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Basalt Fiber-Reinforced Polymer Composites: Properties, Applications, and Future Prospects

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Basalt Fiber-Reinforced Polymer (BFRP) composites represent a significant advancement in material science, combining the robust properties of basalt fibers with the versatile characteristics of polymer matrices. This article explores the fundamental properties of BFRP composites, including their mechanical, thermal, and tribological attributes. BFRP composites offer several advantages over other composite materials, including superior resistance to corrosion and environmental degradation, a high strength-to-weight ratio, and better sustainability due to the natural basalt fibers, which are non-toxic, abundant, and cost-effective compared to carbon and glass fibers. The discussion extends to the materials used in BFRP composites, such as epoxy and vinyl ester polymers, as well as the different forms of basalt fibers, including woven fabrics and chopped

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strands. The manufacturing processes, including hand lay-up, filament winding, pultrusion, and vacuum-assisted resin transfer molding (VARTM), are examined for their impact on the quality and performance of BFRP composites. The article highlights the diverse applications of BFRP composites across various industries, including automotive, aerospace, construction, energy, sports equipment, and electro-technical sectors. Future prospects for BFRP composites are optimistic, with advancements in production technologies, hybrid composite development, and increased emphasis on environmental sustainability poised to enhance their performance and reduce costs. This comprehensive review underscores the potential of BFRP composites to play a pivotal role in the evolution of high-performance, eco-friendly materials in engineering and industrial applications.

Keywords: Basalt; fiber; polymer; composites; properties.

1. INTRODUCTION

Fiber-reinforced polymer (FRP) composites mark a significant leap forward in material science and engineering, providing a versatile, high-performance alternative to traditional materials like metals and ceramics. These composites are made up of a polymer matrix reinforced by high-strength fibers such as basalt, glass, carbon, or aramid [1]. This combination results in a material that is both lightweight and durable, offering a high degree of adaptability to various industrial and engineering applications, largely due to its flexible design possibilities. Among the many types of FRP composites, basalt fiber-reinforced polymers (BFRP) are particularly notable for their distinctive properties and growing use in high-performance applications. Basalt fibers are produced from basalt, a natural igneous rock formed by volcanic activity. The production process involves melting basalt at temperatures between 1,400 and 1,600°C and extruding the molten material into continuous fibers. These fibers boast high strength, excellent thermal stability, and resistance to corrosion, positioning them as a strong alternative to more conventional fibers such as glass and carbon [2].

The polymer matrix in BFRP composites is generally made from thermosetting or thermoplastic polymers, such as epoxy, polyester, vinyl ester, or polyamide. When combined with basalt fibers, the polymer gains significantly improved properties compared to the matrix or fibers used individually [3]. The reinforcement process enhances mechanical strength, thermal resistance, and durability while reducing the overall weight—an essential feature for industries needing strong, easy-to-handle materials. Moreover, incorporating various inorganic fillers alongside basalt fibers allows for the further tailoring of the composite's properties, increasing their versatility and performance. The growing environmental concerns have led to an increased preference for natural sources over traditional synthetic ones, due to the latter's negative environmental impact [4-6]. Environmental concerns have sparked growing interest in basalt fibers as a more sustainable option compared to synthetic fibers like glass and carbon. Unlike synthetic alternatives, which involve energy-intensive manufacturing and a large environmental footprint, basalt fibers are sourced from abundant volcanic rock, making them both environmentally friendly and cost-efficient. Basalt fiber production requires minimal chemical processing and lower energy consumption than glass or carbon fibers, thereby lessening its environmental impact. Additionally, basalt fibers are fully recyclable, making them an attractive option for industries increasingly focused on sustainability and waste reduction [7].

When it comes to performance, BFRP composites offer an exceptional combination of properties that often exceed those of traditional materials such as steel, aluminum, and reinforced concrete, but at a much lower weight. These composites display high tensile strength, stiffness, and resistance to fatigue, making them well-suited for load-bearing applications in industries like construction, automotive, aerospace, and marine engineering. Unlike metals, which are susceptible to corrosion and rust in harsh environments, BFRP composites are highly resistant to chemicals, moisture, and saltwater, which significantly prolongs their lifespan and reduces maintenance costs. This corrosion resistance is particularly valuable in structures exposed to aggressive conditions, such as bridges, offshore platforms, and chemical plants. Another key advantage of BFRP composites is their excellent thermal stability, as they maintain their mechanical properties even at elevated temperatures. This makes them suitable for applications in industries where materials are subject to heat, fire, or rapid thermal cycling, such as aerospace, automotive, and industrial machinery sectors [8]. Basalt fibers' ability to withstand high temperatures without degradation ensures the reliability and safety of BFRP composites in challenging environments. Additionally, BFRP composites can be designed to meet specific performance needs by adjusting the type, orientation, and volume fraction of basalt fibers within the polymer matrix. This level of customization allows for the creation of complex shapes and optimized structural performance, further enhancing the composite's versatility [9]. The unique chemical composition and structural features of BFRP composites are the foundation of their superior mechanical, thermal, and chemical properties. Understanding these properties is critical for maximizing the performance of BFRP composites across various industries. As the demand for lightweight, strong, and eco-friendly materials rises, BFRP composites are set to play an increasingly important role in applications ranging from construction and infrastructure to high-performance transportation and energy sectors [10]. This article aims to explore the comprehensive properties of BFRP composites, investigate their current industrial applications, and assess their future prospects as a leading material in the advancement of sustainable and high-performance engineering solutions.

2. FABRICATION OF BFRP COMPOSITES

2.1 Materials Used

2.1.1 Types of polymers

Epoxy Polymers: Epoxy polymers are essential to a variety of industries due to their versatile properties and applications. They are characterized by their high strength, excellent adhesion, and resistance to environmental degradation. The chemical structure of epoxy polymers typically consists of an epoxide group that undergoes a curing process, which can be induced by heat or a catalyst. This curing process forms a rigid, cross-linked network, enhancing the material's mechanical properties and stability. Epoxy polymers are widely used in applications such as adhesives, coatings, and electrical insulation. In composite materials like fiberglass, epoxy serves as the matrix that binds the fibers, providing structural integrity. Additionally, due to their high strength-to-weight ratio, epoxy polymers are commonly employed in the aerospace and automotive industries for the fabrication of structural components [11,12].

