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BAZALT ASOSIDAGI KOMPOZIT MATERIALLAR

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Anotatsiya. Hozirgi kunda yuqori samaradorlikka ega, bardoshli va ekologik xavfsiz kompozit materiallarga bo‘lgan talab ortib bormoqda. Shu sababli bazalt asosidagi kompozit materiallar ilmiy va amaliy jihatdan katta qiziqish uyg‘otmoqda. Ushbu maqolada bazalt asosidagi kompozitlarning asosiy turlari, jumladan polimer matritsali, metall matritsali hamda sement/beton matritsali kompozitlarning tarkibi, tayyorlash usullari, xossalari va qo‘llanilish sohalari ko‘rib chiqilgan. Tadqiqotda bazaltning armaturalovchi komponent sifatida kompozitlarning mexanik mustahkamligi, issiqlik barqarorligi, korroziyaga chidamliligi va umumiy ekspluatatsion xususiyatlarini yaxshilashdagi roli yoritilgan. Shuningdek, turli matritsalarda bazaltdan foydalanishning afzalliklari, mavjud muammolari va istiqbollari

muhokama qilingan. Natijalar bazalt asosidagi kompozitlarning qurilish, transport, mashinasozlik va boshqa sanoat tarmoqlarida keng qo‘llash imkoniyatiga ega ekanligini ko‘rsatadi.

Kalit so‘zlar: bazalt tolasi, bazalt minerali, kompozit materiallar, polimer matritsa, metall matritsa, sement matritsasi, beton kompozitlari, armaturalash, mexanik xossalar, issiqlik barqarorligi, korroziyaga chidamlilik.

Аннотация. В настоящее время возрастает потребность в высокоэффективных, долговечных и экологически безопасных композиционных материалах. В связи с этим композиты на основе базальта вызывают значительный научный и практический интерес. В статье рассмотрены основные типы базальтовых композитов, включая материалы с полимерной, металлической и цементно-бетонной матрицей, а также их состав, методы получения, свойства и области применения. Особое внимание уделено роли базальта как армирующего компонента, способствующего повышению механической прочности, термической стабильности, коррозионной стойкости и эксплуатационных характеристик композитов. Кроме того, обсуждаются преимущества использования базальта в различных матрицах, существующие проблемы и перспективы дальнейшего развития. Результаты показывают высокий потенциал базальтосодержащих композитов для применения в строительстве, транспорте, машиностроении и других отраслях промышленности.

Ключевые слова: базальтовое волокно, базальтовый минерал, композиционные материалы, полимерная матрица, металлическая матрица, цементная матрица, бетонные композиты, армирование, механические свойства, термическая стабильность, коррозионная стойкость.

Abstract. Currently, the demand for high-performance, durable, and environmentally friendly composite materials is continuously increasing. In this regard, basalt-based composite materials have attracted significant scientific and practical interest. This article reviews the main types of basalt-based composites, including polymer matrix, metal matrix, and cement/concrete matrix composites, with particular emphasis on their composition, fabrication methods, properties, and application areas. The study highlights the role of basalt as a reinforcing component in improving the mechanical strength, thermal stability, corrosion resistance, and overall performance of composite materials. Furthermore, the advantages, current challenges, and future development prospects associated with the incorporation of basalt in various matrices are discussed. The findings demonstrate that basalt-based composites possess considerable potential for widespread applications in construction, transportation, mechanical engineering, and other industrial sectors.

Keywords: basalt fiber, basalt mineral, composite materials, polymer matrix, metal matrix, cement matrix, concrete composites, reinforcement, mechanical properties, thermal stability, corrosion resistance.

INTRODUCTION. Composite materials represent one of the most rapidly developing fields in modern materials science. The demand for composite materials with superior properties, such as high strength, low density, corrosion resistance, and long service life, has increased significantly in recent years. Replacing conventional metals and alloys with composite materials in various applications offers opportunities to reduce structural weight, decrease energy consumption, and improve economic efficiency.

