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Critical Review on Basalt Fibre as Reinforcement in Different Applications

F. Antony Leo[1], N.Sathishkumar[2] ,K.Saravanan[3], K.Pravinkumar[4], S. Iruthaya Agastin[5], R M. Waseem Ali[6], K.Hariharan[7]

Abstract

Basalt fiber (BF), derived from volcanic rocks, has emerged as an attractive reinforcement material due to its remarkable properties, including high strength, stiffness, thermal stability, and eco-friendliness. This review critically examines the applications of BF as reinforcement in various fields, such as civil engineering, aerospace, automotive, and biomedical sectors. The performance of BF-reinforced composites in terms of mechanical, thermal, electrical, and biological properties is evaluated. The challenges and opportunities associated with the use of BF as reinforcement are analyzed, focusing on issues related to compatibility, dispersion, and interfacial bonding between BF and matrix materials. Additionally, this review compares BF with traditional reinforcement fibers such as glass and carbon fibers, providing insights into their mechanical, thermal, and environmental properties. Furthermore, the paper discusses the recycling challenges of BF-reinforced composites and suggests strategies for enhancing sustainability. The high cost of BF and its impact on commercial adoption are also analyzed. This comprehensive review aims to provide a state-of-the-art overview and shed light on the prospects of BF as a promising reinforcement material across diverse applications.

Keywords: Basalt fiber, reinforcement, composites, mechanical properties, thermal properties, electrical properties, biological properties, civil engineering, aerospace, automotive, biomedical, compatibility, dispersion, interfacial bonding, surface modifications, processing techniques, future research directions

INTRODUCTION

Basalt is a naturally occurring material found in volcanic rocks formed from solidified lava, with a melting point ranging from 1500°C to 1700°C. Its properties are significantly affected by the cooling rate during the quenching process, which determines its final state. complete crystallization. Basalt is mainly composed of two essential minerals: plagiocene and pyroxene, and the main constituent is SiO_2, followed by Al_2O_3. Basalt has many advantages over other rocks, such as high hardness, density, durability, and resistance to weathering and corrosion [1]. Basalt fiber (BF) is an advanced material developed by the former Soviet Union after three decades of research, with its first industrial production taking place in 1985 at a fiber laboratory in Ukraine. The manufacturing process involves heating basalt rock to temperatures between 1450-1500°C and extruding the molten material through platinum/rhodium crucible bushings to form fibers. BF is available in both chopped and continuous fiber forms, making it

***Author for Correspondence**
F. Antony Leo

[1,5,6]Sudent, Department of Mechanical Engineering, St. Joseph's College of Engineering, Old Mahabalipuram Road, Kamaraj Nagar, Semmancheri, Chennai, Tamil Nadu, India
[2,4]Assistant Professor, Department of Mechanical Engineering, St. Joseph's College of Engineering, Old Mahabalipuram Road, Kamaraj Nagar, Semmancheri, Chennai, Tamil Nadu, India
[3]Assistant Professor, Department of Mechanical Engineering, Agni College of technology, Old Mahabalipuram Road, Thazhambur, Chennai, Tamil Nadu, India
[7]Associate Professor, Department of Mechanical Engineering, Dr Mahalingam College of Engineering and Technology, Udumalai Road, Annamalai Nagar, Pollachi, Tamil Nadu, India
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suitable for textile manufacturing and various composite applications. It can be processed using standard equipment and techniques, and since no additional additives are required during production, it offers a cost-effective advantage [2].BF has many advantages over synthetic fibers, such as high strength, stiffness, thermal stability, and environmental friendliness. BF has a higher tensile strength, modulus of elasticity and increase in concrete stiffness than other fibers. BF has a higher chemical stability than glass fibers, as shown by the acidity coefficient and pH value tests. BF has a lower thermal conductivity and sound absorption coefficient than glass fibers, which makes it suitable for building thermal insulation and sound absorption materials. BF has a lower hygroscopicity and dielectric loss angle than glass fibers, which makes it more resistant to moisture and electric interference [3]. BF is considered safe for health, unlike asbestos, due to its distinct morphology and surface characteristics, which prevent carcinogenic and toxic effects.. Rats inhaling air containing asbestos and BF for 6 months showed that asbestos fibers killed the rats, while BF did not cause any harm. Fibrous particles with a diameter of 1.5 µm or smaller and a length of at least 8 µm should be managed and disposed of following standard asbestos handling procedures.. Fibers falling within the following three criteria are of concern: fibers with diameters lower than 1.5 µm (some say <3.5 µm), fibers with length-to-diameter ratio greater than 3:1, and fibers that are durable and biopersistent [4]. TBF has gained growing recognition as an innovative reinforcement material for producing hybrid composites and laminates. Hybrid composites/laminates are fabricated by embedding or reinforcing two or more foreign materials within a common host matrix, which results in a synergistic effect and superior properties. Hybrid composites/laminates can improve the physical and mechanical properties of carbon fiber reinforced plastic (CFRP) by replacing the layers of carbon fibers with ductile fibers, such as BF. This can lead to cost savings and enhanced composite performance [5].A key potential use of BF lies in reinforcing concrete.. Concrete has low tensile strength, so fibers like BF are added to act as reinforcement and improve strength.BF has been shown to improve the mechanical characteristics of concrete, including tensile, flexural, and compressive strength. The physical properties of concrete like setting time increase with more BF, while properties like shrinkage and workability decrease. BF provides durability benefits to concrete like improved resistance to acids, chlorides, and freeze-thaw cycles. BF reinforced concrete performs better than ordinary concrete [6]. This paper aims to provide a critical review on BF as reinforcement in different applications, such as civil engineering, aerospace, automotive, and biomedical. The paper will discuss the properties, production, processing, and performance of BF and BF reinforced composites. The paper will also analyze the challenges and opportunities of using BF as reinforcement, such as the compatibility, dispersion, and bonding issues between BF and matrix materials. The paper will also provide some suggestions for future research directions, such as improving the surface modification, design, and optimization of BF reinforced composites. This paper will enrich the domain of structural engineering and contribute a lot to the future researchers working on BF reinforced composites.

