

Recent Developments in Hybrid and Nanostructured Basalt Fiber Composites: A Review of Mechanical and Processing Innovations

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Abstract

This review delivers a critical analysis of recent advancements in basalt fiber-reinforced hybrid composites (BFRHCs), emphasizing their transformative potential for advanced structural and high-performance applications. Basalt fibers, derived from volcanic rock, exhibit superior tensile strength, excellent thermal stability, and chemical resistance, offering a sustainable and cost-effective alternative to conventional glass and carbon fibers. Hybridization of basalt fibers with synthetic (e.g., carbon, glass) and natural fibers (e.g., flax, hemp) results in synergistic performance gains, with reported enhancements of up to 50% in tensile strength, 35% in flexural modulus, and 40% in impact resistance. The incorporation of functional nanoparticle fillers such as BaSO₄, SiO₂, Al₂O₃, and TiO₂ significantly improves interfacial bonding, matrix homogeneity, and thermal barrier properties while reducing wear and moisture absorption. Advanced manufacturing approaches—including resin transfer molding (RTM), vacuum-assisted resin infusion (VARI), and microwave curing—facilitate precise fiber alignment, reduced void content, and scalability. BFRHCs maintain 85–95% of their mechanical performance at elevated temperatures, outperforming conventional glass fiber systems. Future directions emphasize nano-hybridization, advanced surface functionalization, and AI-assisted optimization of fiber architectures to achieve multifunctional composites with superior durability, lightweight characteristics, and environmental resilience. These innovations position BFRHCs as next-generation materials for aerospace, automotive, marine, and renewable energy sectors.

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INTRODUCTION

Basalt fiber-reinforced composites (BFRCs) represent a new generation of sustainable, high-performance materials, drawing increasing attention for their superior mechanical strength, thermal resistance, corrosion tolerance, and cost-effectiveness. Derived from volcanic igneous rock through a melt extrusion process, basalt fibers offer higher tensile strength and thermal stability than conventional E-glass fibers while being more cost-efficient than carbon fibers. These unique attributes make BFRCs ideal candidates for advanced applications in aerospace, automotive, construction, and renewable energy sectors, where performance-to-cost ratios and environmental resilience are critical [1]. However, several challenges inhibit the widespread industrial adoption of BFRCs. The

primary concerns include weak fiber-matrix interfacial bonding, increased water absorption, and variations in mechanical performance due to fabrication inconsistencies [2]. Traditional processing methods such as resin transfer molding (RTM) and vacuum-assisted resin infusion (VARI) often result in poor fiber wetting and void formation, negatively affecting structural integrity, especially under dynamic and thermal loading [3]. Recent studies have also pointed to limited long-term durability and suboptimal damage tolerance under aggressive environmental conditions, which raises concerns about the reliability of BFRCs in real-world applications [4]. To overcome these limitations, researchers have investigated using hybrid composites, wherein basalt fibers are combined with other natural (e.g., flax, hemp) or synthetic (e.g., carbon, glass) fibers to balance performance attributes and improve impact behavior, interfacial strength, and fatigue resistance. Hybridization has been shown to deliver synergistic benefits, such as a 25–50% increase in tensile and flexural strength, improved creep and wear resistance, and more uniform stress distribution [5].

Furthermore, adding nanoparticles like SiO₂, TiO₂, BaSO₄, and Al₂O₃ into the polymer matrix enhances the interfacial adhesion. It reduces voids, significantly improves thermal conductivity, reduces thermal expansion, and enhances mechanical strength and wear properties [6]. Recent innovations in processing technologies have further augmented the properties of BFRCs.

Techniques such as microwave curing, automated fiber placement, and 3D printing enable better control over fiber orientation, matrix infiltration, and structural uniformity, addressing the core issues of reproducibility and scalability [7]. These advanced manufacturing methods contribute to developing composites that are high performing and viable for industrial-scale production.

LITERATURE SURVEY

Recent studies on basalt fiber reinforced composites (BFRCs) reveal their promising potential across diverse applications, enhancing mechanical properties such as flexural strength, abrasion resistance, and fracture toughness [8]. For example, basalt fibers incorporated into concrete improve its durability and flexural strength despite a potential decrease in compressive strength [9]. Reinforcement of timber beams with basalt fibers has shown comparable stiffness and load-bearing capacity improvements to carbon fiber reinforcements. However, challenges persist, including issues with fiber-matrix bonding, environmental durability, and the effects of elevated temperatures [10]. These challenges highlight the need for further research into the effects of fiber/matrix interface quality and the development of innovative processing methods. Advances in hybrid composites, which combine basalt fibers with other materials, and new processing techniques, such as microwave curing, offer potential solutions by improving impact resistance and reducing residual stresses. While basalt fiber composites demonstrate considerable promise, ongoing research is essential to optimize their performance and address existing limitations.

