed-derived carbon was then stored in an airtight container to prevent contamination and moisture absorption, ensuring its suitability as a reinforcement in the composite fabrication process.

2.2.2 Mold Preparation and Composite Formation

The preparation of the mold is a crucial step in composite fabrication, ensuring proper shaping, easy demolding, and preventing defects such as adhesion or irregular curing [55]. To facilitate a smooth release of the composite, the mold was first lined with masking tape, creating a non-stick barrier. A layer of release agent (Vaseline) was then applied, further reducing the risk of adhesion between the polyester resin and the mold surface. These steps were essential in preventing mechanical damage to the specimens during demolding, ensuring dimensional accuracy, and maintaining the integrity of the composite structure. For precise composite formation, the mass of the polyester resin was determined based on its density (1.22 g/cm³) and the mold volume (132 cm³, including a 10% allowance for expansion and overflow prevention). A systematic calculation was performed to adjust the weight fractions of carbon reinforcement while maintaining the correct resin volume

(see Table 1). The percentage of carbon varied from 0% to 2.0%, with corresponding adjustments in polyester mass to maintain a consistent total mass. This controlled formulation ensured that each specimen had a uniform composition, allowing for reliable comparisons in mechanical performance. The thickness of the glass fiber (0.78 mm) was considered negligible in volume calculations, as its impact on the overall mass distribution was minimal.

Table 1. Composition of Carbon-Reinforced Polyester Composites

Carbon content (%)	Polyester content (%)	Carbon mass (g)	Polyester mass (g)	Polyester volume (ml)
0	100	0	161	132
0.5	99.5	0.8	160	131.2
1.0	99.0	1.6	159.4	130.7
1.5	98.5	2.4	158.6	130
2.0	98.0	3.2	158	129.5

The composite formation process began with the preparation of the control specimen, which consisted solely of polyester resin. The required volume of 132 ml of resin was measured and placed in a mixing container. To initiate the curing reaction, 2% of the volume of the catalyst and activator was added. The mixture was then vigorously stirred to ensure homogeneity and prevent agglomeration before being poured into the pre-prepared mold for curing. For the 0% carbon composite reinforced with glass fiber, the glass fiber mat was first cut to match the mold dimensions. The same procedure was followed for the resin preparation, after which half of the resin mixture was poured into the mold. The glass fiber mat was then placed into the mold, and the remaining resin mixture was poured over it, ensuring uniform wetting before the curing process.

For the carbon-reinforced composites, the percentage of date seed-derived carbon varied from 0.5% to 2.0% by weight, with corresponding reductions in polyester resin volume. In each case, the pre-cut glass fiber mat was positioned in the mold. The required amount of polyester resin was measured, and 2% of catalyst and activator was added, followed by the weighted carbon particulate, which was mixed thoroughly to achieve uniform dispersion. The first half of the mixture was then poured into the mold, after which the glass fiber mat was carefully placed. The remaining mixture was then added to ensure even distribution. The specimens were left to cure under controlled conditions, allowing the composite to solidify and develop its mechanical properties. This systematic variation of carbon content facilitated the evaluation of its effect on the composite's mechanical and durability performance. Figures 2 and 3 present the real and schematic images of the composite curing process.

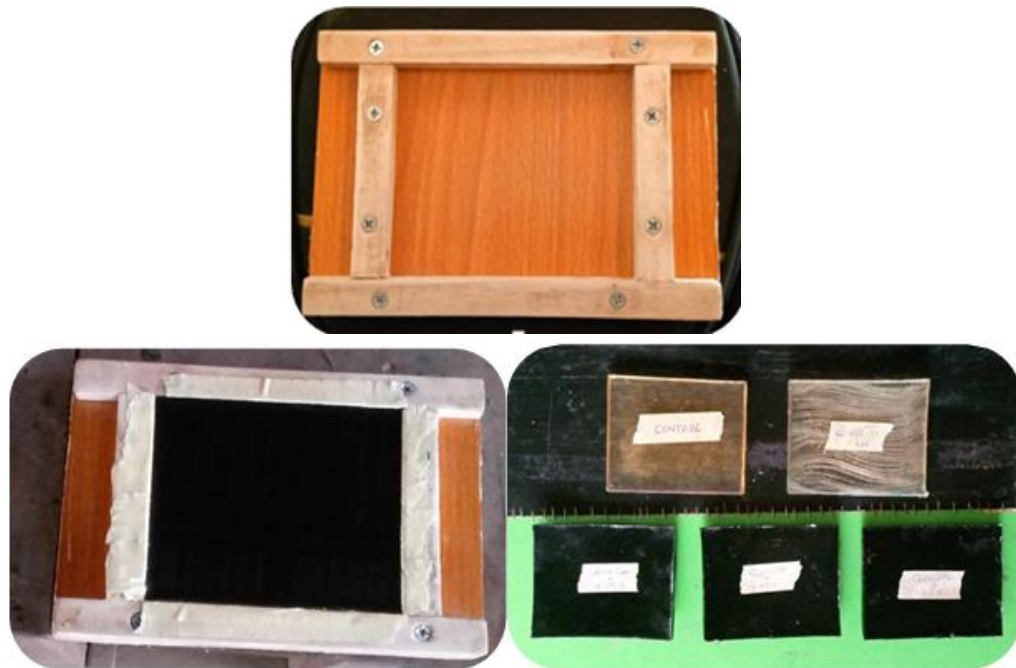


Fig. 3- Curing and formation of the composites

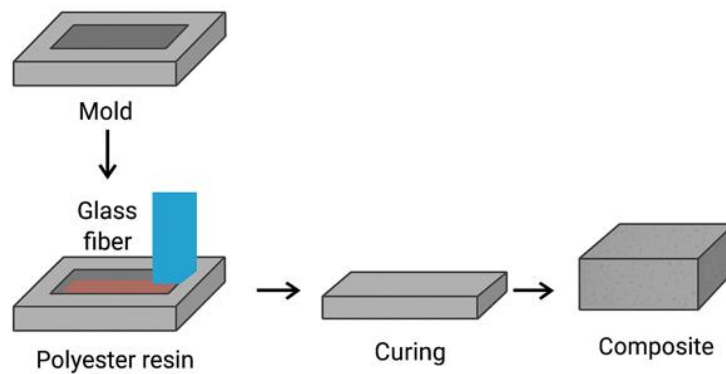


Fig. 2- Schematic diagram of the curing process

2.2.3 Water Absorption Test

Water absorption tests were conducted following the standard procedure outlined in ASTM D570 (“Standard Test Method for Water Absorption of Plastics”). Rectangular specimens (2 cm × 2 cm) from each composite formulation were dried in an oven at 60 °C for 24 h, cooled to room temperature in a desiccator, and then weighed to the nearest 0.001 g (initial dry mass, W_0) (see Figure 4). The samples were subsequently immersed completely in distilled water at ambient temperature (25 °C) for 168 hours (7 days), a duration commonly used in marine polymer composite studies. After immersion, specimens were surface-dried with lint-free paper, reweighed (W_1), and the water absorption percentage was calculated using:

$$\text{Water Absorption (\%)} = \frac{W_1 - W_0}{W_0} \times 100 \quad (1)$$



Fig. 4- Specimens for the water absorption

2.2.4 Characterization

The charcoal-fired furnace played a critical role in the carbonization process of date seeds, converting them into fine carbon particulates suitable for composite reinforcement. This furnace, powered by charcoal and liquid gas, provided the high temperatures necessary to induce pyrolysis, ensuring the controlled thermal decomposition of organic matter in an oxygen-limited environment. The furnace was manually operated with a blower to maintain consistent heating, which was essential for achieving uniform carbonization.

To evaluate the microstructural characteristics of the composites, a Scanning Electron Microscope (SEM) (JOEL-JSM 7600F) was utilized. SEM analysis provided high-resolution imaging of the fiber-matrix interface, fracture surfaces, and dispersion of carbon particulates, offering critical insights into the material's structural integrity [56]. This was complemented by mechanical testing equipment, including a bending machine for flexural strength assessment, a compression machine to determine the composite's ability to withstand compressive loads, and an impact testing machine to measure the toughness and energy absorption capability of the composite under sudden force. Further mechanical evaluations were conducted using a Shore D durometer, a specialized hardness testing machine designed to assess the composite's resistance to indentation and surface deformation. This test provided valuable data on the polymer matrix's ability to withstand wear and mechanical stress over time.

Energy absorption of the composites was evaluated using a Charpy impact test machine (Model XJU-22, Jinan Testing Equipment Co., China). Rectangular specimens with dimensions of $2\text{ cm} \times 2\text{ cm}$ were prepared in accordance with ASTM D6110-18 (Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics). Each specimen was positioned horizontally across the machine supports with a central V-notch of 2 mm depth. The pendulum hammer was released from a fixed height and struck the specimen at the midpoint until fracture occurred. The absorbed impact energy was automatically recorded by the machine as the difference between the hammer's initial potential energy and its residual energy after fracture.

The combination of these diverse testing methods ensured a comprehensive analysis of the composite's mechanical, microstructural, and durability properties, making it possible to evaluate the feasibility of glass fiber–date seed carbon reinforced composites for marine applications.

3 Results and Analysis

3.1 Mechanical Properties: Tensile Strength and Young's Modulus

The tensile properties of the composites, as presented in Figure 5 and Table 2, reveal significant variations in Young's modulus across different carbon reinforcement percentages.