BASALT FIBRE: AN OVERVIEW

Basalt fiber (BF) is a durable inorganic silicate fiber obtained from natural volcanic basalt rock. It is recognized for its superior mechanical strength, resistance to high temperatures, strong chemical stability, and eco-friendly manufacturing process [7].BF-reinforced polymers (BFRPs) have been widely used in various industries due to their good corrosion resistance and designability, making them suitable for electrical equipment applications such as new conductors, insulating pull rods, and composite cross-arms.BF is composed of alumina ($Al2O3$), iron oxide ($Fe2O3$ + FeO), and other components, which provide it with good thermal stability and durability. Compared to traditional glass fiber (GF) and carbon fiber (CF), BF has better mechanical properties and is more cost-effective BF-based composites have been studied extensively in the field of electromagnetic shielding, water treatment, catalytic function, and fire insulation.BF is also used in the construction industry to reinforce concrete, improving its mechanical properties and durability[8].

It has been found to increase the strength and toughness of concrete, arrest thermal cracks, and enhance resistance to sulfate and chloride attack.BF-based composites have been developed for various applications, including metal composites, engineering plastics, and concrete reinforcement[9]. The physical form of basalt fiber is shown in **Figure 1**.

Figure 1. Basalt Fiber.

Formation and Processing

Basalt fiber (BF) is produced from basalt rock through a series of steps. The production process involves melting basalt rock at temperatures around 1400 to 1500°C, extruding the molten material through nozzles to form continuous filaments, and then forming these filaments into strands using lubricants. The final step includes winding the strands to form tubes. The diameter of the filaments can range from 7 to 17 microns depending on the speed of fiber and temperature of the melt[9].The composition of basalt fiber includes oxides of magnesium, calcium, sodium, potassium, iron, and traces of alumina. These fibers are rich in minerals and possess excellent properties such as sound insulation, heat resistance, vibration stability, and chemical durability. Basalt fibers are known for their high resistance to high temperatures and durability[10].Basalt fiber production waste can also be utilized effectively. The waste products from basalt fiber production can be used as microarray additives in concrete and other cement or gypsum-based solutions. This waste utilization process significantly reduces environmental pressure compared to similar glass or mineral materials. Basalt fiber waste can be repurposed for various applications, contributing to sustainable practices in material production[11].

Chemical Composition

Basalt fiber contains a high concentration of oxides, including silicon, aluminum, iron, magnesium, calcium, sodium, and potassium[12]. The chemical composition of basalt rocks includes approximately 52.8% SiO_2 and 17.5% Al_2O_3[13]. Basalt fibers are known for their high rigidity, low elongation, excellent mechanical properties, and resistance to chemicals and moisture[14]. Additionally, basalt fibers exhibit superior thermal stability and good resistance to moisture, making them a popular choice for various applications in industries such as clean energy and power grids[15][16]. Basalt fibers are environmentally friendly, easily recyclable, and have properties that surpass those of E-glass fibers in terms of thermal stability and resistance to corrosive conditions[17]. Overall, the chemical composition of basalt fiber includes a combination of oxides that contribute to its exceptional properties and suitability for diverse industrial applications[18]. The detailed chemical constituents and their roles are summarized in **Table 1**. A graphical representation of basalt fiber's chemical composition is illustrated in **Figure 2.**

Table 1. Constituent and composition of the basalt fiber.