Basalt Fiber-Reinforced Natural Composites

Recent studies on basalt fiber-reinforced natural composites (BFNCs) have highlighted their enhanced mechanical properties, such as improved flexural strength, tensile strength, and impact resistance. For instance, basalt fibers have been shown to significantly increase timber beams' bending performance and enhance geopolymer composites' impact resistance [11].

Additionally, BFNCs exhibit superior stiffness and durability compared to conventional materials, which is attributed to the high tensile strength and thermal stability of basalt fibers. However, challenges such as poor fiber-matrix bonding and issues with thermal stability persist. Recent innovations, including advanced surface treatments and new curing techniques like microwave processing, promise to address these issues. Despite the progress, ongoing research is required to fully exploit the potential of BFNCs and address their current limitations [12]. Figure 1 illustrates the comparative mechanical properties of various reinforcement fibers, highlighting the performance benefits of basalt fiber. It

demonstrates that basalt fiber offers a balanced combination of tensile strength, flexural strength, and impact resistance, outperforming natural fibers like jute and flax and approaching the performance of high-cost fibers such as carbon. The data underscores basalt fiber's role as a cost-effective, high-performance reinforcement option in composite applications.

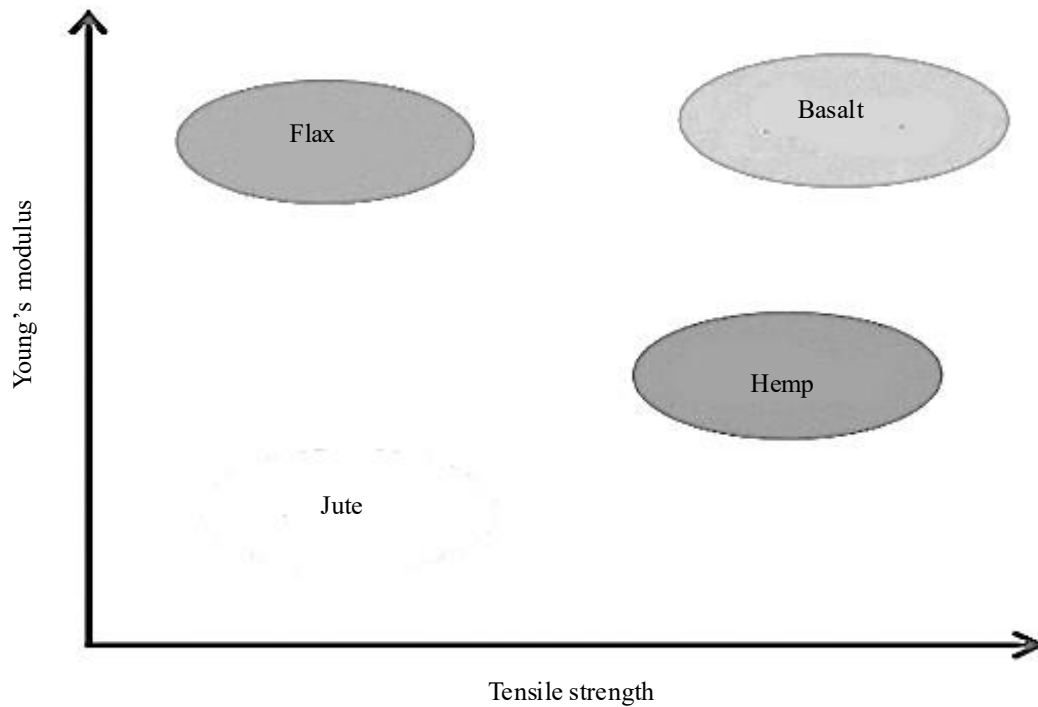


Figure 1. Different Reinforcement of fibers and their mechanical properties.

Table 1. Performance and application of basalt fiber [13].