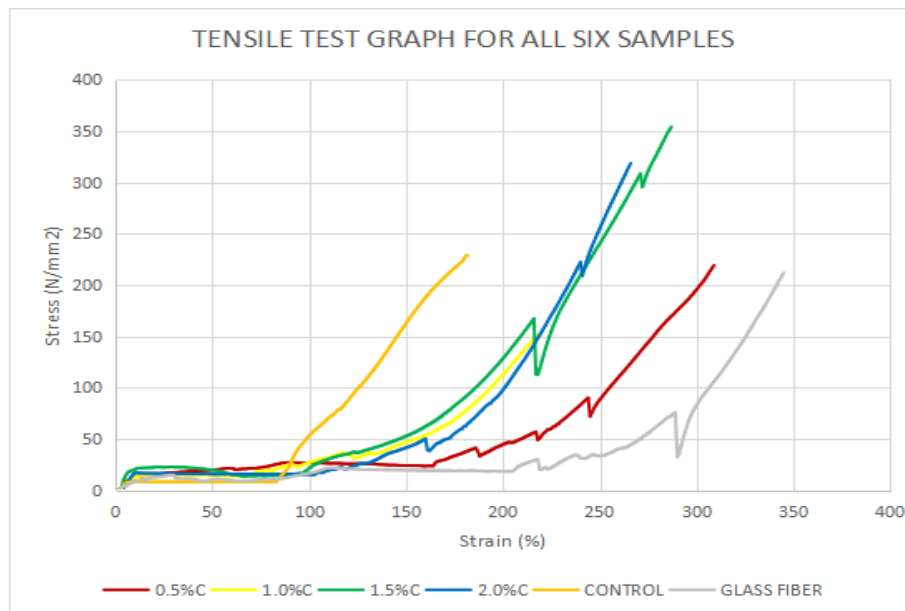


Fig. 5- Tensile test graph for all the samples

Table 2. Young's Modulus of Glass Fiber–Carbon Reinforced Polyester Composites

Specimen	Young's Modulus
Control	4460.289
Glass Fiber	3562.062
0.5%C	2315.51
1.0%C	1333.538
1.5%C	3446.231
2.0%C	4844.308

The composite with 2.0% carbon exhibited the highest Young's modulus (4844.308 MPa), indicating an increased ability of the material to resist elastic deformation under tensile loading. This aligns with findings from Pei et al [57], who demonstrated that carbon reinforcement, particularly at higher weight percentages, enhances the tensile modulus of polymer

composites by providing a rigid network that restricts polymer chain mobility. However, this improvement in modulus was accompanied by reduced elongation at break, reflecting a decrease in ductility. Similar observations have been noted in other studies [58], where the trade-off for higher modulus is diminished deformability. Importantly, it should be noted that tensile strength (maximum stress before fracture) and Young's modulus (slope of the elastic region) are distinct properties: while higher carbon content increased modulus in this study, the strength improvements were less pronounced. This distinction is crucial in application contexts such as submarine hulls, where both high tensile strength to resist fracture and sufficient ductility to absorb dynamic loads are required.

In contrast, the composite with 1.0% carbon displayed the lowest Young's modulus (1333.538 MPa), indicating greater deformability under tensile loading but reduced tensile strength. This finding is consistent with the work of DeArmitt and Rothon [59], who noted that lower filler concentrations in polymer composites often result in reduced modulus due to insufficient reinforcement of the polymer matrix. The 0.5% carbon composite, with a Young's modulus of 2315.51 MPa, strikes a balance between modulus and ductility, making it a promising candidate for applications requiring moderate strength without excessive brittleness. This corroborates the observations of Sathishkumar et al. [60], who highlighted that optimal filler concentrations are critical for achieving a balance between mechanical properties and processability in fiber-reinforced composites. The control specimen (pure polyester resin) exhibited a Young's modulus of 4460.289 MPa, which is higher than that of the glass fiber-reinforced sample without carbon (3562.062 MPa). This unexpected result may be attributed to the inherent brittleness of pure polyester resin, which, while displaying a relatively high modulus, lacks the toughness imparted by fiber reinforcement.

The tensile test results underscore the importance of optimizing carbon content to achieve the desired mechanical properties for specific applications. The 2.0% carbon composite, while exhibiting the highest tensile strength, may not be ideal for submarine hulls due to its reduced flexibility, which could lead to brittle failure under dynamic loading conditions. On the other hand, the 0.5% carbon composite offers a more balanced combination of strength and flexibility, making it a more suitable candidate for marine applications where impact resistance and durability are paramount. These findings are supported by Natarajan et al [61], who emphasized that the mechanical performance of composites in extreme environments is highly dependent on the interplay between reinforcement content and matrix properties. Hence, future research must focus on further optimizing the carbon content and exploring hybrid reinforcement strategies to enhance both tensile strength and toughness, ensuring the material's suitability for high-stress marine applications.

3.2 Flexural Modulus

The flexural performance of the composites, as demonstrated by the flexural modulus values (see Figures 6 and 7), provides critical insights into the material's ability to withstand bending stresses without permanent deformation. The composite reinforced with 0.5% carbon exhibited the highest flexural modulus (95,639.879 MPa), indicating an enhanced resistance to elastic flexural deformation. Supporting this finding, Rajak et al. [24] reported that moderate carbon reinforcement can significantly improve the flexural properties of polymer composites by creating a more cohesive interface between the matrix and the reinforcement. The improved modulus observed in the 0.5% carbon composite suggests that a lower carbon content may facilitate more efficient stress distribution across the material, thereby reducing the likelihood of crack initiation and propagation under loads. This improvement is particularly relevant for applications such as submarine hulls, where materials must endure complex multiaxial stress states without compromising structural integrity.

In contrast, the composite with 2.0% carbon displayed the lowest flexural modulus (57062.565 MPa), indicating reduced strength and greater susceptibility to flexural deformation. This finding is consistent with the observations of [59], who noted that excessive filler content can lead to agglomeration and poor interfacial bonding, thereby weakening the composite's overall mechanical performance. The 1.0% carbon composite, with a flexural modulus of 65857.751 MPa, further supports this trend, as it exhibited lower modulus compared to both the 0.5% and 1.5% carbon composites. This suggests that there is an optimal threshold for carbon reinforcement beyond which the material's flexural performance begins to degrade. The control specimen (pure polyester resin) and the glass fiber-reinforced sample without carbon exhibited flexural moduli of 84694.274 MPa and 80873.606 MPa, respectively. While these values are relatively high, they are surpassed by the 0.5% carbon composite, underscoring the synergistic effect of combining glass fiber with moderate carbon reinforcement to enhance flexural modulus.

The flexural test results highlight the importance of balancing carbon content to achieve optimal mechanical performance. The 0.5% carbon composite, with its exceptional flexural modulus, emerges as a strong candidate for

applications requiring high resistance to flexural stresses. This is particularly significant for submarine hulls, which must maintain structural integrity under varying hydrostatic pressures and dynamic loads. However, the reduced flexural performance of the 2.0% carbon composite raises concerns about the potential for brittle failure under high-stress conditions, as noted by Natarajan et al [61].

