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REVIEW

Basalt Fiber for Pavements in China: Properties, Standardized Design, and Construction Practices

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ABSTRACT: Basalt fiber (BF), derived from abundant volcanic rock in China, represents a sustainable reinforcement material for pavement engineering, addressing challenges like durability, corrosion, and environmental impact. This comprehensive review synthesizes BF's properties, including high tensile strength (3000–4800 MPa), thermal stability (−269°C to 700°C), and superior chemical resistance compared to steel or polypropylene fibers. Production involves melting basalt at 1450°C–1500°C, with China leading in resources and standards like JT/T776.1-2010. Applications in asphalt concrete enhance rutting resistance by 30%–50% and fatigue life by 20%–40%, while in cement concrete, BF improves crack resistance and impermeability by 30%–55%. BF composite rebars offer corrosion-free alternatives for bridges and pavements, reducing energy consumption to 46% of steel equivalents. Engineering practices, including mix designs and construction methods, demonstrate economic viability and sustainability benefits, aligning with China's "Made in China 2025" initiatives. Future prospects emphasize hybrid systems and standardization for broader adoption.

KEYWORDS: Basalt fiber; pavement engineering; asphalt concrete; cement concrete; composite rebars

1 Introduction

Pavement engineering is essential for contemporary infrastructure development, guaranteeing safe, durable, and efficient transportation systems [1]. With the rapid acceleration of global urbanization and increasing traffic loads, the necessity for new materials that improve pavement performance and foster sustainability has reached unprecedented levels [2,3]. Basalt fiber (BF), an innovative material generated from natural volcanic rock, emerges as a noteworthy reinforcement [4]. As shown in Fig. 1, BF produced by melting basalt rock at high temperatures (around 1400°C–1500°C) and extruding it into fine filaments, represents a high-performance material with roots in natural geology [5]. Unlike synthetic fibers such as glass or carbon, basalt fiber is manufactured from abundant, renewable basalt deposits, making it an eco-friendly alternative without the need for chemical additives during production. Its inherent properties include exceptional tensile strength ranging from 2600 to 4840 MPa [6], high modulus of elasticity (89–110 GPa), excellent thermal stability (up to 700°C without degradation), and superior resistance to corrosion, alkalis, and acids [7]. These attributes have positioned basalt fiber as a versatile reinforcement in various civil engineering applications, from structural composites to geotechnical solutions.

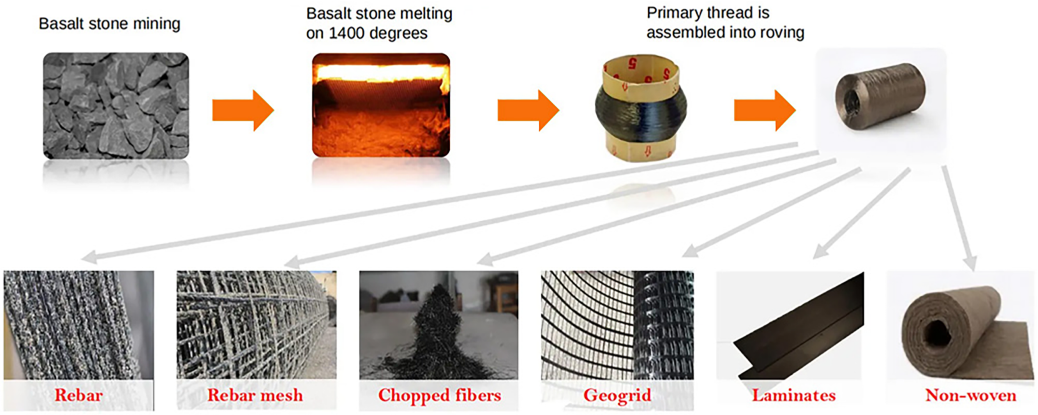


Figure 1: Production process and applications of BF products [8].