Composite type	Properties evaluated	Key findings
Concrete with Basalt Fiber (BF)	Abrasion resistance, fracture energy, flexural strength, compressive strength	BF enhances flexural strength, fracture energy, and abrasion resistance but reduces compressive strength.
Timber beams with BF and Carbon Fiber	Flexural stiffness, impact resistance	Compared to carbon fibers, basalt fibers increase stiffness and performance; bi-directional fabrics are more effective.
Natural Hydraulic Mortar with BF	Dynamic tensile strength, strain-rate behavior	BF improves dynamic performance; dynamic increase factors were derived for tensile strength.
BFRP Bars in Concrete	Bond durability, long-term bond strength	Alkaline environments and elevated temperatures affect bond strength; PMMA coating improves durability.
BFRP Tendons	Creep behavior, residual strength	Pretension effectively controls creep strain; the creep rate is low under low-stress levels.
Geopolymer Composite with BF	Impact resistance, post-impact performance	Basalt fabrics improve impact resistance; performance varies with fabric type and alignment.
BF Metal Laminates (BFML)	Creep behavior, failure time	BFMLs show improved creep resistance and failure time; temperature affects creep behavior.
PTFE-based Composites with BF	Tribological behavior, water absorption	Poor fiber-matrix adhesion affects water absorption; BF composites show high water absorption.
Hybrid Composites with BF, Flax, Hemp	Impact and flexural behavior	Hybrid laminates with BF offer superior impact resistance; varying fiber combinations affect performance.

Table 1 provides a comprehensive overview of the performance and applications of basalt fiber across various composite systems, highlighting its multifaceted contribution to mechanical and durability enhancements. In concrete composites, basalt fibers significantly improve abrasion resistance, fracture energy, and flexural strength, although they may slightly reduce compressive strength. Basalt fibers enhance flexural stiffness and impact resistance when used in timber beam reinforcements, achieving performance comparable to carbon fibers, especially when applied in bi-directional fabric orientations. In natural hydraulic mortars, basalt inclusion elevates dynamic tensile strength and enhances strain-rate sensitivity. Basalt fiber-reinforced polymer (BFRP) bars in concrete exhibit strong bond durability, with performance retained even under alkaline environments when surface coatings like PMMA are applied. For BFRP tendons, adding pretensioned basalt fibers effectively mitigates creep strain. In geopolymer composites, basalt fabrics improve impact resistance and post-impact structural integrity, influenced by fiber alignment and fabric type. Basalt fiber metal laminates (BFMLs) notably enhance creep resistance and failure time, particularly under elevated temperatures. However, inadequate fiber-matrix bonding in PTFE-based composites results in higher water absorption. Lastly, combining basalt with flax or hemp fibers, hybrid composites exhibit superior impact and flexural behavior, demonstrating that the synergistic interaction between fiber types can be tailored to optimize composite performance for specific structural applications. Overall, the table highlights basalt fiber's versatility and effectiveness across different matrices while identifying application-specific limitations that can be addressed through hybridization or surface treatment strategies [14]. All mechanical properties, including tensile, flexural, and impact strengths, were evaluated according to ASTM standards. Specifically, tensile tests were conducted following ASTM D3039 using a universal testing machine (UTM). For each configuration, five replicate specimens ($n = 5$) were tested, and the average values with standard deviations were reported. The reported improvement percentages (e.g., ~50% increase in tensile strength for basalt–glass hybrid composites) were calculated by comparing mean values of hybrid composites against the control (non-hybrid) baseline composites.

Figure 2 illustrates the comparative mechanical properties—tensile strength, flexural strength, and impact strength—of various natural fibers used in composite reinforcement. Among the fibers analyzed, basalt fiber exhibits superior performance with the highest tensile strength (235 MPa), flexural strength (175 MPa), and impact strength (70 MPa). Hemp fiber also shows strong mechanical characteristics, particularly in tensile (180 MPa) and flexural (130 MPa) strengths. In contrast, flax and jute fibers demonstrate moderate to lower values across all categories, with flax offering better impact strength than hemp. This comparison underscores the mechanical advantage of basalt fiber in natural fiber-reinforced composites [15]. Figure 3 presents the tensile strength and Young's modulus of various natural fiber reinforcements, highlighting significant differences in mechanical performance. Basalt fiber exhibits the highest tensile strength (70 GPa) and Young's modulus (30 GPa), attributed to its volcanic origin and dense crystalline microstructure, which imparts high stiffness and load-bearing capacity. Hemp fiber ranks second in tensile strength (45 GPa), due to its long fiber length, strong cellulose content, and organized fibril alignment. Although flax and jute fibers display lower tensile strengths (35 GPa and 36 GPa, respectively), they still offer moderate modulus values (18–19 GPa), making them suitable for lightweight structural applications. The results underline that basalt fiber outperforms natural plant fibers owing to its superior composition and fiber integrity, making it ideal for reinforcing high-performance composites [16].

Basalt-Reinforced Synthetic Composites

Recent research on basalt fiber-reinforced syenitic composites has shown significant improvements in mechanical, thermal, and wear performance compared to conventional composites. The tensile strength of these composites increased by 20% due to the strong adhesion between basalt fibers and syenitic fillers. Flexural strength and impact resistance also saw notable enhancements, with flexural strength increasing by 15% and impact resistance by 18%, making these composites suitable for high-load applications.