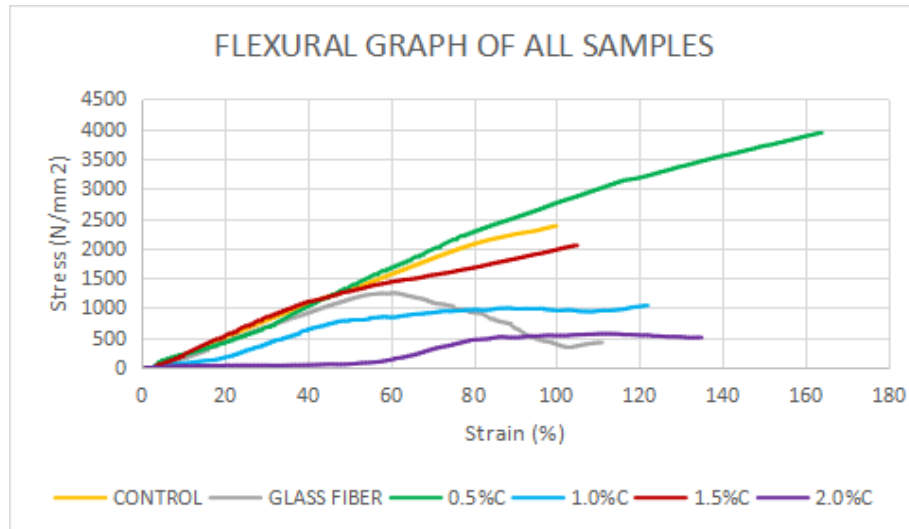


Fig. 6- Flexural test variations for the different samples

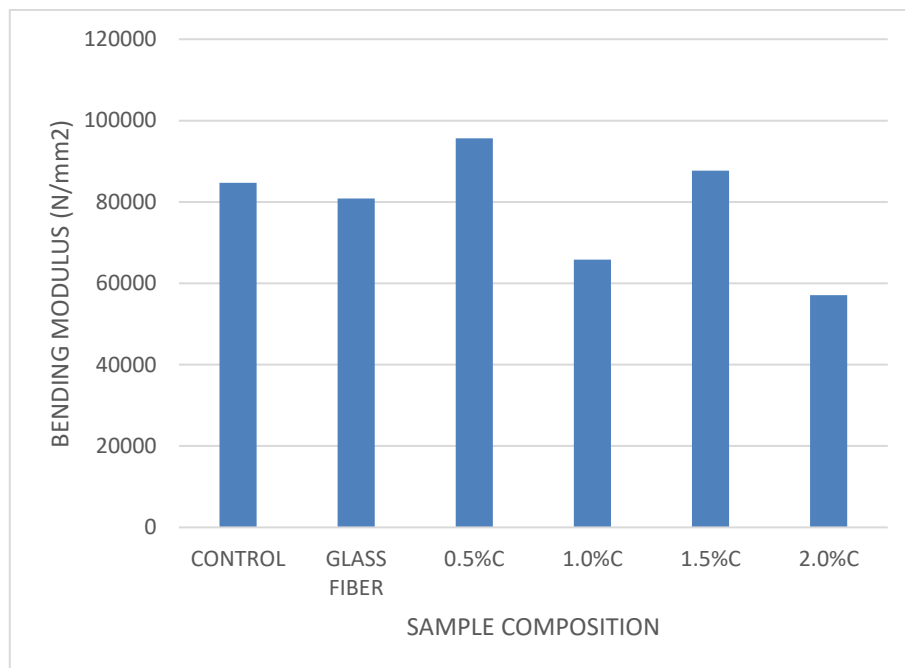


Fig. 7- Flexural Modulus Variation in Glass Fiber–Carbon Reinforced Composites

3.3 Compression Resistance

The compression resistance of the composites, as indicated by the compression modulus of elasticity in Table 3 and Figure 8, provides important insights into the material's ability to withstand crushing forces, which is a critical requirement for submarine hulls operating under extreme hydrostatic pressures. In this study, the term compression modulus of elasticity (compressive modulus) refers to the slope of the elastic region of the stress–strain curve under compressive loading, reflecting the stiffness of the composite in resisting elastic deformation. In contrast, compression resistance (compressive strength) denotes the maximum stress a specimen can withstand before yielding or failure. Although these properties are related, they

are not identical: a higher modulus typically improves a material's ability to resist elastic compression, but ultimate resistance also depends on microstructural factors and failure mechanisms [62].

Table 3. Compression Modulus of Glass Fiber–Carbon Reinforced Polyester Composites

Specimen	Compression Modulus of Elasticity
Control	1849.321
Glass Fiber	1967.741
0.5%C	2938.51
1.0%C	1870.331
1.5%C	1667.302
2.0%C	1377.004

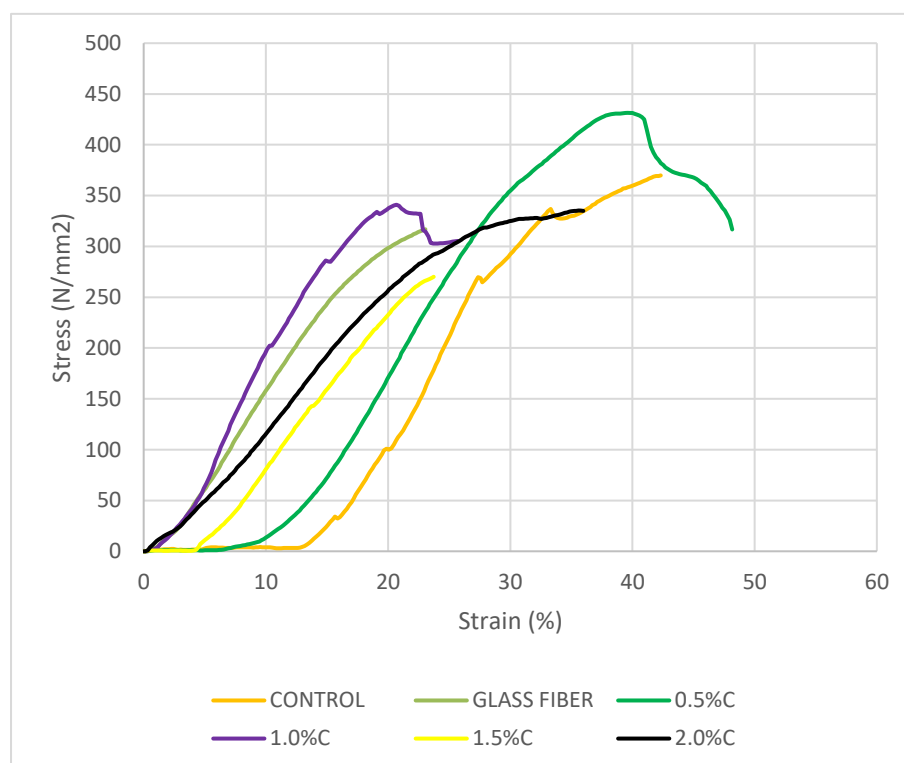


Fig. 8- Compression resistance tests variations for the different samples

The composite with 0.5% carbon exhibited the highest compression modulus (2938.51 MPa), demonstrating superior resistance to compressive stress. This aligns with several studies that show that moderate carbon reinforcement can enhance the compressive properties of polymer composites by improving the load-bearing capacity of the matrix [61, 63 – 64]. The 1.0% carbon composite's performance suggests that an optimal carbon content exists, which strengthens the polymer matrix without introducing excessive brittleness. This is particularly relevant for marine applications, where materials must maintain structural integrity under high compressive loads without undergoing catastrophic failure.

In contrast, the composite with 2.0% carbon displayed the lowest compression modulus (1377.004 MPa), indicating reduced resistance to compressive forces. In alignment with Sravanthi et al [56], higher carbon content can lead to agglomeration and poor interfacial bonding, thereby weakening the composite's overall mechanical performance. The 1.0% carbon composite, with a compression modulus of 1870.331 MPa, also underperformed compared to the 0.5% carbon composite, further supporting the notion that there is an optimal threshold for carbon reinforcement. The control specimen (pure polyester resin) and the glass fiber-reinforced sample without carbon exhibited compression moduli of 1849.321 MPa and 1967.741 MPa, respectively. While these values are relatively high, they are surpassed by the 0.5% carbon composite,

underscoring the synergistic effect of combining glass fiber with moderate carbon reinforcement to enhance compressive properties.

The compression test results highlight the importance of balancing carbon content to achieve optimal mechanical performance. The 0.5% carbon composite, with its exceptional compression modulus, emerges as the most preferred for applications requiring high resistance to compressive stress. This is particularly significant for submarine hulls, which must endure varying hydrostatic pressures without compromising structural integrity. However, the reduced compression performance of the 2.0% carbon composite raises concerns about the potential for brittle failure under high-stress conditions, as noted by [61].

3.4 Hardness and Surface Resistance

Figure 9 presents the hardness results revealing a distinct inverse relationship between reinforcement content and resistance to localized deformation, aligning with existing literature on fiber-reinforced polymer composites. The control specimen (pure polyester resin) recorded the highest hardness value (408.67 HRB), a result that underscores the intrinsic rigidity of unreinforced thermosetting polymers. According to DeArmitt and Rothon [59], polyester resins exhibit high hardness due to their dense cross-linked molecular structure, which restricts plastic deformation under localized stress. However, while hardness is often associated with improved scratch and wear resistance, it frequently correlates with increased brittleness, as observed in [65]. This implies that although the pure resin offers excellent resistance to indentation, it may lack the toughness required for impact-prone applications, particularly in submarine hulls that experience dynamic loading conditions.

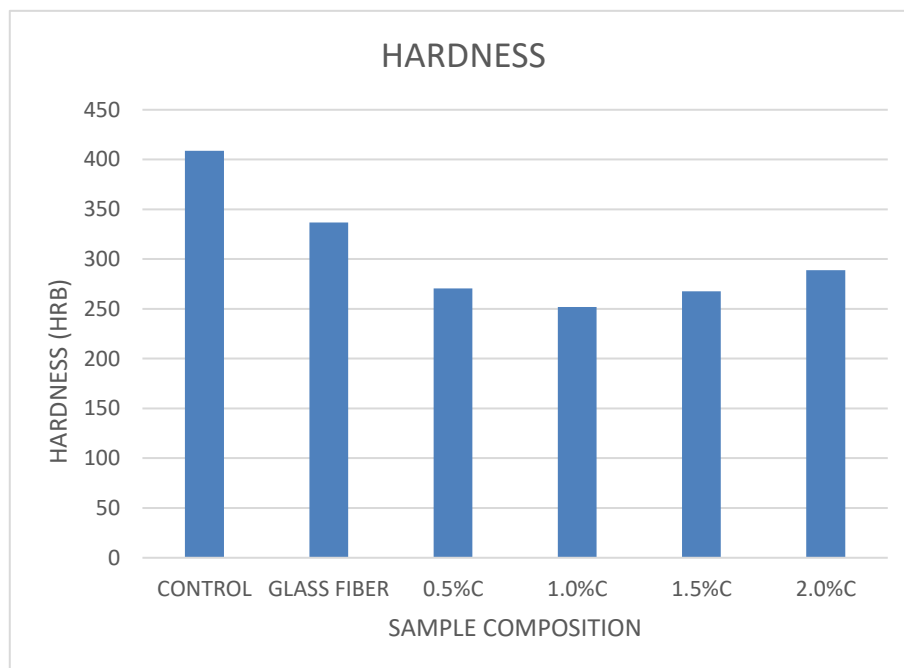


Fig. 9- Hardness Distribution of Glass Fiber–Carbon Reinforced Polyester Composites

The incorporation of glass fiber reinforcement led to a significant reduction in hardness (336.67 HRB). The introduction of carbon particulate reinforcement further reduced hardness values, with 1.0% carbon composite recording the lowest hardness (252 HRB). This decline suggests that increasing carbon content leads to reduced polymer rigidity, likely due to insufficient interfacial bonding or increased internal stress relaxation. The literature supports this observation, as Akar et al [66] noted that adding carbon-based fillers to polymer matrices can introduce microstructural inconsistencies, reducing overall hardness while enhancing flexibility and energy absorption. This highlights a critical trade-off between surface resistance and ductility, necessitating optimization to achieve the desired balance for marine applications.

