Basalt Fiber Composites in Military and Defense Applications

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Basalt fiber is an emerging inorganic reinforcement derived from volcanic rock. It offers a unique combination of high strength, thermal stability, and chemical resistance, making it attractive for military and defense applications. This chapter provides a comprehensive overview of basalt fiber-reinforced composites in defense and military fields, including their material properties, manufacturing methods, current and potential applications, recent innovations, environmental impacts, challenges, and future outlook by highlighting that basalt fiber composites can provide weight savings, cost advantages, and environmental benefits over traditional materials including reduced corrosion and lower embodied energy compared to steel or glass fiber. Their uses in ballistic protection (personal armor and vehicular armor), aerospace components (radomes, rocket motor insulation), naval structures (non-corrosive marine composites), and defense electronics (electromagnetically-transparent housings) are summarized. The chapter also addresses current limitations, such as limited production scale, variability in fiber quality, and the need for more design data, which have constrained widespread defense adoption. Innovations, including hybridization with aramid, carbon fibers, natural fibers, and nano-engineering, are discussed in terms of the performance of composites for defense applications. Finally, the challenges and future potentials for using basalt fiber as a reinforcing agent for composites in emerging military applications are indicated.

**1. Introduction**

Advancements in fiber-reinforced composite materials have continually influenced the design of military and defense systems by enabling lightweight, durable, and high-performance components. Basalt fiber is a relatively recent addition to the family of structural fibers (alongside glass, aramid, carbon, etc.), derived from the rapid cooling of molten basalt lava into fine filaments [1]. First developed in the 1920s and refined during Cold War military research, continuous basalt fibers were initially classified for defense due to their excellent thermal and mechanical properties [2,3]. After declassification in the 1990s, basalt fibers have become increasingly accessible for civilian and defense applications [4]. Basalt fiber-reinforced polymer composites (BFRCs) are now recognized for offering a balance of performance and cost that fills the gap between traditional E-glass and high-end carbon or aramid fibers [1,5].

Basalt fibers are produced by melting quarried basalt rock and extruding filaments, without the chemical additives required in glass fiber production [6,7]. This “single feed” process yields a fiber with a complex mineralogical composition (rich in silica, alumina, and iron oxides) that imparts advantageous properties such as high strength, high elastic modulus, and especially superior temperature and chemical resistance [6,8]. Basalt fibers are also inherently non-flammable and exhibit low electrical conductivity, desirable attributes for defense applications requiring fire resistance and electromagnetic transparency [9,10].

Despite their promise, basalt fiber composites have seen limited adoption in defense sectors, especially compared to well-established materials like aramid (Kevlar®) in armor or carbon fiber in aerospace. Key reasons have been the relatively nascent manufacturing base, inconsistent fiber properties from different sources, and sparse design data for engineers to rely on [5,11]. Basalt fibers currently cost more than E-glass (though still much less than aramid or carbon) and have not been produced at the same scale, though global production is rapidly growing [12]. However, growing interest and research output, especially over the last decade, have significantly improved the understanding of basalt composites. There is now a critical mass of studies demonstrating basalt fiber’s applicability in ballistic armor [13,14], explosive blast protection [15], aircraft and naval structures [16], and even electronics housings and radomes [10]. This chapter aims to compile and synthesize this body of knowledge.

The following sections outline the fundamental properties of basalt fibers and their composites (Section 2), including how their chemical makeup differs from other fibers and the implications for mechanical and thermal behavior. Section 3 describes manufacturing techniques for continuous basalt fibers and composite fabrication methods suitable for defense components. In Section 4, major defense-related application areas are discussed in depth: ballistic protection, where basalt composites have been tested as alternatives or supplements to aramid and polyethylene armor [13,17]; aerospace, including missile and aircraft components such as heat shields and radomes [10]; naval structures, leveraging basalt’s non-corrosive nature for marine use [16]; and military electronics, where basalt’s dielectric and thermal properties can be advantageous. Section 5 highlights recent innovations, including hybrid composites such as basalt with carbon or aramid layers, that synergize properties [18,19], nano-engineered BFRCs for multi-functionality [20] that aim to overcome current limitations. Environmental considerations (Section 6) are crucial for military adoption in an era emphasizing sustainability; basalt fibers offer potentially “greener” credentials versus glass or carbon, both in production and end-of-life disposal [3,12]. The challenges and limitations (Section 7) impeding basalt fiber’s broader use in defense, ranging from fiber cost and variability to certification hurdles, are addressed. Finally, Section 8 and the Conclusion provide an outlook on future developments, including expected improvements in fiber quality, cost reduction with scaling, and niche defense applications where basalt fiber composites could be applied in the next decade.

This chapter demonstrates that basalt fiber composites have matured into viable materials for many military and defense applications, validated by numerous studies. While not a wholesale replacement for carbon or aramid, basalt fibers carve a valuable niche where a combination of strength, high-temperature endurance, environmental resistance, and affordability is required [7,21]. With continued research and development addressing current gaps, basalt composites will likely see increasingly widespread deployment in defense systems, contributing to lighter, safer, and more sustainable military platforms. The starting point is a detailed look at basalt fiber’s properties and how they compare to conventional reinforcement fibers.

**2. Properties of Basalt Fibers and Composites**

**2.1 Physical and Chemical Composition**

Basalt is an igneous rock rich in silica and metal oxides. Continuous basalt fibers inherit a complex chemical composition from their parent rock, typically containing ~45–55% SiO₂, 14–18% Al₂O₃, 7–12% Fe₂O₃, 8–11% CaO, and smaller fractions of MgO, Na₂O/K₂O, TiO₂, and other contaminants. Unlike E-glass (which contains significant B₂O₃ and very little iron), basalt naturally has no boron oxide and a higher iron content [8]. Both are silica-based (~50% SiO₂), but basalt’s elevated Fe₂O₃ (~10%) acts as a nucleating agent that improves thermal stability, and basalt lacks the ~10% B₂O₃ found in E-glass [8,22]. Iron and other metal oxides give basalt fiber its brown tint instead of the white of glass fiber and contribute to its high melting point and fire resistance [21].



Figure 1. Photographs of sized (A) 3 mm and (B) 12 mm; and desized (C) 3 mm, (D) 12 mm short basalt fiber samples.

Properly produced basalt fibers have smooth surfaces and circular cross-sections similar to glass fiber. The fibers can be produced as continuous rovings or chopped strands [23]. Figure 1 shows the sized and desized short basalt fiber with various lengths.

Basalt’s chemical durability is generally excellent: fibers resist water absorption (no internal voids) and are immune to UV radiation degradation, which differs from organic fibers because they can photodegrade [21]. These behaviors are discussed further in Section 2.4 on durability. Overall, the chemical makeup gives basalt fiber a unique profile: more thermally stable and chemically robust than E-glass, though slightly denser, and without the health concerns associated with boron or fluorine additives [3].

In summary, basalt fiber’s composition and structure yield a material that is physically similar to glass fiber but with distinctive advantages that are valuable for defense: high thermal endurance, non-flammability, and good chemical durability. These traits originate from basalt’s mineral content, particularly the absence of low-melting fluxes similar to boron and the presence of iron and magnesium oxides. Next, the mechanical properties that basalt fibers and their composites can achieve, and how this compare with other fibers commonly used in military applications, are reported.

**2.2 Mechanical Properties**

Under tensile loads, basalt fibers behave as a linear elastic, brittle material up to failure, much like other inorganic fibers [6]. The tensile strength of commercially available continuous basalt fibers typically ranges from about 2.8 to 4.8 GPa, which is comparable to or slightly higher than E-glass fiber (≈2.5–3.8 GPa) and approaches the lower end of S-glass fiber (4.5–4.9 GPa) [7,8]. Basalt fiber’s elastic modulus lies around 79–93 GPa, again higher than E-glass (~72 GPa) and approaching S-glass (~88–91 GPa) [7]. Its elongation at break is typically ~3.1% [8]. These values position basalt fiber as a higher-performance alternative to general-purpose glass fiber. Figure 2 compares the tensile strength of basalt fibers with E-glass, S-glass, aramid (Kevlar®), and a standard carbon fiber, showing basalt in an intermediate position as stronger than E-glass and aramid, though not reaching the peak strengths of S-glass or high-grade carbon [7,27].

Several studies attribute basalt fiber’s strength variability to chemical composition and production quality differences. In a study, it was found that higher Al₂O₃ content in basalt (increasing from 10% to 24%) raised fiber tensile strength from nearly 1.7 GPa to 2.5 GPa, which indicates that not all “basalt fibers” are equal, and careful selection of basalt source and melt chemistry is critical. Manufacturing defects like microscopic flaws on fiber surfaces also affect strength significantly, but have minimal effect on stiffness [6]. Another research compared basalt from different sources and noted tensile strength improvements with optimized chemistry and sizing treatments [8]. Applying appropriate silane sizings to basalt fibers can improve their strength by mitigating surface flaws and enhancing fiber-matrix bonding. Indeed, sized basalt fibers achieved notable improvements in composite strength and adhesion, comparable to the effect of sizing on glass or carbon fibers [28].

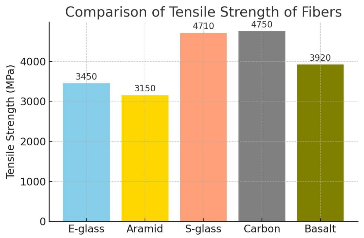


Figure 2. Tensile strength of common reinforcement fibers.

For defense applications, fiber tensile properties translate to composite performance in tension, flexure, etc. Basalt fiber-reinforced polymers generally show better mechanical performance than E-glass FRPs of similar construction. For example, one study reported that a basalt/epoxy laminate had about 20% higher flexural strength than a comparable E-glass/epoxy laminate, and higher interlaminar shear strength [7]. Basalt/epoxy composites retained more flexural strength after aging than glass/epoxy, indicating greater long-term stability according to the related publication [11]. Basalt fiber composites often exhibit slightly higher fracture toughness and impact resistance compared to glass fiber composites [18,29]. This has been attributed to basalt’s higher strain to failure, which is found to be 3.1% against 2.5% for E-glass, and possibly better fiber/matrix interface adhesion in some cases [30]. In one set of ballistic impact tests, pure basalt-fiber composite panels absorbed more energy than comparable glass-fiber panels, highlighting basalt’s efficient energy absorption via fiber fracture and delamination [14]. These ballistic results are discussed further in Section 4.1.

The comparative stacked bar chart displayed in Figure 3 implies that BF has higher tensile strength and elastic modulus in addition to a high density level with respect to other commercial fibers [31].

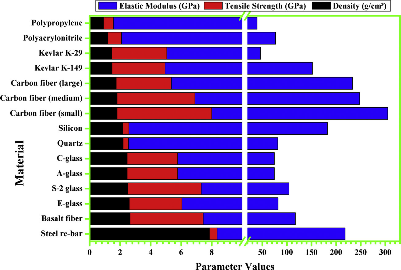


Figure 3.Comparison of the mechanical behavior and density of basalt fiber withdifferent known materials. Adapted with permission from reference 31. Copyright 2015 Elsevier.

Compared to aramid fibers (Kevlar®), basalt’s tensile strength is in the same range in Kevlar 29 and 49, which have tensile strengths in the range between 2.9 and 3.6 GPa [27]. However, aramid has a much lower modulus, ranging from 70 to 120 GPa depending on grade, with respect to basalt (85 GPa). This means basalt composites are generally stiffer than aramid composites, albeit slightly heavier. Kevlar excels in extreme toughness and strain-to-failure, 3.5% or higher, giving it superior ballistic absorption in flexible armor [13]. Basalt cannot replicate the high toughness of woven aramid in soft armor. Still, in rigid armor plates, basalt fiber layers can provide structural stiffness and multi-hit durability alongside aramid [17]. Basalt’s higher compressive strength and stiffness can help distribute impact loads, while aramid layers provide ductility, so hybrid basalt/aramid armors have improved overall performance [18]. Basalt is sometimes seen as a compromise between glass and aramid, which is stronger and stiffer than glass but less expensive than aramid [1]. The hybridization effect of BF with aramid fiber has been well studied, in which the synergy between the two fibers donates improved thermal and mechanical resistance of epoxy-based composites [32-36].

Basalt also has the advantage of electrical insulation. In contrast, carbon fibers are electrically conductive and can cause galvanic corrosion issues when bonded to metals, a crucial consideration in naval and aerospace contexts [16]. Basalt’s higher failure strain means basalt composites tend to be more damage-tolerant than carbon composites. Accordingly, they can undergo more deformation before catastrophic failure, which is beneficial for absorbing impact or shock [19]. Several military research programs have examined hybrid basalt–carbon laminates to combine basalt’s ductility with carbon’s stiffness. For instance, adding basalt fiber layers to a carbon/epoxy laminate significantly increased impact damage resistance in a recent study [37]. Thus, while carbon fiber remains unmatched for high-stiffness/low-weight requirements, such as aircraft wing spars, basalt fibers can play a complementary role where a mix of strength, toughness, and electrical insulation is required.

As a summary, basalt fibers provide mechanical properties sufficient for many defense applications and a decent strain to failure of 3%. Basalt composites often outperform E-glass composites in strength and toughness and are competitive with more expensive fibers in specific metrics [11]. Table 1 summarizes the mechanical properties of fibers relevant to defense applications, illustrating basalt’s intermediate position among them.

Table 1. Typical properties of reinforcement fibers (single filaments) used in composites

| **Fiber Type** | **Density (g/cm³)** | **Tensile Strength (GPa)** | **Elastic Modulus (GPa)** | **Elongation (%)** | **Notable Attributes** |
| --- | --- | --- | --- | --- | --- |
| **E-Glass (E)** | 2.55 | 3.1–3.8 | 72–76 | ~4.8 | General-purpose glass fiber (cheap) |
| **S-Glass (S)** | 2.49 | 4.5–4.8 | 88–91 | ~5.5 | High-strength glass fiber |
| **Basalt** | 2.70 | 3.0–4.8 | 79–93 | ~3.1 | Natural volcanic fiber (no additives) |
| **Aramid (Kevlar)** | 1.44 | 2.9–3.6 | 70–120 | 2.8–3.6 | Organic fiber, very tough, low density |
| **Carbon (std mod)** | 1.75 | ~4.0 | ~230 | ~1.8 | PAN-based carbon (high stiffness) |
| **Carbon (high str)** | 1.80 | ~5.5–6.0 | ~300 | ~2.0 | PAN-based carbon (ultra-high strength) |

Basalt fiber’s tensile strength (3.0–4.8 GPa) is clearly higher than E-glass and overlaps with the lower range of S-glass, while its modulus is moderately higher than E-glass. Basalt’s elongation (3%) is lower than E-glass (~4.8%) but higher than carbon’s (1.5–2%). These figures support why basalt fiber is considered a performance upgrade from E-glass in structural composites [7]. The following section on thermal properties will further distinguish basalt fiber from other fibers, as its mechanical performance at elevated temperatures is a key advantage.