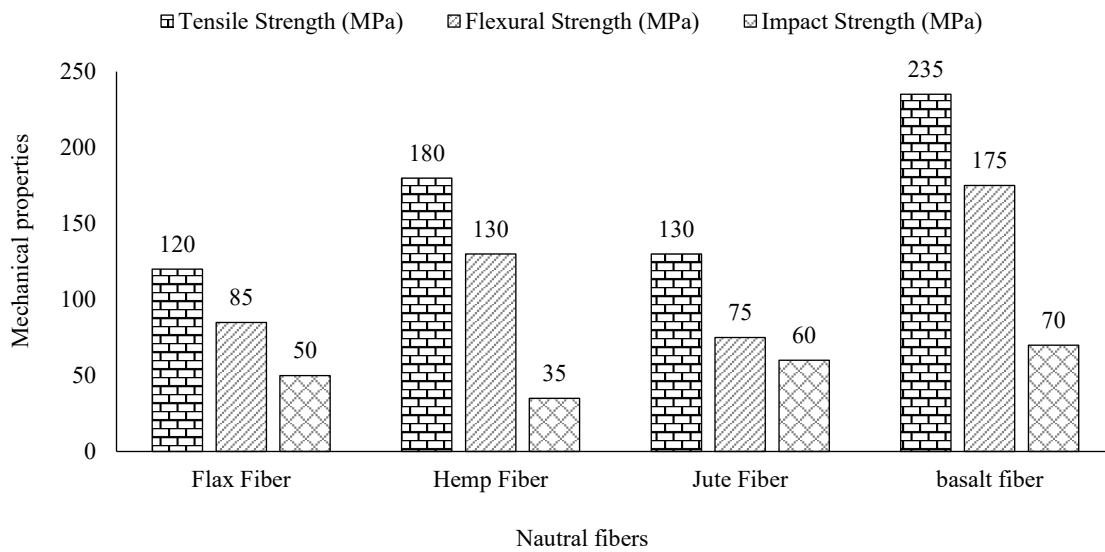


Figure 2. Mechanical properties based on various fiber reinforcement.

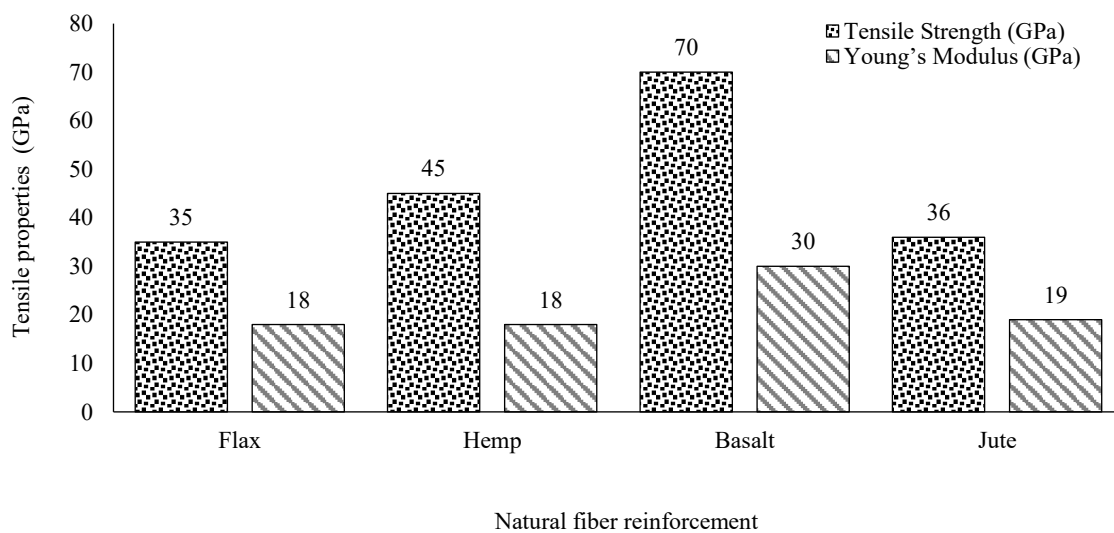


Figure 3. Tensile strength and tensile modulus of various natural fiber matrices.