CONSTITUENT	**COMPOSITION**	**PROPERTIES/CHARACTERISTICS**
Silicon Dioxide (SiO_2)	~52.8%	• Key component providing rigidity and mechanical strength
Aluminum Oxide (Al_2O_3)	~17.5%	• Contributes to high rigidity and mechanical properties
Iron, Magnesium, Calcium, Sodium, and Potassium Oxides		• Enhance thermal stability, chemical resistance, and moisture resistance • High rigidity, low elongation, excellent mechanical properties • Superior thermal stability compared to E-glass fibers • Environmentally friendly and easily recyclable

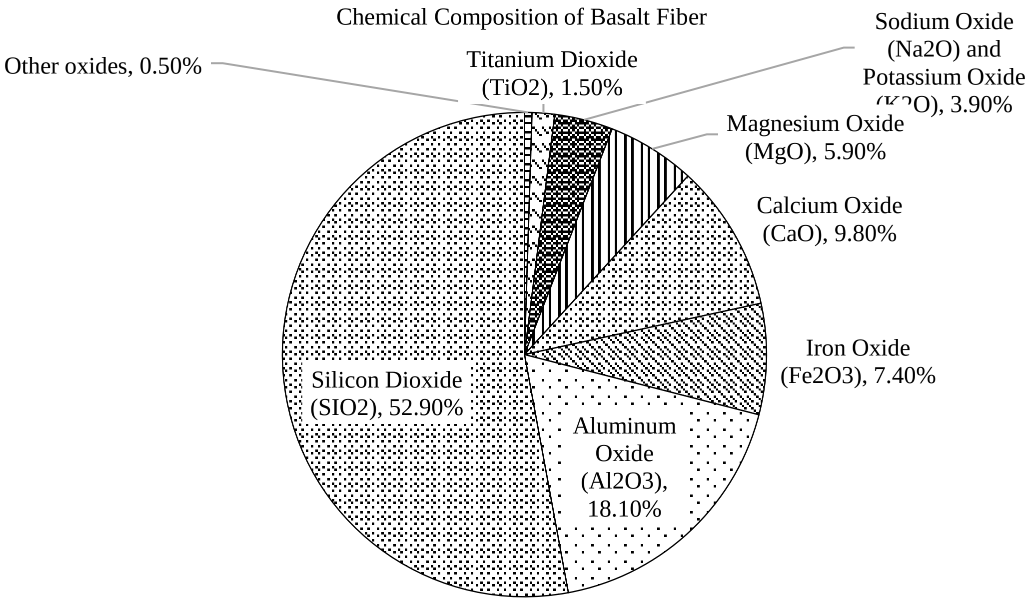

Figure 2. Chemical composition of the basalt fiber.

Advantages

Basalt fibers have a higher elastic modulus and tensile strength compared to other fibers like glass fibers, carbon fibers, and aramid fibers[19]. Basalt fibers possess outstanding durability in both acidic and alkaline conditions, making them ideal for diverse applications.[20].Basalt fibers have good thermal stability, with melting and working temperatures up to 600°C[21].Basalt fibers are made from naturally occurring materials and are recyclable, making them eco-friendly[22].Basalt fibers are produced from abundant basalt stone, which results in low production costs[23].Basalt fibers are resistant to moisture, making them suitable for outdoor applications[24].Basalt fibers are non-toxic and do not contain heavy metals, ensuring human safety during handling[25].

Limitations

Basalt fibers are more expensive than E-glass fibers[26].Specific design guidelines for basalt fibers are not provided by internationally recognized engineering code authorities[27].Basalt fibers have not been widely adopted in some industries, such as the aerospace industry, due to their limited applications[28]. Proper precautions should be taken during handling to prevent inhalation of basalt fiber particles, as they may cause abrasion. [29].

Recycling Challenges of Basalt Fibre Reinforced Composites

One of the significant challenges associated with basalt fiber-reinforced composites (BFRCs) is their recycling and disposal. Unlike thermoplastic-based composites, which can be melted and reprocessed, BFRCs based on thermosetting matrices are difficult to recycle [29]. Current solutions include mechanical grinding, thermal decomposition, and chemical treatments to recover fibers. However, these processes are energy-intensive and may degrade fiber properties. Future research should focus on developing efficient recycling techniques that retain fiber strength while ensuring environmental sustainability [30].

Impact of Cost on Basalt Fibre Adoption

Despite its excellent properties, the relatively high production cost of BF limits its widespread use in commercial applications. The cost of raw materials, high-temperature processing, and specialized equipment contribute to its pricing disadvantage compared to glass fibers[31]. Efforts to reduce costs include optimizing production processes, increasing large-scale manufacturing, and developing hybrid composites that combine BF with other cost-effective fibers. Addressing these economic challenges will be crucial in expanding BF applications in mainstream industries [32].

APPLICATIONS OF BASALT FIBRE REINFORCED COMPOSITES (BFRCS):

Basalt fiber reinforced composites find diverse applications across various industries due to their exceptional properties. These applications and their corresponding properties are listed in **Table 2.** Some key applications of basalt fiber reinforced composites include:

Table 2. Applications of basalt fiber.