Vinyl Ester Polymers: Vinyl ester polymers are known for their excellent resistance to corrosion, chemical stability, and toughness. These polymers are formed through the cross-linking of ester and vinyl groups, resulting in a thermoset polymer that combines the benefits of both epoxy and polyester resins. The cross-linking ability of vinyl ester polymers contributes to their superior performance in harsh environments, making them ideal for use in chemical processing, marine, and automotive applications [13]. The physical properties of vinyl ester polymers, such as their impact resistance and durability, make them a preferred choice in applications where long-term exposure to corrosive environments is a concern. These polymers are also used in the production of composite materials, where they enhance the overall mechanical performance and lifespan of the final product [12,13].

2.1.2 Basalt fiber forms

Overview of Basalt Fibers: Basalt fibers are derived from basalt, a natural volcanic rock, and are known for their unique combination of properties, including high strength, thermal stability, and resistance to chemical and environmental degradation. These fibers are produced by melting basalt rock at high temperatures and extruding the molten material into continuous fibers [14]. The resulting fibers are lightweight, durable, and environmentally friendly, making them suitable for a wide range of applications.

Woven Fabrics: Woven basalt fiber fabrics are textiles created by weaving continuous basalt fibers together in various patterns, such as plain weave or twill weave. These fabrics are valued for their flexibility, ease of handling, and ability to conform to complex shapes. Woven basalt fabrics are commonly used in the aerospace, automotive, construction, and marine industries, where they reinforce composite structures like hulls, panels, and concrete elements [15].

Chopped Strands: Chopped basalt fiber strands are short segments of basalt fibers, typically ranging from a few millimeters to several centimeters in length [15]. These strands are highly adaptable and can be easily integrated into different resin systems, making them suitable for a variety of manufacturing processes. Chopped strands are used in applications such as injection molding, non-woven mat production, and reinforcement of thermoplastic and thermoset composites, where they contribute to the material's strength, elasticity, and ability to conform to intricate shapes [16].

2.2 Manufacturing Processes

2.2.1 Hand lay-up

Hand lay-up is a manual process used in the fabrication of composite parts, offering simplicity, flexibility, and suitability for small to medium-sized production runs or custom components. The process begins with the preparation of the mold surface, which is cleaned and treated with release agents to prevent the composite part from sticking. Basalt fiber reinforcements are then manually placed onto the mold, ensuring proper alignment and orientation to achieve the desired mechanical properties. Resin is applied to the fibers using brushes or rollers, thoroughly impregnating the fibers and ensuring complete wet-out. To eliminate air bubbles and ensure good bonding between the fibers and resin, rollers or squeegees are used. Depending on the resin system, the composite part is allowed to cure at room temperature or under controlled conditions, such as with heat or pressure. Once curing is complete, the part is carefully removed from the mold [17].