In civil engineering, basalt fiber's significance emerged in the late 20th century, with initial uses in Russia and Ukraine where basalt resources are plentiful [5,9]. For instance, basalt fiber reinforced polymers (BFRP) have been employed as alternatives to steel rebar in bridges and buildings, reducing corrosion-related failures that plague traditional materials in harsh environments like coastal or de-icing salt-exposed areas [4]. The transition to pavement engineering amplifies BF's value. Pavements, subjected to repetitive loading, thermal cycling, and environmental stressors, often suffer from cracking, rutting, and fatigue [10]. Traditional reinforcements like steel or polypropylene fibers provide some benefits but come with drawbacks such as high weight, susceptibility to rust, or environmental concerns from petroleum-based production. BF addresses these by integrating seamlessly into asphalt and cementitious mixtures.

Studies show that short-cut BFs, typically 6–24 mm in length, enhance the crack resistance and deformability of asphalt composites by bridging micro-cracks and distributing stresses more evenly [11]. In cement concrete pavements, BFs improve flexural strength and impact resistance, making them ideal for high-traffic roads or airport runways [5]. For example, incorporating BFs into asphalt mixtures has been shown to increase rutting resistance by up to 30%–50%, fatigue life by 20%–40%, and low-temperature cracking resistance through better viscoelastic behavior [12]. Mechanical enhancements stem from the fiber's high aspect ratio and surface roughness, which promote strong interfacial bonding with the binder. Thermally, BF's low conductivity helps mitigate heat-induced distress in hot-mix asphalt, a common issue in warmer climates. Moreover, in geotechnical contexts, BF geotextiles reinforce subgrades, preventing soil erosion and improving load-bearing capacity in soft terrains. Also, BF outperforms steel fiber and polypropylene fiber in improving concrete performance due to its superior tensile strength, chemical stability, thermal resistance, and natural compatibility with cement [13,14]. It enhances concrete's crack resistance, impermeability, impact resistance, and durability while being cost-effective compared to steel fiber and requiring less modification than polypropylene fiber [15]. BF can withstand extreme temperatures (−269°C to 700°C), resists corrosion in acidic and alkaline environments, and provides excellent insulation and UV resistance [16]. Its finer diameter and better dispersion in concrete enable stronger bonding and improved structural properties, making it ideal for challenging environments and high-performance applications [17].

Despite these advantages, current pavement materials face limitations such as vulnerability to environmental degradation, high maintenance costs, and limited longevity under heavy loads, contributing to frequent repairs and resource waste. BF adoption, while promising, encounters challenges including higher initial production costs, limited scalability due to concentrated manufacturing facilities and raw material inconsistencies, and a lack of comprehensive industry standards, which can hinder widespread implementation in regulated sectors like infrastructure.

Sustainability in pavement engineering encompasses reducing environmental footprints, enhancing resource efficiency, and promoting circular economy principles. This context fuels the demand for innovative, eco-conscious materials. Recycled aggregates, warm-mix asphalt, and bio-based binders have gained traction, but fiber reinforcements such as BF multifaceted benefits. As a naturally occurring material, BF production avoids synthetic chemicals, and its recyclability aligns with circular economy goals, fibers can be reused in new mixes without significant property loss. Environmentally, it lowers the carbon footprint: Life-cycle assessments indicate that BF-reinforced pavements reduce emissions by 20%–30% over their extended service life due to decreased maintenance needs [18]. Engineering practice, such as spanning mix design and construction techniques, shows clear cost-effectiveness and sustainability gains, in line with China's "Made in China 2025" agenda [19].

This paper pursues eight integrated aims. First, we synthesize the fundamentals of BF, its origin, basalt ore chemistry, and key mechanical, chemical, and physical properties, including compatibility with silicates. Second, we benchmark BF against steel, glass, polypropylene, lignin, and polymer fibers in terms of performance, durability, constructability, and sustainability. Third, we evaluate chopped BF in asphalt concrete (AC), detailing mechanisms, mix design and dispersion, dosage ranges, laboratory and field performance (tensile/fatigue, rutting/cracking, moisture and temperature stability), and economic viability. Fourth, we assess basalt chopped fiber in cement concrete, covering performance indicators, mix design, dosage optimization, crack control, toughness and durability, comparative benchmarking with steel and polypropylene, and cost analyses. Fifth, we examine BF composite bars (BFRP) for pavements and bridges, including properties, functions, construction methods, economics, standards, and multi-project case evidence. Unidirectional cloth, geogrids, and structural profiles were also investigated, focusing on construction methods, performance metrics, and application domains. We document basalt rock wool performance and applications. Finally, we analyze energy consumption and embodied impacts relative to steel bars and other composites to quantify sustainability benefits and inform standards and design guidance.

