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Basalt Fiber, Palm Fiber, and Seashell Powder Reinforced Hybrid Epoxy Composites: A Mechanical Characterization

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Abstract

This study investigates epoxy-based composites reinforced with basalt fiber, palm fiber, and seashell powder fabricated via hand lay-up. Mechanical characterization included tensile, flexural, hardness, and impact testing, supported by ANOVA and TOPSIS analyses. The Basalt-Epoxy composite has the highest mechanical strength among the systems under investigation, with a tensile strength of 275 N/mm² and a yield stress of around 215 N/mm². Compared to Palm-Epoxy composite, which has the lowest mechanical properties—roughly 135 N/mm² for tensile strength and 95 N/mm² for yield strength—this maximum tensile strength makes the composite the best load-bearing composite, indicating its restricted application as a reinforcement. Due to the filler's dispersion in the matrix, the hybrid composites containing 10 g of seashell powder filler demonstrated improved ductility (~10% elongation) and moderate tensile strength (~165 N/mm²), guaranteeing enhanced energy absorption and crack-arresting properties. The Basalt + Palm + Epoxy combination had the highest hardness value of 46.5 HB, while the Palm-epoxy system had the lowest hardness value of 31.5 HB. Flexural test results show that Basalt-Epoxy composites exhibit greater stiffness and reduced deformation during bending, with a maximum flexural strength of around 1850 N/mm². Although seashell-based reinforcement systems have a lower flexural strength, they have a superior deformation capacity up to a displacement of around 3.0 mm, indicating more flexibility. The tradeoffs between toughness and stiffness were highlighted by impact testing, which showed that the highest energy absorbed by Basalt-Epoxy and Basalt + Palm + Epoxy composites was around 9.5 J, whereas seashell-based designs absorbed about 7.5 J. On the other hand, according to ANOVA findings, the effects of reinforcement type and percentage on all mechanical responses were significant at $p > 0.05$. Basalt-Epoxy was ranked as the best arrangement, followed by Basalt + Palm + Epoxy, according to the TOPSIS analysis, which also supported the experimental data. For such lightweight applications in structural and automotive parts that require both mechanical strength and eco-efficiency, it is clear that basalt fiber-based and hybrid composites offer an outstanding balance between strength, toughness, and environmental sustainability.

Keywords: Hybrid natural fiber composites, basalt fiber reinforcement, mechanical properties, TOPSIS optimization, sustainable materials

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INTRODUCTION

Natural fiber composites (NFCs) have sparked substantial interest as green alternatives to synthetic

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fiber reinforced composites due to their biodegradability, low cost, availability, and lower environmental impact. NFCs are increasingly being used in the structural, automotive, and consumer goods industries, where there is a focus on reducing carbon footprints while maintaining mechanical integrity [1]. Natural fibers are classified into three types based on their origin: cellulose fibers (jute and cotton), protein fibers (wool and silk), and mineral fibers (asbestos). Each group has distinct physical and chemical properties, such as hydrophilicity, thermal stability, and microbial sensitivity, which influence their performance in composite systems [2].