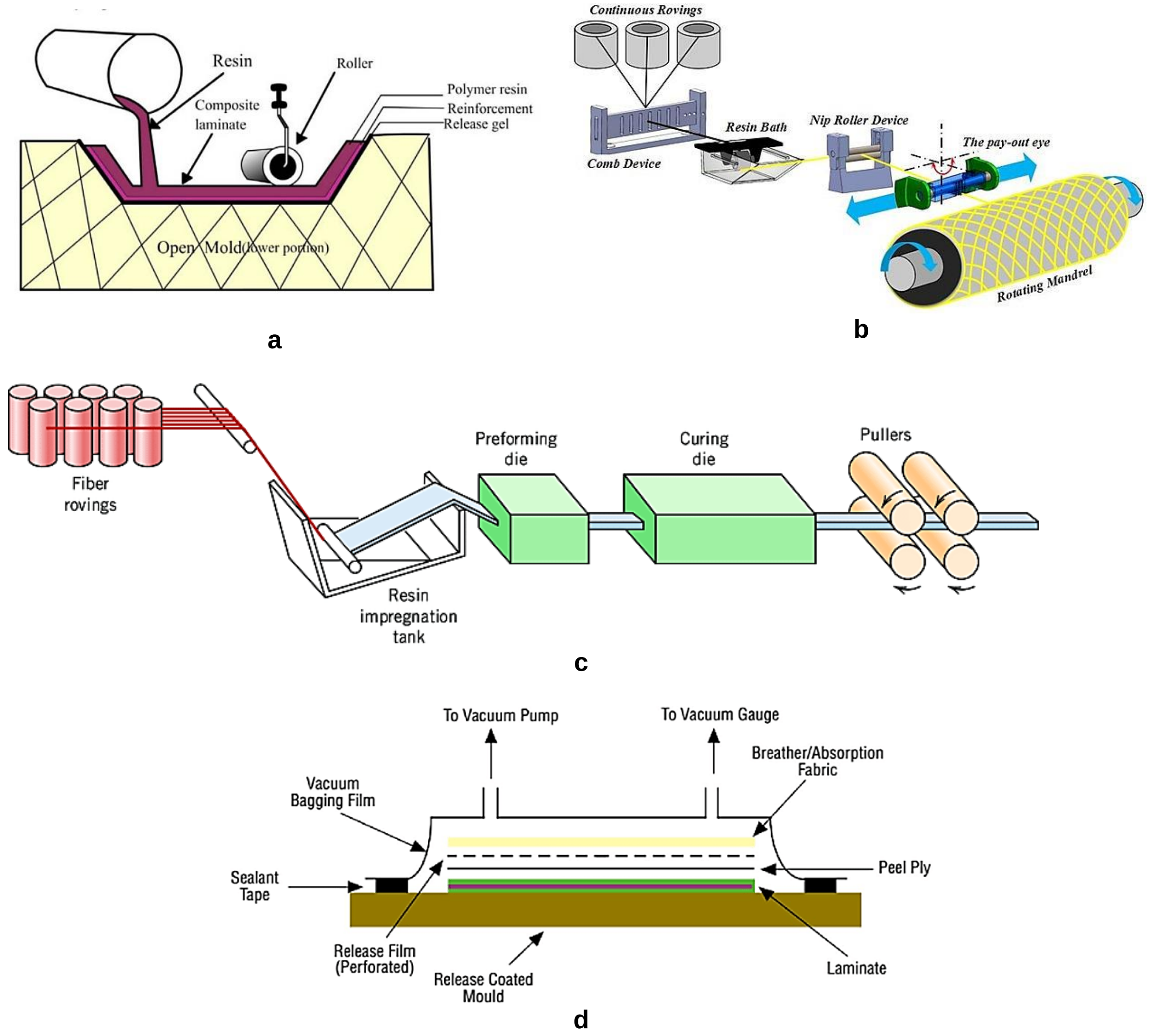


Fig. 1. Manufacturing process techniques a) Hand lay-up Process b) Filament winding Process, c) Pultrusion Process d) Vacuum-assisted Process

2.2.2 Filament winding

Filament winding is a semi-automated or fully automated process used to manufacture composite products, particularly those with axisymmetric or cylindrical shapes, such as pipes, tanks, and pressure vessels. This process is favored for its efficiency, consistency, and ability to produce high-strength components. The process starts with the preparation of the mandrel or mold, which is treated with release agents. Continuous basalt fibers (in the form of rovings or yarns) are then wound around the rotating mandrel in predetermined orientations and patterns. Resin is applied to the fibers either during the winding process (wet winding) or beforehand (dry winding), ensuring thorough impregnation and adherence. Compaction tools or pressure rollers are used to achieve good fiber-to-resin contact and to remove any trapped air. The wound composite is then cured, typically using heat, to achieve the desired mechanical properties and dimensional stability. After curing, the composite part is removed from the mandrel or mold [18,19].

2.2.3 Pultrusion

Pultrusion is a continuous manufacturing process used to produce composite profiles and structural shapes with consistent quality and high production rates. This method is particularly advantageous for producing long, continuous profiles, such as beams, channels, and rods. In the pultrusion process, continuous basalt fibers are drawn from creels and passed through an impregnation system or resin bath, where they are fully wetted with resin. The impregnated fibers are then pulled through a heated die or mold, which shapes the composite profile. As the composite passes through the die, heat is applied to initiate the curing process, solidifying the material. The cured composite profile is continuously pulled through the pultrusion machine, cut to the desired lengths, and cooled if necessary [20].

2.2.4 Vacuum-Assisted Resin Transfer Molding (VARTM)

Vacuum-assisted resin transfer molding (VARTM) is a low-pressure manufacturing process used to produce large, complex composite parts with minimal void content and excellent fiber wet-out. This process is well-suited for applications requiring high-quality, durable composites, such as in the aerospace, automotive, and marine industries. The VARTM process begins with the preparation of the mold surface, which is treated with release agents. Dry or pre-impregnated basalt fiber preforms are then placed into the mold cavity. The mold is sealed with a vacuum bag, and infusion mesh and ports for resin inlet and vacuum extraction are properly positioned. A vacuum is applied to remove air from the mold cavity, after which resin is introduced under controlled pressure to fully impregnate the fibers. The resin-infused composite is allowed to cure, typically under heat, resulting in a high-quality part with excellent mechanical properties [19, 20].

3. MECHANICAL, THERMAL, AND TRIBOLOGICAL PROPERTIES OF BFRP COMPOSITES

3.1 Mechanical Properties

I.D.G. Ary Subagia and colleagues [21] conducted a detailed investigation into the effects of incorporating tourmaline (TM) micro/nano particles on the mechanical properties of basalt fiber-reinforced epoxy composite laminates (BFRP). The study focused on varying the concentration of TM particles within the epoxy matrix, testing a range from 0.5% to 2% by weight. These TM-infused basalt/epoxy laminates were fabricated using vacuum-assisted resin transfer molding (VARTM), which ensured that the basalt fibers were thoroughly impregnated with the epoxy resin that contained TM particles. Mechanical performance was assessed through tensile and flexural testing, adhering to ASTM standards. The results demonstrated significant improvements in both tensile and flexural strength and modulus due to the incorporation of TM particles. Notably, the laminate containing 1% TM, in conjunction with a surfactant (C4), exhibited the most substantial gains, including a 16% increase in both tensile and flexural strength compared to the baseline basalt/epoxy composite. Additionally, the tensile modulus increased by 27.4%, and the flexural modulus saw an impressive 153.3% improvement over the neat composite. F. Sarasini et al. [22] studied the hybridization of basalt fibers with carbon fibers in epoxy laminates, particularly investigating how different hybrid stacking configurations affect mechanical properties and impact resistance. Two types of hybrid laminates were fabricated: one with a sandwich-like stacking arrangement and another with an intercalated sequence of alternating basalt and carbon fiber layers. These hybrid laminates were subjected to quasi-static mechanical tests, including four-point bending, as well as low-velocity impact tests at energy levels of 5, 12.5, and 25 joules. Non-destructive evaluation methods, such as ultrasonic phased array scanning and acoustic emission monitoring, were used to examine the damage evolution post-impact. The results indicated that the hybrid laminates with an intercalated configuration displayed superior energy absorption capacity during impact, which improved the overall mechanical resilience and damage tolerance of the laminates.

Xin Wang and co-authors [23] explored design optimizations for basalt fiber-reinforced polymer (BFRP) composites aimed at applications in long-span cable-stayed bridges. The study focused on addressing the limitations associated with BFRP cables, particularly in terms of their mechanical and fatigue properties. The research involved experimental analysis of the mechanical behavior and fatigue performance of BFRP cables, as well as investigating the hybrid effect of fiber reinforcement. The findings provided optimized design parameters for improving the material performance and structural efficiency of BFRP cables, thereby enhancing their viability for use in large-scale infrastructure projects like cable-stayed bridges. Denni Kurniawan et al. [24] examined the effects of atmospheric pressure glow discharge plasma polymerization on basalt fibers and the resulting influence on the mechanical and thermal properties of polylactic acid (PLA)-based composites. The basalt fibers were exposed to plasma treatment for different durations—ranging from 0.5 to 6 minutes—to determine the optimal exposure time for enhancing fiber-matrix adhesion and overall composite performance. Molecular linkage analysis and surface morphology characterization of the plasma-treated fibers were conducted to assess the changes induced by the plasma treatment. The study revealed that a 4.5-minute plasma treatment produced the best mechanical properties in terms of tensile strength and modulus, as well as improved water resistance and thermal stability in the resulting BF/PLA composites.