2 Mechanical Properties of Basalt Fiber

BF derived from natural volcanic rock, has gained significant attention as a sustainable and high-performance alternative to traditional reinforcements like glass fibers (Table 1). Produced through a process similar to that of glass fibers but with lower energy consumption and no additives, BFs offer superior mechanical, thermal, and chemical properties. They exhibit excellent tensile strength, elastic modulus, and chemical stability, making them resistant to high temperatures, alkaline environments, and corrosion [20]. These characteristics enable BFs to be used in a wide range of applications, including polymer, metal, and concrete matrices, as well as hybrid composites. Due to their eco-friendliness, cost-effectiveness, and versatility, BFs are increasingly being adopted in industries such as construction, automotive, aerospace, and energy [21].

Table 1: E-Glass and BFs properties compared [22].

Property	E-Glass	BF
Density (g/cm^3)	2.56	2.8
Elastic modulus (GPa)	76	89
Tensile strength (GPa)	1.4–2.5	2.8
Elongation to fracture (%)	1.8–3.2	3.15

(Continued)

Table 1 (continued)

Property	E-Glass	BF
Specific E modulus (GPa/g/cm^3)	30	31.78
Specific tensile strength (GPa/g/cm^3)	0.5–1	1

3 Application of Basalt Fiber in Asphalt Concrete

BF significantly enhances the properties of asphalt and asphalt mixtures by improving viscosity, mechanical strength, and deformation resistance. The addition of BFs increases asphalt viscosity, as indicated by changes in penetration and softening point, making these parameters suitable for evaluating fiber-modified asphalt. Experimental results suggest an optimal fiber content of 0.3%–0.4%, where splitting strength and stiffness modulus are maximized without significant further improvements at higher dosages. The fibers form a reinforcing network within the asphalt mixture, bridging cracks and increasing resistance to deformation and crack propagation. These effects are attributed to the enhanced interface strength between the aggregate and asphalt, as well as the increased surface area provided by the fine BFs. BFs also improve Marshall stability and water stability, making them a promising additive for enhancing asphalt pavement performance [23]. Chopped BFs for asphalt concrete are made from natural basalt ore, which is melted at 1450°C–1500°C and continuously drawn into homogeneous long fibers. These continuous fibers are then processed using special techniques to produce chopped BFs with excellent compatibility with asphalt. Depending on the different types and characteristics of asphalt mixtures, chopped BFs for asphalt are treated differently to better suit various types of asphalt mixtures (Fig. 2).


(a) (b)

Figure 2: Applications of basalt short-cut fibers in asphalt pavement Construction (**a**) Basalt short-cut fibers, (**b**) Constructed asphalt pavement.

3.1 Standards and Specifications for BF-Asphalt Concrete

The standard "*Highway Engineering-Basalt Fiber and Its Products, Part 1: Basalt Chopped Fiber*" [24] outlines the technical requirements and specifications for basalt chopped fiber used in highway engineering. The "*Technical Specifications for Asphalt Pavement Construction*" [25] specifies that fibers added to asphalt mixtures should include lignin fibers and mineral fibers. It recommends the use of mineral fibers, such as those made from basalt, while discouraging the use of asbestos fibers due to their potential harm to the environment and human health. The proportion of fiber stabilizers should be calculated as a percentage of the total asphalt mixture mass, with the mineral fiber content for Stone mastic asphalt (SMA) pavements being no less than 0.4%, with adjustments as necessary [26]. JTG D40-2011 standard [27] provides comprehensive instructions on pavement structure design, material selection, and construction techniques, ensuring the durability, load-bearing capacity, and performance of cement concrete pavements. It addresses factors such as traffic load, environmental conditions, and subgrade preparation, while also emphasizing quality control measures and sustainability. As an essential document for highway construction projects, it supports the development of long-lasting and cost-effective concrete pavement systems.