Interestingly, the 2.0% carbon composite (289 HRB) exhibited a slight rebound in hardness, suggesting that beyond a certain threshold, carbon particulates may enhance surface resistance through particle reinforcement mechanisms. Pei et al

[57] indicate that at higher filler concentrations, carbon particulates can act as secondary hardening agents, impeding localized plastic flow and increasing scratch resistance. However, excessive carbon content may also lead to agglomeration, introducing microstructural defects that weaken the composite's mechanical integrity. These findings reinforce the complexity of hardness optimization in hybrid composites, where the interplay between fiber reinforcement, particulate fillers, and matrix adhesion dictates overall performance.

3.5 Impact Toughness and Energy Absorption

Survivability in high-impact environments demands a material's ability to dissipate energy effectively without succumbing to catastrophic failure. The impact toughness result, as shown in Figure 10, reveals an intricate balance between reinforcement content and fracture resistance, a balance that defines the structural reliability of composites in dynamic load-bearing applications such as submarine hulls. Among the tested specimens, the 0.5% carbon composite demonstrated the highest impact energy absorption (0.137 J), signifying an optimal reinforcement-matrix synergy where stress is diffused across the composite rather than concentrated at failure points. The polymer matrix, supplemented by a restrained amount of carbon, retains sufficient ductility to deform under impact rather than fracture, a crucial attribute for materials exposed to unpredictable stresses in underwater environments.

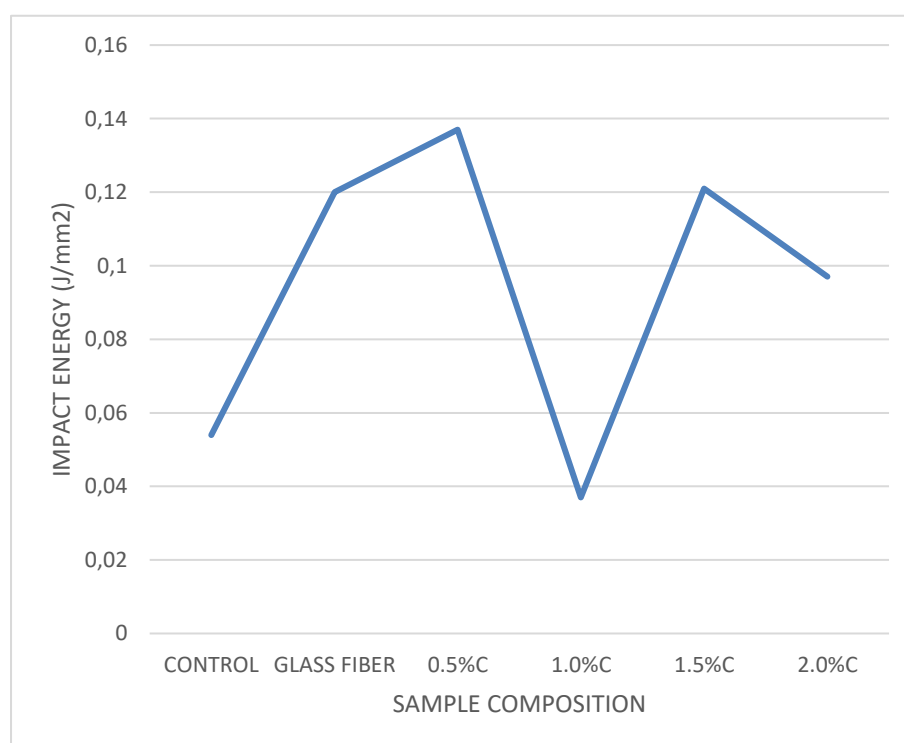


Fig.10- Impact Energy Absorption of Glass Fiber–Carbon Reinforced Polyester Composites

A deviation from this optimized reinforcement ratio manifests in brittle tendencies, as seen in the 1.0% carbon composite, which recorded the lowest impact energy absorption (0.037 J). Such a sharp decline suggests that an increase in carbon content beyond a critical threshold undermines energy dissipation mechanisms, potentially due to filler agglomeration and reduced polymer chain mobility, a phenomenon also documented by [59]. The 2.0% carbon composite (0.097 J) further reinforces this trend, performing below both 0.5% and 1.5% carbon composites, indicating that excessive filler content induces microstructural weaknesses that serve as fracture initiation sites rather than reinforcing elements. The control specimen (pure polyester resin, 0.054 J) and the glass fiber-only composite (0.12 J) establish a baseline, confirming that while glass fiber provides structural reinforcement, the introduction of moderate carbon content (0.5%) amplifies impact resistance through energy redistribution across the fiber-polymer interface.

What emerges from these findings is not merely a hierarchy of impact performance but a blueprint for reinforcement optimization, particularly for applications where materials must endure high-strain rates without premature failure. The dominance of the 0.5% carbon composite underscores the necessity of controlled reinforcement dispersion, where neither

deficiency nor excess leads to structural compromise. This principle is pivotal in marine engineering, where impact-resistant hulls must mitigate the risks of external mechanical shocks and underwater collisions. However, the diminished toughness observed in the 1.0% and 2.0% carbon composites raises critical concerns regarding brittle failure thresholds, as highlighted by [61]. Future advancements may involve hybrid reinforcement strategies, such as the incorporation of nano-fillers or graded composite structures, to refine energy absorption mechanisms while preserving the composite's overall mechanical stability [67].

3.6 Density and Buoyancy Characteristics

Density testing was performed to assess the material's compactness and its implications for buoyancy in marine environments, a critical factor for submarine hull design where weight reduction and buoyancy are paramount. According to Figure 11, the control specimen, composed of pure polyester resin, exhibited the highest density (1740 kg/m^3), which is consistent with the inherent density of unfilled thermoset polymers [68]. In contrast, the composite with 1.0% carbon displayed the lowest density (970 kg/m^3), a significant reduction that aligns with [12] who demonstrated that carbon reinforcement, particularly at lower concentrations, can reduce the overall density of polymer composites by introducing porosity and reducing the mass of the polymer matrix. This reduction in density is particularly advantageous for marine applications, as it enhances buoyancy and reduces the overall weight of the submarine hull, thereby improving energy efficiency and maneuverability.

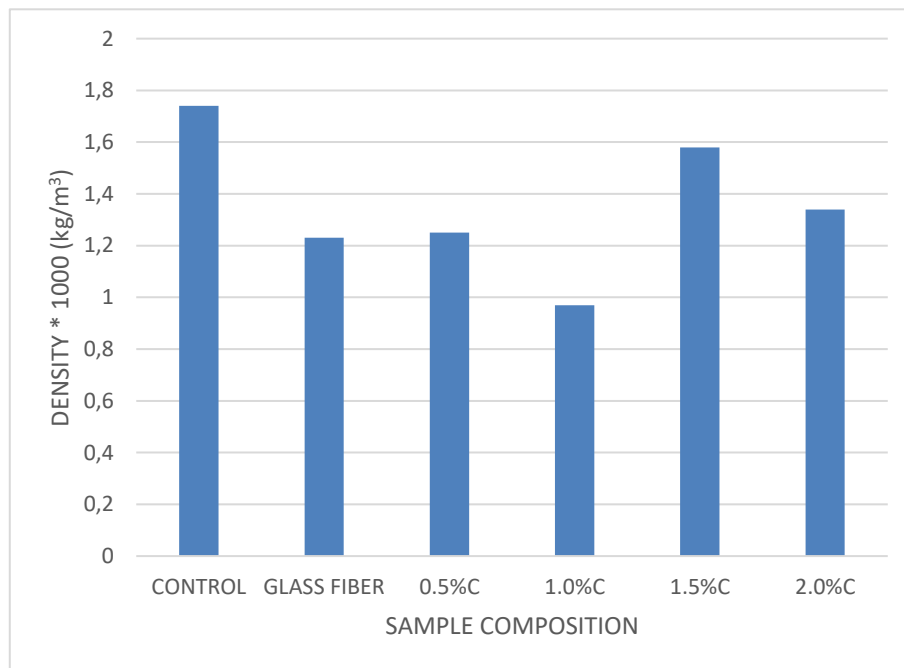


Fig. 11- Density Distribution of Glass Fiber–Carbon Reinforced Polyester Composites

The glass-fiber-reinforced sample without carbon had a density of 1230 kg/m^3 , which is lower than the control but higher than the 1.0% carbon composite. This suggests that while glass fiber reinforcement contributes to weight reduction, the addition of carbon at optimal concentrations can further enhance this effect. The carbon-reinforced composites exhibited densities ranging from 1250 kg/m^3 (0.5% carbon) to 1580 kg/m^3 (1.5% carbon), indicating that carbon content plays a significant role in determining the material's density. The 1.5% carbon composite, with a density of 1580 kg/m^3 , is notably denser than the 0.5% and 1.0% carbon composites, which is consistent with the observations that higher carbon content can lead to increased density due to the higher mass of carbon particles and potential agglomeration [61]. These findings underscore the importance of optimizing carbon content to achieve a balance between mechanical properties and density, ensuring that the material remains lightweight without compromising structural integrity.