Salvatore Carmisciano and colleagues [25] performed a comparative analysis of basalt and E-glass woven fabric-reinforced composites. The laminates used in this study had identical fiber volume fractions and weave patterns, enabling a direct comparison of their mechanical performance. Flexural and interlaminar shear strength (ILSS) tests were conducted to evaluate the mechanical properties of the composites. The results demonstrated that basalt fiber composites had a higher flexural modulus and ILSS compared to E-glass composites. Although the flexural strength of the basalt composites was slightly lower, they exhibited similar electrical properties. SEM analysis of the fracture surfaces provided insights into the failure mechanisms, suggesting that basalt fibers hold promise as a viable alternative to E-glass fibers in polymer matrix composites, especially in applications where higher stiffness and interlaminar strength are desired. V. Manikandan et al. [26] investigated the mechanical properties of basalt fiber-reinforced unsaturated polyester composites, fabricated using a hand layup process at room temperature. The focus of this study was on the effects of surface treatments using NaOH and H2SO4 on the tensile, shear, and impact strengths of the composites. Mechanical testing, including tensile strength, interlaminar shear strength, and impact strength measurements, was carried out using a universal testing machine and an Izod impact tester. The results indicated that surface treatments significantly improved the fiber-matrix adhesion, as revealed by SEM analysis of the fracture surfaces. These treatments resulted in enhanced mechanical properties of the basalt fiber composites, making them more suitable for demanding applications.

In a follow-up study, F. Sarasini et al. [27] revisited the hybrid carbon/basalt laminate configurations, focusing on their post-impact residual mechanical properties. The study tested different stacking configurations—sandwich-like and intercalated—under varying impact energy levels (5, 12.5, and 25 joules). Quasi-static four-point bending tests were conducted to assess the damage sustained by the laminates after impact. Non-destructive testing methods, including ultrasonic phased array and acoustic emission, were employed to analyze the extent of damage and the failure mechanisms. The results reinforced earlier findings that intercalated configurations, where basalt and carbon layers alternate, provide enhanced energy absorption and superior post-impact mechanical performance compared to sandwich-like configurations. I.D.G. Ary Subagia et al. [28] expanded their investigation on TM particle incorporation in basalt fiber-reinforced epoxy composites by testing different TM loadings ranging from 0.5% to 2% by weight. The TM particles were embedded within the epoxy matrix, and the composites were fabricated using vacuum-assisted resin transfer molding (VARTM). Tensile and flexural tests were performed according to ASTM standards, with the results showing that TM particles significantly improved both the tensile and flexural strength and modulus of the composites. Optimal mechanical performance was observed with 1% TM loading combined with surfactant (C4), leading to a 16% improvement in tensile and flexural strength and a 27.4% increase in modulus, compared to the neat composite. Akin Akinci et al. [29] investigated the tribological behavior of low-density polyethylene (LDPE) composites filled with basalt particles at various loadings (10%, 30%, 50%, and 70% by weight). Wear tests were conducted under dry sliding conditions at different sliding speeds (0.5, 1.0, and 1.5 m/s) and applied loads (5, 10, and 20 N). The study found that increasing the basalt content in the LDPE composites significantly reduced the friction coefficient, dropping from 0.51 to 0.13 as the basalt loading increased. However, the wear rate increased with both sliding speed and load, indicating that basalt content plays a critical role in enhancing the wear resistance of LDPE composites while simultaneously reducing friction. T. Czigany et al. [30] explored the mechanical properties of hybrid composites made from polypropylene reinforced with a combination of basalt, hemp, glass, and carbon fibers. The composites were produced using carding, needle-punching, and pressing techniques, with the fibers treated with a maleic acid anhydride and sunflower oil mixture to enhance interfacial adhesion. Mechanical testing, supported by microscopic examination, revealed that the surface treatment significantly improved the strength characteristics of the hybrid composites. Acoustic emission techniques were also employed to correlate mechanical properties with sound waves generated during failure, providing further insights into the reinforcement mechanisms within these hybrid composites.

3.2 Tribological Properties

Harsha et al. [31] conducted a detailed investigation into the abrasive wear behavior of polyaryletherketone (PAEK) composites using a rubber wheel abrasion test (RWAT) setup and a pin-on-disc machine under varying loads and sliding distances. Their findings indicated that the specific wear rate (Ko) for two-body abrasive wear (single pass) was 30–50 times higher than for three-body abrasive wear. For two-body abrasive wear in multipass conditions, the specific wear rate was five to twelve times greater than that of three-body abrasive wear. Furthermore, the study explored the relationship between mechanical properties and abrasive wear performance, with SEM analysis providing insight into the wear mechanisms at different experimental conditions. J Li et al. [32] produced glass fiber (GF)-reinforced polyimide (PI) composites filled with graphite particles using hot press molding. These composites were tested for wear and friction properties under dry sliding conditions using a ring-on-block test rig. SEM analysis of the transfer coating on the counterpart and the worn surfaces of the PI composites helped in understanding the wear mechanisms. The study revealed that increasing normal loads reduced the friction coefficient of the composites in dry sliding, while the addition of graphite significantly improved the wear resistance of the GF-reinforced PI composites.