**2.3 Thermal and Fire Resistance**

One of the most significant advantages of basalt fiber for military applications is its excellent performance under high temperatures and fire. Basalt has a useful working temperature far above organic fibers and even above most glass fibers. Typical basalt fibers can retain integrity up to about 700°C, with a softening point around 960°C [38]. In contrast, E-glass begins to soften and lose strength around 600°C, and aramid fibers start to decompose at nearly 500°C, charring and losing strength at much lower temperatures [9,13]. Carbon fibers can endure very high temperatures in inert conditions, but in composites, the polymer matrix chars long before fiber failure [39].

Basalt fibers are non-combustible stemming from their mineral nature. In a research study, basalt/epoxy samples retained a greater proportion of their original strength after being heated to 650–750°C, whereas glass/epoxy degraded more severely [39]. Enhanced flame retardancy and thermal stability performances were achieved by the integration of short BF into various polymers, including PE [40], PP [41,42], ABS [43], PLA [44,45], and PBT [46].

Additionally, basalt fiber has relatively high thermal conductivity for an insulator, as 0.03–0.04 W/mK, similar to wool, higher along fibers, which helps composites dissipate heat and avoid hotspots [47]. This property can benefit applications like rocket motor insulation or thermal protection systems, where basalt fiber-reinforced composites can spread and withstand intense heat loads. For example, basalt fabric/phenolic ablators have been used to protect the motor wall in solid rocket motor casings and liners. Combustion temperatures in motors exceed 2760°C and pressures higher than 10 MPa, but basalt fiber-based ablatives gradually erode rather than catastrophically burn, providing reliable insulation throughout the motor burn [48]. Basalt fibers have been proposed as replacements for asbestos or aramid fibers in rocket insulation due to their ability to withstand such extreme conditions. These materials showed stability at higher than 2000°C flame temperatures and charred predictably without structural failure [38].

Under sustained moderate heat, basalt fibers outperform glass in retaining strength. It was found that heating basalt fibers to 300°C caused less degradation in tensile strength compared to E-glass fibers under the same treatment. Basalt fibers kept 90% of their room-temperature strength after brief exposure to 300°C, whereas E-glass dropped more due to structural relaxation and annealing effects [38]. At 500–600°C, basalt begins to weaken significantly, with roughly 50% strength retention at 700°C [2], yet many polymeric fibers like aramid or polyethylene would be destroyed entirely well below those temperatures. This property is crucial for applications like fire-resistant composites in naval ships or armored vehicles, where basalt-reinforced panels can maintain integrity during a fire event. For instance, basalt/phenolic laminates used in ship bulkheads have satisfied stringent fire safety standards, remaining intact and insulating against fire longer than comparable glass fiber laminates [15]. Basalt composites can thus provide valuable minutes of fire resistance, helping to contain onboard fires and limit structural damage until suppression systems engage.

Basalt’s high melting point (1350°C) can also be used where molten metal or extreme heat exposure occurs [47]. In ballistic contexts, this translates to basalt fiber composites that better stand out from incendiary or tracer rounds. Thermoplastic armor laminates with basalt fiber facings have shown improved resistance to behind-armor burn-through when hit by incendiary rounds, as the basalt layer does not ignite and helps contain sparks. Similarly, in heat shields, basalt fibers maintain their mechanical contribution at temperatures that would melt polymer fibers.

Beyond fire, basalt fibers tolerate cryogenic conditions and large thermal swings with minimal thermal expansion mismatch in polymer matrices [21]. This can benefit aerospace components exposed to high heat and extreme cold conditions, including re-entry vehicle surfaces or fuel tank structures. Basalt composites have been investigated for cryogenic fuel tanks, showing good dimensional stability from –150°C up to high temperatures [5].

In summary, basalt fibers grant composites exceptional thermal stability and fire resistance, a key differentiator from most organic and even standard glass fibers. Accordingly, structures can be made more fireproof and heat-tolerant for defense applications, such as engine nacelles, blast barriers, or electronic enclosures that survive fires or heat blasts longer. These advantages are particularly relevant to aerospace and naval applications discussed in Sections 4.2 and 4.3. The following section examines how basalt composites hold up against other environmental factors like moisture, chemicals, and weathering, another critical aspect of field deployment.

**2.4 Environmental Durability**

Military equipment must function reliably in harsh environments, including marine exposure, tropical humidity, abrasive sand, and chemical exposure. Basalt fiber composites generally exhibit good durability under such conditions, often superior to glass fiber composites.

Moisture and Weathering: Basalt fibers also resist ultraviolet radiation and oxidation since there are no organic bonds to break, as in polymers. Thus, under sunlight and weather, basalt composites primarily see degradation in the resin only, not the fibers. In a natural weathering test, basalt/phenolic laminates retained more tensile strength than glass/phenolic after 12 months in outdoor conditions, owing to basalt’s inertness.

Chemical Resistance: As noted earlier, basalt fibers resist acidic environments. For instance, it was found that basalt/epoxy rebar rods exhibited similar or slightly better mechanical retention than glass/epoxy rods after long-term seawater and alkaline exposure. Over 7.5 years of natural seawater immersion, basalt/epoxy composites lost only about 20% flexural strength at 40°C, demonstrating suitability for marine use [16]. Saltwater has minimal chemical effects on basalt fibers, exhibiting no corrosion, as with steel.

Radiation: Resistance to high-energy radiation of BF is beneficial for space or nuclear defense systems, including missile silo liners or satellite structures where radiation resistance is needed.

Friction and Wear: Basalt fibers’ hardness (Mohs ~5–6) can improve a composite’s wear resistance. In brake pads or clutches, basalt fiber additives have been shown to enhance high-temperature wear properties. A hybrid brake friction material with ceramic and basalt fiber was developed, with superior fade resistance and less wear at 300°C compared to traditional organic fiber materials [50]. This suggests uses in military vehicle brake systems or high-wear surfaces such as aircraft arresting gear components. Basalt fibers in concrete also reduce crack formation and improve abrasion resistance similar to steel fibers, but without corrosion [51].

In conclusion to Section 2, the distinctive properties of basalt fiber composites can be summarized: Mechanically, they are strong and stiff, outdoing E-glass and approaching higher-end fibers in some respects. Thermally, they far exceed organic fibers in fire resistance and retain strength to much higher temperatures than glass. Chemically and environmentally, they offer excellent resistance to moisture, UV, and many corrosives, making them highly durable. These characteristics form the basis for the various defense applications discussed next.

**3. Manufacturing of Basalt Fiber Composites**

To fully leverage basalt fibers in defense applications, it is essential to understand how they are produced and how composite components are fabricated. The quality and cost of basalt fiber products depend heavily on manufacturing processes. This section covers (3.1) the production of continuous basalt fibers from raw rock, and (3.2) methods to manufacture basalt fiber composite parts, including weaving, lay-up, and molding techniques, focusing on defense-oriented fabrication like armor panels and large structural parts.

**3.1 Basalt Fiber Production**

Manufacturing continuous BF is, in principle, more practical than glass fiber because it uses a single raw material, basalt rock, without requiring multi-component batch mixing [5]. However, it comes with its own challenges. Figure 4 illustrates commercial basalt fiber production steps, starting from crushed and melted basalt rock to handle fiber form. The typical process is as follows:

1. Melting: Crushed basalt rock is melted in an electric or gas-heated furnace at 1400–1500 °C.

2. Extrusion: The molten basalt is extruded through platinum–rhodium bushings to form continuous filaments.

3. Drawing: The filaments are attenuated to 9–20 μm diameters.

4. Sizing: Fibers are coated with a sizing agent (typically silane-based) to improve handling and adhesion.

5. Winding: Continuous filaments are collected as rovings or chopped into short fibers.

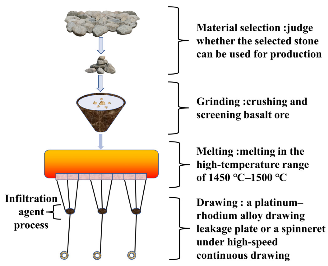


Figure 4.Production process of basalt fiber. Adapted with permission from reference 52. Copyright 2022 MDPI under CC-BY 4.0 license.

Quality control in basalt fiber making is crucial, in which chemical composition is monitored to ensure consistent fiber properties, and fibers are tested for diameter and strength. Modern plants use computer-controlled feeding and fiber-forming to maintain uniformity. Different basalt ores are sometimes blended to achieve the desired composition. Treating the basalt rock to remove certain minerals (similar to devitrification catalysts) can improve fiber quality. Some manufacturers also tailor the sizing chemistry to intended applications, such as a special sizing for vinyl ester matrix if the basalt fiber will reinforce polyester/vinyl ester composites in marine use. Continuous fiber for composites is usually required for defense-related areas, so the spinneret method is the focus.

In summary, producing basalt fiber involves melting natural rock and extruding filaments, which is a process conceptually simple yet requiring sophisticated control. The equipment is identical to that used for glass fiber, and indeed, many innovations in glass fiber manufacturing, such as advanced bushing design and improved sizings are transferable to basalt fiber production [5]. As production scales and becomes more widespread globally, costs are expected to decrease, making basalt fiber composites more economically attractive for defense applications [12]. With basalt rovings or fabrics in hand, the next step is to make composite parts covered below.

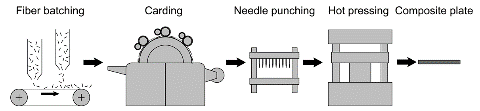


Figure 5.Illustration of a basalt fiber composite plate. Adapted with permission from reference 5. Copyright 2022 MDPI under CC-BY 4.0 license.

**3.2 Composite Fabrication Techniques**

Basalt fiber-reinforced composites can be fabricated using virtually all the methods applicable to glass or carbon fiber composites. The choice depends on the application, such as ballistic armor panels, which might be made by hand lay-up or compression molding, while missile casings might use filament winding. Figure 5 outlines a common technique to develop a composite plate, and special considerations for basalt fibers are listed below:

• Prepreg Lay-up and Autoclave Molding: Basalt fibers can be made into prepregs (pre-impregnated tapes or fabrics with resin) similarly to carbon fiber. Several suppliers offer basalt/epoxy prepreg for aerospace use [5]. These can be laid into molds and autoclaved to produce high-quality parts. One example is a UAV radome made via basalt fiber/epoxy prepreg, which benefited from basalt’s radar transparency and was cured in an autoclave for precision [10]. Basalt fibers easily withstand typical cure temperatures (120°C for epoxies) without issues. Vacuum bagging and oven curing is also used for simpler basalt composite parts or when autoclave access is limited.

• Hand Lay-up and Vacuum Bagging: Hand lay-up of basalt fabric layers and vacuum bag curing is common for large or low-volume parts like vehicle armor panels or ship decks. Basalt fabrics, including plain weave and twill, are cut and laid in a mold, and resin is applied as a wet lay-up or infused, then consolidated under vacuum and cured [53]. For instance, a prototype ballistic panel was made by laying up 60 layers of basalt and carbon fabrics with epoxy and vacuum-bagging [17]. After curing, basalt/epoxy laminates can be demolded and trimmed like other FRPs. This method is prevalent in small manufacturers or R&D labs for fabricating armor test panels and helicopter fairings.

• Compression Molding: This process is often used for flat armor plates or automotive parts. Chopped basalt fiber composites (sheet molding compound, SMC) have been developed as a sustainable alternative to glass fiber SMC [54]. For military vehicle panels, multiple layers of basalt fabric can be stacked with resin and pressed in a heated press to consolidate a thick laminate quickly. The resulting molded plates had low void content and uniform thickness, making them suitable for armor.

• Filament Winding: For cylindrical or dome-shaped structures, including rocket motor cases, pressure vessels, domes, continuous basalt rovings can be filament-wound. Basalt filament winding has been demonstrated for compressed natural gas (CNG) cylinders and small boat hulls [5]. In defense, one can envisage filament-wound missile casings or launch tubes using hybrid basalt/carbon fibers to add fire resistance. Because basalt fibers bond well with epoxies, filament winding yields dense, high-fiber-volume laminates. One must account for basalt’s slightly lower strain-to-failure than glass to avoid fiber breakage during winding of minimal radius curves, but generally the same winding tensions and patterns used for glass fiber translate to basalt [2]. After winding, the parts are typically cured in an oven. Basalt fiber winding has also been used to develop rocket motor insulation rings and re-entry heat shield components, where the fiber architecture needs to be circumferential.

• Pultrusion: Basalt fibers are very suitable for pultrusion, as they pull fibers through a resin bath and heated die to make continuous profiles like rods or beams. Basalt fiber rebars for concrete reinforcement constitute a significant product made by pultruding basalt rovings with a resin, mostly vinyl ester, and forming a sand-coated rod [55]. Since they are non-magnetic, these rebars have applications in fortifications, runways, and radar station foundations. The pultrusion process for basalt is identical to that for glass or carbon FRP rebars, and basalt’s hardness can yield a slightly rougher rod surface, improving bonding with concrete [55]. Other pultruded items include ladder rails, antenna mast sections, and tool handles for military use. Basalt fiber gives these products good dielectric strength and corrosion resistance [3].

• 3D Weaving and Braiding: Basalt fibers can be 3D-woven or braided into complex preforms for composites. In one project, a 3D braided basalt fiber cylinder was made as a potential linerless pressure vessel structure for a satellite, taking advantage of basalt’s microcrack resistance and low CTE [15]. The braided basalt preform was resin-infused to create a thick-walled composite. Braiding and 3D weaving equipment must be fitted with guides that can handle basalt’s abrasiveness; otherwise, basalt rovings braid well, similar to glass. This approach could produce net-shape preforms for components like helmet shells or stiffeners in vehicle hulls, reducing fabrication steps.