3.2 Construction Method for BF-Asphalt Concrete

3.2.1 Materials

To ensure the quality of materials, coarse and fine aggregates, as well as fillers, must meet the required standards, and non-compliant materials are prohibited from entering the mixing plant. Storage areas for aggregates should be hardened with effective drainage systems to prevent contamination, and different materials must be separated by walls to avoid mixing. Fine aggregates and mineral powder must be covered to prevent moisture, as wet fine aggregates can affect feeding quantity and production output. The quality of BF must be inspected prior to construction, ensuring compliance with the JT/T776.1 [24]. Additionally, BF should be stored indoors or under shelter, with loose fibers protected from moisture and clumping during transport and use.

3.2.2 Mix Design

The gradation design of asphalt mixtures must comply with the Specifications for Design of Highway Asphalt Pavements (JTG D50-2006) and the Test Procedures for Asphalt and Asphalt Mixtures in Highway Engineering (JTJ 052-2000). The mix design process for BF asphalt mixtures consists of four stages: theoretical mix design, target mix design, production mix design, and trial production with testing of road sections. The design should adhere to the requirements outlined in the Technical Specifications for Asphalt Pavement Construction (JTG F40-2004) to determine the gradation and fiber content. BF content is calculated as a percentage of the total mixture mass, with 0.4% recommended for SMA pavements and 0.3% for Asphalt Concrete (AC) pavements.

3.2.3 Mixing BF-Asphalt Mixture

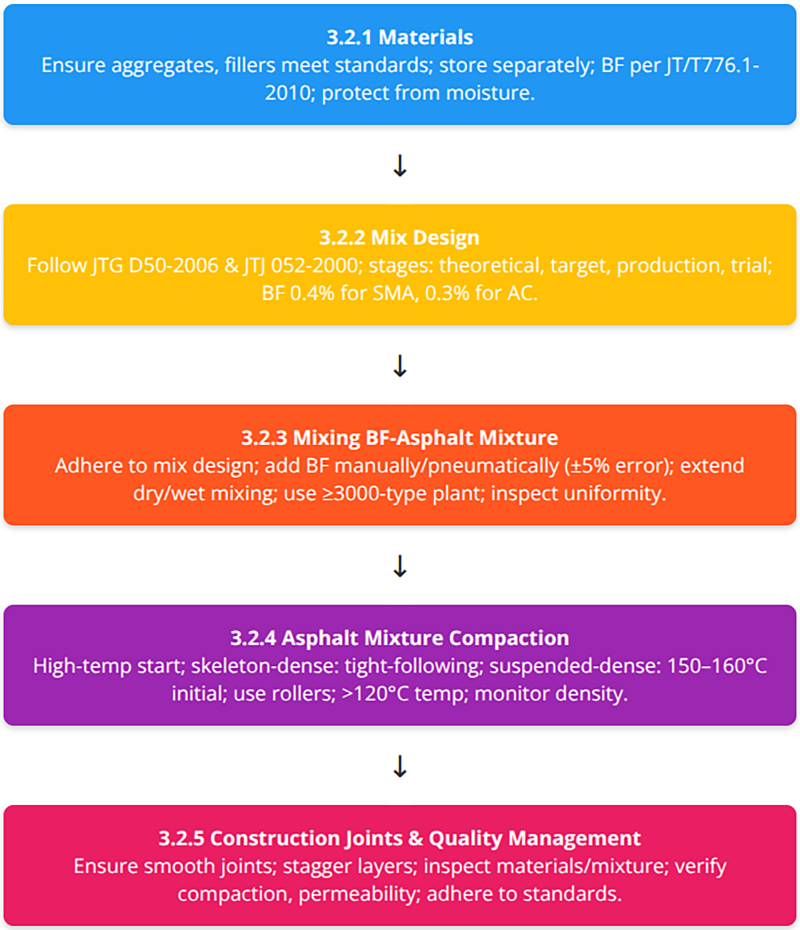
Mixing BF asphalt mixtures must strictly adhere to the verified mix design, with BF content determined based on the actual plant mixing capacity for each batch. BF can be added either manually or via pneumatic feeding equipment, with manual feeding requiring pre-measured quantities and pneumatic feeding calibrated to an allowable error margin of ±5%. Mixing temperatures should follow the "*Technical Specifications for Asphalt Pavement Construction*" (JTG F40-2004) and may be slightly increased due to the higher viscosity caused by BF. It is recommended to add BF during the dry mixing stage with aggregates and mineral powder, extending dry mixing by 5 s for even dispersion. After adding asphalt, wet mixing should be extended by 2 s to ensure full coating of fibers and aggregates. Asphalt mixture production should use a 3000-type or larger batch-type asphalt mixing plant to maintain sufficient output and continuous paving, especially in low temperatures. Quality inspections must confirm even fiber dispersion and uniformity of the mixture while monitoring for abnormalities like color inconsistencies, excessive smoke, segregation, or leakage, with adjustments made as necessary.