B Suresha et al. [33] studied the mechanical and three-body abrasive wear behavior of silicon carbide-filled E-glass fabric-reinforced epoxy (SiC-G-E) and E-glass fabric-reinforced epoxy (G-E) composites. Mechanical testing was conducted using a universal testing machine, while three-body abrasive wear tests were performed using a rubber wheel abrasion tester under two distinct weights and four abrading distances. The results showed that wear volume loss increased with abrading distance, whereas the specific wear rate decreased with increasing distance and load, indicating a wear resistance improvement under more severe conditions. Harsha et al. [34] conducted experimental tests on different PAEK matrices to evaluate the effects of load, solid lubricants, abrasive mass, and reinforcing fibers in three-body abrasive wear scenarios. Utilizing a rubber wheel abrasion test rig with angular silica sand particles as abrasives, the study found that the ketone/ether ratios in the PAEK matrices significantly influenced the wear behavior under high loads. Fiber reinforcement was found to degrade the abrasive wear resistance of the neat PAEK matrix, and combining fiber and particle fillers further reduced the wear performance.

CA Chairman et al. [35] investigated the three-body abrasive wear behavior of basalt-epoxy (B-E) and glass-epoxy (G-E) composites under various abrading distances and loads using a rubber wheel abrasion test. The results showed that basalt-epoxy composites had superior wear resistance compared to glass-epoxy composites under similar test conditions. SEM analysis of the worn surfaces revealed plowing grooves and fractured fibers, suggesting that the superior mechanical properties of basalt fibers contributed to the enhanced wear resistance of the B-E composite. J Zhang et al. [36] explored the friction and wear properties of continuous carbon fiber-reinforced polyetheretherketone (CFRP-PEEK) composites under dry sliding conditions. The study evaluated the effects of load and sliding speed on the wear and friction behavior. Tribological tests demonstrated that higher load and sliding speed reduced the friction coefficient but increased the wear rate. SEM analysis of the worn surfaces revealed that fiber-matrix adhesion significantly affected the wear mechanisms, and the study proposed that improved adhesion could enhance the wear resistance of CFRP-PEEK composites, particularly under high load and speed conditions. Harsha et al. [37] examined the wear and friction characteristics of hybrid polyetherketoneketone (PEKK) composites reinforced with a combination of glass and carbon fibers under different loads and sliding speeds. The results showed that the wear rate of the hybrid composite increased with higher loads and sliding speeds, while the friction coefficient decreased. The reduction in friction was attributed to the synergistic effect of combining glass and carbon fibers, which enhanced the composite's overall tribological performance.

3.3 Thermal Properties

Ary Subagia et al. [38] reported that adding TM particles to basalt/epoxy composites improved not only mechanical properties but also thermal stability. Thermogravimetric analysis (TGA) showed that the onset temperature for thermal degradation increased with TM content, indicating enhanced thermal resistance. The incorporation of 1% TM was found to be optimal, providing the best balance between mechanical and thermal properties.

X. Wang et al. [39] explored the effect of varying the basalt fiber content on the thermal properties of BFRP composites intended for long-span bridge applications. Differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA) were used to measure the glass transition temperature (Tg) and thermal stability of the composites. The study found that higher basalt content led to an increase in Tg and improved thermal stability, making the composites more suitable for structural applications in environments with temperature fluctuations.

Denni Kurniawan et al. [40] evaluated the thermal conductivity of PLA composites reinforced with plasma-treated basalt fibers. The study found that plasma treatment improved interfacial bonding between the fibers and the matrix, which, in turn, enhanced the thermal conductivity of the composites. The optimal plasma exposure time (4.5 minutes) not only maximized mechanical properties but also improved the thermal conductivity of the composites, making them more effective for applications requiring efficient heat dissipation.

F. Sarasini et al. [27] also assessed the thermal behavior of carbon/basalt hybrid laminates. The study utilized thermomechanical analysis (TMA) and DSC to evaluate the thermal expansion and glass transition temperature of the hybrid laminates. The results showed that the intercalated hybrid configuration offered better thermal stability and lower thermal expansion than the sandwich-like configuration, suggesting that basalt fibers contributed to the improved thermal performance of the hybrids.