In recent years, basalt-based composite materials have received considerable attention due to their unique physical, chemical, and mechanical characteristics. Basalt is a natural volcanic rock, and fibers produced from basalt exhibit high mechanical strength, excellent thermal resistance, chemical inertness, and environmental compatibility. In addition, the wide availability of basalt resources and the relatively simple processing technology make these materials economically attractive.

Depending on the type of matrix employed, basalt-based composites can generally be classified into polymer matrix, metal matrix, and cement/concrete matrix composites. Polymer matrix basalt composites are extensively used in automotive, aerospace, and construction industries because of their lightweight nature and excellent mechanical performance. Metal matrix basalt composites are suitable for applications requiring high temperature resistance and enhanced wear performance. Cement and concrete matrix basalt composites significantly improve the strength, crack resistance, and durability of construction materials.

The main objective of this article is to analyze the principal types of basalt-based composite materials, their properties, advantages, and potential applications in various industrial sectors.

A wide range of composite materials can be obtained by incorporating basalt fibers into polymer, metal, or cement-based matrices. The main categories include:

1. Polymer matrix basalt composites
2. Metal matrix basalt composites
3. Cement/concrete matrix basalt composites

Polymer matrix basalt composites are typically produced by reinforcing polymers such as epoxy resins, polyamides, or polypropylene with basalt fibers. These composites combine low density with high strength and excellent resistance to corrosion. Owing to these properties, they are widely utilized in the automotive industry, civil engineering, and aerospace applications, where lightweight, durable, and reliable materials are of paramount importance.