The implications of these density variations for buoyancy and submarine hull design are profound. Lower-density materials, such as the 1.0% carbon composite, offer enhanced buoyancy, which is critical for maintaining the submarine's ability to float and maneuver efficiently. According to Ang et al [69], reducing the weight of submarine hull materials can

significantly improve operational efficiency and reduce energy consumption. However, the trade-off between density and mechanical properties must be carefully considered. While the 1.0% carbon composite offers the lowest density, its mechanical performance in other tests, such as impact toughness and compression resistance, may not be optimal. Conversely, the 0.5% carbon composite, with a density of 1250 kg/m³, strikes a balance between reduced density and enhanced mechanical properties, making it a promising candidate for submarine hull applications.

3.7 Microstructural Analysis

The microstructural analysis of the composites using SEM-EDS provides profound insights into the material's internal architecture, interfacial bonding, and elemental composition. The micrograph of the control specimen (pure polyester resin) reveal a relatively smooth and homogeneous surface, indicative of a well-cured thermoset polymer matrix see Figure 12. This is consistent with the findings that pure polyester resins typically exhibit a uniform microstructure [70]. However, the EDS analysis reveals the presence of silicon (Si) and calcium (Ca) peaks, suggesting the inclusion of silica (SiO₂) and calcium carbonate (CaCO₃) as fillers. These fillers are commonly added to polyester resins to enhance mechanical properties such as fire resistance. The presence of magnesium (Mg), sodium (Na), and sulfur (S) peaks further indicates the use of additives or impurities, which may have been introduced during the resin formulation or curing process.

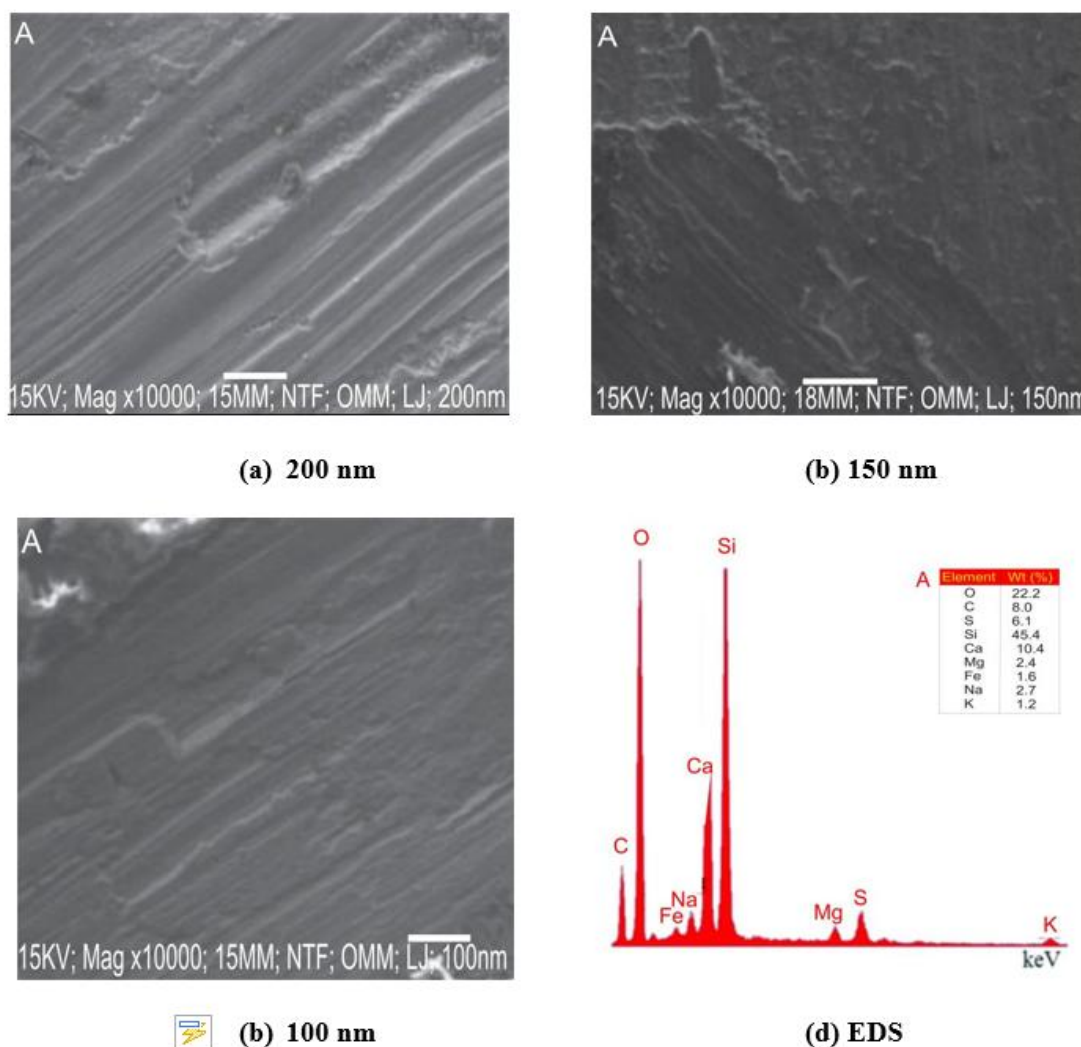


Fig. 12- SEM Micrograph of the Control Specimen (Polyester Resin) Showing Surface Morphology

The SEM micrographs of the glass fiber-reinforced composite exhibit a well-defined microstructure, highlighting the uniform integration of glass fibers within the polyester resin matrix (see Figure 13). The fibers appear well-distributed, with minimal voids or defects, indicating good interfacial bonding between the fibers and the matrix. This is critical for achieving

optimal mechanical performance, as poor interfacial bonding can lead to stress concentrations and premature failure [61]. The EDS analysis confirms the presence of silicon (Si) and oxygen (O) as major peaks, consistent with the composition of glass fibers, which are typically made of silica (SiO_2). The presence of sodium (Na), magnesium (Mg), and calcium (Ca) peaks suggests that the glass fibers are of the soda-lime variety, commonly used in composite applications due to their balance of mechanical properties and cost-effectiveness. Trace amounts of sulfur (S) and iron (Fe) may indicate the presence of additives or impurities, which could influence the material's performance under certain conditions.