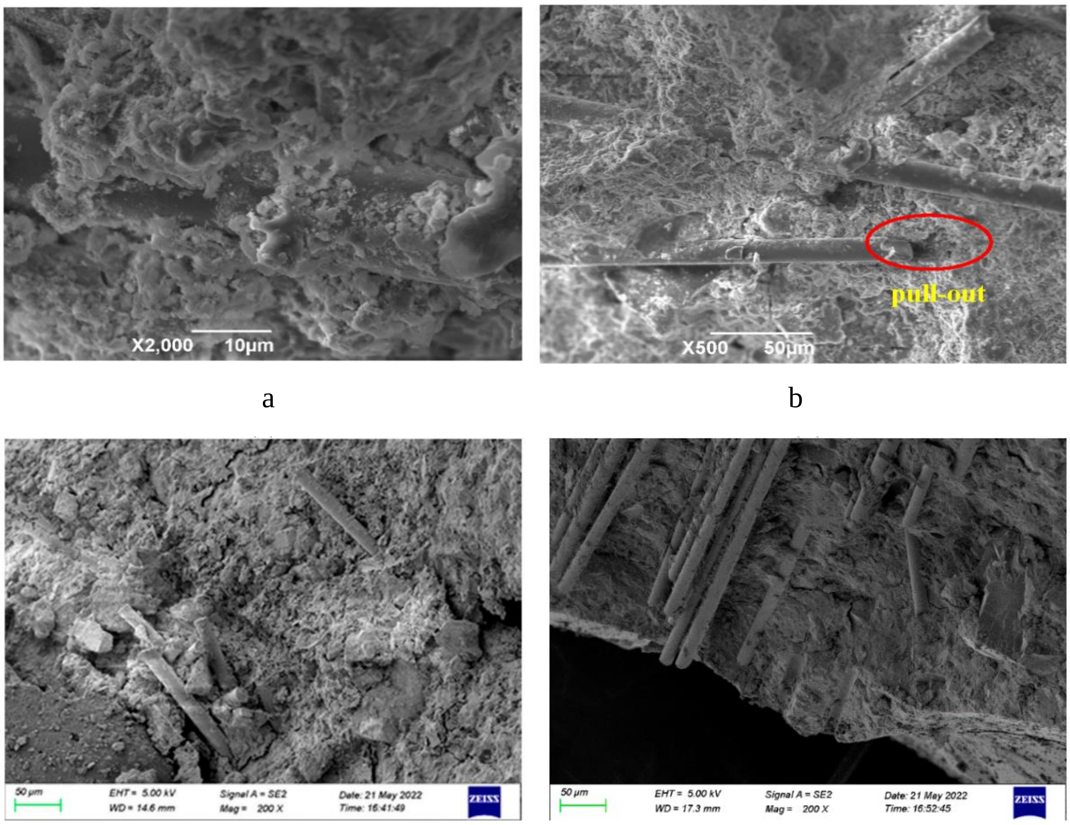
3.4 Microstructure Analysis

Microstructure analysis refers to the investigation of small-scale structures within materials, typically at a microscopic or nanoscopic level. This type of analysis is essential across various disciplines such as materials science, metallurgy, and biology, as it provides insights into the properties and behaviors of materials.

Scheffler et al. [41] reported that hydroxyl ions in alkaline solutions react with H20-SiO-Si groups in glass networks, leading to the dissolution of silicate and the hydration of surfaces. The corrosion rate is influenced by the chemical composition of the fiber, the type of alkaline solution, as well as the exposure time and temperature. In this study, the aging of glass and basalt fibers with different compositions in NaOH and cement solutions was evaluated, revealing that calcium ions modify the corrosion mechanism by inhibiting corrosion. The strength distributions were assessed using a Weibull distribution function. Shokrieh et al. [42] studied the behavior of basalt/epoxy composites under stress corrosion, focusing on the mechanical properties when subjected to bending and immersed in a 5% sulfuric acid solution. Research on the durability of fiber-reinforced polymer composites is limited, particularly for basalt fibers and their composites. This study investigated the degradation of mechanical properties, such as bending strength, modulus of elasticity, and fracture energy, for composites under different stress states. The results showed the effects of high-stress conditions on the degradation of these properties.

Nasir et al. [43] examined the corrosion behavior of basalt fibers and the crack formation process when exposed to sulfuric acid. The corrosion behavior and non-siliceous ion leaching from fiber surfaces were analyzed using EDX and SEM techniques. In contrast to E-glass fibers, basalt fibers exhibited spiral and axial cracks at longer exposure durations, demonstrating better strength retention compared to E-glass fibers. Kumosa et al. [44] explored the impact of nitric acid on modified polyester, epoxy, and vinyl ester resins without applying mechanical loads. The study focused on stress-corrosion crack initiation in unidirectional E-glass/polymer composites. These materials are commonly used in overhead transmission lines. Results indicated that crack initiation rates increased with the number of exposed fibers, though further stress-corrosion damage did not occur after crack initiation.

Barczewski et al. [45] studied the thermomechanical properties of polylactide (PLA) composites reinforced with basalt powder (BP) and micrometric basalt fibers (BMF) in varying weight percentages. The composites were produced through melt processing and annealing to create a highly crystalline structure. Post-processing led to significant improvements in the thermomechanical stability of PLA composites filled with BMF and BP. Bonsu et al. [46] assessed the long-term durability of glass and basalt fiber-reinforced vinyl ester epoxy (GFRP and BFRP) composites in marine environments. The composites were aged in seawater for extended periods, and mechanical testing revealed moisture-related degradation, including fiber breakage and debonding. Scanning electron microscopy (SEM) confirmed the structural changes that occurred with aging.



a b

c d

Fig. 2. Microstructure images of BFRC's [52,53]

Praveenkumara et al. [47] highlighted the use of hybrid composites to improve material performance. By incorporating two or more similar or dissimilar fibers into a composite, hybridization enhances mechanical properties. Synthetic fillers were added to polymer composites to strengthen the fiber-matrix interface and improve material properties. Vinod et al. [48] reviewed the development of bio-based materials, focusing on biofibers, biopolymers, biofilms, and biocomposites. The review discussed advancements in processing techniques and applications, emphasizing the role of these materials in promoting sustainability by reducing waste and emissions. Post et al. [49] discussed the role of mineral fillers in improving the mechanical properties of biobased and biodegradable polymers. While biobased polymers have gained attention due to their environmental benefits, their mechanical properties often lag behind those of traditional plastics. The use of fillers like mica, kaolin, and calcium carbonate can address these limitations.

Cerny et al. [50] investigated composite materials with enhanced thermal resistance through partial pyrolysis, using basalt fabric as reinforcement. Different pyrolysis methods were tested to optimize mechanical properties, including flexural strength and fracture toughness. SEM and light microscopy were used to study the composites' microstructures, showing favorable results at final pyrolysis temperatures of 650–750 °C. Carmisciano et al. [51] conducted a comparative study of basalt and E-glass woven fabric reinforced composites. The study focused on flexural and interlaminar properties, showing that basalt fiber composites exhibited higher flexural modulus and interlaminar shear strength (ILSS) compared to E-glass composites. SEM analysis of fractured surfaces provided insights into failure modes and areas of concern, highlighting the potential of basalt fibers as reinforcement in polymer matrix composites (PMCs). Figs. 2a and 2b shows the microstructure images of basalt fiber reinforced composites before and after fracture testing respectively. The fiber between the cracks transferred the load to the matrix on both sides, such that the concrete at the crack continued to bear the load, while the stress concentration between the cracks was alleviated. Figs. 2c and 2d shows basalt fibers in concrete. The randomly distributed fibers were staggered in the matrix in a grid-like structure.