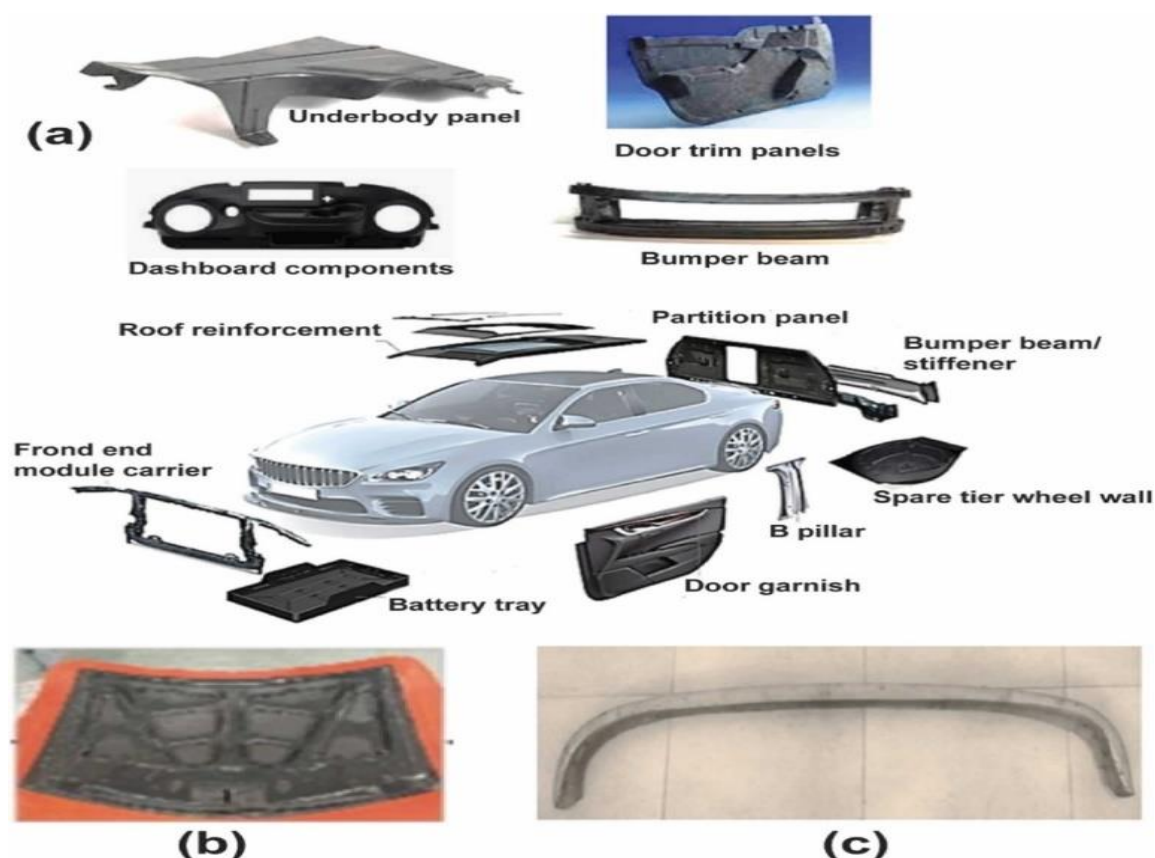


Figure 1. Applications of basalt fiber-reinforced polymer composites in the automotive sector: (a) various car components manufactured from basalt composites, (b) an engine hood produced from basalt composite, and (c) an automobile bumper (2).

At elevated temperatures, the storage modulus of polypropylene composites reinforced with 20% basalt fibers and modified with 10% MOSw was found to be comparable to that of composites containing 20% basalt fibers and 5% MOSw. However, the presence of agglomeration issues in polypropylene composites with 10% MOSw resulted in a reduction of both storage and loss moduli in the 20% basalt + 10% MOSw system. This observation highlights the sensitivity of hybrid composites to filler dispersion.

Nevertheless, the synergistic incorporation of basalt fibers and MOSw fillers significantly enhanced the viscoelastic behavior of the modified composites compared to neat polypropylene, as reflected by the improved storage and loss modulus values [1].

In recent years, interest in employing basalt fibers as substitutes for glass and carbon fibers has grown significantly due to their high tensile strength, elevated elastic modulus, and improved deformation behavior. Based on the low-velocity impact (LVI) response of basalt/aramid and basalt/nylon composites, several researchers have proposed the potential use of basalt fibers in ballistic applications. Indeed, basalt fiber has been identified as a promising material for lightweight armor systems [2].

The mechanical performance of basalt fiber-reinforced composites is superior to that of glass fiber-reinforced composites, further confirming the suitability of basalt fibers as

reinforcements in polymer composites. It was reported that silanized basalt composites exhibited a 34% increase in flexural strength and a 60% enhancement in Young’s modulus compared to untreated counterparts. These results demonstrate that incorporating basalt fibers as reinforcements in natural fiber-based composites can markedly improve both the mechanical properties and service performance of polymer matrix resins [3].

Although basalt fibers are derived directly from natural basalt rock, the chemical composition of the fibers shows minimal variability, with standard deviations of less than 1% across different production batches. However, variations in fiber diameter are more pronounced, ranging from 10.2% to 16.9%, reflecting differences in process control during the fiber-spinning stage [4].

The damage mechanisms in composites are considerably more complex compared to isotropic and homogeneous materials, as they involve multiple failure modes such as fiber breakage, matrix cracking, interfacial debonding, transverse cracking, and delamination [5]. Hybrid composites reinforced with basalt fibers in a polypropylene matrix have been fabricated using carding, needle-punching, and compression molding techniques. In addition to basalt, other fibers such as hemp, glass, and carbon were incorporated. To achieve sufficient interfacial adhesion, the fibers were surface-treated with a reactive mixture of maleic anhydride and sunflower oil. The hybrid effect in these composites was evaluated as a function of both fiber content and fiber combination. Surface treatment significantly enhanced the mechanical properties of the hybrid composites, as verified by both mechanical testing and microscopic analysis [6]. To mitigate severe corrosion and to retain excellent mechanical properties of basalt fibers in cementitious matrices over extended service periods, alkali-resistant (AR) components are uniformly incorporated within the fibers. The most widely used alkali-resistant additive is zirconium oxide, commonly introduced from AR-glass fibers. Studies have shown that a thin, stable, zirconium-rich hydrated layer formed on the fiber surface effectively slows down the diffusion of OH^- ions into the fiber core, thereby reducing progressive network degradation under alkaline environments [7].