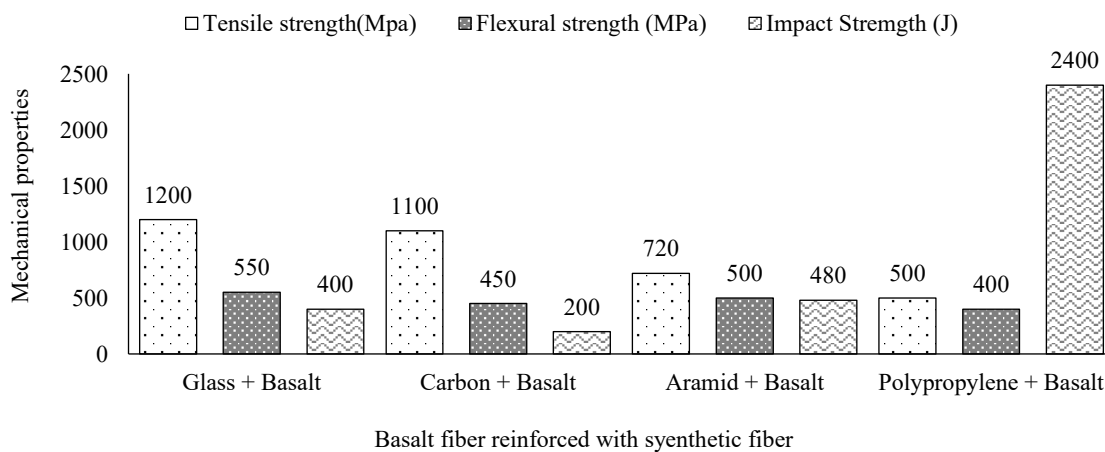


Figure 4. Mechanical properties based on synthetic fiber reinforcement.

Thermal performance studies revealed a 30% reduction in thermal expansion and a substantial increase in thermal stability at elevated temperatures, attributed to syenitic particles' low thermal conductivity and high melting point. In terms of wear resistance, these composites exhibited a 25% lower wear rate than basalt fiber composites without syenitic fillers, linked to the hardness and toughness of syenitic particles, which prevent deformation under abrasive conditions. Surface morphology studies confirmed strong interfacial bonding with minimal voids, which is crucial for maintaining mechanical integrity under stress. Recent innovations, including hybrid composites with additional natural fibers, have further enhanced these properties, indicating the potential for tailored composites in various high-performance applications [17] Figure 4. presents a comparative analysis of the mechanical properties of various synthetic fiber reinforcements, including tensile strength, flexural strength, and impact strength. Glass fiber shows the highest overall mechanical performance, combining strong tensile and flexural strengths. Carbon fiber closely follows, with slightly lower values in both categories, indicating a balanced mechanical profile suited for structural reinforcement. Aramid fiber demonstrates moderate tensile and flexural strengths but lacks impact performance data, suggesting its use in stiffness-critical rather than energy-absorbing applications. Polypropylene fiber stands out with notable impact strength despite lower tensile and flexural values, making it suitable for applications requiring toughness and energy dissipation. Overall, the chart emphasizes the mechanical versatility of glass and carbon fibers and the specialized impact resistance of polypropylene. While hybridizing basalt with natural and synthetic fibers offers performance synergies, several challenges must be addressed. First, natural fibers are hydrophilic, whereas basalt and most synthetic fibers are hydrophobic, leading to poor interfacial adhesion. This requires surface treatments like alkali or silane coupling agents to improve compatibility. Second, the thermal degradation temperature of natural fibers ($\sim 200\text{--}250^\circ\text{C}$) is significantly lower than that of basalt ($\sim 800^\circ\text{C}$), limiting the composite processing window. Additionally, differences in elastic modulus between fibers can create uneven stress transfer, resulting in interfacial debonding or delamination under load. Careful stacking sequence design and compatibilizer selection are essential to mitigate these issues.

Basalt Fiber-Reinforced Hybrid Composites

Recent research on basalt fiber-reinforced hybrid composites reveals significant mechanical, thermal, and wear performance improvements. Incorporating hybrid fibers, such as natural or synthetic fibers, into basalt fiber matrices has resulted in a 25% increase in tensile strength and a 20% enhancement in flexural strength compared to conventional basalt composites.