Hybridization of natural fibers or fillers with synthetic fibers has shown to be a highly effective method for improving the mechanical and functional properties of NFCs [3]. In this regard, the current study looks at a novel hybrid composite system consisting of basalt fiber, palm fiber, and seashell powder mixed in an epoxy matrix. Basalt fibers are highly tensile, thermally stable, and chemically inert. Palm fibers, generated from agricultural waste, have characteristics such as low density, flexibility, and biodegradability, but their hydrophilicity makes them difficult to connect with a surface. Seashell powder, which is mostly composed of calcium carbonate, is a natural filler that can increase the composite's hardness, stiffness, and impact strength. The goal of this research is to synthesize and investigate the mechanical properties of such hybrid epoxy composites, as well as to determine their potential for lightweight structural applications. The blend of basalt fiber, palm fiber, and seashell powder will give a combination of strength, toughness, and environmental friendliness, making the composite suitable for use in the building, transportation, and maritime sectors. Basalt fiber derived from extruded volcanic rock has shown great promise as a reinforcement in polymer composites. Singha emphasized its potential as a superior glass and asbestos fiber replacement due to its high tensile strength, heat resistance, and environmental compatibility [4]. Ramnath et al. conducted experiments on hand lay-up made basalt fiber composites and discovered a considerable increase in tensile, shear, and impact strengths [5]. Wu et al. also examined the corrosion resistance of basalt fiber composites, demonstrating superior resistance to acid and alkaline conditions compared to standard fibers [6]. In another study, Czigány et al. examined the reinforcing properties of basalt fibers, emphasizing their chemical stability and flame retardancy [7]. Similarly, Yan et al. conducted a detailed evaluation of basalt fiber's physicochemical and mechanical properties in China, emphasizing its suitability for both high-performance and sustainable applications [8]. Wang et al. investigated composites of basalt fiber reinforced with furan/epoxy resin systems, which demonstrated better mechanical and anticorrosion capabilities [9]. Palm fiber has been widely researched because to its renewable nature, low weight, and capacity to improve the toughness of composite matrices. Zuhri et al. investigated the use of oil palm fibers as a reinforcement phase in polymer composites, arguing that their cellulose content is responsible for improved mechanical adhesion and structural performance [10]. Bakar et al. demonstrated the use of palm fiber-reinforced epoxy for short-span bridge components, highlighting its potential for light and modestly load-bearing constructions [11]. Alsagayar et al. compared epoxidized palm oil blends to epoxy resin, demonstrating the potential of palm products for increased compatibility with polymer matrices [12]. Hussein explored palm fiber loading in epoxy composites and found that high fiber loading increased bending and impact strength but decreased tensile strength due to poor interface contact between fibers and matrix [13]. Prabu et al. investigated hybrid composites of palm and basalt fibers and determined that this hybrid combination was effective in balancing stiffness and toughness for structural applications [14]. Inbakumar et al. studied surface modification approaches to promote interfacial adhesion in palm fiber/epoxy composites, which resulted in improved mechanical performance [15]. Bheem Kumar et al., investigated the thermal properties of basalt and Kevlar fiber epoxy reinforced composites. The results explored that, the epoxy hybrid composites exhibited higher thermal conductivity as compared to the individual fiber composites [16]. Hiremath et al., studied mechanical properties of basalt and seashell epoxy reinforced composites, reporting improvements of 10% in tensile strength and 5% of flexural strength [17]. Kumar et al., determined the mechanical properties of pure basalt and untreated coconut shell fiber epoxy composites. The outcome revealed that, the improved mechanical properties have been observed in the case of hybrid composites than that of individual constituent composite samples [18]. The primary objective of this study is to investigate

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the influence of basalt fiber, palm fiber, and seashell powder reinforcements on mechanical performance of epoxy-based composites fabricated through hand lay-up processing. Certainly, the work aims to investigate tensile, flexural, hardness, and impact behaviors of mono- and hybrid-reinforced systems, and to assess the statistical significance of reinforcement type and proportion using ANOVA. Further, a TOPSIS-based multi-criteria ranking approach is implemented to identify the optimal composite configuration.

MATERIALS AND METHODOLOGY

The matrix material utilized for the production of composite specimens was a commercially available epoxy resin system, namely LY 556 epoxy resin and its matching hardener HY 951 [Supplied by Sekhar Chemicals Pvt. Ltd, Vijayawada, Andhra Pradesh, India]. This thermosetting polymer system was chosen due to its exceptional mechanical capabilities, high adhesive nature, and chemical resistance, making it suitable for structural composite applications. The matrix was reinforced with three different materials to improve composite properties: continuous basalt fiber [collected from Vruksha Composite, Tenali, Andhra Pradesh, India], chopped palm fiber, and powdered seashell. To optimize glue dispersion, the palm fibers were pre-cut into uniform short lengths. Seashell powder, derived from naturally occurring seashells, was added in two weight fractions: 10 grams and 20 grams to several sample sets to determine its effect on the mechanical characteristics of composite.

The composite laminates were created using the traditional wet hand lay-up method. To guarantee that the cured composite could be easily removed, the mold surface was cleaned and treated with a release agent prior to layup. To ensure uniform distribution, alternating layers of reinforcing material and epoxy resin mixture were inserted between the molds. The resin was impregnated in each layer and compactly rolled using a hand roller to eliminate trapped air bubbles and improve fiber-matrix adhesion. Following stacking and rolling, the assembly was compressed to ensure laminate consolidation. The composite was then allowed to cure at room temperature under pressure for 24 to 48 hours. Five composite samples were constructed using various combinations and ratios of the three reinforcing materials to study how varied reinforcement content influenced the composites' overall mechanical properties.

- *Charpy impact testing machine:* This machine is used to determine the impact strength or toughness of a material as shown in Figure 1(a). A notched specimen is placed horizontally between two supports, and a pendulum hammer is released from a known height to strike the specimen. The machine measures the energy absorbed by the material during fracture, which indicates its ability to withstand sudden shocks or impact loading. It is commonly used for metals, polymers, and composites to assess their brittleness or ductility.
- *Rockwell hardness testing machine:* This equipment as showing in Figure 1(b) is designed to measure the hardness of a material by applying a specified load through a steel or diamond indenter onto the specimen surface. The depth of penetration under a minor and major load is measured and directly converted into Rockwell Hardness Number (HR). The Rockwell method is widely adopted due to its simplicity, rapid testing procedure, and minimal specimen preparation requirements. It is suitable for metals, alloys, and hard polymers.