Basalt Fiber Reinforced PLA Composites

Poly(lactic acid) (PLA) is widely employed as the primary matrix material for composite filaments. Due to its rigidity and high wear resistance, PLA-based composites are increasingly used in the manufacturing of mechanical components. Among thermoplastic feedstocks for fused deposition modeling (FDM), PLA is one of the most commonly utilized materials because of its excellent printability, making it an attractive choice as a base matrix for composite filaments. However, because of its crystalline phase at room temperature, PLA is typically considered a stiff and brittle matrix, which limits the functional performance of 3D-printed parts intended for end-use applications.

Polycaprolactone (PCL), on the other hand, has a lower glass transition temperature than ambient conditions and serves as a soft elastomeric phase. This feature enables PCL to exhibit

enhanced shape recovery and self-healing behavior under loading and heating conditions. Thus, thermoplastic matrices designed with a rigid PLA phase and a flexible PCL phase can provide 3D-printed parts with tunable stiffness and toughness. Basalt filler-reinforced PLA composites were fabricated through a multistep process. Initially, PLA pellets and basalt fillers were dried to remove moisture. The dried materials were then compounded using an extrusion process to produce composite filaments. Subsequently, the prepared filaments were utilized for manufacturing test specimens via 3D printing technology. Finally, the morphological, mechanical, thermal, and water absorption properties of the printed composites were evaluated. The overall experimental workflow adopted in this study is illustrated in Figure 2.