4. APPLICATIONS AND FUTURE PROSPECTS OF BFRP COMPOSITES

4.1 Applications of BFRP Composites

4.1.1 Automotive and aerospace industry

In the automotive industry, basalt fiber-reinforced composites are increasingly utilized in the production of car headliners. The key advantage of basalt fibers in this context is their excellent recyclability, which enhances the environmental sustainability of car headliner manufacturing. These composites typically consist of a core with adhesive layers on opposing sides, with basalt fiber-reinforced composite (FRC) materials applied next to each adhesive layer. Moreover, basalt fiber composites are also used in automobile brake pads and clutch facings. The inclusion of basalt FRC materials in these components offers several benefits over other fiber-reinforced composites, such as those made with glass fibers. These advantages include enhanced durability leading to a longer service life, improved wear and friction resistance, superior shock absorption, higher operational temperature tolerance, and better resistance to chemicals and moisture. Additionally, basalt composites are considered eco-friendly, further underscoring their benefits in automotive applications[54]. The aerospace industry also sees the application of BFRP composites, particularly in aircraft interiors. Panels, overhead bins, and seating arrangements made from BFRP composites are not only lightweight, which contributes to overall fuel efficiency, but also offer excellent fire resistance, ensuring passenger safety. In unmanned aerial vehicles (UAVs), BFRP composites are used in structural components to reduce weight and enhance aerodynamic performance, allowing for longer flight durations and improved manoeuvrability [55].

4.1.2 Construction industry

In the construction sector, basalt fibers are increasingly utilized across various applications. One of the primary uses is in the production of basalt composite rebars for reinforcing concrete, which offers several benefits over traditional steel and glass fiber rebars. Notable advantages of basalt rebars include enhanced fracture toughness compared to steel, reduced weight, superior resistance to chemicals and moisture, excellent thermal stability, ease of processing, and good electrical conductivity. Additionally, basalt rebars are particularly valuable in marine environments and chemical plants due to their exceptional resistance to corrosion. For constructing interior partitions, elevator shafts, and hallways that require high fire resistance and the ability to withstand elevated temperatures, basalt fibers are an ideal reinforcement material. They provide excellent fire resistance and thermal stability, making them suitable for manufacturing these construction panels. In road engineering, incorporating short basalt fibers into asphalt concrete can significantly enhance pavement performance. These fibers improve tensile strength, fracture toughness, and resistance to deformation, contributing to more durable and resilient road surfaces. For offshore wind installations, which typically rely on steel structures prone to corrosion and moisture degradation, basalt fiber-reinforced polymers (FRPs) offer a promising substitute. Their superior mechanical properties, along with excellent moisture and corrosion resistance, make them suitable for replacing steel in floating structures like towers and platforms [56].

4.1.3 Energy sector

In the energy sector, basalt fiber-reinforced composites (FRCs) present a viable alternative to E-glass FRCs, which are commonly used in wind turbine components such as main spars and wing shell sections. Carbon fiber composites are often used in conjunction with glass fiber composites to create hybrid laminates for the spar cap sections of large wind turbine blades, aiming to maximize bending stiffness. By integrating basalt FRCs, manufacturers could potentially enhance the performance, recyclability, and environmental friendliness of the blades, improving the cost-to-quality ratio [57].

4.1.4 Sports equipment

Basalt fiber-reinforced polymers are extensively used in sports equipment due to their exceptional moisture resistance and durability against corrosion. This makes them ideal for water sports gear such as kayaks, canoes, paddles, and water skis. Additionally, basalt FRCs are employed in the production of various other sports items, including bicycle frames, tennis rackets, skis, and snowboards [58].

4.1.5 Electro-technical applications

Basalt fabrics are increasingly utilized in electro-technical applications due to their superior properties compared to traditional fiberglass materials. These fabrics can serve as a foundational component for producing advanced insulation materials. When subjected to preliminary metallization, basalt fabrics exhibit effective shielding against electromagnetic radiation. Basalt's versatility extends across a broad temperature range, from approximately -260°C to 650°C, far surpassing E-glass, which is typically usable from -6°C to 450°C. This extensive temperature tolerance makes basalt a viable replacement for asbestos in many applications, thanks to its excellent heat insulation properties. Additionally, basalt materials can substitute for glass in various insulating applications. Tapes made from basalt fibers are particularly useful for insulating electrical cables, providing protection against fire hazards during power transmission. These fibers maintain their insulating properties even at very low temperatures, making them ideal for low-temperature insulation needs. In the power industry, basalt fibers are employed in several ways, including as fillers, braiding, and tapes for fire-resistant cable components. They are also used in transformer stations for screens, protection, and insulation, and in motor insulation applications [59-60].

4.2 Future prospects

The outlook for Basalt Fiber Reinforced Polymer (BFRP) composites is exceptionally promising, driven by ongoing advancements in production technologies and an increasing emphasis on sustainable materials. As manufacturing techniques evolve, the potential applications for BFRP composites are expected to broaden significantly, while production costs are anticipated to decrease. Emerging technologies such as automated lay-up, filament winding, and additive manufacturing (3D printing) are poised to revolutionize BFRP production. Automated lay-up techniques enhance the precision and efficiency of layer placement in composite fabrication, while filament winding enables the creation of cylindrical and spherical structures with high strength-to-weight ratios. Additive manufacturing opens up new possibilities for producing complex geometries and customized composite components that were previously difficult or impossible to achieve with traditional methods. These advancements are likely to make the production of BFRP composites more cost-effective and versatile, facilitating their use in a wider array of industries, including aerospace, automotive, and renewable energy [52,58].