INDUSTRY	APPLICATIONS	KEY PROPERTIES
Construction Industry	• Tubes, bars, pipes, fittings • Internal heat & sound insulation • Chemical & wear-resistant coatings • Composite pipes for transportation	• High strength & stiffness • Fire resistance • Chemical resistance • Durability
Concrete Reinforcement	• Bridges,tunnels, railway sleepers	• Fire resistance • Tensile strength • Durability
Geotextiles	• Asphalt pavements • Drainage systems • Erosion control • Landfill liners • Pavement Reinforcement	• Water permeability • Filterability • Durability • Weather resistance
Building Materials	• Concrete reinforcement • Building composites (panels, flooring, roofing) • Ropes & fabrics	• High tensile strength • Corrosion resistance • Thermal insulation • Lightweight
Automotive Industry	• Car parts (bumpers, underbody components) * Thermal & sound insulation * Brake pads & mufflers * CNG cylinders * Headliners & interior parts	• High strength & low weight • Impact resistance • Thermal stability • Attractive aesthetics

Building and Construction Sector

Basalt fibers are utilized in the production of tubes, bars, pipes, and fittings, as well as for internal heat and sound insulation in floors, walls, frame walls, boiler shells, tanks, chimneys, and fire-resistant structures.Basalt products are utilized for chemical and wear-resistant protective coatings for tanks, pipelines (especially oil pipelines), high-pressure vessels, wastewater filters, and corrosion-resistant tanks and pipes. Basalt composite pipes are used for the transportation of petroleum, petroleum products, gases, corrosive liquids, bulk materials, and both hot and cold water supply.

Concrete Reinforcement

Basalt fibers are extensively used in the construction field for concrete reinforcement due to their excellent fire resistance. They find applications in civil structures like bridges, tunnels, and railway sleepers.

Geotextiles

Basalt fiber geotextiles have several applications due to their excellent water permeability, filterability, durability, and weather resistance[33]. Some key applications of basalt fiber geotextiles include,Basalt fibers are used in geosynthetics to achieve prolonged asphalt pavements, improving the road's performance and durability[34].Basalt fiber geotextiles are employed in drainage systems to enhance water permeability and filterability, preventing soil erosion and improving water management[35].Basalt fiber geotextiles are used in erosion control applications, such as protecting slopes and embankments from soil erosion and landslides[36]. Basalt fiber geotextiles serve as landfill liners, preventing leachate and contaminants from spreading, thereby protecting the environment [37]. Additionally, they are employed in pavement reinforcement to enhance the strength and longevity of roads and other paved structures [38].

Construction Materials

Basalt fiber is widely used in building materials due to its outstanding properties, including high tensile strength, corrosion resistance, and excellent thermal insulation [39]. Some notable applications of basalt fiber in construction include When used as reinforcement in concrete, basalt fiber enhances strength and reduces the likelihood of cracking [39].By combining basalt fiber with resin, durable composites can be created for various building products such as insulation panels, flooring, and roofing [40]. Basalt fiber can be woven into fabric or rope, which serves as additional structural support or a flexible, fire-resistant material in construction [41].Since basalt rock is naturally abundant and the fiber production process is energy-efficient, it is considered an environmentally friendly option [42].Unlike certain reinforcement materials, basalt fiber is resistant to corrosion, leading to increased longevity and lower maintenance costs [43].Being lighter than materials like steel, basalt fiber provides a more suitable alternative for specific applications [44].

Automotive Industry

Basalt fiber has gained significant attention in the automotive industry due to its exceptional properties and benefits.Basalt fiber-reinforced composite materials are used for various car parts such as bumpers, underbody components, hoods, fairings, spoilers, and electric drive car bodies. These materials offer high strength, low weight, impact resistance, stability in different environments, and good durability[45].Basalt fibers are utilized in the production of thermal and sound insulation materials for automotive applications. These materials provide excellent thermal resistance, soundproofing characteristics, and durability to vibrations and alternating loads[46].Basalt fibers are used as fillers in brake pads and mufflers due to their superior friction coefficient stability and great silencing properties. Notably, Toyota has successfully incorporated basalt fibers in their car mufflers for better performance[47].Basalt fiber is employed in the production of CNG cylinders for cars due to its mechanical properties, extended temperature range, resistance to chemically aggressive conditions, and eco-friendliness[48]. Due to their appealing dark-brown color, excellent mechanical properties, fire resistance, and cost-effectiveness, basalt fibers are utilized in car headliners and interior components.

The recyclability of basalt fibers makes them a sustainable choice for car manufacturers[49].Auto manufacturers utilize thermoplastic fiber composites reinforced with basalt fibers as alternatives to metal components. These materials offer outstanding mechanical properties, high-temperature resistance, and environmental advantages like recyclability [50].

Basalt fiber's versatility, durability, thermal stability, and eco-friendly nature make it a promising material for various automotive applications, offering a viable alternative to traditional materials like glass fibers or carbon fibers [51].

Basalt Fibre in Construction Materials

BF has been increasingly used in reinforced concrete, prefabricated structures, and geotextiles. In concrete reinforcement, BF improves tensile strength, flexural properties, and resistance to acid, chloride, and freeze-thaw conditions, making it a viable alternative to traditional steel reinforcement [52]. Prefabricated basalt-reinforced panels enhance the durability of construction materials, reducing maintenance costs and increasing the lifespan of structures. Geotextiles made from BF provide superior drainage, erosion resistance, and environmental protection. Compared to steel, BF is lighter, non-corrosive, and thermally stable, making it ideal for infrastructure projects [53].