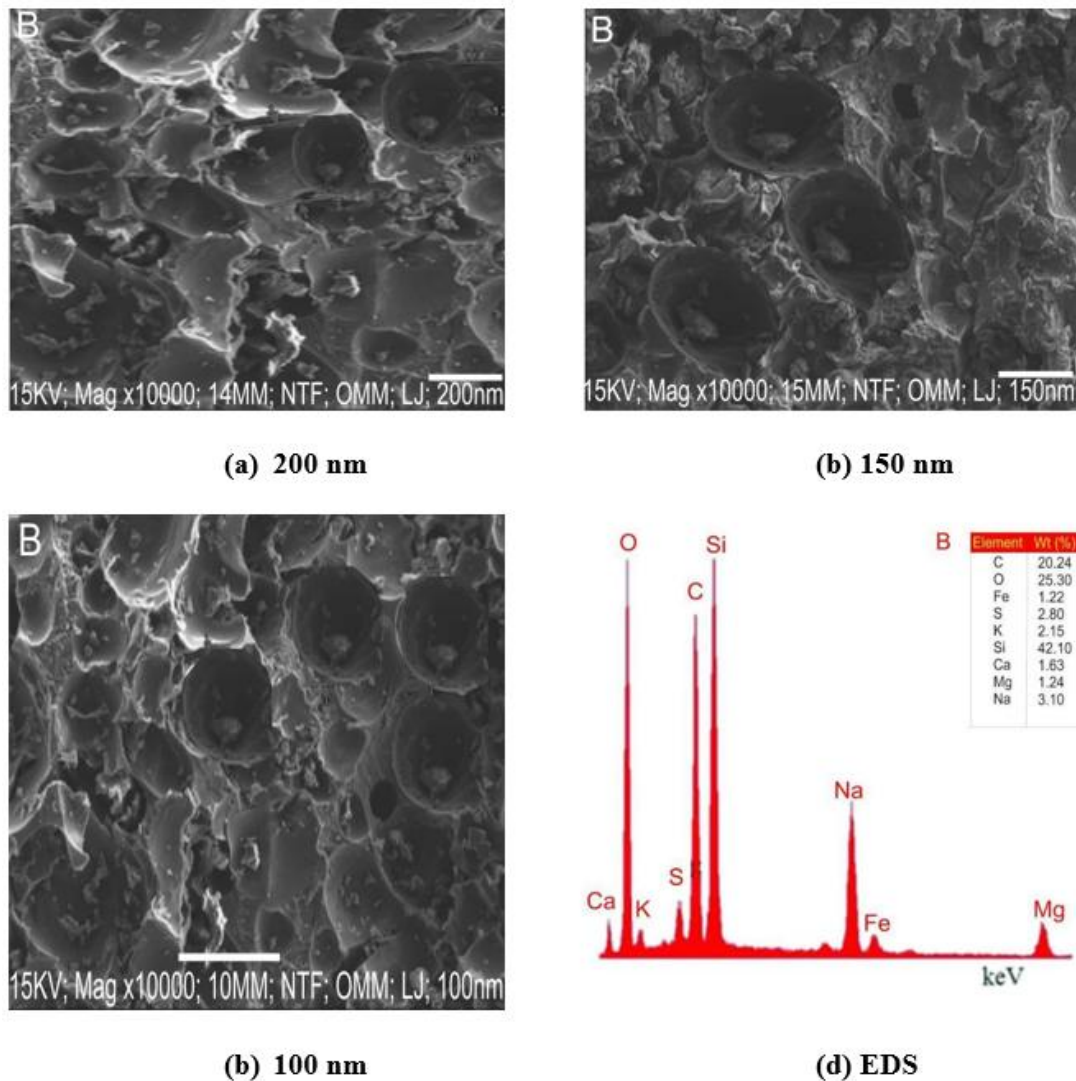


Fig. 13- SEM micrographs of the glass fiber-reinforced composite

The SEM micrographs of the hybrid composite, incorporating glass fibers and 0.5% carbon, depict a highly structured morphology, where carbon particles are uniformly distributed within the polyester matrix, complementing the reinforcement provided by the glass fibers (Figure 14). The carbon particles appear to be well-distributed, with no significant agglomeration, suggesting effective mixing and interfacial bonding. The EDS analysis confirms the presence of carbon (C) as a distinct peak, corresponding to the 0.5% carbon reinforcement. The silicon (Si) and oxygen (O) peaks indicate the presence of glass fibers, while the sodium (Na), potassium (K), magnesium (Mg), and calcium (Ca) peaks suggest the use of soda-lime glass fibers. The trace amounts of iron (Fe) may indicate impurities or contamination during processing, which could affect the material's performance under certain conditions.

The control specimen, with its smooth and homogeneous microstructure, exhibits relatively low mechanical performance due to the absence of reinforcing phases. In contrast, the glass fiber-reinforced composite demonstrates improved mechanical properties, owing to the presence of well-distributed glass fibers that enhance stress transfer and load-bearing capacity. The

hybrid composite, with both glass fibers and carbon particles, exhibits the most complex microstructure, with carbon particles providing additional reinforcement and improving interfacial bonding. This agrees with extant literature that confirms that hybrid composites often exhibit superior mechanical properties due to the synergistic effects of multiple reinforcement phases [12, 61].

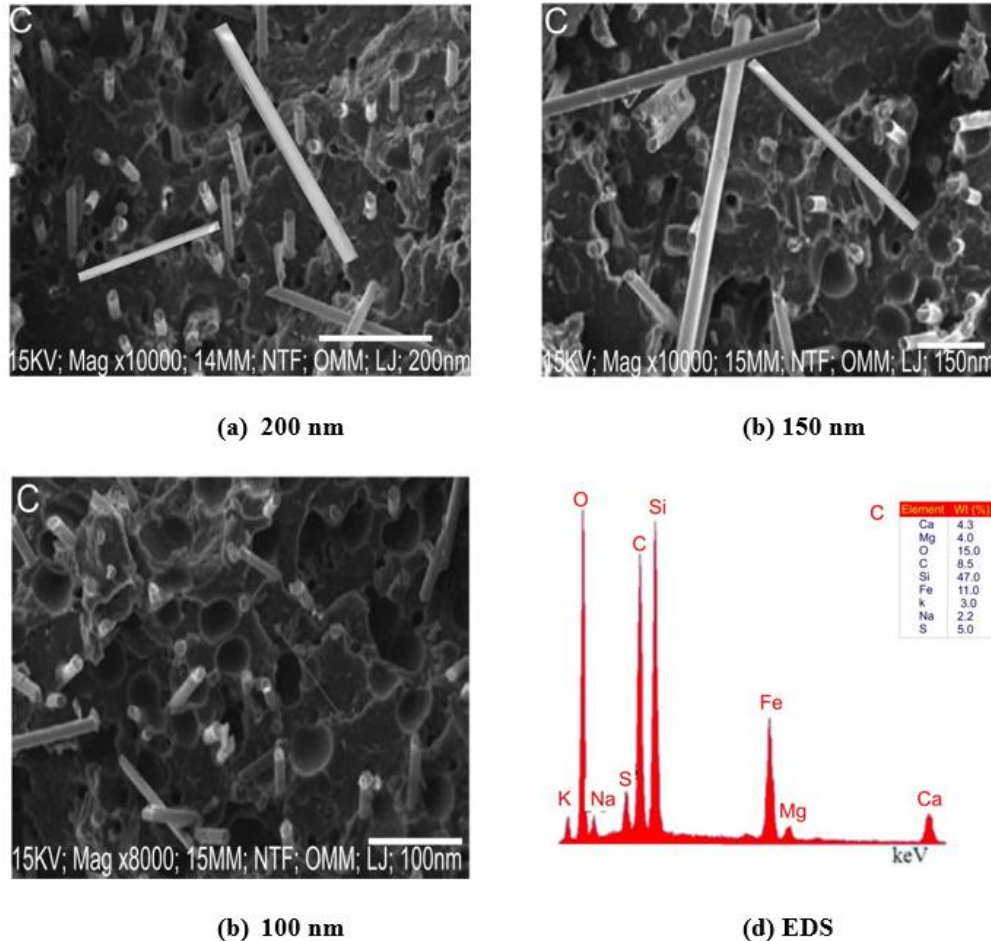


Fig.14- Micrograph of the Hybrid Composite

4 Conclusion

This study evaluated the mechanical, microstructural, and environmental performance of glass fiber composites reinforced with carbon derived from date seeds for potential submarine hull applications. The key findings are as follows:

- Reinforcement composition strongly influenced mechanical properties. The 0.5% carbon composite exhibited the best overall performance, with superior impact resistance (0.137 J) and flexural modulus (95,639.879 MPa), making it a promising candidate for dynamic load-bearing marine applications.
- High carbon loading reduced performance. The 2.0% carbon composite achieved the highest tensile modulus (4844.308 MPa) but showed reduced flexibility and impact resistance, consistent with agglomeration effects and poor interfacial bonding at excessive filler contents.
- Microstructural analysis (SEM/EDS) confirmed that moderate carbon reinforcement improved fiber–matrix adhesion, while excessive carbon led to clustering and compromised structural integrity.
- Density and buoyancy advantages were observed, with the 1.0% carbon composite showing the lowest density (0.97 g/cm³) without sacrificing structural capacity.

- No measurable water absorption was recorded in any of the composites, indicating strong hydrophobicity and resistance to moisture-induced degradation in marine environments.
- Among the formulations tested, the 0.5% carbon composite provides the most balanced set of properties—impact resistance, flexural performance, buoyancy, and durability—highlighting its potential as a viable alternative to conventional metallic materials for submarine hull structures.

In summary, this study establishes glass fiber and carbon-reinforced polyester composites as a viable alternative to traditional metallic submarine hull materials, offering a compelling balance of strength, toughness, buoyancy, and environmental resilience. Among the tested formulations, the 0.5% carbon composite emerges as the most promising, combining impact resistance, and lightweight properties essential for marine engineering applications. However, achieving an optimal balance between reinforcement concentration, structural efficiency, and environmental adaptability remains paramount. These findings lay the foundation for future material innovations, contributing to the development of next-generation composite solutions tailored for high-performance marine and underwater structures.

5 Acknowledgement

The authors hereby appreciate and acknowledges the Africa Centre of Excellence for Sustainable Power and Energy Development, ACE-SPED, University of Nigeria, Nsukka; Energy materials research group, University of Nigeria, Nsukka, Nigeria; and Faculty of Engineering and Built Environment, University of Johannesburg, Auckland Park, South Africa for their supports

The Author gives the publisher the consent to publish the work.

6 Conflict of interest

There is no conflict of interest in this work

REFERENCES

- [1]- H. McGeachy, The changing strategic significance of submarine cables: old technology, new concerns. *Aust. J. Int. Aff.* 76(2) (2022) 161-177. doi:10.1080/10357718.2022.2051427.
- [2]- J. C. Daidola, Hull structural material selection for high speed vessels. *Nav. Eng. J.* 134(2) (2022) 113-124.
- [3]- J. C. Daidola, Construction costs of titanium hull variants—game changer? *Nav. Eng. J.* 132(4) (2020) 97-104.
- [4]- S. J. Yeo, S.Y. Hong, J.H. Song, Deep-reinforcement-learning-based hull form optimization method for stealth submarine design. *Int. J. Nav. Archit. Ocean Eng.* 16 (2024) 100595. doi:10.1016/j.ijnaoe.2024.100595.
- [5]- M. Ćorak, Z. Šperanda, J. Čokić, J. Parunov, Structural analysis of tourist submarine with acrylic hull, In: *Sustainable Development and Innovations in Marine Technologies*. CRC Press, 2022.
- [6]- A. F. Vermeulen, Coastal border control using magnetic field signatures, In: *NL ARMS Netherlands Annual Review of Military Studies 2018: Coastal Border Control: From Data and Tasks to Deployment and Law Enforcement*. Springer Nature (2018).
- [7]- Y. Wu, Z. He, F. Wang, R. Luo, J. Zhang, Y. Cao, Impact of pressure hull implosion on ultra-high pressure chambers. *Ships Offshore Struct.* (2025) 1–10. doi:10.1080/17445302.2025.2462567.
- [8]- M. Saravanan, D. B. Kumar, A review on navy ship parts by advanced composite material. *Mater. Today: Proc.* 45(7) (2021) 6072–6077. doi:10.1016/j.matpr.2020.10.074
- [9]- C. Baley, P. Davies, W. Troalen, A. Chamley, I. Dinham-Price, A. Marchandise, V. Keryvin, Sustainable polymer composite marine structures: Developments and challenges. *Prog. Mater. Sci.* 145 (2024) 101307. doi:10.1016/j.pmatsci.2024.101307
- [10]- E. Dinneya-Onuoha, V. S. Aigbodion, A. Ogbodo Agbo, Unlocking the optimization of electrical properties of epoxy-carbon nanotube composites modified with waste eggshell particles via the Taguchi–Grey method. *Oxf. Open Mater. Sci.* 4(1), (2024) itae015. doi:10.1093/oxfmat/itae015.
- [11]- A. Raheem, K. M. Subbaya, Performance evaluation of hybrid polymer composite materials in marine applications: A review. *Mater. Today: Proc.* In press (2023). doi:10.1016/j.matpr.2023.01.346
- [12]- F. Rubino, A. Nisticò, F. Tucci, P. Carlone, Marine application of fiber reinforced composites: A review. *J. Mar.*