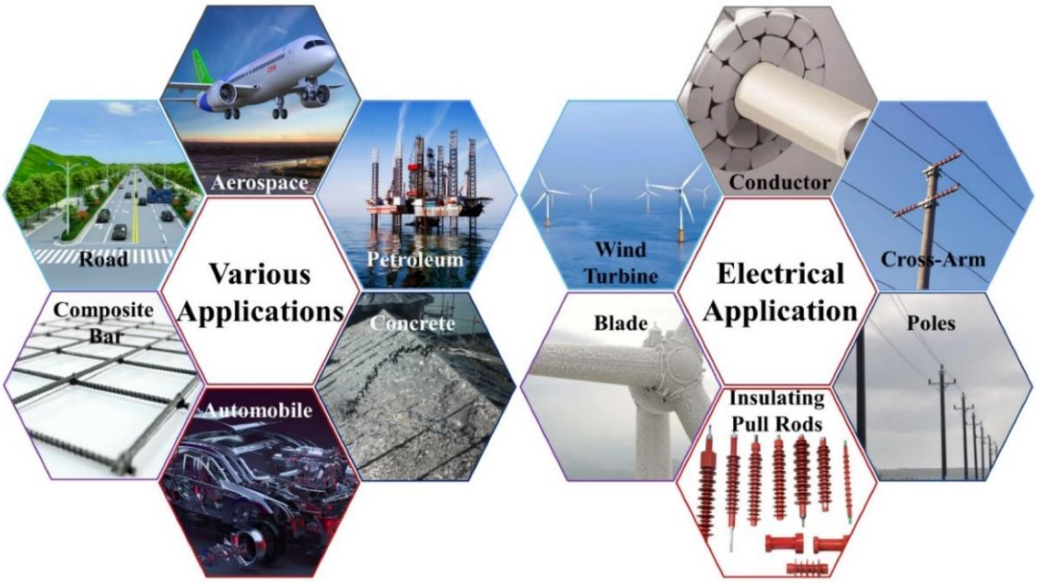


Fig. 3. Applications of BFRP Composites [62]

Emerging applications for BFRP composites span sectors that demand materials with superior mechanical properties and environmental sustainability. The construction industry is a prime example, where BFRP composites can replace steel in reinforced concrete due to their excellent corrosion resistance. In automotive and aerospace sectors, BFRP composites are increasingly used for lightweight structures, improving fuel efficiency without compromising strength. Further, as renewable energy systems grow, BFRP composites can be applied in wind turbine blades and solar panel frames, offering durability and sustainability. Looking ahead, the development of hybrid BFRP composites—by integrating basalt fibers with carbon, glass, or natural fibers—will likely dominate future research. This hybridization could result in materials with enhanced properties, including improved impact resistance, thermal stability, and chemical resistance, making them suitable for even more demanding environments, such as offshore oil rigs or space structures.

One of the most exciting prospects in the field of BFRP composites is the creation of hybrid materials that combine basalt fibers with other reinforcing fibers such as carbon or glass. These combinations, alongside advanced resin systems—including bio-based and nanocomposite resins—could further tailor the mechanical, thermal, and chemical properties of BFRP composites. Hybrid composites can harness the high strength and stiffness of carbon fibers, the impact resistance of basalt fibers, and the chemical resistance of advanced resin systems, providing materials with superior performance for critical applications. For instance, in the aerospace industry, hybrid BFRP composites can offer the strength-to-weight ratios necessary for flight, while their corrosion resistance makes them ideal for harsh operating conditions [61].

In comparison to other fiber-reinforced composites, such as Carbon Fiber Reinforced Polymers (CFRP) and Glass Fiber Reinforced Polymers (GFRP), BFRP composites hold a unique position. While CFRP composites boast superior tensile strength and stiffness, they are considerably more expensive to produce and less environmentally friendly. GFRP composites, on the other hand, are more affordable but are prone to degradation in harsh chemical environments and lack the high thermal stability of basalt fibers. BFRP composites, with their balance of cost, mechanical strength, and resistance to environmental degradation, offer a middle ground between CFRP and GFRP. However, BFRP composites may have limitations in applications where extreme stiffness is required, as basalt fibers, while strong, do not reach the tensile performance levels of carbon fibers [63, 64].

Environmental sustainability remains a critical area where BFRP composites have significant potential. Basalt fibers are derived from abundant natural volcanic rock, offering a lower environmental impact than synthetic fibers like carbon or glass. The use of basalt fibers contributes to reducing the overall carbon footprint of composite materials. As industries and consumers increasingly prioritize eco-friendly materials, BFRP composites are positioned to play a pivotal role in achieving sustainability goals. Moreover, innovations in recycling and waste management of basalt composites at the end of their service life promise to further minimize environmental impact. As manufacturing technologies advance and environmental concerns become more urgent, BFRP composites will likely become more integral to various industries, further driving their adoption and integration [55].

With the increasing emphasis on eco-friendly materials and high-performance composites, BFRP composites are well-positioned to lead the way in future material development. Their potential for hybridization, sustainability, and cost-effectiveness makes them strong competitors in the global composite materials market, ensuring their relevance in the construction, automotive, aerospace, and renewable energy sectors for years to come [53,54].

Future research directions could focus on optimizing BFRP composite performance through enhanced hybridization techniques and the integration of nanomaterials for superior strength, toughness, and functional properties. Additionally, developing sustainable resin systems to complement basalt fibers could make BFRP composites even more environmentally friendly. Another key area for exploration is the lifecycle analysis (LCA) of BFRP composites, assessing their long-term performance, recyclability, and cost-effectiveness compared to other fiber-reinforced materials. These advancements are expected to expand the applications of BFRP composites into more advanced engineering fields, making them a material of choice for addressing modern industrial challenges [65].

5. CONCLUSIONS

The exploration of Basalt Fiber-Reinforced Polymer (BFRP) composites reveals their exceptional promise and versatility as advanced materials. BFRP composites, derived from basalt fibers and various polymer matrices, offer a unique combination of high strength, thermal stability, and resistance to environmental degradation, surpassing many traditional materials in performance. The properties of BFRP composites make them suitable for a wide range of applications, including automotive, aerospace, construction, energy, sports, and electro-technical fields. The manufacturing processes for BFRP composites, such as hand lay-up, filament winding, pultrusion, and vacuum-assisted resin transfer molding (VARTM), enable the creation of high-quality composites tailored to specific requirements. These processes ensure that BFRP composites maintain their superior mechanical and thermal properties while being produced efficiently.

Looking ahead, the future of BFRP composites is promising. Advances in manufacturing technologies, the development of hybrid composites, and a growing focus on sustainability are expected to further enhance their performance and reduce production costs. The potential for BFRP composites to contribute to environmentally sustainable engineering solutions is particularly noteworthy, given their natural origin and recyclability. As industries continue to seek materials that combine strength, durability, and eco-friendliness, BFRP composites are well-positioned to meet these demands. Their continued evolution and integration into various applications highlight their role as a leading material in the pursuit of advanced, high-performance, and sustainable engineering solutions.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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