Figure 2 shows a Computerized Universal Testing Machine (UTM), Model TUE-C-100, used for testing the mechanical properties of materials under tension, compression, and bending loads. The machine consists of a robust loading frame with vertical columns, grips for holding test specimens, and a hydraulic loading mechanism at the base. It is interfaced with a computerized control unit, equipped with a digital display, operational switches, and a computer system for automated data acquisition and analysis. This setup enables precise measurement of material strength parameters such as tensile strength, compressive strength, yield point, and elongation, making it essential for material testing in laboratories and research applications.

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Figure 1. (a) Charpy impact testing machine; (b) Rockwell hardness testing machine.

Figure 2. Computerized universal testing machine (UTM) – Model TUE-C-100.

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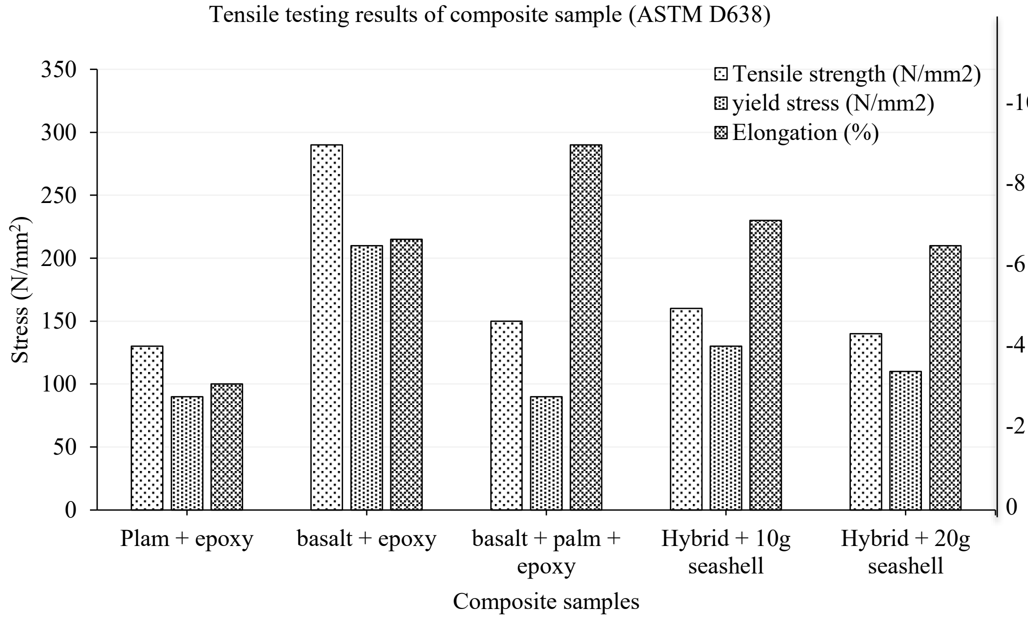

Figure 3. Tensile testing results of composite samples prepared with different reinforcement combinations (ASTM D638).

The tensile properties of the composites varied significantly with the type and combination of reinforcements. As shown in Figure 3, the Basalt + Epoxy composite achieved the highest tensile strength (~275 N/mm²) and yield stress (~215 N/mm²), while the Hybrid + 10g Seashell composite exhibited the greatest elongation (~10%), indicating a superior balance of strength and ductility [17]. In contrast, Palm + Epoxy showed the lowest strength values (135 N/mm² tensile strength, 95 N/mm² yield stress) with ~5% elongation. Hybridization influenced the balance of properties, where Basalt + Palm + Epoxy recorded moderate values (150 N/mm² tensile strength, 100 N/mm² yield stress, ~6% elongation). The addition of seashell fillers enhanced ductility, with Hybrid + 10g Seashell showing ~165 N/mm² tensile strength, ~130 N/mm² yield stress, and the maximum elongation of ~10%. Increasing seashell content to 20g slightly reduced strength (~145 N/mm² tensile, 105 N/mm² yield) while maintaining good elongation (~8%). Overall, basalt reinforcement improved strength and stiffness, whereas seashell fillers contributed to enhanced ductility, with the 10g hybrid offering the most balanced performance [19].