PROPERTIES OF BFRCS

Basalt Fiber Reinforced Composites (BFRC) are a class of advanced materials that have gained significant attention in various industries due to their exceptional properties. This section offers a concise overview of BFRC while emphasizing its key properties. Basalt Fiber Reinforced Composites are a type of composite material that consists of basalt fibers embedded in a matrix material, typically polymer-based. Basalt fibers are produced from volcanic rock, making them a sustainable and eco-friendly alternative to traditional fiber materials like glass or carbon fibers[54]. The characteristics of BFRC can be customized for specific applications by modifying factors such as fiber content, fiber orientation, and the choice of matrix material. Some of the key properties of BFRC include:

Mechanical Properties (Tensile Strength, Modulus, Impact Resistance)

Basalt Fiber Reinforced Composites (BFRC) exhibit excellent mechanical properties, making them a valuable material for various applications. Here are the key mechanical properties of Basalt Fiber Reinforced Composites. Basalt fibers have a high tensile strength, ranging from 2600 to 4840 MPa. This property makes BFRC suitable for applications requiring materials with strong resistance to pulling forces[55].The elastic modulus of basalt fibers falls within the range of 80–115 GPa. A high modulus signifies the material's capability to withstand deformation when subjected to tensile stress, enhancing its overall structural strength and stability.[56]. Basalt Fiber Reinforced Composites demonstrate good impact resistance, enhancing their durability and ability to withstand sudden loads or shocks. This characteristic is vital for applications that demand high impact resistance, such as structural components and automotive parts [57]. Compared to conventional fibers like glass or carbon, basalt fibers exhibit enhanced mechanical properties [58]. Their exceptional tensile strength, high modulus of elasticity, and excellent impact resistance make them an ideal option for applications that require strong and long-lasting materials. The distinctive blend of these mechanical attributes makes Basalt Fiber Reinforced Composites a highly promising material for diverse industries, including aerospace, construction, and automotive [59]. A visual comparison of performance levels of basalt fibers is shown in **Figure 3.**

Thermal Properties (Heat Resistance, Insulation

Basalt Fiber Reinforced Composites (BFRC) exhibit remarkable thermal properties that make them suitable for various applications requiring heat resistance and insulation[60]. Here are the key thermal properties of Basalt Fiber Reinforced Composites:Basalt fibers with suitable fineness and density offer low thermal conductivity, making them excellent materials for thermal insulation applications. The superfine basalt fiber with a unit diameter of 1-3μm and a density of 140Kg/m3 has a thermal conductivity of 0.030W/(m·K) at -96℃.

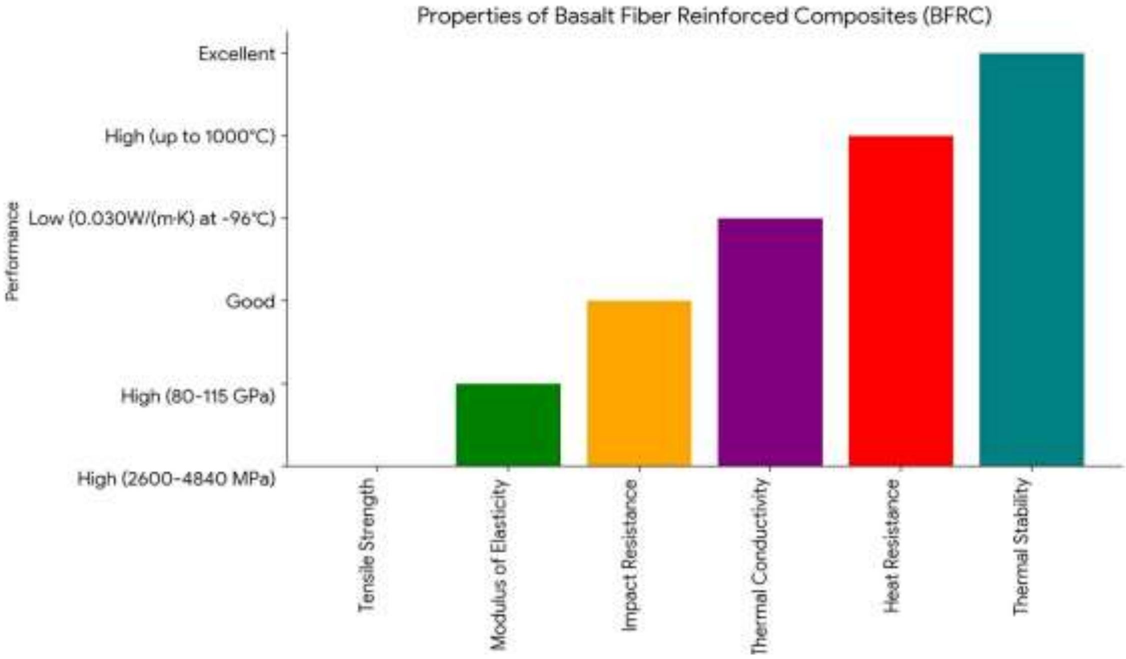

Figure 3. Properties of basalt fiber at various performance grade.