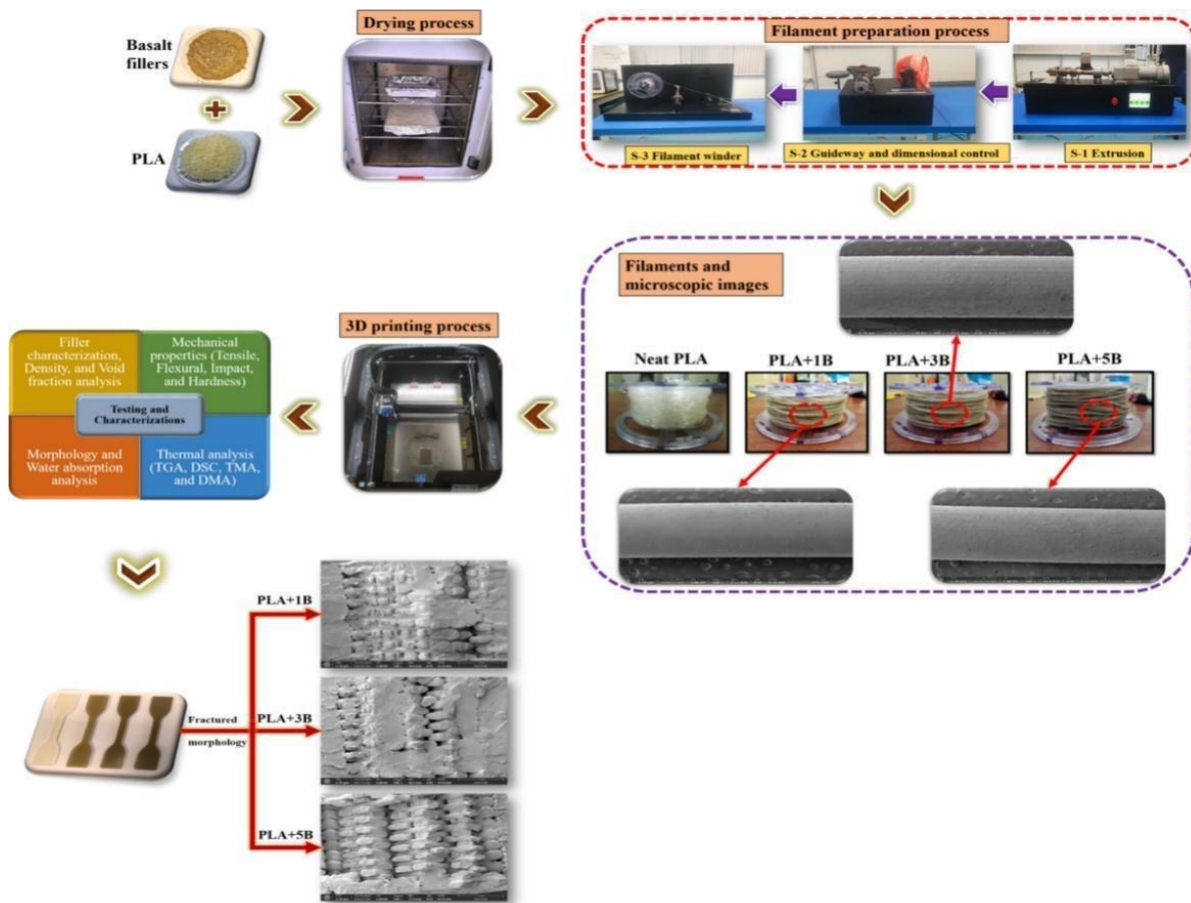


Figure 2. Schematic illustration of basalt filler reinforced PLA filament fabrication, 3D printing process, and characterization of printed composites.

Basalt fiber reinforcement in thermoplastic composites offers a cost-effective alternative to carbon fiber reinforcements. Such PLA–basalt fiber composites combine economic efficiency with improved mechanical reliability, positioning them as promising candidates for structural and functional applications in additive manufacturing [8].

Basalt powder can be employed as a cost-effective filler to enhance the thermal resistance of epoxy matrices. Due to its fine-grained structure and the presence of hard crystalline phases

such as diopside and augite, basalt powder contributes to improved wear, abrasion, and chemical resistance of the resulting composites [9].

In addition, basalt fibers are capable of reducing the rate of thermal degradation by 30–60%, while increasing the thermal stability of the composites up to approximately 300 °C. The peaks of the DTGA curves shift toward higher temperatures compared with neat epoxy, which can be attributed to the reduced resin fraction in the composites. Different reinforcement morphologies exert nearly similar influences on the thermal performance of basalt fiber reinforced polymers (BFRPs).

Dynamic mechanical analysis (DMA) has been applied to investigate the thermomechanical characteristics of cured epoxy networks. This approach allows the evaluation of key viscoelastic parameters, including storage modulus (E'), loss modulus (E''), and the mechanical damping factor ($\tan \delta$) [10].

Furthermore, the incorporation of polymers containing hydroxyl, carboxyl, or epoxy functional groups can further improve the interfacial properties of fiber-reinforced polymer composites. Functionalized additives with branching structures enhance adhesion through intermolecular interactions and phase separation processes, thereby strengthening the matrix–fiber bonding [11].

This study also emphasizes that vinyl ester resins reinforced with modified basalt fibers exhibit superior corrosion resistance compared with their unmodified counterparts, highlighting the potential of basalt-based fillers and reinforcements for long-term durability in aggressive environments [12].

In this study, woven basalt fibers and carbon fibers were selected as reinforcing materials, while epoxy resin served as the matrix to fabricate hybrid composite laminates. Samples with different lamination configurations were manufactured using the vacuum-assisted resin transfer molding (VARTM) process.

It was observed that the C composite (containing only carbon fibers) fractured into three distinct pieces under flexural loading, indicating a brittle failure mechanism. In contrast, the B composite (comprising only basalt fibers) exhibited a less brittle fracture pattern, demonstrating improved integrity and flexibility compared to the carbon-based laminate [13].

Furthermore, this research investigated the effect of basalt fiber recovery on the mechanical performance of basalt fiber reinforced composite laminates through a thermal recycling process conducted in air at 500 °C. The basalt fibers displayed remarkable thermal stability, with only 1.75% weight loss recorded during the treatment. Importantly, the recovered fibers retained their original woven architecture, which enabled their reuse in the fabrication of new laminates [14].

Any load applied to a composite is first transferred through the polymer matrix and subsequently transmitted to the fibers across the fiber–matrix interface. Therefore, this interfacial region plays a decisive role in determining the ultimate properties of the composite. Enhanced interfacial adhesion can be achieved either by modifying the fiber surface via chemical or plasma

treatment, or through bulk modification of the matrix by incorporating coupling agents such as maleic anhydride grafted polypropylene (PP-g-MA) [15].