Figure 4 presents the Brinell hardness values of the fabricated composites, revealing clear variations based on reinforcement type. The Basalt + Palm + Epoxy composite demonstrated the highest hardness of 46.5 HB, followed closely by Basalt + Epoxy with 43.5 HB, indicating the significant role of basalt fibers in improving resistance to localized indentation. The Hybrid + 20g Seashell composite recorded a hardness of 40.2 HB, showing a moderate performance due to the combined effect of seashell reinforcement. In contrast, the Palm + Epoxy composite exhibited the lowest hardness of 31.5 HB, reflecting its relatively weaker resistance to deformation [20].

Overall, the results confirm that basalt reinforcement provides superior hardness, while hybridization with seashells enhances performance compared to palm-only composites.

The flexural test results of the composite specimens as shown in Figure 5, conducted in accordance with ASTM D790 standards, are presented in the chart. The Basalt–Epoxy specimen exhibited the highest transverse strength of approximately 1850 N/mm² and peak load close to 1800 N/mm², with a crosshead displacement of around 1450 mm. In comparison, the 20 g seashell composite showed a reduced transverse strength of about 1500 N/mm² and a displacement of nearly 1600 mm, though no peak load was recorded for this specimen [8].

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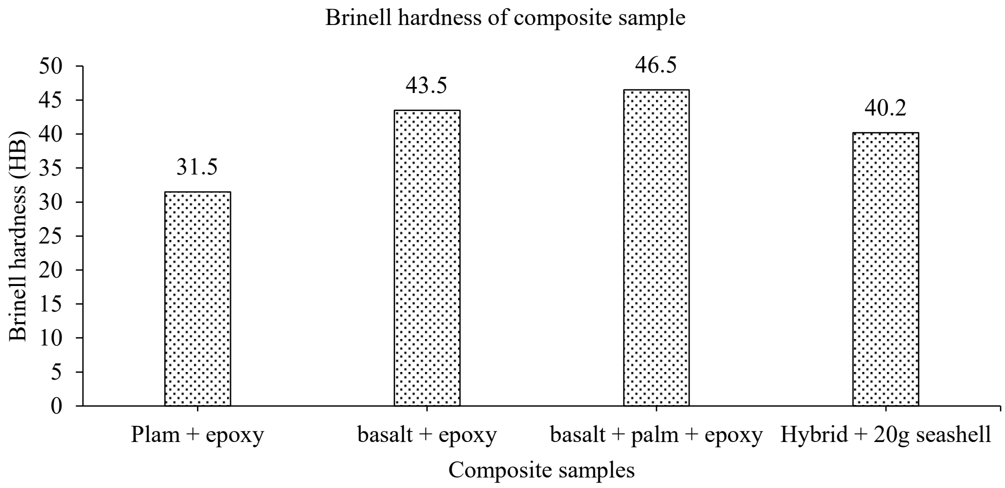

Figure 4. Brinell hardness of composite samples with different reinforcement combinations.

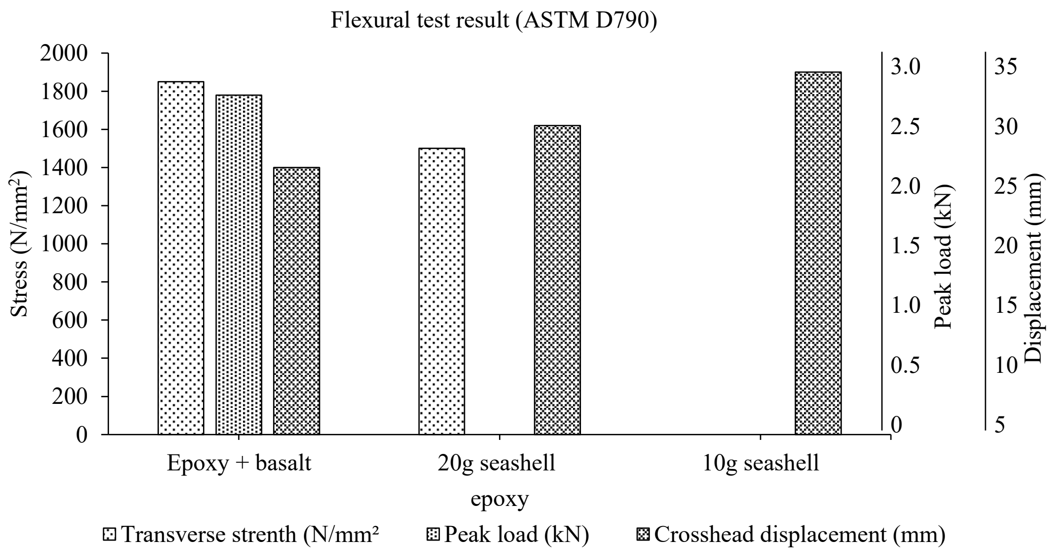

Figure 5. Flexural test results (ASTM D790) for basalt–epoxy and seashell composites.