This exceptional insulation property allows basalt fibers to be used in sound absorption materials widely applied in industries like aviation, shipbuilding, and machinery[61].Basalt fibers exhibit high heat resistance, with a use temperature reaching up to 600-700 degrees centigrade. When combined with other materials, the temperature resistance can reach up to 1000 degrees C, making them suitable for applications requiring fire resistance such as fireproof firewalls, safety fire doors, and cable hanger lines in high-rise buildings and civilian structures[62].Basalt fibers are drawn from melted basalt rock at high temperatures (around 1500-1700 °C), resulting in excellent thermal stability. This property allows BFRC to maintain their structural integrity and performance under extreme temperature conditions[63].Basalt Fiber Reinforced Composites offer a unique combination of thermal properties, including exceptional heat resistance, insulation capabilities, and thermal stability[64].

Chemical Resistance

Basalt Fiber Reinforced Composites (BFRC) exhibit notable chemical resistance properties, making them suitable for various applications where exposure to different chemicals is a concern. [65]Here are the key aspects of Basalt Fiber Reinforced Composites in terms of chemical resistance Basalt fibers demonstrate high corrosion resistance, making them suitable for applications in corrosive environments. They exhibit resistance to alkalis, acids, and other chemicals, ensuring the durability and longevity of components made from BFRC[66].While basalt fibers are generally resistant to various chemical-exposure conditions, studies have shown that they may be relatively less resistant compared to carbon fibers under certain chemical environments. Despite this, basalt fibers still offer good chemical resistance properties that make them a viable choice for applications requiring protection against chemical degradation[67]. Basalt fibers are non-toxic, adding to their appeal in applications where environmental and health considerations are important. This property makes BFRC a safe and sustainable option for industries looking to minimize the impact of their materials on the environment[68].Basalt Fiber Reinforced Composites offer a balance of chemical resistance, durability, and non-toxicity, making them a valuable material for various industries. Their ability to withstand exposure to different chemicals, coupled with their corrosion resistance properties, positions BFRC as a reliable choice for applications requiring robust materials that can withstand challenging chemical environments [69].

PROCESSING AND MANUFACTURING OF BFRCS

Basalt Fiber Reinforced Composites (BFRC) are manufactured through a series of processing steps that involve the production of basalt fibers and the integration of these fibers into a matrix material to create composite structures[70-74]. Here is an introduction to the processing and manufacturing of The production of BFRC starts with the creation of basalt fibers, which are extracted from basalt rock. This rock is heated to extremely high temperatures, typically between 1400-1700°C, until it becomes molten. The molten material is then passed through fine nozzles to form continuous basalt fibers. To enhance their bonding with the matrix material in composite manufacturing, these fibers are treated with sizing agents.Next, an appropriate matrix material is selected based on the desired properties of the final composite, such as strength, stiffness, and resistance to environmental factors. Common matrix options include thermoset resins like epoxy and polyester, as well as thermoplastic resins such as polypropylene and polyamide.Once both the basalt fibers and the matrix material are ready, they are combined using various fabrication techniques to produce the BFRC components. Common manufacturing methods include hand lay-up, filament winding, pultrusion, and resin transfer molding. During fabrication, the basalt fibers are arranged in specific orientations to optimize the mechanical properties of the composite structure.After the composite structure is formed, it undergoes a curing process where the matrix material is hardened to bond with the basalt fibers[75][76]. This curing process can involve heat or chemical reactions depending on the type of resin used. After production, the BFRC component may undergo various finishing processes such as trimming, sanding, painting, or surface treatment to attain the required appearance and dimensionsThe processing and manufacturing of Basalt Fiber Reinforced Composites involve intricate steps from basalt fiber production to composite fabrication and post-processing. By carefully selecting materials, optimizing fiber-matrix adhesion, and utilizing appropriate fabrication techniques, manufacturers can create high-performance BFRC components for a wide range of applications in industries such as automotive, aerospace, construction, and marine engineering[77][78]. An eco-efficiency comparison of basalt- and steel-fiber-reinforced concrete is presented in **Figure 4**.