- Sci. Eng. 8(1) (2020) 26. doi:10.3390/jmse8010026
- [13]- S. Suryanto, A. R. Prabowo, R. Adiputra, S. Ehlers, M. Braun, I. Yaningsih, R. Wijaya, A review of composite materials for marine purposes: Historical perspective and current state. *Procedia Struct. Integr.* 72 (2025) 427–435. doi:10.1016/j.prostr.2025.08.123
- [14]- H. C. Viljoen, N. Mahomed, L. H. Cupido, G. P. Mitchell, Effect of corrosion thinning on depth of operation: Case study of an HY-80 steel submarine pressure hull. *Mar. Struct.* 81 (2022) 103103. doi:10.1016/j.marstruc.2021.103103
- [15]- O. El Hawary, L. Boccarusso, M. P. Ansell, M. Durante, F. Pinto, An overview of natural fiber composites for marine applications. *J. Mar. Sci. Eng.* 11(5) (2023) 1076. doi:10.3390/jmse11051076
- [16]- P. Choudhari, V. Kulkarni, S. Khandal, Review on efforts to improve the mechanical performance of fiber-reinforced polymer (FRP) composites under the marine environment. *J. Inst. Eng. India: Ser. C* 105(1) (2024) 241–269. doi:10.1007/s40032-023-01009-9
- [17]- S. Kappenthuler, S. Seeger, Holistic evaluation of the suitability of metal alloys for sustainable marine construction from a technical, economic and availability perspective. *Ocean Eng.* 219 (2021) 108378. doi:10.1016/j.oceaneng.2020.108378
- [18]- S. Kappenthuler, S. Seeger, (2021). Assessing the long-term potential of fiber reinforced polymer composites for sustainable marine construction. *J. Ocean Eng. Mar. Energy* 7(2) (2021) 129–144. doi:10.1007/s40722-021-00187-x
- [19]- M. Massou, N. Babu, G. Xian, Experimental study on the mechanical properties of CFRP/epoxy composite plates under seawater immersion. *Struct.* 54 (2023) 48–57. doi:10.1016/j.istruc.2023.05.042
- [20]- W. Ma, R. Elkin, Application of sandwich structural composites. In: *Sandwich Structural Composites*. Routledge, First Edition, 2021.
- [21]- E. P. Koumoulos, A. F. Trompeta, R. M. Santos, M. Martins, C. M. D. Santos, V. Iglesias, C. A. Charitidis, Research and development in carbon fibers and advanced high-performance composites supply chain in Europe: A roadmap for challenges and the industrial uptake. *J. Compos. Sci.* 3(3), (2019) 86. doi:10.3390/jcs3030086.
- [22]- A. Sayam, A. M. Rahman, M. S. Rahman, S. A. Smriti, F. Ahmed, M. F. Rabbi, M. O. Faruque, A review on carbon fiber-reinforced hierarchical composites: mechanical performance, manufacturing process, structural applications and allied challenges. *Carbon Lett.* 32(5) (2022) 1173–1205. doi:10.1007/s42823-022-00358-2.
- [23]- N. Van de Werken, H. Tekinalp, P. Khanbolouki, S. Ozcan, A. Williams, M. Tehrani, (2020). Additively manufactured carbon fiber-reinforced composites: State of the art and perspective. *Addit. Manuf.* 31 (2020) 100962. <https://doi.org/10.1016/j.addma.2019.100962>.
- [24]- D. K. Rajak, P. H. Wagh, E. Linul, Manufacturing technologies of carbon/glass fiber-reinforced polymer composites and their properties: A review. *Polymers* 13(21), (2021) 3721. <https://doi.org/10.3390/polym13213721>.
- [25]- K. Kawajiri, K. Sakamoto, Environmental impact of carbon fibers fabricated by an innovative manufacturing process on life cycle greenhouse gas emissions. *Sustain. Mater. Technol.* 31 (2022) e00365. <https://doi.org/10.1016/j.susmat.2021.e00365>.
- [26]- S. Z. H. Shah, S. Karuppanan, P. S. M. Megat-Yusoff, Z. Sajid, Impact resistance and damage tolerance of fiber reinforced composites: A review. *Compos. Struct.* 217 (2019) 100–121. <https://doi.org/10.1016/j.compstruct.2019.03.021>.
- [27]- E. Pakdel, S. Kashi, R. Varley, X. Wang, Recent progress in recycling carbon fibre reinforced composites and dry carbon fibre wastes. *Resour. Conserv. Recycl.* 166 (2021) 105340. <https://doi.org/10.1016/j.resconrec.2020.105340>.
- [28]- P. M. Gore, B. Kandasubramanian, (2018). Functionalized aramid fibers and composites for protective applications: a review. *Ind. Eng. Chem. Res.* 57(49) (2018) 16537–16563. <https://doi.org/10.1021/acs.iecr.8b04903>.
- [29]- A. He, T. Xing, Z. Liang, Y. Luo, Y. Zhang, M. Wang, W. Xu, Advanced aramid fibrous materials: Fundamentals, advances, and beyond. *Adv. Fiber Mater.* 6(1) (2024) 3–35. <https://doi.org/10.1007/s42765-023-00332-1>.
- [30]- O. Çelik, A. Yaşar, B. Karaçor, Properties of basalt/aramid fiber reinforced hybrid composites compared to carbon fiber composites. *Polym. Compos.* 44(6) (2023) 3509–3521. <https://doi.org/10.1002/pc.27339>.
- [31]- S. Siengchin, A review on lightweight materials for defence applications: Present and future developments. *Def. Technol.* 24 (2023) 1–17. <https://doi.org/10.1016/j.dt.2023.02.025>.
- [32]- A. Pai, C. R. Kini, S. Shenoy, Development of materials and structures for shielding applications against blast and ballistic impact: A detailed review. *Thin-Walled Struct.* 179 (2022) 109664. doi:10.1016/j.tws.2022.109664
- [33]- M. S. Abed, P. S. Ahmed, J. K. Oleiwi, B. M. Fadhil, Low velocity impact of Kevlar and ultra high molecular