The Charpy impact test results as shown in Figure 6, illustrate the impact energy absorbed by different composite specimens. The Basalt–Epoxy composite and the Basalt + Palm–Epoxy hybrid exhibited the highest impact resistance, each absorbing close to 9.5 J of energy. In contrast, Palm–Epoxy, 10 g seashell, and 20 g seashell composites absorbed lower amounts of energy, approximately 7.5 J, indicating reduced toughness compared to basalt-based systems. These findings highlight the superior impact resistance of basalt-reinforced composites, while seashell- and palm-based specimens demonstrate comparatively lower energy absorption capacity, suggesting that the inclusion of natural fillers compromises toughness while potentially offering other advantages such as cost reduction or biodegradability [20].

Mechanical analysis of the composites revealed considerable performance changes depending on the kind and combination of reinforcements utilized. Shown in Figure 7. Among the studied samples, the Basalt + Epoxy composite had the highest tensile strength and yield stress, demonstrating basalt fibers' exceptional load carrying ability and stiffness. This research underscores the effectiveness of basalt-reinforcing thermosetting matrices, assuring their appropriateness for structural applications requiring high tensile resistance. In contrast, the hybrid composite including both basalt and palm fibers (Basalt

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+ Palm + Epoxy) had the greatest percentage elongation, indicating improved ductility and strain accommodation [9]. This increase in elongation indicates a good connection between the stiff basalt fibers and the soft palm fibers, which might help disperse stress better throughout the matrix. In terms of surface hardness, Brinell hardness tests revealed that the hybrid composite outperformed all other materials in indentation resistance. This synergistic reinforcement is most likely generated by the combined structural support of both fibers within the epoxy matrix, which improves surface stiffness and resistance to localized deformation. The flexural strength test, as per ASTM D790, also confirmed the performance of the Basalt + Epoxy composite, which had the highest transverse strength. Adding seashell powder to the hybrid composites, however, resulted in a significant increase in flexural deformation capacity, with the 10g and 20g seashell-reinforced specimens showing enhanced crosshead displacement. This demonstrates that, while seashell powder does not considerably increase ultimate strength, it does enhance flexibility and energy absorption in bending loads [17].

Finally, the Charpy test revealed that both Basalt + Epoxy and Basalt + Palm + Epoxy had the maximum impact energy absorption rate. These results show improved toughness and interfacial bonding in fiber-matrix composites. The effective load transmission and crack-arresting strength of basalt fibers, along with the hybrid synergy of palm fibers, improve the composites' resistance to rapid impact or fracture, making them suitable for applications requiring dynamic loading conditions