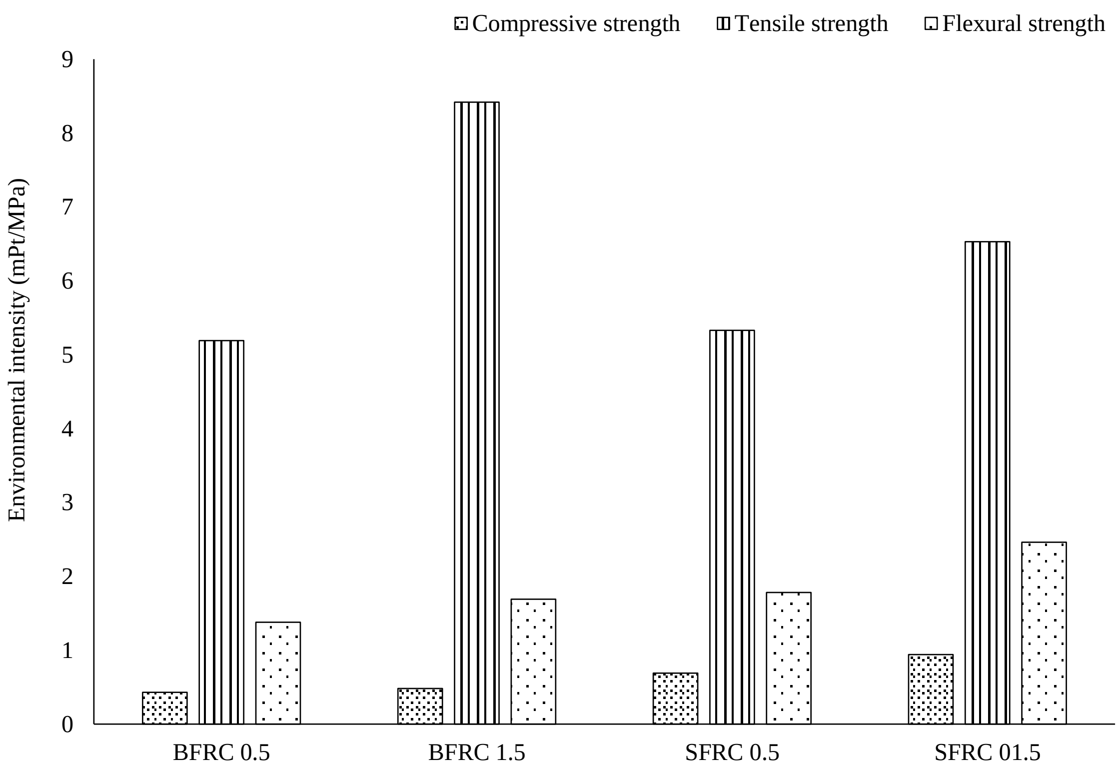

Figure 4. Shows the Eco-efficiency comparison of concrete reinforced by basalt and steel fibers.

Compatibility with Different Matrix Materials

Basalt fibers exhibit good compatibility with a variety of matrix materials, making Basalt Fiber Reinforced Composites (BFRC) a versatile and effective material for various applications. Here are some insights into the compatibility of basalt fibers with different matrix materials Basalt fibers are known for their excellent thermal stability,[79] which allows them to be compatible with various matrix materials, including thermoset resins like epoxy and polyester. The high heat resistance of basalt fibers ensures that they can withstand the curing temperatures required for these matrix materials, leading to strong adhesion and compatibility[80].Basalt fibers possess good chemical resistance, making them compatible with different types of cement and other matrix materials used in construction applications. This compatibility ensures that BFRC components maintain their structural integrity and performance even in corrosive environments[81].Basalt fibers' high tensile strength and modulus make them compatible with matrix materials that require reinforcement for enhanced mechanical properties. Whether used with thermoplastic or thermoset matrices, basalt fibers contribute to improved strength, stiffness, and impact resistance in the resulting composites[82].Basalt fibers are non-toxic and environmentally friendly, enhancing their compatibility with a wide range of matrix materials without posing health or safety concerns. This non-toxic nature makes basalt fibers a preferred choice for composite manufacturing across different industries[83].The compatibility of basalt fibers with various matrix materials is a key factor in the successful production of high-performance BFRC components. Their resistance to harsh chemical environments is visualized in **Figure 5**. Their thermal stability, chemical resistance, mechanical properties, and non-toxic nature contribute to their versatility and effectiveness in different applications, ranging from construction to automotive and beyond [84].

Different Processing Techniques

Basalt fiber, derived from volcanic rocks, offers excellent mechanical properties and environmental benefits. Various processing techniques enhance its performance in composites:Basalt fibers are produced by melting raw material at high temperatures, typically around 1450°C[85].The fibers are composed of minerals like plagioclase, magnetite, and pyroxene, providing them with unique properties[86].

Figure 5. Chemical resistance of the basalt fiber in construction applications.

Basalt fibers are known for their outstanding thermal stability, strong resistance to moisture and chemicals, excellent insulating properties, and ease of manufacturing.Surface modification techniques like silane coupling agents improve adhesion to polymer matrices, enhancing mechanical characteristics [87]. Understanding the interface properties of basalt fibers is crucial for optimizing their performance in composites. Surface treatments like zirconia coatings and sizing agents contribute to better adhesion and durability of basalt fibers in composite materials [88].

Basalt fiber composites can be a sustainable alternative to glass fiber composites due to their higher service temperature and chemical resistance..Processing studies have shown that optimizing material preparation and using compatibilizers can significantly enhance the mechanical properties of basalt fiber composites with different matrices like polypropylene and polycarbonate [89]. These processing techniques highlight the versatility and potential of basalt fibers in various industries, offering a sustainable and high-performance alternative for composite materials. The various processing techniques used for basalt fiber are illustrated in **Figure 6**.