In the case of basalt fibers, however, the conventional thermal treatments applied to carbon fibers cannot be employed, since exposure to temperatures above 300 °C results in a significant reduction of fiber strength due to alterations in their crystalline structure [16].

Once basalt fiber reinforced polymers (BFRPs) are fabricated and molded, additional machining is often required to achieve the desired dimensional accuracy and tolerance. Unlike isotropic metallic materials, BFRPs exhibit anisotropy, which gives rise to specific material removal mechanisms [17].

Moreover, hybridization of basalt fibers with carbon fibers not only yields a cost-effective composite but also reduces the variability in the tensile properties typically observed in conventional CFRPs. The incorporation of basalt fibers into carbon fiber laminates has been shown to increase absorbed impact energy, enhance crack propagation resistance, improve laminate flexibility, and promote progressive damage distribution while preventing catastrophic failure and delamination [18].

From a mechanical perspective, continuous basalt fibers are competitive with glass fibers. The elastic modulus of basalt fibers strongly depends on their chemical composition, yet it is generally comparable to, or slightly higher than, that of glass fibers, while their tensile strength and elongation at break are superior [19]. Another notable feature of basalt fibers is their good compatibility with matrix materials, even though certain studies have explored surface treatments aimed at modifying their morphology and improving wettability [20].

Since the long-term chemical durability of mineral fibers cannot be precisely measured or determined, they are usually compared after accelerated exposure tests under identical experimental conditions. The corrosion rate is influenced by multiple parameters, including temperature, exposure duration, fiber composition, the chemical constituents of the surrounding medium, and any protective coatings applied to the fibers [21]. The influence of basalt fibers on the thermal performance of intumescent coatings has also been investigated. However, one of the main challenges lies in the dispersion of basalt fibers. When incorporated into coatings, they often tend to agglomerate, leading to non-uniform structures that may compromise fire resistance. Nevertheless, the introduction of dispersing agents can significantly enhance the distribution of basalt fibers within intumescent coatings, thereby improving their effectiveness [22].

Basalt fiber (BF) is a multifunctional reinforcement distinguished by its resistance to acids and alkalis, as well as its excellent thermal stability across a broad temperature range (from –260 °C up to 700 °C), whereas glass fibers can typically operate only between –50 °C and 300 °C. In addition, basalt fibers exhibit good wettability and a variety of other outstanding characteristics [23]. Another significant feature of basalt fibers is their strong compatibility with matrix phase materials. Consequently, they have been widely employed as reinforcements in polymers such as

epoxy, polyester, and vinyl ester resins. Among these, epoxy resin has become the most commonly used matrix for basalt-fiber-reinforced composites, owing to its favorable mechanical properties, resistance to moisture uptake, durability against corrosive liquids and harsh environments, good weathering performance, low curing shrinkage, and broad versatility [24].

Recently, basalt fibers have gained considerable attention as a potential competitor in concrete reinforcement due to their excellent mechanical performance and environmentally friendly production process. In general, the tensile strength of basalt fibers is slightly higher than that of E-glass fibers and several times greater than that of steel fibers. In addition to conventional chopped basalt fibers (BF), a novel reinforcement product known as *minibars* (MBs) has been developed. These minibars are essentially scaled-down versions of basalt fiber-reinforced polymer rebars [26].

Experimental investigations revealed that the incorporation of PVA fibers significantly enhanced the post-cracking flexural response compared to basalt fibers. Beams containing 3% PVA fibers by volume exhibited a pronounced strain-hardening behavior, along with an improvement in post-cracking flexural strength. This indicates that higher PVA fiber contents made the beams stiffer and more ductile. In contrast, beams with higher proportions of basalt fibers demonstrated a strain-softening behavior [27].