• Hybrid Composite Fabrication: When basalt fibers are combined with other fibers such as carbon, aramid, and glass, in a single component, manufacturing usually involves either co-weaving or layered lay-up. For example, a hybrid carbon/basalt armor might be made by alternating layers of carbon fabric and basalt fabric during lay-up. Both fabrics can be co-cured in one step if the same resin is used. In a study, carbon and basalt plies with epoxy were successfully co-cured, yielding a well-bonded hybrid laminate [17]. Similarly, basalt and carbon rovings can be wound in filament winding in alternating bands to create a hybrid structure [37]. The only caution is to account for different thermal expansions during cure, since carbon has near-zero CTE and basalt has moderate. However, hybrids have cured without issue by managing the cure cycle to avoid residual stress in practice. Hybrid lay-ups are increasingly used to tailor composite behavior (as discussed in Section 5).

No fundamentally new equipment is needed to fabricate basalt composites; existing composite manufacturing technology suffices. Some minor considerations: basalt fiber’s abrasiveness can wear steel tooling slightly faster, such as cutting blades for fabrics may dull faster than when cutting carbon or aramid. Using carbide or diamond-coated tools for cutting cured basalt composites is recommended for production, as HSS tools may lose sharpness due to basalt’s hardness [22]. Basalt fibers also have a higher friction coefficient than glass, which can affect handling in processes similar to weaving or filament winding techniques. However, they may require a bit more tension to slide into place. However, most composite shops find the learning curve for basalt to be minimal if they are accustomed to fiberglass [1].

For bonding and joining, basalt composites behave like other FRPs. They can be drilled and bolted, though care is needed to prevent delamination as with glass or carbon composites. Adhesive bonding is often preferred for mounting hardware to basalt composite panels in armor applications; ceramic strike-faces are bonded onto basalt composite backings with structural adhesive [56].

As a summary, basalt fiber composites can be manufactured with standard techniques, meaning they can be introduced into existing military manufacturing pipelines without requiring new processes, which is a significant practical advantage. From a manufacturing standpoint, the key to more widespread adoption will be increased availability of consistent quality basalt fiber prepregs and textiles [5]. Efforts like the development of basalt fiber 3D fabrics and automation of basalt composite fabrication, such as robot-assisted lay-up, are underway, which could open up new design possibilities and reduce costs.

Having established how basalt composite components can be made, we now turn to specific applications in military and defense where these materials are making an impact or hold significant potential (Section 4).

**4. Applications in Defense Products**

This section explores how basalt fiber composites are applied or investigated in various defense sectors. The major categories are ballistic protection, including personal armor, vehicle armor, blast protection, aerospace systems such as aircraft and spacecraft components, missiles, naval structures like boats, ship parts, marine infrastructure, and military electronics and equipment, including radomes, antenna covers, and electronics enclosures. In each case, the relevant properties of basalt fibers, such as high energy absorption, non-magnetic behavior, or thermal stability, are highlighted along with examples from recent studies or field trials.

**4.1 Ballistic Protection**

Lightweight ballistic protection is a critical need for personal armor like helmets, vests, and vehicle and aircraft armor. Traditional armor materials include aramid fibers (Kevlar® and Twaron®) for soft armor and ceramic plates or high-performance fibers (carbon, UHMWPE) for hard armor. Basalt fiber composites have emerged as a promising component in armor systems, often as a supplement or replacement for glass/aramid layers [13,14].

Ballistic Fabrics and Soft Armor: Basalt fiber woven fabrics can be used in a role similar to aramid fabrics in multilayer soft armor, though basalt alone is not as effective in stopping projectiles as aramid due to its higher density and brittleness. However, basalt fabrics reduce trauma and improve multi-hit durability when used in hybrid designs. Natural fiber armors were reviewed, and it was noted that while most plant-based fibers have limitations for ballistic use, basalt, as a mineral, can handle ballistic shock better and offers environmental benefits. Some hybrid armors use basalt fabric plies behind aramid to act as a catcher layer that resists perforation of fragments after the aramid dissipates most energy. Basalt’s higher modulus can help reduce back-face deformation. In one comparative test, a vest design combining Kevlar and basalt fabric layers showed nearly 10% less back-face signature in clay, indicating reduced blunt trauma compared to an all-Kevlar vest of equal weight [13]. Basalt fabrics are also naturally flameproof, adding fire protection to body armor, which pure aramid armor lacks. Accordingly, aramid fibers will combust and char under flame, whereas basalt remains intact [9]. This can improve survivability when incendiary devices or flash fires accompany ballistic threats.

Hard Armor Plates: Basalt fiber-reinforced composites have been studied in rigid armor plates as the primary ballistic material or as backing layers for ceramics. One of the first major studies tested basalt/epoxy laminates as backing for alumina ceramic plates in body armor. They found basalt/epoxy backings performed comparably to conventional E-glass/epoxy backings in stopping 7.62×51 mm NATO rounds, offering better heat resistance [56]. More recent research showed that a pure basalt/epoxy laminate composed of nine layers cross-plied absorbed more kinetic energy from a 9 mm FMJ projectile than an equivalent glass/epoxy or even a hybrid carbon–glass/epoxy panel. Specifically, the basalt/epoxy panel had the highest ballistic limit and absorbed the most energy, whereas a sandwich involving carbon–glass–carbon absorbed approximately 63% less energy than the basalt hybrid [14]. This demonstrates basalt composites’ capacity for dissipating impact energy through extensive fiber fracture and delamination, a desirable trait in armor. In a ballistic test finding, a basalt fiber composite panel showed less penetration depth than a carbon fiber composite panel for the same projectile threat. Hybridization of BF with aramid fiber led to improved ballistic performance of thermoplastic-based amors [19].

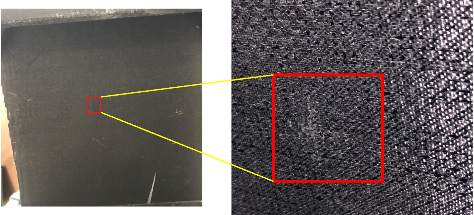


Figure 6.Photographs of the fracture surface of BF-reinforced epoxy-based armor plates after a ballistic impact test. Adapted with permission from reference 17. Copyright 2021 SAGE.

Hybridization with basalt has been shown to improve the multi-hit performance of armor. The hybrid epoxy armor plates with carbon and basalt fabric layers and a small addition of hexagonal boron nitride (h-BN) nanoparticles were fabricated as shown in Figure 6. The plate with basalt layers and h-BN had the lowest average penetration depth (4.3 mm indent) among those tested, versus 5.5 mm for the all-carbon plate, after a series of 9 mm bullet impacts [17]. The shape change of armors, such as swelling on the front and back surfaces after a ballistic impact test, can be seen in Figure 6. The basalt layers helped catch fragments, and the h-BN further enhanced energy dissipation by promoting fiber pull-out friction. All basalt-containing armors in their study successfully stopped 9 mm rounds at velocities reaching 370 m/s, meeting NIJ Level II criteria. This suggests that basalt fibers can work in synergy with other materials to create armor with improved performance, especially under repeated hits or combined threat scenarios, including impact and fire resistance.

Another potential use is vehicle armor. BF-reinforced composites can replace conventional E-glass/phenolic armor panels in vehicles or add an extra layer of protection with less weight penalty than all-steel solutions. Studies on ballistic panels for armored vehicles found that basalt fiber laminates perform similarly to E-glass laminates against fragment-simulating projectiles and small-caliber rounds [57]. They also have better environmental durability, vital for vehicle armor exposed to weathering and temperature extremes. A notable advantage for vehicles and aircraft is basalt’s non-conductivity; unlike carbon fiber armor, basalt armor does not create electromagnetic interference or stray currents. Thus, it can be mounted directly on metallic hulls without risk of galvanic corrosion or interference with onboard antennas [16]. In one fielded example, a naval patrol boat was retrofitted with interior spall liners made of basalt fiber composite to reduce secondary fragments upon impact. The basalt liners were lightweight, fireproof, and did not interfere with the vessel’s magnetic signature or electronics [15]. Figure 7 illustrates the fracture morphology of composite plates damaged by a sharp impactor at 50 J, indicating the failure process of the two composites containing unidirectional and woven BF. The sharp impactor may readily perforate the composites by compressing the fibers while avoiding rupturing the bundles. As a result, the fibers' high axial tensile strength benefit is not completely obtained, and the low velocity impact resistance of unidirectional basalt fiber composites to sharp impactors is inferior to that of the woven basalt fiber composites [58].

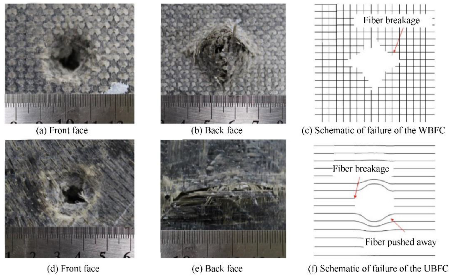


Figure 7.Photographs of damaged composites: (a) front face, (b) back face, and (c) schematic of failure of the woven basalt fiber composites; (d) front face, (e) back face, and (f) schematic of failure of unidirectional basalt fiber composites. Adapted with permission from reference 58. Copyright 2020 Elsevier.

Blast and Fragment Protection: Basalt composites have been tested for resisting blast-driven fragments and shrapnel. It was reported that basalt fiber laminates retained more post-blast integrity than glass fiber ones in a simulated explosion, due to basalt’s higher temperature stability and cohesive char formation. Similarly, basalt fiber blankets have been used experimentally to wrap around reinforced concrete columns to contain explosion damage, performing slightly better than glass fiber wraps in maintaining confinement after a blast [15]. For vehicle blast floors (to mitigate mine blast effects), basalt/phenolic panels show promise because they do not burn and can absorb impact by delamination, similar to phenolic fiberglass panels but with potentially higher post-blast strength [57].

Helmets: There have been prototypes of helmet shells using basalt fiber-reinforced composites as an environmentally friendly alternative to aramid or glass fiber composites. One such combat helmet prototype made of basalt fiber/phenolic composite was tested to NIJ Level IIIA. It achieved the required ballistic performance, such as stopping 9 mm threats and exhibiting excellent fire resistance [59]. The basalt helmet shell was slightly heavier than a comparable Kevlar helmet but offered better resistance to high temperatures. Accordingly, it would maintain protection in a fuel fire, whereas Kevlar loses integrity [60]. The production of basalt composite helmets is also simpler in terms of not requiring polyaramid fiber weaving or the health hazards of aramid dust [61]. While not yet in widespread service, basalt combat helmets could become feasible, especially as material costs come down. They would provide a combination of ballistic and fire protection beneficial for vehicle crews or riot troops. The basalt/epoxy laminate exhibited higher energy absorption and lower indentation by about 5 mm than the carbon/glass laminate, with nearly 15 mm for similar areal density, indicating basalt’s effectiveness in dissipating impact energy. Curved hybrid composites involving aramid fiber and basalt fiber were developed with several combinations of aramid and basalt fabric interlayers [62]. Integration BF positively affected the performance of curved composites, which can be used as helmets, as shown in Figure 8.

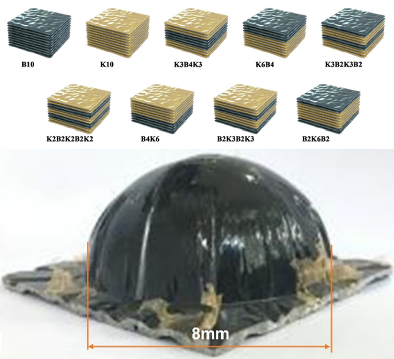


Figure 8.Photographs of the fracture surface of BF-reinforced epoxy-based armor plates after a ballistic impact test. Reproduced with permission from reference 62. Copyright 2024 Inst. Nat. Cercetare-Dezvoltare Text. Pielarie under CC-BY 4.0 license.

In summary, basalt fiber composites are proving effective as ballistic protection materials, especially in hybrid armor systems. In all roles, they may not fully replace high-performance fibers such as aramid or polyethylene. Still, they can augment them, improving properties like multi-hit durability, flame resistance, and long-term stability. Basalt’s performance is clearly superior to E-glass in ballistic contexts, making it a better choice for backing plates or spall liners inside armored vehicles to catch spalling metal fragments. Given the continual demand for lighter, more robust armor, ongoing research into basalt fiber weaves, specialized coatings such as nano-reinforcements, and hybrid composite architectures is expected. The attractive combination of decent ballistic performance, environmental robustness, and lower cost compared to aramid or ceramic fibers makes basalt fiber composites a strong candidate for next-generation armor materials in military use.

**4.2 Aerospace and Aviation**

Basalt fiber composites in aerospace applications leverage their high-temperature resilience, vibration damping, and dielectric properties. Both aircraft and spacecraft can potentially benefit from basalt composites in certain components:

Aircraft Structures: While carbon fiber composites dominate primary load-bearing airframe parts, basalt fiber composites have been considered for secondary structures or as replacements for glass fiber components in aircraft. One key area is engine nacelles and firewalls, where materials must withstand intense heat and fire in the event of an engine fire. Basalt fiber/phenolic panels provide excellent fire protection and could replace heavier metallic firewalls or less fireproof glass fiber laminates [15]. Because basalt composites maintain structural integrity longer in a fire, they could give aircraft greater safety margins. Basalt composites also have good acoustic damping, potentially valuable for engine nacelle linings to reduce noise [50]. Additionally, basalt’s resistance to jet fuel and hydraulic fluids due to its inertness makes it suitable for engine compartment structures. Another application of BFRC is the sound isolation material in aircraft structures [63,64].

Other aircraft uses are radomes and antenna covers. Radomes protect radar and communication antennas on aircraft and missiles, and ships are typically made from glass fiber composites or specialized quartz fiber composites for their radio transparency. Basalt fibers have dielectric properties similar to E-glass and have been successfully used in SATCOM radomes with excellent results. For example, a satellite communication radome was developed using a basalt fiber-reinforced composite, which was tested to meet industry standards. It was found to have better electromagnetic transparency with a lower dielectric constant than the equivalent glass fiber radome, which the researchers attributed to basalt’s mineral composition and possibly lower moisture absorption [10]. The basalt radome also withstood hail impact and marine salt spray without degradation. Given the push for higher-frequency communication in military aircraft, which requires radomes with minimal RF loss, basalt fiber composites offer a combination of mechanical strength and favorable dielectric properties needed for next-generation radomes and antenna domes [5].