COMPARISON WITH OTHER REINFORCING FIBRES

Basalt fiber stands out in comparison to other reinforcing fibers due to its unique properties and advantages: Basalt fiber exhibits higher mechanical properties compared to other fibers like steel, with better strength characteristics and resistance to alkaline, acidic, and salt attack [90]. It has a tensile strength ranging from 400-695 ksi (2800-4800 MPa) and an elastic modulus of 12,500-13,000 ksi (86-90 GPa), making it a robust reinforcement material.Basalt fiber is eco-friendly, stable, and non-reactive, making it an ideal reinforcement material for various applications [91]. Its production process involves using basalt rock as the sole raw material, which contributes to its sustainability and environmental friendliness.Basalt fiber competes with E-glass fibers in the marketplace, offering similar mechanical properties but with additional advantages like a wider application temperature range (-452°F to 1,200°F), higher oxidation resistance, compression strength, and shear strength.Despite its high production cost compared to E-glass fibers, basalt fibers are positioned competitively in terms of pricing and are expected to become more cost-effective as production scales up.Basalt fiber composites are gaining attention for their high potential in structural composites and FRPs due to their superior properties compared to glass, aramid, and carbon fibers [92].

A comparative summary of the mechanical properties of basalt fiber and other reinforcement fibers is given in Table 3. While basalt fibers are yet to be fully recognized by international code authorities for civil infrastructure applications, ongoing research is expected to further establish their structural behavior and design guidelines[93].In summary, basalt fiber emerges as a promising reinforcement material with superior mechanical properties, environmental benefits, and a competitive position in the market compared to other reinforcing fibers like steel and E-glass.

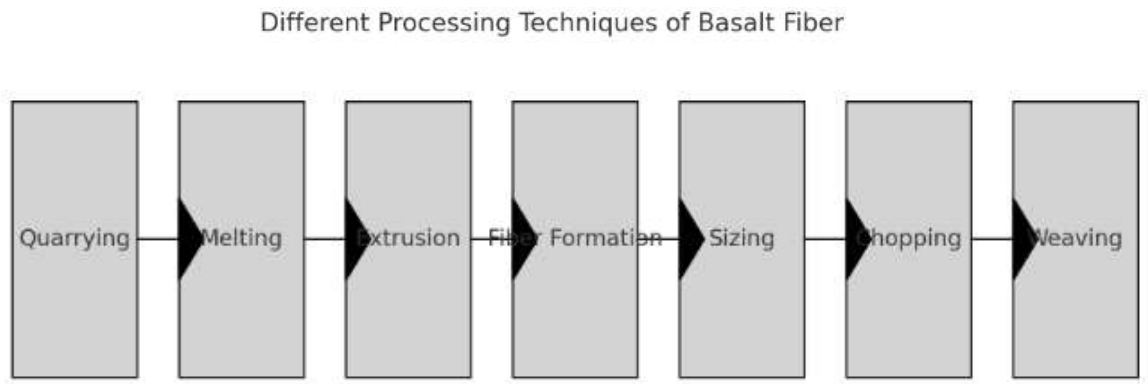

Figure 6. Different processing techniques of basalt fiber.

Table 3. The comparison of property between basalt fiber with other fibers.

Property	Basalt fiber	E-glass fiber	Carbon fiber	Steel
Tensile Strength (MPa)	2800-4800	1500-3500	3500-7000	Varies
Elastic Modulus (GPa)	86-90	70-76	230-430	200-210

Comparison of Basalt Fibre with Glass and Carbon Fibres

Basalt fiber exhibits unique advantages when compared to glass and carbon fibers. Mechanically, basalt fiber has a higher tensile strength than glass fiber but lower than carbon fiber. Its elastic modulus is greater than that of E-glass fiber but lower than carbon fiber, making it a competitive option for structural reinforcement. Thermally, basalt fibers have excellent heat resistance, outperforming glass fibers in extreme conditions. Environmentally, basalt fibers are more sustainable since they are derived from natural volcanic rock and require less energy for production compared to carbon fibers [94]. However, basalt fibers still face competition due to their relatively high cost and limited awareness in industrial applications.

CONCLUSION

Basalt fiber presents a viable substitute for conventional materials like glass and carbon fibers. It boasts multiple benefits, including a superior strength-to-weight ratio, remarkable thermal stability, and strong resistance to chemicals and UV radiation. Additionally, basalt fiber is considered more eco-friendly than other fiber options since it originates from natural sources and has a reduced carbon footprint. However, its adoption is hindered by cost constraints and recycling challenges. Addressing these issues through improved production efficiency and sustainable recycling methods can enhance the commercial viability of basalt fiber. In summary, its distinctive characteristics position basalt fiber as a game-changer in the composites industry, making it a highly desirable choice for applications across aerospace, automotive, construction, and renewable energy sectors.

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