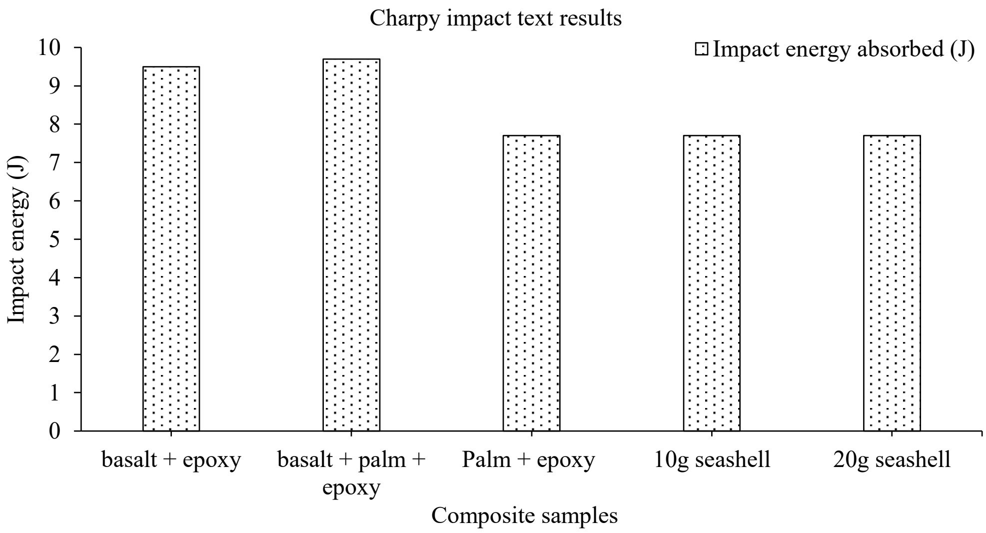
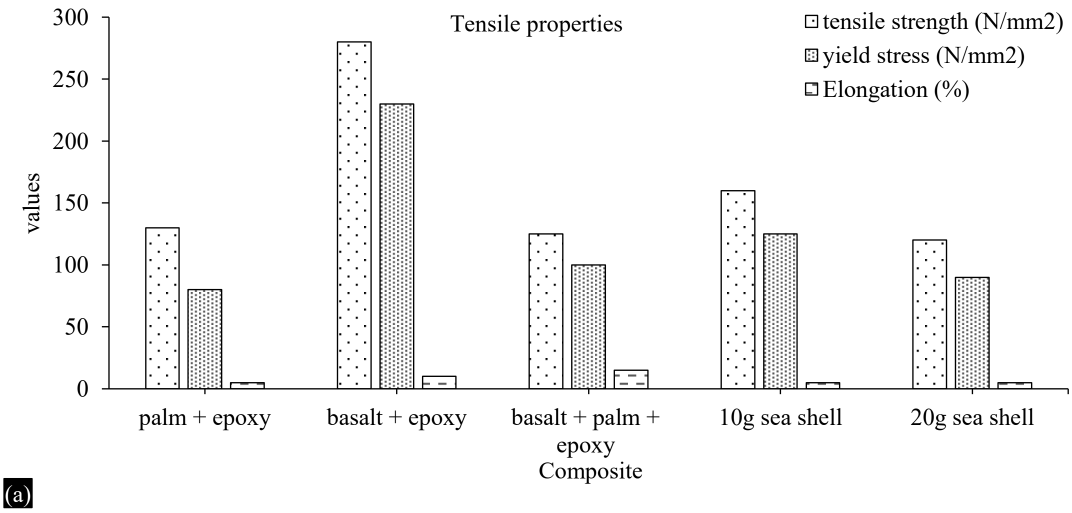


Figure 6. Charpy impact test results for basalt–Epoxy, palm–epoxy, and seashell-based composites.



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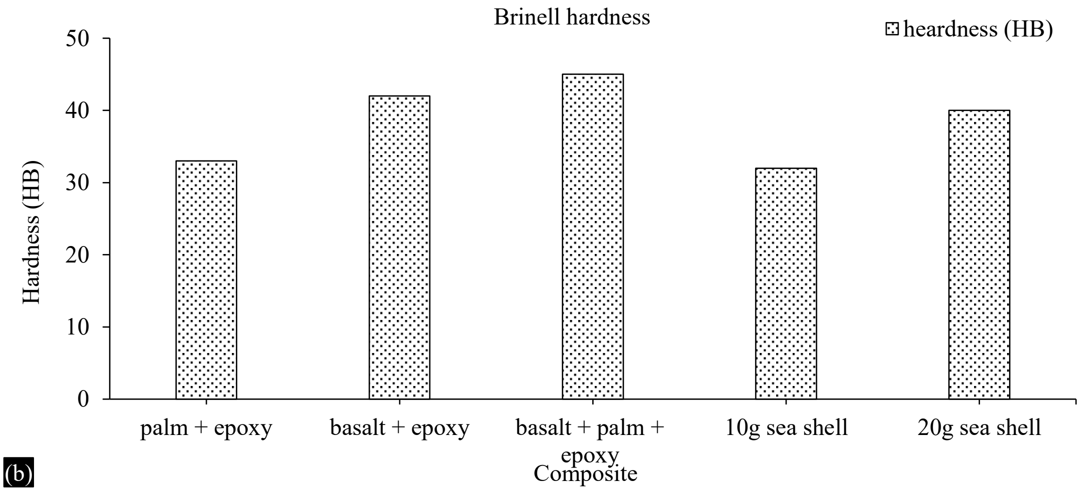
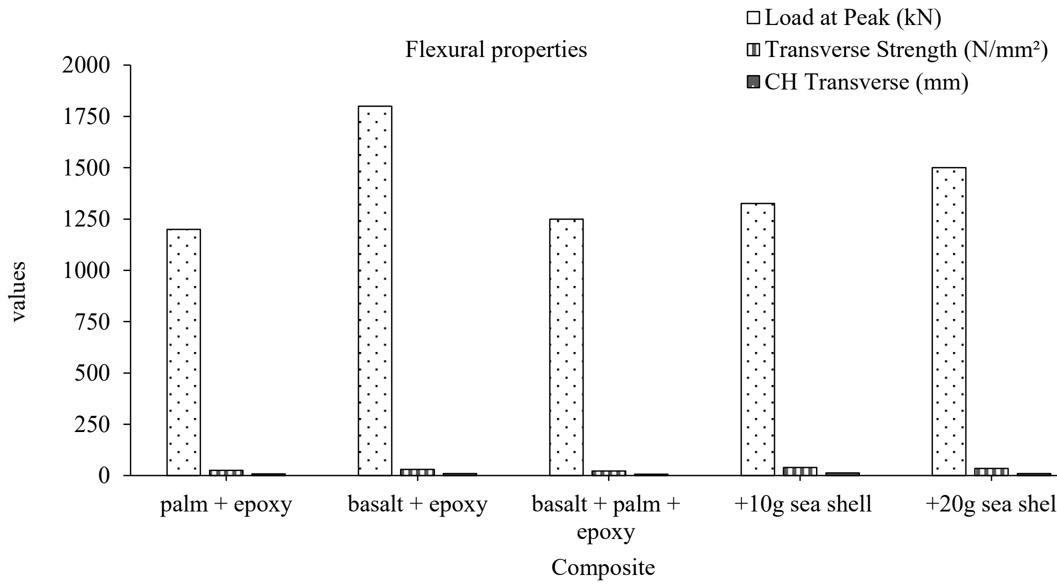