Missile and Rocket Components: Basalt fiber composites find a natural application in rocket motor casings and insulation, as mentioned in Section 2.3. Many solid rocket motors for tactical missiles and launch vehicles use filament-wound composite cases to save weight over steel. While carbon/epoxy is common for high-performance motors, basalt/epoxy or basalt/phenolic cases are of interest for their lower cost and better behavior in fire. Accordingly, in the case of a rocket motor engulfed in an external fire or propellant deflagrating, a basalt case may hold together longer than a carbon one, which loses strength as the epoxy matrix burns [38]. Basalt fiber also does not conduct electricity, which is advantageous in munition casings to avoid issues with stray currents or lightning strikes. One study on a small rocket motor reported that a basalt fiber case had only 10% lower burst pressure than a carbon fiber case of the same design, but was about 30% cheaper to manufacture [5]. Hybrid carbon–basalt systems are also an option for achieving a balance of stiffness and toughness. Basalt fiber/phenolic composites make excellent ablative materials for rocket motor insulators and nozzles by replacing legacy materials like asbestos/phenolic resin systems [48]. For example, the insulation layer in a solid rocket booster was reformulated with basalt fabric and phenolic resin and showed improved resistance to cracking after multiple thermal cycles [38].

Basalt composites can serve in thermal protection systems (TPS) for re-entry vehicles or spacecraft. The Russian space program has studied basalt fiber tiles for spacecraft heat shields because they handle high heat fluxes well and are more impact resistant than brittle carbon-carbon TPS [4]. Basalt fiber felt is also a good high-temperature insulator. There was an experiment using basalt fabric as the outer layer of a deployable heat shield; the basalt layer ablated in a controlled fashion and protected the underlying structure during re-entry simulations [5]. Although carbon or ceramic TPS are still used for the most extreme re-entry conditions, basalt-based TPS might be used in smaller re-entry systems or as a backup safety layer due to their reliability and ease of manufacture. According to the research reported by Militký [38], a fracture was observed for BF caused by inhomogeneity in fiber volume after BF was exposed to thermal treatment at 250 oC for 1 hour, as shown in Figure 9.

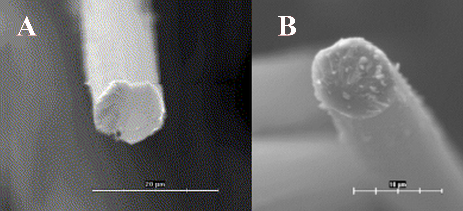


Figure 9.SEM images of the longitudinal portion of broken BF. (A) Untreated. (B) Heat treated. Adapted with permission from reference 38. Copyright 2002 Elsevier.

Unmanned Aerial Vehicles (UAVs): Many UAVs and drones use composite airframes for weight efficiency. Basalt fiber composites can be attractive for UAVs that need to operate in extreme environments or near high electromagnetic fields. For example, military drones might be exposed to electronic countermeasures, where a conductive carbon structure could inadvertently act as an antenna. Basalt’s radio transparency is beneficial if antennas are embedded in the wings or body. A case study involved a drone designed to sample volcanic gases; it used basalt fiber composite propeller blades specifically so they could withstand the hot, acidic plume during flights, where traditional carbon fiber blades degraded [5]. The basalt blades remained unaffected by the corrosive environment and maintained balance. Similarly, for high-altitude long-endurance (HALE) UAVs that face intense UV and ozone at altitude, basalt composites offer UV resilience that could extend airframe life compared to some polymeric materials.

BF is increasingly being considered for use in UAVs due to its advantageous properties, such as high strength, heat resistance, and corrosion resistance. These properties make BF suitable for various UAV components, including kerf, RC elements, insulation layers, and ropes, potentially enhancing performance and durability [65-67].

Helicopter Components: Helicopter rotor blades have historically used E-glass fiber due to its damage tolerance; basalt fiber could be a future alternative or supplement with potentially longer service life in marine environments like naval helicopter blades, since salt does not weaken basalt fibers as it can corrode glass fiber over time [16]. BF-reinforced composites also have inherent vibration damping since they are less stiff than carbon and more akin to glass in damping behavior, which can reduce blade vibration and noise. Some research prototypes of helicopter tail rotor blades made with basalt/epoxy showed slightly improved vibration characteristics and similar strength to standard glass/epoxy blades, suggesting feasibility [21]. In turbofan engines, basalt fiber-reinforced thermoset composites are being considered for static components like stator vanes or inlet guide vanes that require fire resistance in case of engine fire. They could replace metal or glass fiber components, save weight while meeting fire safety regulations [15].

Space Structures: In satellites, basalt fiber could replace some E-glass components (like printed circuit board substrates or structural panels) since basalt can handle the space environment, such as vacuum, radiation [4]. Notably, basalt fiber is being explored for in-situ resource utilization on the Moon or Mars. Lunar or Martian, basalt could be melted into fibers on-site to build habitats or radiation shields. While this is speculative, it underlines basalt fiber’s versatility. For current space applications, basalt composites may be used in secondary structures where extreme stiffness is not required but durability in radiation and temperature extremes is beneficial. For example, instrument enclosures on planetary landers, or structural rods on satellites, where carbon’s conductivity is problematic for plasma interactions. Moreover, 3D-printed BF-reinforced ABS parts were produced for in-space applications that provide microgravity and X-ray shielding behaviors [68] as represented in Figure 10.

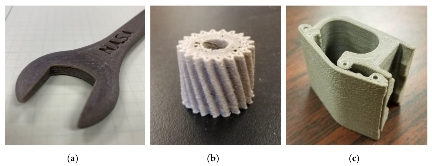


Figure 10.3D-printed ABS/BF composite objects: (a) Wrench, (b) Helical gear, (c) Handrail clamp. Adapted with permission from reference 68. Copyright 2019 MDPI under CC-BY 4.0 license.

In summary, basalt fiber composites find specific niches in aerospace: wherever fire, heat, or dielectric properties are key, basalt is an excellent fit. They are not likely to replace carbon fiber in primary load-bearing roles given carbon’s superior stiffness-to-weight ratio. Still, they can complement or substitute for glass fiber in many places with added benefits. Additionally, basalt’s eco-friendly nature, stemming from no toxic fumes, is potentially recyclable by re-melting, aligning with the aviation industry’s goals to use more sustainable materials. As basalt fiber availability increases and more data on long-term aerospace performance emerges, we may see more parts, including interior panels, cargo liners, and engine bay components, in military aircraft made from basalt composites to leverage their flame resistance and durability.

**4.3 Naval and Marine Structures**

Naval applications harness basalt fiber’s outstanding corrosion resistance and non-magnetic properties. The marine environment is harsh on materials: saltwater causes metals to corrode and can degrade glass fibers over time, and magnetic signatures are a concern for minesweeping vessels. Basalt fiber composites offer solutions on both fronts.

Boat and Ship Hulls: Basalt fiber-reinforced polymers have been tried in boat hulls as an alternative to E-glass composites. For example, a patrol boat prototype was built with a basalt fiber/vinyl ester hull. The hull panels showed higher impact strength in drop tests than conventional fiberglass, and they retained mechanical properties better after prolonged salt spray exposure [15]. Basalt fibers do not rust or degrade in saltwater, so composite hulls or superstructures made with basalt can have a longer service life with less maintenance [16]. Basalt’s non-flammable nature is an added safety factor in ships. In this case, a basalt composite deck will not support a fire like a wood deck might, nor melt like aluminum. A notable advantage for naval vessels is basalt’s non-magnetic nature. This is critical for minesweeper and minehunter vessels, which are often built from non-metallic materials to minimize magnetic signatures. Basalt composites share that very low magnetic signature, essentially transparent to magnetic fields, and could be used in hulls or minesweeper structures to reduce detectability further [16]. Naturally brownish-gold basalt could also serve as a built-in visual camouflage for specific environments, though naval vessels are usually painted.

Rebars and Structural Reinforcement: Basalt fiber-reinforced polymer rebar is gaining use in marine and coastal construction, like port structures, seawalls, and bridges, because it does not corrode like steel rebar. In a defense context, this is useful for naval bases and fortifications in marine environments. Concrete piers reinforced with basalt rebar will not suffer rebar rust that can spall concrete, thus improving longevity [12]. For example, a naval dockyard in Italy replaced corroded steel reinforcement with BFRP bars in a retrofit, resulting in extended service life. Also, basalt rebar’s lack of conductivity means if electromagnetic stealth is needed, as in a submarine pen’s concrete structure, basalt rebar does not form conductive loops or radar-reflective grids as steel would. Basalt fibers have also been used in polymer concrete overlays on ship decks to provide a non-slip, corrosion-free wearing surface [21].

Naval Vessel Components: Interior structures of ships, like bulkheads, decks, and wall panels, made from basalt fiber composites can reduce weight and eliminate corrosion issues. For instance, sections of a naval ship’s superstructure were prototyped in basalt/phenolic sandwich panels, achieving weight reduction and meeting fire safety standards for ship structures since basalt/phenolic is self-extinguishing and maintains strength in fire [15]. Basalt composites can also withstand marine diesel fuel and oils without degradation and are helpful for engine room gratings or fuel storage areas.

Sonar Domes and Underwater Systems: Basalt fiber composites may also be suitable for sonar domes on ships/submarines. These domes must be acoustically transparent and durable in seawater. Historically, glass fiber is used; basalt could potentially offer improved durability and equal acoustic transparency. Moreover, basalt’s density (2.7 g/cm³) is closer to that of seawater than carbon fiber’s (1.8 g/cm³), which could be advantageous for acoustic impedance matching. The Russian Navy reportedly tested a basalt fiber composite sonar dome coating that resisted biofouling and impact better than previous glass fiber coatings [4]. Additionally, basalt composites' non-conductive, non-magnetic nature is attractive for underwater equipment casings and remotely operated vehicle (ROV) frames to avoid interference with sensitive instruments like compasses or magnetometers.

Offshore and Coastal Defense Structures: Many militaries have radar installations, bunkers, and other coastal infrastructure where sea spray and saltwater are prevalent. Basalt fiber composites can be used to reinforce or construct these with exceptional longevity. Basalt fiber sheets are used to wrap and strengthen concrete piles and columns in marine environments because they resist chloride penetration much better than steel and glass FRP wraps [4]. In one instance, basalt fiber jackets were applied to bridge pilings in a coastal region and showed no signs of degradation after years of tidal exposure, whereas steel hoops had failed. For defensive seawalls or barriers, basalt fiber concrete reinforcement provides strength without corrosion, reducing lifecycle costs. Basalt composites have even been proposed for floating naval docks and modular pontoons to avoid corrosion and reduce magnetic signature.

Submersibles and Underwater Vehicles: ROVs and AUVs, increasingly used in naval operations, often utilize composite pressure housings to save weight. Basalt/epoxy pressure housings have been tested in small submersibles, which offer the benefit of being non-magnetic and maintaining strength in cold seawater by improving the vehicle’s stealth and instrument accuracy [21]. Basalt composite enclosures also do not interfere with acoustic sensors the way metal might. A prototype AUV hull of a hybrid carbon-basalt composite reduced the vehicle’s acoustic signature since the basalt layers dampened vibrations normally radiated by a complete carbon structure [18]. Figure 11 demonstrates the fracture behavior of vinyl ester-based laminate samples containing BF. Composite sample tended to retain its structural stability after exposure to seawater, indicating that BF exhibits fracture resistance in underwater and deep-sea applications [69].



Figure 11.Seawater-agedBF-reinforced vinyl ester-based laminate composites. Adapted with permission from reference 69. Copyright 2022 MDPI under CC-BY 4.0 license.

In short, basalt fiber composites excel in marine conditions. For navies, they present materials that can extend the life of vessels and structures while cutting down on maintenance due to corrosion. The non-magnetic aspect is a particular boon for stealth and minesweeping applications. Given that glass fiber composites are already used in minehunters, switching to basalt fiber could be a logical upgrade for future classes to gain even better durability and possibly improved structural performance. FRP’s mechanical behavior after seawater aging was comparable to that of traditional E-glass FRP [16]. As that data accumulates, basalt composites will likely find a firm place in naval engineering and infrastructure.

**4.4 Military Electronics and Equipment**

Basalt fiber composites intersect with military electronics and general equipment in several ways. Key attributes of interest include basalt’s electrical insulation, electromagnetic wave transparency, and thermal stability in housing electronics.

Electronics Housings and Enclosures: Sensitive military electronics often require RF-transparent enclosures for antennas or enclosures that do not interfere with magnetic fields. Basalt fiber composites can be used to fabricate instrument housings, radomes (as discussed in 4.2), and communication device cases. For example, a ground radar’s electronics casing was prototyped in basalt fiber composite to allow unhindered passage of its own radio signals while providing robust environmental protection [10]. The basalt composite case proved extremely rugged, which can survive drops and vibration. Unlike a metal case, it added no weight for corrosion allowances or electromagnetic shielding since transparency was desired in this context. Basalt composite cases also have a stealth benefit: composite cases do not reflect radar as strongly as metal ones, so equipment can be more easily camouflaged from enemy radar. This is relevant for assets like field generators, radar units, or missile fire control systems that one might want to harden without making them more detectable [40].

Additionally, basalt fibers withstand the high temperatures that electronic components can generate. Circuit boards and power electronics are sometimes mounted on composite panels for insulation. Traditionally, E-glass/epoxy is used for printed circuit boards; basalt/epoxy laminates have been explored as a higher-temperature PCB substrate for specialized high-power electronics [25]. They found that basalt fiber-reinforced PA66 composites maintained dielectric performance at elevated temperatures better than glass fiber ones. In high-power military radars or lasers, basalt composite structural parts can double as heat-tolerant insulators that won’t ignite or deform if electronics overheat.