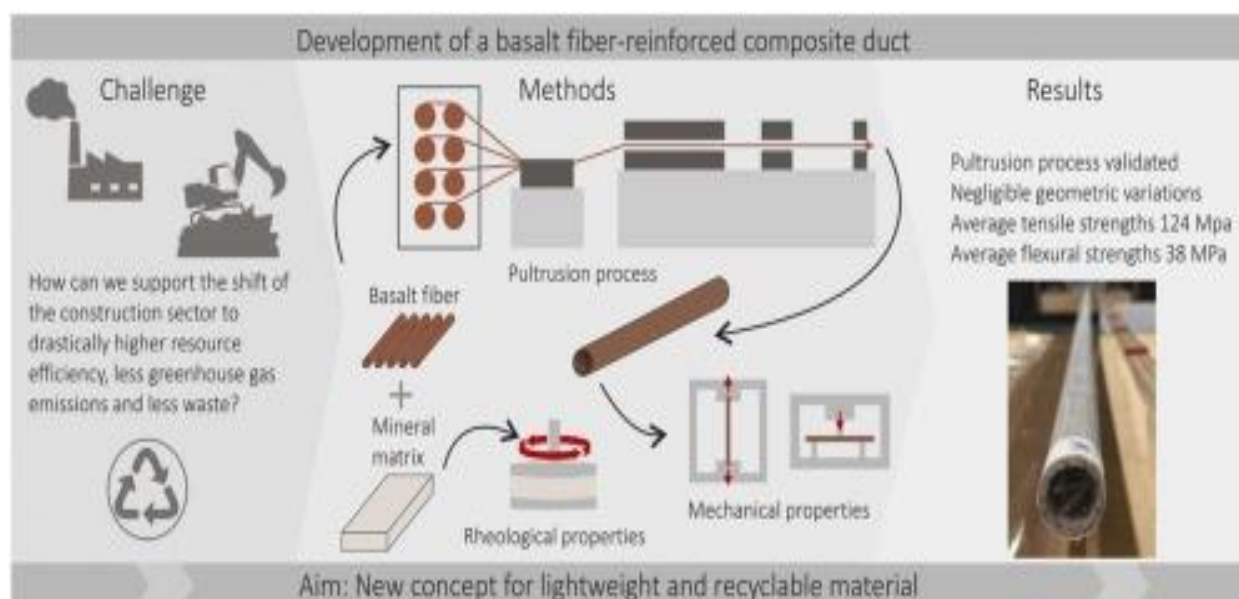


Figure 3. Development of Basalt Fiber-Reinforced Composite Pipes

This infographic illustrates the manufacturing process of composite pipes reinforced with basalt fibers. Using the pultrusion technique, basalt fibers are combined with a mineral-based matrix to produce pipes that are strong, lightweight, and environmentally recyclable. The process provides significant advantages, such as enhanced mechanical properties (124 MPa tensile strength and 38 MPa flexural strength), along with sustainable production that requires relatively low resource consumption (Fig. 3) [28].

CEMENT/CONCRETE MATRIX BASALT COMPOSITES

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Basalt fiber-reinforced cementitious matrices (BFRCMs) are typically prepared with open fabric meshes, where basalt rovings are aligned in two directions—usually orthogonal—and assembled using techniques such as weaving, knitting, tufting, or winding. In this system, the cementitious material not only serves as the matrix phase but also functions as a binder to the substrate on which the FRCM is applied [31].

CONCLUSION

The analysis revealed that basalt-based composite materials are characterized by high mechanical strength, excellent thermal stability, corrosion resistance, and long-term durability. Polymer matrix basalt composites are widely utilized in transportation and mechanical engineering industries due to their low weight and high specific strength. Metal matrix basalt composites exhibit superior performance under high-temperature and severe loading conditions. Cement and concrete matrix basalt composites enhance the mechanical strength, crack resistance, and service life of construction materials.

Nevertheless, further investigations are required to better understand the interfacial interactions between basalt reinforcements and different matrices, improve interfacial bonding, and optimize manufacturing processes. Overall, basalt-based composite materials demonstrate substantial potential as promising alternatives to conventional materials in a wide range of modern industrial applications.

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