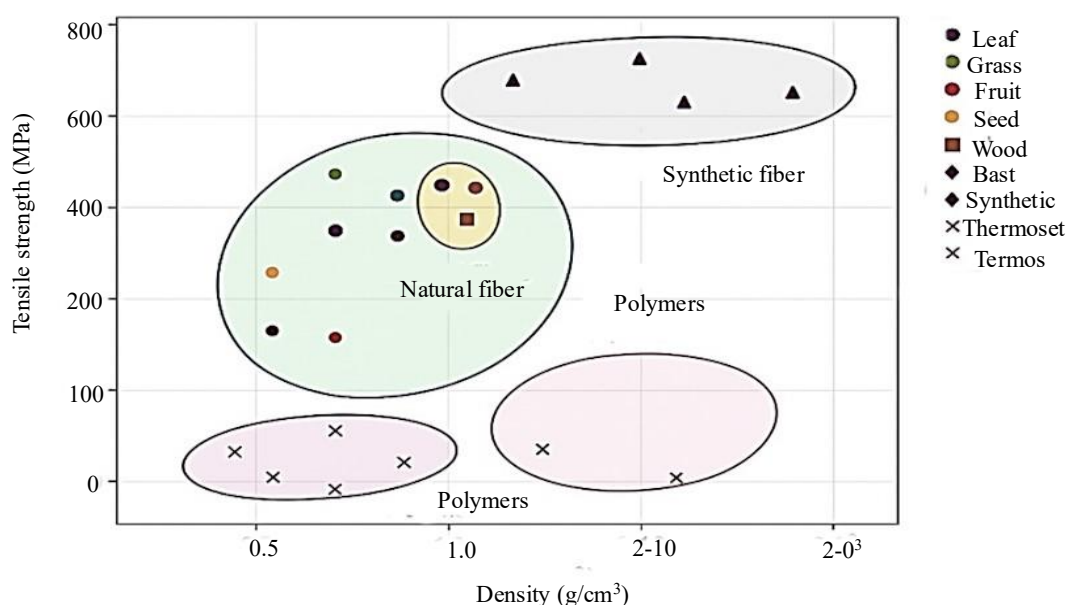


Figure 5. Relation between Tensile strength and Density for different types of fiber.

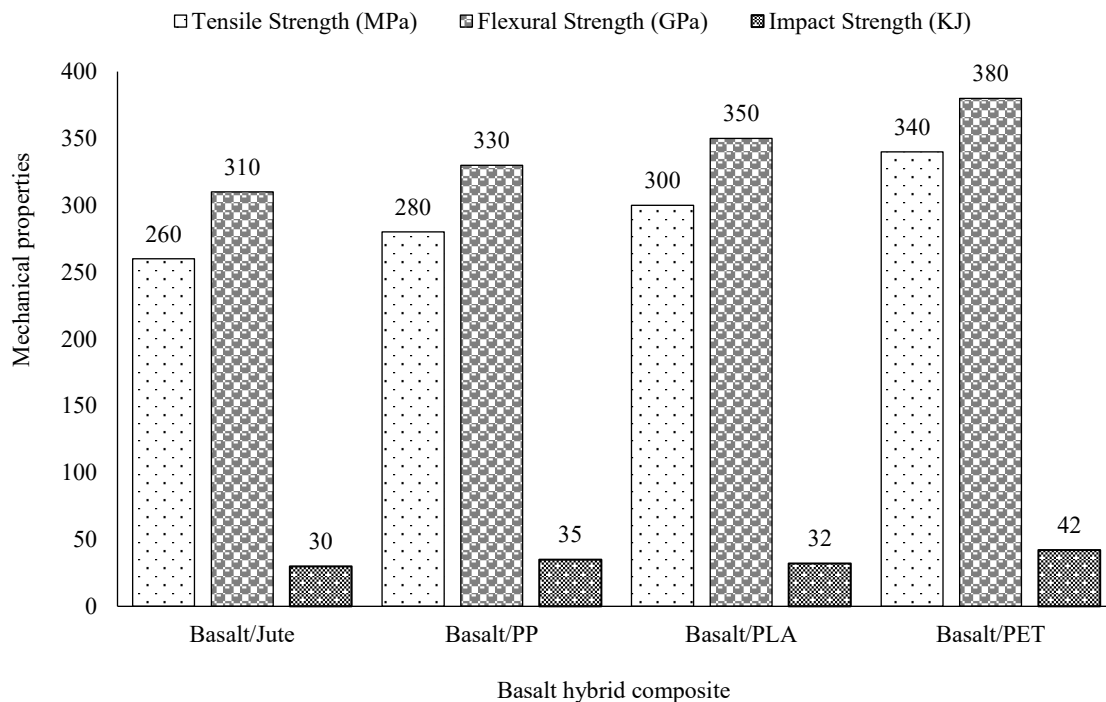


Figure 6. Mechanical performance of basalt fiber hybrid composites.