EMI Shielding and Signatures: Electromagnetic shielding technology can be utilized in military operations to protect equipment from jamming assaults and interference. In the defense sector, electromagnetic interference (EMI) has been used to spy and destroy conventional weaponry [70]. Interestingly, basalt fibers are insulators, but basalt composites can be combined with conductive fillers to create EMI shields. Carbon nanotubes grew on basalt fibers in a composite, achieving a material with significant electrical conductivity that could serve as an EMI shielding layer while retaining basalt’s base mechanical properties [20]. Such multifunctional BFRCs could be used in electronic enclosures where structural strength and EMI shielding are needed, as in a military vehicle’s electronics bay, where you want to harden circuits against EMP (electromagnetic pulse).

**5. Innovations and Emerging Trends**

Basalt fiber composites are a relatively young field, and numerous innovations are being developed to enhance their performance and broaden their applicability in defense. This section highlights some emerging trends, such as fiber surface modifications, hybrid composite designs, integration of nanomaterials, and novel basalt-based composite systems, including thermoplastics and 3D-printed composites. These innovations aim to overcome limitations, including strength, toughness, interface bonding, and multi-functional capabilities.

Fiber Surface Treatments and Coatings: One area of innovation is improving the fiber-matrix interface and fiber durability through surface treatments. Researchers have experimented with coating basalt fibers with nano-silica, alumina, or zirconia to create a protective layer to increase fiber strength retention in harsh environments [28]. Silane coupling agents are commonly used sizings, but newer treatments using plasma etching or sol-gel coatings can deposit thin ceramic or polymer layers that significantly enhance bonding. For example, it was reported that basalt fibers treated with a nano-silica coating had 15% higher interfacial shear strength in epoxy and better alkaline resistance [71]. Another approach is grafting carbonaceous materials onto basalt fibers. This created a hierarchical fiber with fuzzy CNTs, dramatically increasing surface area and roughness. In basalt/epoxy composites, CNT-grown fibers exhibited improved interlaminar shear strength and endowed the composite with electrical conductivity [20]. Conductive basalt fibers could dissipate static charge or provide EMI shielding, while still serving as structural reinforcement.

Hybrid Fiber Composites: Hybridization, combining basalt fibers with other fiber types, is a major trend in tailoring composite properties. Systematic research has shown that hybrids often outperform single-fiber systems in certain metrics. It was studied that woven basalt-carbon hybrid laminates and found that placing basalt layers on the outside improved impact damage tolerance as they absorbed impact energy, increasing by 30% due to basalt’s higher strain-to-failure, which mitigated brittle carbon failure [18]. Similarly, hybrid basalt-aramid composites have been investigated in which interlayer hybrids of basalt and Kevlar in an epoxy matrix were produced, and a 20% increase in Charpy impact resistance was reported compared to pure aramid composites, attributing this to basalt fibers bridging cracks and providing compressive strength where aramid is weaker [72]. In aerospace, basalt fibers are being hybridized with flax or hemp natural fibers to create composites with lower environmental impact yet improved moisture resistance versus pure natural fiber composites [73]. Such basalt-natural fiber hybrids could see non-critical use in military vehicles or shelters, providing a green composite with acceptable performance. Hybrid addition of BF with natural flax fiber to PLA-based composites resulted in high mechanical strength and thermal stability, besides environmentally friendly character [74]. Another interesting hybrid is basalt compounded with steel fiber in concrete for force protection structures. In this case, basalt fibers control shrinkage cracking and add tensile capacity. In contrast, discrete steel fibers donate ductility and higher absolute strength, thanks to the combination, yielding ultra-high-performance concretes with synergy in mechanical properties [75]. The summary of hybrid composites of BF-based composites is listed in Table 2.

**Table 2.** Summary of hybrid composites reinforced with basalt fiber

| **Fiber Type** | **Polymer Matrix** | **Reference** | **Improved Performance** |
| --- | --- | --- | --- |
| Ceramic fiber | Phenolic resin | [50] | Wear |
| Nanoparticle | Epoxy resin  Epoxy resin  Bisphthalonitrile | [33]  [35]  [76] | Impact resistance  Mechanical  Microwave absorption |
| Glass Fiber | Epoxy resin  ABS  Epoxy resin | [14]  [77]  [57] | Impact resistance  Mechanical  Impact resistance |
| Aramid Fiber | Epoxy resin  Epoxy resin  Epoxy resin  Epoxy resin  Epoxy resin  PLA  Epoxy resin  Epoxy resin  Epoxy resin  Epoxy resin  Epoxy resin | [60]  [19]  [32]  [34]  [35]  [78]  [36]  [59]  [61]  [62]  [72] | Impact resistance  Ballistic  Bending & Tensile  Mechanical, Thermal  Mechanical  Mechanical, Thermal  Mechanical  Mechanical  Ballistic  Impact resistance  Impact resistance |
| Carbon fiber | Epoxy resin  Epoxy resin  Epoxy resin  ABS  Epoxy resin  Epoxy resin  Vinyl ester | [14]  [17]  [34]  [77]  [18]  [29]  [37] | Impact resistance  Ballistic  Mechanical, Thermal  Mechanical  Impact resistance  Flexural resistance  Fatigue |
| Natural fibers | ABS  PLA  PLA  Epoxy resin  PLA  PLA | [79]  [74]  [80]  [81]  [82]  [83] | Viscoelastic  Mechanical, Thermal  Mechanical  Mechanical  Insulation  Hygrothermal aging |

Nano-Engineered Basalt Composites: The addition of nanoparticles or nanofibers to basalt composites is being explored to enhance mechanical or functional properties, as mentioned in CNT-grown basalt fibers [20]. Other work includes dispersing graphene nanoplatelets in basalt/epoxy to improve toughness or wear resistance [84]. In a study conducted, hexagonal boron nitride nano-powder was found to be another additive [85]. Similarly, used by Gumus in hybrid armor: only 1% h-BN added to epoxy improved ballistic performance by promoting more fiber pull-out as h-BN acted as a solid lubricant at the fiber interface, delaying fiber breakage [17]. On the structural side, embedding electrospun nanoscale fibers like polyamide or carbon nanofibers at basalt laminate interfaces has improved interlaminar toughness [86]. These nanofiber interleaves act as crack arrestors. For military uses, nano-enhanced basalt composites can be multi-functional. For example, a basalt/epoxy plate with embedded magneto-strictive nanoparticles could serve as a structural health monitor, changing magnetic properties under stress in terms of the concept studied by Zhou [87]. While still in R&D, such capabilities could allow in-situ monitoring of composite armor or airframes for damage.

Thermoplastic Basalt Composites: Most current basalt composites use thermoset matrices, but there is growing interest in thermoplastic matrices, including PP, PA, and PEEK, due to their toughness and re-formability. Basalt fiber’s high temperature tolerance suits it well to thermoplastic processing. Researchers have developed basalt fiber-reinforced polypropylene composites for automotive parts and found that while short basalt fibers improve tensile properties modestly, continuous basalt fiber/PP can dramatically boost strength [88]. In defense applications, thermoplastic basalt composites could benefit impact helmets or shield components since they can undergo plastic deformation without cracking. Also, they allow welding or reshaping with heat on the field. One particular innovation is BF-reinforced 3D-printed polymers combine chopped basalt fibers with thermoplastic filaments for additive manufacturing. Studies show that incorporating 10–20 wt% basalt fiber loadings in PLA, thermoplastic polyurethane (TPU), or ABS filaments increases the stiffness, modulus, and heat deflection temperature of 3D-printed parts [79,89,90]. The printed parts maintain basalt’s fire resistance, which could be useful for printing custom brackets or housings for military equipment that need to withstand heat. For example, a drone engine mount printed in basalt fiber-ABS that doesn’t soften when the engine gets hot. Although these printed composites don’t reach the strength of continuous fiber parts, their convenience and rapid production may make them valuable for prototyping or low-load applications.

Recycling and Sustainable Practices: Another emerging trend is making basalt composites more sustainable, which has implications for the life-cycle of defense equipment. Unlike many composites, basalt fiber can be relatively easily recycled by grinding or re-melting [3]. Researchers are looking at ways to reclaim basalt fibers from cured composites. One method is thermal decomposition of BF into a polymer matrix that can endure the heat required to burn off resin, allowing fiber recovery with strength loss [91]. Efforts are also in progress to use recycled basalt fibers from manufacturing scrap or end-of-life components in non-critical applications. For instance, recycled chopped basalt fibers have been added to concrete and shown to improve strength and durability [12] still. In an era where disposal of composite waste is problematic, basalt offers a more eco-friendly profile. Additionally, basalt fibers are combined with bio-based matrices like bio-epoxy or PLA to create fully sustainable composites [92]. The defense sector has an interest in such materials for green base infrastructure or for use in humanitarian missions where environmental impact is a concern.

High-Temperature Polymer Composites: Given basalt’s thermal strengths, pairing basalt fibers with advanced matrices like polyimides or ceramic matrices for extremely high-temperature composites is explored. Basalt fiber-reinforced polyimide, such as PMR-15 type laminates, has been studied for use up to 300°C in engine components [93]. Basalt fibers handle the cure and use temperatures and are cheaper than carbon fibers, often used in polyimide composites. For hypersonic applications, a basalt fiber-reinforced ceramic matrix composite (CMC) concept is being investigated. BFs in a geopolymer or silicon carbide matrix could yield a material capable of 800–1000°C continuous use [94]. If successful, such CMCs might serve in missile nose cones or rocket nozzles at a lower cost than current carbon or SiC fiber CMCs, albeit with lower performance. The substitution of CMCs with fiber-reinforced composites, which is attributed to the reduced weight advantage, is a primary focus of rocket and missile producers, including Roketsan in Türkiye.

Smart Composites and Sensors: Finally, basalt fiber composites are being integrated with sensor technologies to create smart structures. One example is embedding fiber optic sensors within basalt fiber laminates since basalt’s transparency to specific wavelengths is good and doesn’t interact adversely with the optics. Basalt composites with embedded Bragg grating fiber optics have been demonstrated for strain monitoring [95]. Because basalt doesn’t conduct electricity, it doesn’t interfere with fiber optic signals or other embedded electronics. Another experimental development was a basalt fabric woven with a few carbon fiber tows to provide a built-in strain gauge network, as the basalt provided the main reinforcement. In contrast, as laid in a grid, the carbon tows allowed electrical resistance measurements to detect strain or damage [96]. Such self-sensing armor or airframe components could alert users to impacts or overloading.

In summary, the innovations in basalt fiber composites reflect a vibrant research front. By combining basalt with other materials at micro and nano scales, or by adopting new processing methods, scientists and engineers are greatly expanding the capability envelope of basalt composites. Many of these innovations, including hybridization, nano-additive inclusions, and smart sensing, are directly relevant to defense: they promise composites that are tougher, smarter, and more multifunctional, as in the case of an armor plate that not only stops bullets but also reports the hit location and remains fireproof. As these trends mature and transition from lab to field, we expect basalt fiber composites to become an even more versatile material in the military toolkit.

**6. Environmental Impact and Sustainability**

As the defense sector increases its focus on sustainability and reducing environmental footprint, basalt fiber composites present some notable advantages over traditional materials. This section examines the environmental aspects of basalt fiber production and use: raw material availability, production emissions, recyclability, and potential health impacts. It also contrasts basalt fibers with competitors like glass and carbon regarding eco-efficiency.

Abundant Natural Resource: Basalt rock is one of Earth's most abundant rock types [3]. It forms large geological formations worldwide, ensuring a virtually inexhaustible raw material supply. Unlike carbon fiber, which relies on petroleum precursors (PAN, pitch) or aramid, synthesized from aromatic polymers, basalt fiber comes directly from a natural rock. This inherently makes basalt fiber production less dependent on petrochemicals and mining of multiple minerals [21]. Basalt mining is akin to quarrying limestone or gravel, generally a low-impact operation with no toxic waste and straightforward land reclamation. The energy needed is mainly to melt the rock, not to process numerous chemicals.

Non-toxic and Safe Handling: Basalt fibers are generally considered environmentally benign and non-toxic. As mentioned in Section 2.1, they do not contain heavy metals or harmful components like boron or fluorine that some glass fibers.

End-of-Life and Recycling: The newly proposed approaches could process even cured composites. One concept is to burn off the polymer matrix of a basalt/epoxy composite at the end of its life since basalt fibers can withstand the required temperature of 500°C. The remaining fiber could then be ground and used as filler or remelted. While the mechanical properties of recycled fibers are reduced, they could reinforce secondary products [97]. In contrast, carbon fiber is difficult to remelt and is often just chopped for lower-grade reuse; aramid cannot be reprocessed and usually goes to landfill or incineration [98]. Some European companies have begun collecting end-of-life GFRP boat hulls and using plasma or furnace processes to recover basalt fibers from any parts made of basalt FRP [12].

Environmental Durability (Less Frequent Replacement): The superior durability of basalt composites in corrosive environments (Section 2.4) also has sustainability benefits: structures last longer, reducing the need for replacement and thus saving resources. For example, a basalt fiber-reinforced concrete bridge deck could have a service life decades longer than a steel-reinforced one, avoiding the emissions and disruption of early repair or replacement [12]. In military contexts, infrastructure like piers, bunkers, or airfield components made with basalt FRP reinforcement will likely need less maintenance and create less waste over time [16]. Additionally, vehicles or ships using basalt composites instead of metals may suffer less corrosion and thus require fewer part replacements [5].

Comparative Eco-toxicity: Basalt fibers have been tested for environmental toxicity, such as effects on soil or water, and found to be inert. In a study, BFs immersed in water did not significantly change the pH or release harmful ions [21]. By contrast, certain boron-containing glass fibers can leach borates, which in high concentration can affect aquatic life [3]. Basalt’s main soluble leachate would be metal ions like Ca²⁺and Mg²⁺, which are common in natural waters.

Alignment with Green Procurement: Many defense agencies now have green procurement initiatives. Basalt fiber composites can help products qualify due to their reduced hazardous content and improved lifecycle profile. For example, replacing a part previously made with phenolic-bonded asbestos, as an old material still found in some applications, with basalt/phenolic is a clear environmental and health win. Basalt is described as the asbestos of the future in the sense of usage, but without the health hazards [4]. The U.S. Navy is interested in basalt rebar for wharves and piers because it eliminates epoxy-coated steel, which eventually corrodes and pollutes [99].