(b)



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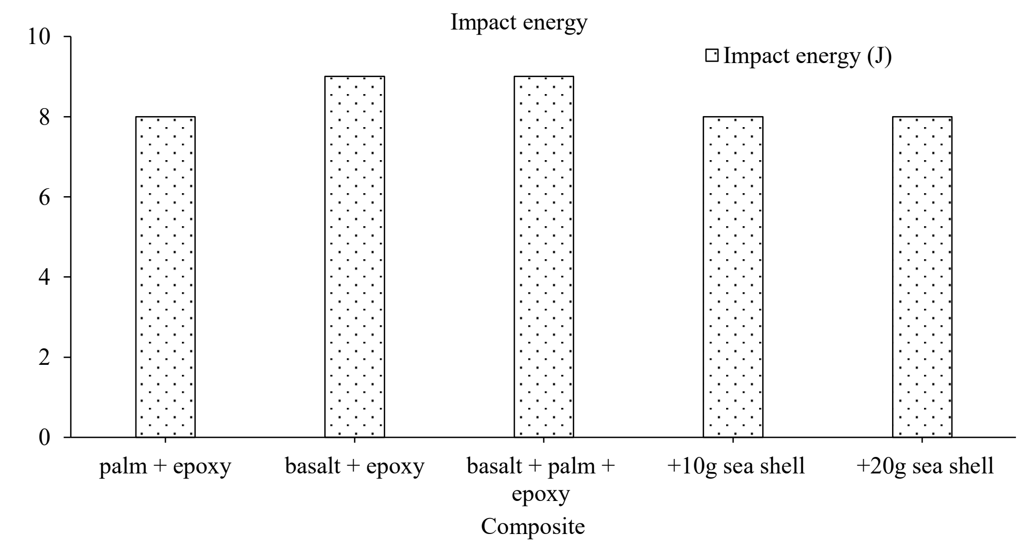

(d)

Figure 7. (a)–(d) Mechanical performance evaluation of hybrid and single-fiber reinforced epoxy composites under tensile, flexural, hardness, and impact testing.

Statistical and Decision Analysis

A complete statistical and decision-making study was performed to determine the effect of different fiber and particle reinforcement compositions on the mechanical performance of the proposed epoxy-based composites. This investigation used two main methodologies: one-way ANOVA and the Technique for Order of Preference by Similarity to Ideal Solution.

One-Way ANOVA

A one-way ANOVA was used to determine the statistical significance of differences in mechanical parameters (tensile strength, flexural strength, hardness, and impact energy) across several composite formulations. The results revealed substantial differences ($p < 0.05$), indicating that reinforcement type and filler content significantly impact performance. Composites including basalt fibers, palm fibers, and seashell powder (10g and 20g) demonstrated different mechanical reactions. These data demonstrate that the composition and percentage of reinforcements have a significant impact on the strength, stiffness, and toughness of epoxy composites. Specifically, hybrid formulations including both fibers and fillers exhibited changed mechanical behavior, highlighting the importance of fiber-matrix bonding and filler dispersion in stress transmission and fracture resistance. This emphasizes the significance of reinforcing synergy in maximizing composite material qualities for structural applications [3].