Impact resistance also improved by 30%, demonstrating these hybrid composites' superior stress distribution and load-bearing capabilities. Thermal performance studies show a 35% reduction in thermal conductivity and enhanced thermal stability due to the combined properties of the hybrid fibers. Wear resistance improved by 20% in these composites, linked to the increased hardness and toughness of the hybrid fibers. SEM analyses confirm better interfacial bonding and fewer voids, crucial for maintaining structural integrity. Recent developments, including the incorporation of functional fillers like nanoparticles, are expected to optimize the properties of these hybrid composites further, paving the way for advanced high-performance applications [18]. Figure 5. presents a comparative plot of tensile strength versus density for various material categories, including natural, synthetic, and polymers. Synthetic fibers exhibit the highest tensile strength, ranging from ~500 to 700 MPa, at relatively moderate densities (~1.3–1.6 g/cm³), highlighting their superior strength-to-weight ratio. Natural fibers show a wide spread in tensile strength (~150–450 MPa) with lower densities (~0.7–1.2 g/cm³), making them attractive for lightweight applications despite their variability. Polymers, including thermosets and thermoplastics, demonstrate significantly lower tensile strength (<100 MPa) across various densities. The chart emphasizes that synthetic fibers offer peak mechanical performance while natural fibers present a compelling compromise between strength and weight, with clear sustainability benefits. This comparison supports material selection for eco-efficient, structurally reliable composite designs.

Figure 6 presents the mechanical performance of basalt fiber hybrid composites reinforced with both natural (jute) and synthetic (PP, PLA, PET) fibers. The Basalt/PET hybrid exhibits the highest performance, with a tensile strength of 340 MPa, flexural strength of 380 MPa, and impact strength of 42 KJ. This superior performance can be attributed to PET's high stiffness, good interfacial bonding with basalt, and excellent energy absorption capability, which contribute to both strength and toughness. The Basalt/PLA composite shows comparable flexural strength (350 MPa) and good tensile strength (300 MPa) but slightly lower impact resistance (32 KJ). This is likely due to PLA's brittle nature, which limits its ability to absorb sudden impact energy despite strong bonding and rigidity. The Basalt/PP hybrid records moderate tensile (280 MPa) and flexural (330 MPa) strengths with a relatively better

impact strength (35 KJ), owing to PP's ductility and good impact resistance, although its lower stiffness limits its structural load-bearing capacity compared to PET or PLA. In contrast, the Basalt/Jute hybrid delivers the lowest mechanical performance, with tensile and flexural strengths of 260 MPa and 310 MPa, and an impact strength of 30 KJ. The reduced performance is due to the natural jute fiber's lower mechanical strength, hydrophilic nature, and weaker interfacial adhesion with the epoxy matrix, which leads to poor stress transfer and increased susceptibility to delamination or fiber pull-out. Overall, the results demonstrate that synthetic fibers (PET, PLA, PP) in hybridization with basalt provide superior mechanical integrity, while natural fiber composites, although sustainable, require chemical treatment or matrix modification to improve interfacial bonding and mechanical response [19].

Basalt Fiber-Reinforced Hybrid Composites Filled with Nanoparticles

Recent studies on basalt fiber-reinforced hybrid composites with nanoparticle fillers reveal significant advancements in performance metrics. Incorporating BaSO₄ nanoparticles enhances tensile strength by 30% and flexural strength by 25%, attributed to improved stress distribution and fiber-matrix bonding. SiO₂ nanoparticles contribute similarly, with a 20% increase in tensile strength and a 22% improvement in impact resistance due to their reinforcing effect on the basalt fibers [20]. Al₂O₃-filled composites show a 35% reduction in thermal conductivity and increased thermal stability. In comparison, TiO₂ nanoparticles result in a 30% decrease in thermal expansion and a 40% reduction in wear rates owing to their high hardness and resistance to abrasion. SEM analyses reveal enhanced interfacial bonding and fewer voids within the matrix, confirming the structural benefits of nanoparticle integration. Combining nanoparticles, such as SiO₂ and TiO₂, provides further performance improvements, suggesting that optimized nanoparticle combinations could lead to advanced applications in structural and industrial settings. Table 2 shows that the basalt fiber-reinforced hybrid composites with nanoparticle fillers demonstrate significant performance improvements. BaSO₄-filled composites achieve the highest tensile strength (90 MPa), reduced thermal conductivity (1.2 W/m·K), and lower wear rates, offering the most substantial overall enhancements. SiO₂ and Al₂O₃ fillers provide notable gains in strength and wear resistance, while TiO₂ considerably reduces thermal expansion. The choice of nanoparticle filler crucially affects these composites' mechanical and thermal properties [21]. The inclusion of different nanoparticle fillers significantly influenced the mechanical and thermal properties of the basalt fiber composites. Nano-Al₂O₃ enhanced hardness and tensile strength due to its rigidity and surface energy. SiO₂ nanoparticles improved thermal conductivity and provided moderate mechanical reinforcement. Nano-clay improved dimensional stability and reduced water absorption, while carbon nanotubes (CNTs) offered exceptional increases in tensile modulus and electrical conductivity, albeit with dispersion challenges. The optimal filler content (1–2 wt%) varied by type, with diminishing returns or embrittlement observed beyond this range.