Carbon Sequestration Potential: Using basalt fibers in carbon-negative composites is an interesting experimental concept. BFs can be embedded in matrices derived from CO₂, like CO₂-cured geopolymers or bio-resins, to develop composites that actually sequester more CO₂ than emitted in their making [100]. While not mainstream yet, this aligns with carbon reduction goals. Geopolymer composites reinforced with basalt fiber have shown promising mechanical properties. They would permanently lock in CO₂ as carbonate minerals since basalt provides alkalis to the geopolymer that capture CO₂ during curing [100]. This could be applicable for military construction projects aiming for net-zero carbon footprints.

In summary, basalt fiber composites offer a more environmentally friendly profile than many alternatives, which is becoming an increasingly important factor in defense procurement. They use plentiful natural resources, entail lower emissions in production, avoid toxic additives, and produce durable products that reduce waste. Challenges remain in recycling composites broadly, but basalt’s inert nature gives it some unique reuse and disposal pathways. As military forces worldwide adopt more sustainable practices, basalt fibers align well with that mission, potentially enabling greener military vehicles, infrastructure, and equipment.

**7. Challenges and Limitations**

Despite the many advantages of basalt fiber composites, particular challenges and limitations have thus far moderated their widespread adoption in defense applications. Acknowledging these issues to understand the hurdles for basalt composites to realize their potential is important fully. Key challenges include variability in fiber quality, relatively limited design data and experience, cost and supply constraints, and some performance gaps relative to specialized fibers.

Variability and Standardization: Basalt fibers can vary in properties depending on the source of the raw basalt and production parameters [6,8]. Until standards are widely implemented, defense contractors may hesitate to specify basalt fibers for critical applications, preferring materials with decades of standardization, similar to aramid or carbon with MIL-spec grades.

Limited Design Allowables and Field Experience: The defense community has extensive design data, including allowables and safety factors for materials like E-glass, carbon, and aramid, backed by years of field service and testing [7]. BF-based composites, being newer, have a much smaller database. Designers thus lack ready-made allowable values like tensile strength knock-downs for open-hole basalt laminates. This forces additional testing and analysis if basalt is to be used, which can be a deterrent in schedule- and budget-constrained programs. Field experience is also limited; only a handful of defense projects using basalt composites have been deployed as some naval structures and a few prototypes of armor. With less service history, risk-averse defense procurement tends to stick to proven materials unless basalt offers a clearly unique benefit. Overcoming this will require demonstration programs and accelerated testing to build confidence [15].

Cost and Supply Chain Issues: Material cost can be a significant factor for defense programs, especially for large-volume items like vehicle armor or construction rebars. If basalt is double the cost of glass for marginal improvement, some may not find it justified. However, it's worth noting that basalt is still much cheaper than aramid ($15–$25/kg) or carbon ($20–$60/kg) [25], so in certain roles it’s cost-effective. Another issue is supplying security since many basalt fiber suppliers are in specific countries, including Ukraine, Russia, and China. Accordingly, there may be geopolitical or trade concerns for defense supply chains. Establishing local production or multiple sources can mitigate this, but until then, reliance on limited foreign sources might be considered a risk for critical defense projects.

Fiber Diameter and Weight: Basalt fibers are generally available in diameters of 13 μm and up, mostly 17 μm for continuous basalt roving [7]. This is slightly thicker than typical E-glass fibers (10 μm) and much thicker than some high-performance fibers (S-glass often ~9 μm, carbon fibers ~5–7 μm). Thicker fibers mean potentially lower fiber count per cross-sectional area and slightly higher minimum achievable composite thickness. For weight-critical designs, basalt composites might weigh more for the same fiber volume fraction simply because the fiber packing is less efficient [1]. Also, thicker fibers can produce a rougher surface finish in thin laminates. While not a major issue, in aerospace, every gram counts, and basalt’s density is also a touch higher than that of E-glass. So in applications where E-glass is strong enough, switching to basalt could marginally increase weight (5-8% heavier for the exact fiber count) unless design adjustments are made [7]. Some manufacturers are developing fine basalt fibers with 9 μm to address this issue. Still, production of very fine basalt filaments is technically challenging due to viscosity and cooling differences from glass [16].

Brittleness and Impact Tolerance: While basalt fibers are considered more ductile than carbon, they are still brittle inorganic fibers. They lack the extreme toughness of aramid or ultra-high molecular weight polyethylene (UHMWPE) fibers. In high-impact or highly flexural applications such as helicopter rotor blades and flexible body armor, basalt might not match the energy absorption of these specialized fibers [13]. For example, para-aramid fiber layers are significantly more effective in soft armor at dissipating bullet kinetic energy than basalt fiber layers of equal weight since basalt is better used in backing/hard layers [13]. Basalt composites also tend to have lower strain to failure than some glass composites due to being stiffer; this can mean less warning before failure. For critical fail-safe designs, this brittleness needs to be accounted for [7]. Researchers are mitigating this with hybrids (as discussed, basalt-aramid, for example). Still, pure basalt FRPs might not suffice when high toughness is required without additional design features.

High-Temperature Creep: One often mentioned issue with glass fibers is creep at elevated temperatures under load. While more heat-resistant, Basalt fibers experience some stiffness loss at high temperatures over time. Studies have shown that basalt/epoxy rods under sustained load at 120°C creeped less than the glass/epoxy system, but still measurable amounts [39]. In very high temperature applications close to basalt’s softening point of 960°C, BFs will start to lose structural capacity, although this is beyond typical use except maybe re-entry shield edges. Still, suppose someone wanted to use basalt in a 600°C environment under stress like a heat-treated tooling or in a hot engine exhaust path, structurally. In that case, they’d need to characterize creep and fatigue in that regime, which currently has sparse data.

Adhesion in Some Matrices: Basalt fibers bond well to many resins, particularly epoxies and phenolics with standard sizings, but their bonding to specific matrices, like unsaturated polyesters or some thermoplastics, can be less than ideal if not correctly sized. Some reports indicate that off-the-shelf unsized basalt fibers have lower interfacial shear strength in polyester resin than E-glass fibers, possibly due to surface chemistry differences [6]. This is a solvable issue with tailored sizings, but as of now, many basalt fibers come with a general-purpose epoxy-compatible sizing by default. So if a military equipment manufacturer wants to use basalt in a vinyl ester matrix common in maritime composites, they should ensure that basalt fibers are obtained with an appropriate sizing or applied post-treatment. Lack of awareness here could lead to suboptimal performance and give basalt a bad reputation.

Matrix Compatibility at Processing: Another practical limitation is that BFs are more chemically stable than glass, which is usually good, but in some specialized composite processes like glass fiber reinforced concrete, GRC, where the glass is dissolved partially by cement to bond, basalt won’t interact the same way. BFs need a coating or treatment to bond well in cement matrices because they do not have the zirconia or other components that give glass fibers an inherent bond with cement hydrates [21]. This has limited their uptake in fiber-reinforced concretes without modifications, though new alkali-resistant basalt or surface-etched fibers are being trialed. Similarly, basalt’s inertness means it won’t form chemical bonds with polyimide matrices like some specialized fibers, like how carbon fibers can form covalent bonding with BMI matrices when treated. BF is a passive reinforcement; while that's fine in most cases, some cutting-edge composite matrices rely on fiber reactivity that is not typical in defense applications.

Perception and Inertia: Finally, there is the soft challenge of perception. BF, sometimes marketed as a miracle fiber or greener alternative to glass and carbon, has sometimes been over-hyped, leading to skepticism. Defense engineers might have seen claims that basalt is as good as carbon in the case of cost fraction. Managing expectations is crucial since it’s a great material in the right slot, but not a cure-all. Overcoming institutional inertia, preferring to use what’s known, will likely require demonstration projects where basalt composites clearly prove their worth in service, and support from procurement policies that value the sustainability and cost benefits basalt can bring [3].

In summary, while basalt fiber composites hold much promise, challenges of quality consistency, limited design data, and specific performance gaps, especially in extremely high-end or ultra-flexible applications, must be addressed. Many of these issues are being worked on through standardization efforts research to generate allowable compiled data which could feed into databases, and technological improvements such as better sizings, more suppliers coming online in different countries. For example, ASTM is developing basalt fiber testing standards. As these challenges are overcome, basalt’s adoption in defense is likely to accelerate, since the fundamental material qualities are sound. Recognizing current limitations ensures that when basalt composites are used, they are applied in ways that play to their strengths and not their weaknesses.

**8. Future Outlook**

Basalt fiber composites are at an inflection point where increasing knowledge and production are set to propel them into a more prominent role across military and defense applications. Looking ahead, one can envision several developments in the next decade that will significantly impact the adoption of basalt composites:

Wider Adoption in Military Infrastructure and Vehicles: In the near future, basalt fiber reinforced concrete and polymeric composites are expected to become common in new military construction and facility upgrades. For example, new hangars and hardened shelters may use basalt-FRP rebar to eliminate corrosion issues and reduce maintenance [99]. Bridge repair kits for combat engineers could feature basalt fiber composite wrap systems to quickly strengthen or repair damaged structures in the field without worrying about corrosion or specialized handling [15]. On military vehicles, basalt composite components are likely to appear first in secondary structures involving engine compartment firewalls, exhaust shrouds, storage lockers, and perhaps floor panels for blast protection [5]. As confidence grows, more primary structural parts could follow, especially in naval vessels, such as whole decks or bulkheads made of sandwich panels with basalt skins. Minesweeper ships could move from glass fiber hulls to basalt fiber hulls for improved durability.

Integration into Personal Protective Equipment: It can be foreseen that next-generation personal armor systems will incorporate basalt fiber composite layers. By 2030, a standard ballistic vest for certain units might include a ceramic strike face, basalt fiber composite backing, and aramid fabric trauma pad. This leverages basalt’s stiffness and fireproof nature by offering partial fire protection to the wearer. Combat helmets might evolve as well, and a hybrid design with basalt fiber outer shells for the environment and blunt impact combined with aramid inner layers for ballistic stopping could emerge to take advantage of basalt’s flame resistance [59]. If manufacturing techniques like automated fiber placement advance for helmet shapes, basalt fiber preforms could be economically molded. The environmental and health safety benefits, such as aramid dust, could also drive militaries to prefer basalt where feasible.

High-Performance Aerospace Components: In aerospace, basalt fiber composites are poised to fill niches that neither glass nor carbon perfectly addresses. For instance, high-speed missile radomes and antenna covers might increasingly use basalt composites, benefiting from their combination of thermal stability and radar transparency [10,70,101]. Basalt could also be used in small satellite structures, especially in constellations where cost-efficiency is key and a slight weight penalty is acceptable. A likely scenario is basalt/PEEK or basalt/epoxy composite systems in secondary satellite structures such as optical benches, battery enclosures, or antenna booms by around 2030, once data on radiation tolerance is fully validated [4]. The push for reusable space vehicles may also find basalt composites functional in thermal protection segments that need moderate structural ability [5].

Advanced Hybrid Systems: In the future, basalt fibers will probably be routinely used in hybrid composites to optimize performance. Material engineers will mix basalt with carbon, aramid, natural fibers, and nanomaterials almost as standard practice by choosing basalt to impart heat resistance or compressive strength to a hybrid laminate. Perhaps a future infantry helmet will combine 2D-woven basalt-carbon fabric: carbon for stiffness and basalt for fire/impact synergy. Likewise, an unmanned underwater vehicle might have a carbon-basalt shell: carbon for stiffness, basalt for non-magnetic stealth. The concept of tailored hybrids refers to basalt not always being used alone but in synergy with others, broadening where it can go [18].

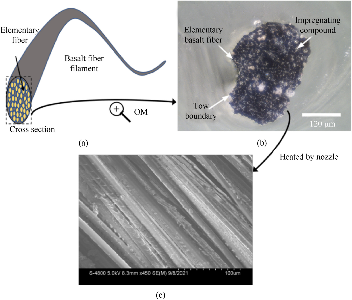


Figure 12.Illustrationof the basalt fiber filament used for 3D printing; (b) Optical microscope image of the cross-sectional details of the filament; (c) SEM image of composite. Adapted with permission from reference 102. Copyright 2023 Elsevier.

3D Printing and Field Fabrication: Another exciting prospect is using BFs in expeditionary manufacturing. In a future forward operating base, one can imagine a containerized system that 3D prints repair parts or fortification components using a composite of chopped basalt fiber and a UV-curable resin. It suits austere environments because basalt fiber can be shipped and handled effortlessly, as it requires no special freezing like prepregs. Defense agencies are already exploring on-site additive manufacturing for parts; adding basalt fiber reinforcement would significantly increase the strength of printed plastic parts [79]. Also, BF could be combined with local materials such as aggregate or even volcanic soil in a relevant terrain to create improvised composites for construction. Additionally, 3D printed composite parts can be used in armor protection since BF donates the resistance against flexural stress [102]. In this case, continuous BF filaments align in the printing direction through ABS-based 3D printing filament to improve its tensile and flexural strength, as illustrated in Figure 12.

Standardization and Certification: Expect to see basalt fiber composites codified in defense and civil standards over the next decade. Organizations like ASTM, MIL, and ISO are developing standards for basalt materials, such as ASTM C1898 for basalt fiber testing. Once basalt-based composites have standardized test methods and design allowables, adoption will be much smoother. It can be a MIL-DTL for basalt fiber cloth, just as we have MIL specs for aramid cloth, enabling procurement of basalt materials with guaranteed properties. Certification of basalt composites for use in critical structures, including naval ship fire divisions, will also become feasible as more fire and structural tests are done. Naval approval authorities like ABS and DNV are already looking at basalt FRP for boatbuilding, which paves the way for acceptance of military ship codes.

Basalt’s unique mix of properties could enable new defense innovations. In a portable blast wall system, panels of BF-reinforced composite that soldiers can quickly assemble to form protective barriers that are flame-proof and durable, taking shrapnel and then being re-used. Additionally, BF is being used in uniforms or gear where heat resistance is needed. Basalt could complement aramid by adding cut resistance and heat blocking or inserting it in gloves for handling hot ordnance. BFs might even find their way into energetics or pyrotechnics as reinforcement in solid rocket propellant liners as already done, or as filaments in explosive matrices to add resilience, although it is speculative.