- weight polyethylene (UHMWPE) reinforced epoxy composites. *Multidiscip. Model. Mater. Struct.* 16(6) (2020) 1617–1630. <https://doi.org/10.1108/MMMS-09-2019-0164>.
- [34]- M. N. Uddin, J. M. George, V. R. Patlolla, R. Asmatulu, Investigating the effects of UV light and moisture ingress on low-impact resistance of three different carbon fiber–reinforced composites. *Adv. Compos. Hybrid Mater.* 2 (2019) 701–710. doi:10.1007/s42114-019-00117-4
- [35]- R. Naveen, M. Kumar, M. Ramesh, R. Abinaya, M. S. Prasath, An investigation on effect of ultraviolet (UV) rays on mechanical properties of epoxy laminates. *Mater. Today: Proc.* In press (2023). <https://doi.org/10.1016/j.matpr.2023.06.257>.
- [36]- G. Atakok, D. Mertgenc Yoldas, Comparison of GFRP (Glass Fiber-Reinforced Polymer) and CFRP (Carbon Fiber-Reinforced Polymer) composite adhesive-bonded single-lap joints used in marine environments. *Sustainability* 16(24) (2024) 11105. <https://doi.org/10.3390/su162411105>.
- [37]- A. B. M. Supian, M. R. M. Asyraf, A. Syamsir, Q. Ma, K. Z. Hazrati, M. N. M. Azlin, S. M. K. Thiagamani, Kenaf/glass fiber-reinforced polymer composites: Pioneering sustainable materials with enhanced mechanical and tribological properties, *Polym. Compos.* 45(16) (2024) 14421–14447. <https://doi.org/10.1002/pc.28785>.
- [38]- E. Natarajan, L. I. Freitas, M. S. Santhosh, K. Markandan, A. A. M. Al-Talib, C. S. Hassan, Experimental and numerical analysis on suitability of S-glass-carbon fiber reinforced polymer composites for submarine hull. *Def. Technol.* 19 (2023) 1–11. <https://doi.org/10.1016/j.dt.2022.06.003>.
- [39]- Y. Zhong, M. Cheng, X. Zhang, H. Hu, D. Cao, S. Li, Hygrothermal durability of glass and carbon fiber reinforced composites – A comparative study. *Compos. Struct.* 211 (2019) 134–143. <https://doi.org/10.1016/j.compstruct.2018.12.034>.
- [40]- G. Hota, W. Barker, A. Manalo, Degradation mechanism of glass fiber/vinylester-based composite materials under accelerated and natural aging. *Constr. Build. Mater.* 256 (2020) 119462. <https://doi.org/10.1016/j.conbuildmat.2020.119462>.
- [41]- A. Murawski, R. Diaz, S. Inglesby, K. Delabar, R. L. Quirino, Synthesis of bio-based polymer composites: fabrication, fillers, properties, and challenges. In: *Polymer Nanocomposites in Biomedical Engineering*. Springer Nature, 2019.
- [42]- I. Peter P, A. A. Adekunle, A review of ceramic/bio-based hybrid reinforced aluminium matrix composites. *Cogent Eng.* 7(1) (2020) 1727167. doi:10.1080/23311916.2020.1727167
- [43]- V. S. Aigbodon, E. Dinneya-Onuoha, Unveiling the anti-corrosion properties of Zn-eggshell particle composite coatings on mild steel in seawater-simulated solution using starch as a modifier. *RSC Adv.* 14(34) (2024) 24548–24560. <https://doi.org/10.1039/D4RA04283B>
- [44]- J. Vidal, D. Ponce, A. Mija, M. Rymarczyk, P. Castell, Sustainable composites from nature to construction: hemp and linseed reinforced biocomposites based on bio-based epoxy resins. *Mater.* 16(3) (2023) 1283. <https://doi.org/10.3390/ma16031283>.
- [45]- A. Maino, G. Janszen, L. Di Landro, (2019). Glass/epoxy and hemp/bio-based epoxy composites: manufacturing and structural performances. *Polym. Compos.* 40(S1) (2019) E723–E731. <https://doi.org/10.1002/pc.24973>.
- [46]- K. S. Al-Zahrani, A. A. Faqeeh, Z. R. Abdulghani, S. P. Thomas, A review on the physicochemical properties and utilization of date seeds in value-added engineering products. *Polym. Bull.* 79(12) (2022) 10433–10490. doi.org/10.1007/s00289-021-04048-3
- [47]- A. E. Ogungbenro, D. V. Quang, K. A. Al-Ali, L. F. Vega, M. R. Abu-Zahra, Synthesis and characterization of activated carbon from biomass date seeds for carbon dioxide adsorption. *J. Environ. Chem. Eng.* 8(5) (2020) 104257. <https://doi.org/10.1016/j.jece.2020.104257>.
- [48]- R. K. Purama, J. N. Al-Sabahi, K. Sudesh, Evaluation of date seed oil and date molasses as novel carbon sources for the production of poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) by *Cupriavidus necator* H16 Re 2058/pCB113. *Ind. Crops Prod.* 119 (2018) 83–92. <https://doi.org/10.1016/j.indcrop.2018.04.013>.
- [49]- C. de la Cruz-Lovera, F. Manzano-Agugliaro, E. Salmerón-Manzano, J. L. de la Cruz-Fernández, A. J. Perea-Moreno, Date seeds (*Phoenix dactylifera* L.) valorization for boilers in the Mediterranean climate. *Sustainability* 11(3) (2019) 711. <https://doi.org/10.3390/su11030711>.
- [50]- C. Fragassa, F. Vannucchi de Camargo, C. Santulli, Sustainable biocomposites: Harnessing the potential of waste seed-based fillers in eco-friendly materials. *Sustainability* 16(4) (2024) 1526. <https://doi.org/10.3390/su16041526>.
- [51]- L. Zaccariello, D. Battaglia, B. Morrone, M. L. Mastellone, Hydrothermal carbonization: a pilot-scale reactor design for bio-waste and sludge pre-treatment. *Waste Biomass Valorization* 13(9) (2022) 3865–3876.

doi.org/10.1007/s12649-022-01859-x.

- [52]- S. Li, Reviewing air pollutants generated during the pyrolysis of solid waste for biofuel and biochar production: toward cleaner production practices. *Sustainability* 16(3) (2024) 1169. <https://doi.org/10.3390/su16031169>.
- [53]- E. K. Sachin, N. Muthu, P. Tiwari, Hybrid recycling methods for fiber reinforced polymer composites: a review. *J. Reinf. Plast. Compos.* 07316844241258557 (2024). <https://doi.org/10.1177/07316844241258557>.
- [54]- K. P. Keboletse, F. Ntuli, O. P. Oladijo, Influence of coal properties on coal conversion processes—coal carbonization, carbon fiber production, gasification and liquefaction technologies: a review. *Int. J. Coal Sci. Technol.* 8 (2021) 817 – 843. doi.org/10.1007/s40789-020-00401-5.
- [55]- O. Okolie, J. Latto, N. Faisal, H. Jamieson, A. Mukherji, J. Njuguna, Manufacturing defects in thermoplastic composite pipes and their effect on the in-situ performance of thermoplastic composite pipes in oil and gas applications. *Appl. Compos. Mater.* 30(1) (2023) 231–306. doi.org/10.1007/s10443-022-10066-9
- [56]- R. A. Nargis, D. A. Jack, Fiber orientation quantification for large area additively manufactured parts using SEM imaging. *Polymers* 15(13) (2023) 2871. <https://doi.org/10.3390/polym15132871>.
- [57]- N. Pei, S. Zhou, C. Xu, J. Shang, Q. Wu, Cluster analysis of acoustic emission signals for tensile damage characterization of quasi-static indented carbon/glass fiber-reinforced hybrid laminate composites. *Compos. Part A: Appl. Sci. Manuf.* 150 (2021) 106597. <https://doi.org/10.1016/j.compositesa.2021.106597>.
- [58]- K. Sravanthi, V. Mahesh, B.N. Rao, Influence of micro and nano carbon fillers on impact behavior of GFRP composite materials, *Mater. Today: Proc.* 37 (2021) 1075–1078. <https://doi.org/10.1016/j.matpr.2020.06.298>.
- [59]- C. DeArmitt, R. Rothon, Particulate fillers: selection and use in polymer composites, In: *Fillers for Polymer Application*. Springer, (2017).
- [60]- T.P. Sathishkumar, P. Navaneethakrishnan, S. Shankar, R. Rajasekar, N. Rajini, Characterization of natural fiber and composites – a review, *J. Reinf. Plast. Compos.* 32(19) (2013) 1457–1476. <https://doi.org/10.1177/0731684413495322>.
- [61]- E. Natarajan, K. Markandan, S.M. Sekar, K. Varadaraju, S. Nesappan, A.D. Albert Selvaraj, G. Franz, Drilling-induced damages in hybrid carbon and glass fiber-reinforced composite laminate and optimized drilling parameters, *J. Compos. Sci.* 6(10) (2022) 310. <https://doi.org/10.3390/jcs6100310>
- [62]- H. Shi, C. Xu, X. Hu, W. Gan, K. Wu, X. Wang, Improving the Young's modulus of Mg via alloying and compositing – a short review, *J. Magnes. Alloys* 10(8) (2022) 2009–2024. <https://doi.org/10.1016/j.jma.2022.07.011>.
- [63]- C.N. Reddy, C.H. Rajeswari, T. Malyadri, S.S. Hari, Effect of moisture absorption on the mechanical properties of jute/glass hybrid sandwich composites, *Mater. Today: Proc.* 45 (2021) 3307–3311. <https://doi.org/10.1016/j.matpr.2020.12.639>.
- [64]- P. Morampudi, K.K. Namala, Y.K. Gajjela, M. Barath, G. Prudhvi, Review on glass fiber reinforced polymer composites, *Mater. Today: Proc.* 43 (2021) 314–319. <https://doi.org/10.1016/j.matpr.2020.11.669>
- [65]- M. Belmonte, P. Miranzo, M.I. Osendi, Contact damage resistant SiC/graphene nanofiller composites, *J. Eur. Ceram. Soc.* 38(1) (2018) 41–45. <https://doi.org/10.1016/j.jeurceramsoc.2017.08.009>.
- [66]- A.O. Akar, U.H. Yildiz, S. Tirkes, U. Tayfun, F. Hacivelioglu, Influence of carbon nanotube inclusions on electrical, thermal, physical and mechanical behaviors of carbon-fiber-reinforced ABS composites, *Carbon Lett.* 32(4) (2022) 987–998. <https://doi.org/10.1007/s42823-022-00332-y>.
- [67]- E. Dinneya-Onuoha, Unlocking renewable energy materials in Nigeria: availability, application, and roadmap for sustainability, *RSC Sustain.* 3(6) (2025) 2534–2566. <https://doi.org/10.1039/D5SU00121H>.
- [68]- V.J. Cruz-Delgado, J.A. Valdez-Garza, J.M. Mata-Padilla, J.G. Martínez-Colunga, C.A. Ávila-Orta, Preparation and characterization of electrically conductive polymer nanocomposites with different carbon nanoparticles. In: *Carbon Nanotubes: Redefining the World of Electronics*. IntechOpen, 2021.
- [69]- J.H. Ang, C. Goh, A.A.F. Saldivar, Y. Li, Energy-efficient through-life smart design, manufacturing and operation of ships in an Industry 4.0 environment, *Energies* 10(5) (2017) 610. <https://doi.org/10.3390/en10050610>.
- [70]- C. Qin, Q. Jin, J. Zhao, Y. Wang, C. Jiang, Study on the mechanical characteristics, heat resistance, and corrosion resistance of unsaturated polyester resin composite, *Buildings* 13(7) (2023) 1700. <https://doi.org/10.3390/buildings13071700>.