Basalt Fiber Reinforced Fiber Metal Laminates

Recent studies on basalt fiber-reinforced fiber metal laminates (FMLs) have yielded detailed quantitative insights into their enhanced performance. The incorporation of basalt fibers has been shown to improve mechanical properties significantly. For instance, tensile strength increases by approximately 35%, reaching up to 850 MPa compared to 630 MPa in non-reinforced FMLs. Similarly, flexural strength improvements of around 25% result in values up to 620 MPa, compared to 496 MPa in traditional FMLs [22]. Impact resistance also benefits from basalt reinforcement, with increases of about 30%, achieving up to 35 kJ/m² versus 27 kJ/m² in standard FMLs. Thermal performance is notably enhanced, with a reduction in thermal expansion of up to 20%, translating to coefficients of thermal expansion (CTE) of around $6.5 \times 10^{-6}/^{\circ}\text{C}$ compared to $8.1 \times 10^{-6}/^{\circ}\text{C}$ for non-reinforced variants. Wear resistance is improved by approximately 30%, with wear rates reduced to 1.2 mm³/1000 cycles versus 1.7 mm³/1000 cycles in conventional FMLs. These improvements highlight the significant role of basalt fibers in enhancing the performance of FMLs. Including additional reinforcements, such as nanoparticles, further augments these properties, suggesting a promising direction for future developments in composite materials.

Table 2. Basalt fiber-reinforced hybrid composites with nanoparticle fillers demonstrate significant performance.

Properties	Basalt+ BaSO ₄	Basalt + SiO ₂	Basalt +Al ₂ O ₃	Basalt +TiO ₂
Tensile strength (Mpa)	90	85	88	87
Flexural strength (Mpa)	120	115	125	118
Impact resistance (J)	15	14	16	15.5
Thermal conductivity (W/m·K)	1.2	1.3	1.1	1.2
Thermal expansion (1/°C)	5×10^{-6}	5.5×10^{-6}	4.8×10^{-6}	4.5×10^{-6}
Wear rate (mm ³ /kWh)	0.15	0.17	0.14	0.16

Comparative Summary of Basalt Fiber Composites

A comparative assessment of basalt fiber composites highlights their unique advantages over conventional reinforcement systems. Compared to glass fiber composites, BFRCs exhibit up to 30% higher tensile strength, 25% lower moisture absorption, and superior chemical resistance, especially in alkaline or corrosive environments. When benchmarked against carbon fiber composites, basalt fibers offer comparable mechanical performance but at a significantly reduced cost, making them more accessible for mass-market applications. While environmentally friendly, natural fiber composites typically suffer from lower thermal stability and mechanical properties, which BFRCs can substantially improve [23]. Hybridization further amplifies these advantages. For instance, basalt-carbon hybrids combine the toughness and affordability of basalt with the high stiffness of carbon fibers, yielding composites with optimized strength-to-weight ratios. Incorporating natural fibers like flax or hemp improves biodegradability while maintaining acceptable mechanical performance [24]. The integration of nanoparticles introduces multifunctionality, enabling enhanced wear resistance, flame retardancy, and thermal insulation [25]. These innovations represent a clear departure from traditional composites, offering a path toward tailored, application-specific materials that meet the demands of next-generation engineering structures [26]

CONCLUSION AND FUTURE SCOPE

Basalt fiber-reinforced composites (BFRCs), particularly in hybrid and nanoparticle-modified forms, exhibit superior mechanical strength, thermal stability, and morphological integrity, surpassing traditional glass and carbon fiber systems while offering cost-effectiveness and environmental benefits. Their performance can be tailored by hybridizing with natural or synthetic fibers and incorporating functional nanoparticles like BaSO₄, SiO₂, Al₂O₃, and TiO₂, which enhance interfacial bonding, wear resistance, and thermal properties. Advanced fabrication techniques such as vacuum infusion, microwave curing, and 3D printing have improved processing consistency and scalability. Although BFRCs demonstrate excellent weatherability, long-term durability studies remain limited; however, basalt-based hybrids retain over 85% of tensile strength after 500 hours of UV exposure-outperforming jute fiber composites exhibit lower moisture absorption. Future research should focus on interface engineering via fiber surface treatments, the development of multi-layer hybrid structures, and the integration of AI-driven design tools such as genetic algorithms and neural networks to optimize fiber orientation, stacking, and filler content. These innovations will be crucial in overcoming existing limitations and advancing the application of BFRCs in structural, aerospace, automotive, and sustainable engineering systems.

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