In conclusion, the future for basalt fiber composites in defense looks bright. As technology and manufacturing progress, many of the current barriers will diminish, allowing basalt to assume a larger share of roles currently dominated by traditional composites or metals. Its middle-ground performance makes it versatile, and improvements can push it further. With global trends emphasizing sustainability and cost-efficiency, basalt’s profile aligns well with what future military systems require: strong yet affordable materials, high-performing yet reliable, and effective without being hazardous to humans or the environment. Basalt fiber-based composites, evolving rapidly from novelty to mainstream, will likely become a staple material in the 21st-century defense inventory.

**9. Conclusion**

Basalt fiber composites have emerged from relative obscurity to become a compelling material option for military and defense applications. Derived from volcanic rock, basalt fibers offer a unique blend of properties: they rival E-glass in strength and modulus, withstand higher temperatures and fire without combusting, resist corrosion and chemical attack better than most synthetic fibers, and are produced from abundant natural resources with potentially lower environmental impact. Over the course of this chapter, we have surveyed the landscape of basalt fiber composites from their fundamental properties and manufacturing methods to a wide array of applications in ballistic protection, aerospace, naval engineering, and electronic equipment.

As a summary, basalt fiber-reinforced composites (BFRCs) have demonstrated significant advantages in specific defense-related roles:

• Ballistic and Blast Protection: BFRC, especially in hybrid configurations, can effectively dissipate ballistic energy and serve as durable backing or structural layers in armor. They add the benefit of fire resistance to armor systems, increasing soldier protection in multi-hazard environments. While not replacing aramid or ceramic in primary stopping power, BF layers improve multi-hit performance and environmental robustness of armor.

• Aerospace Components: BF laminates are being used in radomes, engine firewalls, and other aircraft parts where their combination of mechanical strength, high-temperature stability, and electromagnetic transparency offers a balance that traditional fibers do not. Future military aircraft and spacecraft will likely incorporate BFRCs in secondary structures and thermal protection systems, leveraging basalt’s reliability under thermal and radiation stress.

• Naval and Marine Structures: The immunity of BF to saltwater corrosion and non-magnetic signature has already resulted in its use in naval mine countermeasure vessels, marine infrastructure, and boat hulls. As a direct replacement for glass fiber in marine composites, basalt extends service life and reduces maintenance, which is critical for navies and coastal defense applications.

• Military Electronics and Equipment: BFRCs enable durable, light, and EMI-transparent housings for sensitive electronics. They fill a niche for non-conductive structural materials that can endure heat and not corrode, ideal for radar systems, missile electronics, or portable generators. Additionally, since it has no toxic smoke in fires and recyclable content, the relative eco-friendliness of basalt is an asset as military organizations strive for more sustainable practices.

At the same time, it was acknowledged that the challenges must be managed: ensuring consistent fiber quality, expanding the engineering database, and addressing any cost or performance gaps through continued innovation. These challenges are progressively being overcome. The trend lines are clear – basalt fiber production is scaling up and becoming more standardized, research is pouring in to refine basalt composite technology, and successful field implementations are building confidence in this material.

The broader significance of BFRCs in defense is that they provide a sustainable, high-performance alternative that can reduce dependency on more expensive or less durable materials. In an era where armed forces consider logistics, lifecycle costs, and environmental impacts, basalt is the natural choice for many mid-range applications. It is telling that BF was once classified as strategic material, as its re-emergence now in open commercial and defense use suggests its inherent value was recognized long ago. Now with modern manufacturing, that value can be fully realized across civilian and military domains.

In conclusion, BFRCs are no longer just an interesting laboratory material; they are becoming a practical solution to real-world engineering problems faced by the military fields. As this chapter has detailed, their properties align remarkably well with the demands of ballistic protection, extreme environment operation, maritime durability, and beyond. Through continued R&D and growing field experience, BFRCs are poised to transition from alternative to mainstream in defense composite materials. Basalt fiber composites are anticipated to be an integral component of advanced armor systems, next-generation military vehicles and vessels, and resilient military infrastructure in the coming years. The stone fiber born of ancient lava flows is ready to serve the cutting-edge needs of 21st-century defense technology as strong, reliable, and enduring, much like the basalt rock from which it is derived.

**References**

[1] Mundhe, G. S.; Mahanwar, P. A.; Patil, J. R.; Elamaran, S. A review on basalt fiber and basalt fiber reinforced polymer composites: Advancement and industrial applications. International Journal for Research in Applied Science and Engineering Technology **2023**, *11*(I), 306–320.

[2] Singha, K. A short review on basalt fiber. International Journal of Textile Science **2012**, *1*(4), 19–28.

[3] Jamshaid, H.; Mishra, R. Basalt fiber and its composites: An overview. International Journal of Scientific & Engineering Research **2017**, *8*(4), 101–105.

[4] Yan, L.; Chu, F.; Tuo, W.; Zhao, X.; Wang, Y.; Zhang, P. Review of research on basalt fiber and basalt fiber-reinforced composites in China (I): Physicochemical and mechanical properties. Polymers & Polymer Composites **2014**, *22*(5), 429–442.

[5] Chowdhury, I. R.; Pemberton, R.; Summerscales, J. Developments and industrial applications of basalt fibre reinforced composite materials. Journal of Composites Science **2022**, *6*(12), 367.

[6] Greco, A.; Maffezzoli, A.; Casciaro, G.; Caretto, F. Mechanical properties of basalt fibers and their adhesion to polypropylene matrices. Composites Part B: Engineering **2014**, *67*, 233–238.

[7] Lopresto, V.; Leone, C.; De Iorio, I. Mechanical characterisation of basalt fibre reinforced plastic. Composites Part B: Engineering **2011**, *42*(4), 717–723.

[8] Deák, T.; Czigány, T. Chemical composition and mechanical properties of basalt and glass fibers: A comparison. Textile Research Journal **2009**, *79*(7), 645–651.

[9] Tang, Y.; Liu, Y.; Wang, Y.; Jin, W.; Wu, Z. Flame retardancy and thermal degradation of basalt fiber-reinforced polypropylene composites. Polymer Degradation and Stability **2016**, *130*, 9–15.

[10] Mankodi, H.; Parmar, S. Basalt fibre reinforced material for radome. Journal of the Textile Association **2023**, *83*(5), 343–347.

[11] Fiore, V.; Scalici, T.; Di Bella, G.; Valenza, A. A review on basalt fibre and its composites. Composites Part B: Engineering **2015**, *74*, 74–94.

[12] Fořt, J.; Veselý, V.; Šál, J.; Černý, R. Environmental efficiency aspects of basalt fibers reinforcement in concrete mixtures. Energies **2021**, *14*(22), 7736.

[13] Naveen, J.; Jayakrishna, K.; Sultan, M. T. H.; Amir, S. M. M. Ballistic performance of natural fiber based soft and hard body armour – A mini review. Frontiers in Materials **2020**, *7*, 138.

[14] Doğru, M. H.; Yeter, E.; Göv, İ.; Göv, K. Ballistic impact resistance and flexural performance of natural basalt fiber with carbon and glass fibers in inter-ply hybrid composites. Polymer Composites **2023**, *44*(2), 850–864.

[15] Fiore, V.; Valenza, A.; Beritognolo, M. Basalt fibre reinforced polymer (BFRP) durability in marine environment: Experimental tests and empirical modeling. Applied Composite Materials **2018**, *25*(5), 1045–1057.

[16] Davies, P.; Verbouwe, W. Evaluation of basalt fibre composites for marine applications. Applied Composite Materials **2018**, *25*(2), 299–308.

[17] Gumus, F. B.; Yapici, A. Ballistic behavior of hybrid carbon/basalt fiber reinforced epoxy-hBN composite. Journal of Composite Materials **2024**, *58*(4), 551–563.

[18] Sarasini, F.; Tirillò, J.; Valente, M.; Valente, T.; Cioffi, S.; Iannace, S.; Sorrentino, L. Drop-weight impact behaviour of woven hybrid basalt–carbon/epoxy composites. Composites Part B: Engineering **2014**, *59*, 204–220.

[19] Bandaru, A. K.; Ahmad, S.; Bhatnagar, N. Ballistic performance of hybrid thermoplastic composite armors reinforced with Kevlar and basalt fabrics. Composites Part A: Applied Science and Manufacturing **2017**, *97*, 151–165.

[20] Chhetri, B.; Kim, N.; Yoo, Y. Multifunctional basalt fiber polymer composites enabled by carbon nanotubes and graphene. Composites Part B: Engineering **2023**, *268*, 110852.

[21] Sim, J.; Park, C.; Moon, D. Y. Characteristics of basalt fiber as a strengthening material for concrete structures. Composites Part B: Engineering **2005**, *36*(6–7), 504–512.

[22] Gutnikov, S. I.; Malakho, A. P.; Lazoryak, B. I.; Loginov, V. S. Influence of alumina on the properties of continuous basalt fibers. Russian Journal of Inorganic Chemistry **2009**, *54*(2), 191–196.

[23] Ramachandran, B. E.; Velpari, V.; Balasubramanian, N. Chemical durability studies on basalt fibres. Journal of Materials Science **1981**, *16*(12), 3393–3397.

[23] Selcuk, S.; Ahmetoglu, U.; Gokce, E. C. Basalt fiber reinforced polymer composites (BFRP) other than rebars: a review. Materials Today Communications **2023**, *37*, 107359.

[24] Mingchao, W.; Zhiqiang, L.; Yong, L.; Dong, Z.; Qiang, X. Chemical durability and mechanical properties of alkali-proof basalt fiber and its reinforced epoxy composites. Fibers and Polymers **2013**, *14*(1), 30–35.

[25] Patti, A.; Acierno, S.; Nele, L.; Graziosi, L.; Acierno, D. Sustainable basalt fibers vs. traditional glass fibers: Thermal properties and flow behavior in polyamide 66 composites. Composites Part C: Open Access **2023**, *9*, 100323.

[26] Zhu, D.; Tang, Y.; Rahman, M. Z. Basalt fiber: composites and applications. In Synthetic and Mineral Fibers, Their Composites and Applications, Woodhead Publishing 2024, 337–361.

[27] Singh, S.; Gupta, M. K.; Verma, A.; Sharma, K. K.; Pruncu, C. I. Mechanical performance of Kevlar fiber based polymer composites under various conditions: A review. Polymer Testing **2018**, *65*, 256–277.

[28] Kim, M. T.; Rhee, K. Y.; Park, S. J.; Hui, D. Effects of silane-modified carbon nanotubes on flexural and fracture behaviors of carbon nanotube-modified epoxy/basalt fiber composites. Composites Part B: Engineering **2013**, *44*(1), 751–757.

[29] Subagia, I. A.; Kim, Y.; Tijing, L. D.; Kim, C. S.; Shon, H. K. Effect of stacking sequence on the flexural properties of hybrid composites reinforced with carbon and basalt fibers. Composites Part B: Engineering **2014**, *58*, 251–258.

[30] Scalici, T.; Fiore, V.; Valenza, A. Experimental and theoretical study of basalt fiber composites. Materials & Design **2016**, *109*, 403–413.

[31] Dhand, V.; Mittal, G.; Rhee, K. Y.; Park, S.-J.; Hui, D. A short review on basalt fiber reinforced polymer composites. Composites Part B: Engineering **2015**, *73*, 166–180.

[32] Bozkurt, Ö. Y. Hybridization effects on tensile and bending behavior of aramid/basalt fiber reinforced epoxy composites. Polymer Composites **2017**, *38*(6), 1144–1150.

[33] Demirci, I.; Avcı, A.; Demirci, M. T. Investigation of nano-hybridization effects on low velocity impact behaviors of basalt fiber reinforced composites. Journal of Composite Materials **2021**, *55*(3), 401–414.

[34] Karacor, B.; Ozcanli, M. Thermal and mechanical characteristic investigation of the hybridization of basalt fiber with aramid fiber and carbon fiber. Polymer Composites **2022**, *43*(11), 8529–8544.

[35] Lee, J. W.; Yu, T.; Park, S. J.; Kim, Y. H. Interfacial properties of aramid/basalt fiber reinforced hybrid composites by addition of halloysite nanotube. Modern Physics Letters B **2019**, *33*(14-15), 1940031.

[36] Pai, Y.; Pai K, D.; Kini, M. V. Effect of aramid fabric orientation angle on the mechanical characteristics of basalt-aramid/epoxy hybrid interply composites. Materials Research **2021**, *24*(5), e20210209.

[37] Tirillò, J.; Sarasini, F.; Lampani, L.; De Santis, A.; Valente, M.; Sorrentino, L. On the fatigue behavior of basalt/carbon hybrid basalt-vinylester composites. Composites Part B: Engineering **2014**, *67*, 377–384.

[38] Militký, J.; Kovacic, V.; Rubnerová, J. Influence of thermal treatment on tensile failure of basalt fibers. Engineering Fracture Mechanics **2002**, *69*(9), 1025–1033.

[39] Cherný, R.; Fořt, J.; Drchalová, J. High-temperature properties and mechanical performance of basalt-fiber reinforced geopolymer composites. Journal of Materials Science **2015**, *50*(4), 2007–2015.

[39] Murad, M. S.; Hamzat, A. K.; Asmatulu, E.; Asmatulu, R. Flame-retardant fiber composites: synergistic effects of additives on mechanical, thermal, chemical, and structural properties. Advanced Composites and Hybrid Materials **2025**, *8*(1), 31.

[40] Wu, Q.; Chi, K.; Wu, Y.; Lee, S. Mechanical, thermal expansion, and flammability properties of co-extruded wood polymer composites with basalt fiber reinforced shells. Materials & Design **2014**, *60*, 334–342.

[41] Wang, S.; Zhong, J.; Gu, Y.; Li, G.; Cui, J. Mechanical properties, flame retardancy, and thermal stability of basalt fiber reinforced polypropylene composites. Polymer Composites **2020**, *41*(10), 4181-4191.

[42] Balaji, K. V.; Shirvanimoghaddam, K.; Yadav, R.; Ferdowsi, M. R. G.; Naebe, M. Effect of matrix modification and fiber surface treatment on the properties of basalt fiber reinforced polypropylene composites. Hybrid Advances **2024**, *6*, 100253.

[43] Arslan, C.; Dogan, M. The effect of a phosphorus-based FR on the fire performance and flammability properties of basalt fiber-reinforced acrylonitrile-butadiene-styrene composites. Turkish Journal of Chemistry **2022**, *46*(5), 1702–1709.