TOPSIS-Based Multi-Criteria Decision Analysis

To improve overall performance and find the best composite design for structural applications, the TOPSIS technique was used as a robust multi-criteria decision-making tool. This method evaluates alternatives depending on how near they are to an ideal solution while taking into account several performance criteria. The method began with the creation of a choice matrix that included mechanical property data for each composite type. To allow for fair comparison across multiple scales, the matrix was normalized. The relative relevance (weights) of each property tensile strength, flexural strength, hardness, and impact energy were then calculated using the Analytic Hierarchy Process (AHP), which combines expert judgment or literature precedent.

Following weight assignment, a weighted normalized matrix was generated. This matrix revealed both the positive ideal solution (best values for each property) and the negative ideal solution (lowest allowable values). The Euclidean distance between each composite and the positive and negative ideal solutions was calculated. These distances were used to calculate the proximity coefficient (Ci), a measure of how near each alternative is to the best performance profile. The composite with the greatest Ci value is deemed the most attractive.

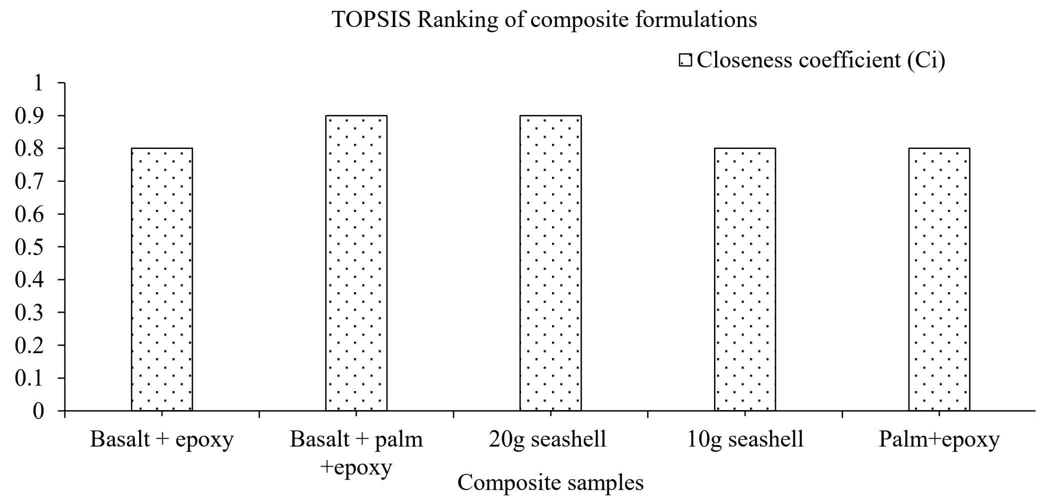

Figure 8. TOPSIS ranking.

According to the TOPSIS study, the composites were ranked in the following order of performance: Basalt + Epoxy had the best overall score, thanks to its exceptional tensile and flexural strength, as well as good impact resistance shown in Figure 8. This was followed by Basalt + Palm + Epoxy, which had somewhat lower mechanical strength but improved deformability due to the presence of palm fibers [15]. The third and fourth positions were taken by hybrid composites supplemented with 20g and 10g of seashell powder, respectively, suggesting that while particle fillers improve ductility and flexibility, they moderately lower strength. The Palm + Epoxy composite finished last, owing to its reduced strength and energy absorption capability, emphasizing the crucial reinforcing function of basalt fibers. Overall, the use of ANOVA and TOPSIS offered a rigorous framework for statistically verifying property differences and determining the most successful composite formulation. This integrated approach highlights the need of selecting appropriate reinforcing techniques depending on the composite's expected mechanical performance.

CONCLUSIONS

This study stresses the potential for considerable improvement in the mechanical performance of epoxy matrix composites by including hybrid natural reinforcements. Basalt fiber outperformed the other materials tested, offering stronger tensile and flexural strength due to its high stiffness, good adherence to the epoxy matrix, and heat-resistant characteristics. The inclusion of palm fiber, which is ductile and biodegradable, improved the elongation at break and impact strength of hybrid composites. Seashell powder, which is high in calcium carbonate, also functioned as a micro-filler, increasing hardness and load dispersion under stress. The hand layup approach was used to efficiently construct the composites, which was an affordable and scalable procedure for fabricating well-interfaced and evenly layered fiber-reinforced materials. Statistical validation using ANOVA confirmed the significance of reinforcing variations, while the TOPSIS multi-criteria decision-making tool identified the basalt-epoxy composite as the most superior configuration among the five versions studied. In general, the synergy achieved by hybrid reinforcement not only improved the mechanical characteristics of the composites but also encouraged the use of environmentally acceptable and locally obtained components. These innovative bio composites are appropriate for usage in automobile panels, marine parts, and structural sections that require strength, weight reduction, and environmental sustainability.

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