[44] Andrzejewski, J.; Michałowski, S. Development of a new type of flame retarded biocomposite reinforced with a biocarbon/basalt fiber system: a comparative study between poly (lactic acid) and polypropylene. Polymers **2022**, *14*(19), 4086.

[45] Yang, W.; Jia, Z.; Chen, Y.; Zhang, Y.; Si, J.; Lu, H.; Yang, B. Carbon nanotube reinforced polylactide/basalt fiber composites containing aluminium hypophosphite: thermal degradation, flame retardancy and mechanical properties. RSC Advances **2015**, *5*(128), 105869–105879.

[46] Arslan, Ç.; Doğan, M. Flame retardancy of basalt fiber-reinforced PBT composite: effect of red phosphorus and TiO2 synergism. Journal of Thermal Analysis and Calorimetry **2023**, *148*(19), 10151–10161.

[47] Hao, L.; Yu, W. Evaluation of thermal protective performance of basalt fiber nonwoven fabrics. Journal of Thermal Analysis and Calorimetry **2010**, *100*(2), 551–555.

[48] US Patent 7968620B2. Rocket motors incorporating basalt fiber and nanoclay compositions and methods of insulating a rocket motor with the same. Assigned to Alliant Techsystems Inc., 2011.

[49] Tao, W.; Wang, B.; Wang, N.; Guo, Y.; Li, J.; Zhou, Z. Research progress on basalt fiber-based functionalized composites. Reviews on Advanced Materials Science **2023**, *62*(1), 20220300.

[50] Ozturk, B.; Arslan, F.; Ozturk, S. Hot wear properties of ceramic and basalt fiber reinforced hybrid friction materials. Tribology International **2007**, *40*(1), 37–48.

[51] Lee, J.; Won, J. P.; Jang, C. I.; Lee, S. W. Long-term properties of basalt fiber-reinforced concrete including wet-dry cycles and high temperature. Construction and Building Materials **2020**, *245*, 118439.

[52] Liu, H.; Yu, Y.; Liu, Y.; Zhang, M.; Li, L.; Ma, L.; Sun, Y.; Wang, W. A review on basalt fiber composites and their applications in clean energy sector and power grids. Polymers **2022**, *14*(12), 2376.

[53] Jagadeesh, P.; Rangappa, S. M.; Siengchin, S. Basalt fibers: An environmentally acceptable and sustainable green material for polymer composites. Construction and Building Materials **2024**, *436*, 136834.

[54] Petti, L.; Vitiello, L.; Iannace, S. Basalt fibers as sustainable and cost-effective alternative to glass fibers in Sheet Molding Compound (SMC). AIP Conference Proceedings **2018**, *1981*(1), 020021.

[55] Presley, M. (2011). Basalt fiber rebar. Monolithic.org, May 2011.

[56] Carmisciano, S.; De Luca, F.; Lamanna, G.; Procopio, A.; Ricciardi, M. R. Basalt fiber reinforced polymer (BFRP) plates for strengthening reinforced concrete members. Composites Part B: Engineering **2011**, *42*(4), 736–744.

[57] Vyas, C.; Jhala, R. Experimental investigation of low‐velocity impact on glass‐basalt hybrid laminates: effect of ply sequence and energy levels. Polymer Composites **2025**, ePub: July 7.

[58] Fu, H. D.; Feng, X. Y.; Liu, J. X.; Yang, Z. M.; He, C.; Li, S. K. An investigation on anti-impact and penetration performance of basalt fiber composites with different weave and lay-up modes. Defence Technology **2020**, *16*(4), 787–801.

[59] Parandoush, P.; Koushyar, H.; Sattari-Far, I. Development of a hybrid basalt/Kevlar fiber composite helmet with improved mechanical performance. Journal of Materials: Design and Applications **2021**, *235*(10), 2402–2414.

[60] Arpatappeh, F. A.; Azghan, M. A.; Eslami-Farsani, R. The effect of stacking sequence of basalt and Kevlar fibers on the Charpy impact behavior of hybrid composites and fiber metal laminates. Journal of Mechanical Engineering Science **2020**, *234*(16), 3270–3279.

[61] Pathak, R. K.; Patel, S.; Gupta, V. K. Efficient design of Kevlar/basalt hybrid composite laminates under ballistic impact. Advanced Composite Materials **2023**, *32*(1), 48–69.

[62] Ruan, F.; Wang, H.; Xia, C.; Yang, Q.; Zou, L.; Xu, Z. Flexural and impact performance of Kevlar/basalt fabric interlayer hybrid curved composites. Industria Textila **2024**, *75*(1), 49–56.

[63] Alexander, J.; Augustine, B. S. M. Influence of microwave post curing on the mechanical and thermal properties of basalt/epoxy composites for aerospace applications. Journal of the Balkan Tribological Association **2016**, *22*(1), 220–234.

[64] Moskvicheva, E. D.; Reznichenko, V. I. The use of basalt plastic for the manufacture of sound insulation panels of an aircraft engine. International Conference on Aerospace System Science and Engineering 2020, 101-113.

[65] Elsheikh, A. H.; Ma, N.; Essa, F. A.; Khedr, M.; Ibrahim, A. M. M. Kerf geometry prediction and optimization in laser cutting of basalt fiber reinforced polymer composites using decision tree and coati optimization algorithm. Results in Engineering **2025**, *26*, 105514.

[66] Sudalaimuthu, G.; Chinnasamy, S.; Sundaram, J.; Chandaka, S.; Das, C. Design, fabrication and analysis of compact unmanned aerial vehicle. In AIP Conference Proceedings **2024**, *3192*, 020081.

[67] Yanko, T.; Datsenko, R.; Karpenko, H. Possibilities of using low-density cc composites for thermal protection of small unmanned aerial vehicles. Transactions on Aerospace Research **2023**, *271*, 45—57.

[68] Coughlin, N.; Drake, B.; Fjerstad, M.; Schuster, E.; Waege, T.; Weerakkody, A.; Letcher, T. Development and mechanical properties of basalt fiber-reinforced acrylonitrile butadiene styrene for in-space manufacturing applications. Journal of Composites Science **2019**, *3*(3), 89.

[69] Bonsu, A. O.; Liang, W.; Mensah, C.; Yang, B. Assessing the mechanical behavior of glass and basalt reinforced vinyl ester composite under artificial seawater environment. Structures **2022**, *38*, 961–978.

[70] Fareez, U. N. M.; Loudiy; A., Erkartal, M.; Yilmaz, C. Basalt fiber reinforced polymers: a recent approach to electromagnetic interference (EMI) shielding. Journal of Polymer Science **2025**, *63*(1), 50–73.

[71] Militký, J.; Morlin, B.; Havelka, P. Improved adhesion of basalt fibers to polymer matrices by nanosilica coating. Fibers and Polymers **2020**, *21*(12), 2688–2695.

[72] Zhu, H.; Yu, B.; Zhang, Z.; Li, Z. Hybrid effects of basalt fibers and Kevlar fibers on the impact behavior of epoxy composites. Polymer Composites **2018**, *39*(S3), E1664–E1673.

[73] Dhakal, H. N.; Zhang, Z. Y.; Richardson, M. O. Effect of water absorption on the mechanical properties of hemp fiber reinforced unsaturated polyester composites. Composites Science and Technology **2018**, *68*(7-8), 1513–1520.

[74] Eselini, N.; Tirkes, S.; Akar, A. O.; Tayfun, U. Production and characterization of poly (lactic acid)-based biocomposites filled with basalt fiber and flax fiber hybrid. Journal of Elastomers & Plastics **2020**, *52*(8), 701–716.

[75] Nematollahi, B.; Sanjayan, J.; Shaikh, F. Matrix design of strain hardening fiber reinforced engineered geopolymer composite. Composites Part B: Engineering **2015**, *89*, 253–265.

[76] Guo, H.; Zhan, Y.; Chen, Z.; Meng, F.; Wei, J.; Liu, X. Decoration of basalt fibers with hybrid Fe3O4 microspheres and their microwave absorption application in bisphthalonitrile composites. Journal of Materials Chemistry A **2013**, *1*(6), 2286-–296.

[77] Lobov, E.; Vindokurov, I.; Tashkinov, M. Mechanical properties and performance of 3D-printed acrylonitrile butadiene styrene reinforced with carbon, glass and basalt short fibers. Polymers **2024**, *16*(8), 1106.

[78] Mazur, K.; Siwy, Z. S.; Adamczyk, A.; Kuciel, S. Synergistic effect of aramid and basalt fibers on mechanical, thermal and dynamic properties of polylactide hybrid composites. Industrial Crops and Products **2023**, *198*, 116630.

[79] Behera, B. K. Preparation and characterization of basalt fiber (BF) reinforced acrylonitrile butadiene styrene (ABS)/cocoanut fiber (CF) hybrid composites: Study on mechanical, thermal and viscoelastic properties. Journal of Thermoplastic Composite Materials **2025**, ePub: May 19.

[80] Ermeydan, M. A.; Aykanat, O.; Altın, Y. Preparation and characterization of hybrid PLA biocomposites reinforced by wood and silane treated basalt fibers or compatibilized by maleic anhydride‐grafted polypropylene (MAPP). Polymer Composites **2024**, *45*(11), 9831–9844.

[81] Reddy, M. I.; Sethuramalingam, P.; Sahu, R. K.; Raju, K. S. R. Jute/basalt fabrics in microcellulosic-filled epoxy composites for lightweight applications. Materials Chemistry and Physics **2024**, *323*, 129640.

[82] Aykanat, O.; Ermeydan, M. A. Production of basalt/wood fiber reinforced polylactic acid hybrid biocomposites and investigation of performance features including insulation properties. Polymer Composites **2022**, *43*(6), 3519–3530.

[83] Gao, X.; Jiang, J.; Chen, L.; Wang, L.; Qu, J.; Mu, W. Influence of hygrothermal aging on mechanical properties of short flax/basalt fiber hybrid composites. Polymer Composites **2025**, ePub: August 19

[84] Sukur, E. F.; Onal, G. Graphene nanoplatelet modified basalt/epoxy multi-scale composites with improved tribological performance. Wear **2020**, *460*, 203481.

[85] Aslan, C.; Karsli, N. G. Investigation of the synergetic effect of hybrid fillers of hexagonal boron nitride, graphene nanoplatelets and short basalt fibers for improved properties of polyphenylene sulfide composites. Polymer Bulletin **2024**, *81*(6), 4969–4992.

[86] Litvinov, I.; Toropovs, N.; Kulakov, V. Mode I interlaminar fracture toughness of basalt fiber/epoxy composites interleaved with electrospun polyamide nanofibers. Composite Structures **2020**, *236*, 111887.

[87] Zhou, J.; Liu, H.; Guo, S.; Zhang, J.; Yuan, L. Self-sensing basalt textile reinforced mortar for damage monitoring of infrastructure. Sensors **2020**, *20*(14), 3860.

[88] Arangelovich, V.; Tiernan, P.; Carroll, A.; Young, T. Mechanical performance of recycled woven basalt fiber-reinforced polypropylene composites. Sustainability **2021**, *13*(4), 1682.

[89] Arslan, Ç.; Tayfun, Ü.; Yılmaz, V. M.; Delikanlı, N. E. Comprehensive investigations of injection molding and additive manufacturing on mechanical and structural characteristics of polylactide composites loaded with basalt fiber involving bio-based compatibilizers. Journal of Vinyl and Additive Technology **2025**, ePub: September 2

[90] Tayfun, U. Application of sustainable treatments to fiber surface for performance improvement of elastomeric polyurethane reinforced with basalt fiber. Journal of Vinyl and Additive Technology **2023**, *29*, 1036–1045.

[91] Singh, S. P.; Singha, K. Basalt fiber: A future material for eco-composite manufacturing. Journal of the Institution of Engineers: Series D **2012**, *93*(2), 95–107.

[92] Puglia, D.; Sarasini, F.; Tirillò, J. Basalt fibre reinforced eco-composites for construction applications: A review. Materials **2018**, *11*(9), 1718.

[93] Kawaguchi, S.; Akasaka, T.; Iwahori, Y. High temperature tensile and creep behavior of basalt and carbon fibers and their composites. Advanced Composite Materials **2018**, *27*(3), 229–242.

[94] Chen, C., Ding, Y., Wang, X., & Bao, L. (2024). Recent advances to engineer tough basalt fiber reinforced composites: A review. Polymer Composites, 45(14), 12559–12574.

[95] Kotov, V.; Trofimov, A.; Bazhenov, S. Structural health monitoring of basalt fiber composites with embedded fiber Bragg gratings. Composite Structures **2019**, *220*, 173–181.

[96] Parlato, M. C.; Porto, S. M. Organized framework of main possible applications of sheep wool fibers in building components. Sustainability **2020**, *12*(3), 761.

[97] Ribeiro, D. C.; Meireles, J.; Louro, C.; Silva, F. J. G.; Peixinho, N. Recycling of waste glass fibers in polymer concrete. Journal of Composite Materials **2017**, *51*(16), 2339–2348.

[98] Oliveira, L. A.; Figueiredo, M.; Meireles, J.; Andre, J. C. Recycling of carbon fiber-reinforced composites – best available technologies, unsolved issues, and automation prospects. Composites Part B: Engineering **2020**, *183*, 107660.

[99] Russell, T.; Wood, G. Using basalt fiber reinforced polymer (BFRP) bars in Navy pier construction for corrosion resistance. ASCE Construction Research Congress Proceedings **2018**, 676–684.

[100] Feng, D.; Provis, J. L.; Deventer, J. S. J. Greenhouse gas emissions and cost analysis of geopolymer pastes in comparison to ordinary Portland cement. Journal of Cleaner Production **2017**, *165*, 234–241.

[101] Wu, G.; Lin, S.; Gao, L.; Yang, Z.; Zha, Y. Analysis of electromagnetic performance of 5.5 m diameter basalt fiber frame radome. In Annual Conference of China Electrotechnical Society, Singapore: Springer Nature Singapore, 2024, 293–300.

[102] Zhang, H.; Sun, W. F. Mechanical properties and failure behavior of 3D printed thermoplastic composites using continuous basalt fiber under high-volume fraction. Defence Technology **2023**, *27*, 237–250.