3.2.4 Asphalt Mixture Compaction

For skeleton-dense asphalt mixtures, compaction should begin immediately at high temperatures using a "tight-following, slow compaction" method to prevent aggregate damage. For suspended-dense mixtures, initial compaction should occur at 150°C–160°C with a 12-t steel roller for static compaction, followed by a 26-t pneumatic roller (2 passes), a 12-t vibratory roller (2 passes), and final static compaction with a 12-t steel roller, ensuring temperatures remain above 120°C. Vibratory rollers should follow principles of tight-following, slow speed, high frequency, and low amplitude. Rollers must operate in parallel, with overlaps of 20 cm for vibratory rollers and 1/3–1/4 width for static rollers. Oil spraying is prohibited; water or release agent solutions may be used. Prompt compaction by sufficient rollers (at least two for initial and secondary passes) should achieve required density within 20–30 m sections, monitored by specialized personnel. Pavement cooling should occur below 50°C before opening to traffic, though water cooling may be used for early access.

3.2.5 Construction Joints and Quality Management

Construction joints in asphalt paving must ensure smooth transitions and structural integrity. Longitudinal joints in tandem paving should leave a 10–20 cm unrolled strip for overlap, compacted as a hot joint, with upper and middle layers staggered by at least 15 cm. Transverse joints require clean cutting, residue removal, tack asphalt application, and steel roller compaction, starting on the existing layer and moving to the new one. Transverse joints must be 20 m away from bridge expansion joints. Quality management includes inspecting raw materials such as asphalt, aggregates, and BF, and monitoring mixture properties like binder ratio, gradation, and compaction temperatures. Surface layer checks focus on thickness, smoothness, density, and friction. Compaction is verified by core drilling or calibrated nuclear gauges. Water permeability must meet an 80% passing rate, with additional testing and surface treatment if necessary. All processes adhere to relevant highway asphalt pavement standards and specifications (Fig. 3).



3.2.1 Materials
Ensure aggregates, fillers meet standards; store separately; BF per JT/T776.1-2010; protect from moisture.

↓

3.2.2 Mix Design
Follow JTG D50-2006 & JTJ 052-2000; stages: theoretical, target, production, trial; BF 0.4% for SMA, 0.3% for AC.

↓

3.2.3 Mixing BF-Asphalt Mixture
Adhere to mix design; add BF manually/pneumatically (±5% error); extend dry/wet mixing; use ≥3000-type plant; inspect uniformity.

↓

3.2.4 Asphalt Mixture Compaction
High-temp start; skeleton-dense: tight-following; suspended-dense: 150–160°C initial; use rollers; >120°C temp; monitor density.

↓

3.2.5 Construction Joints & Quality Management
Ensure smooth joints; stagger layers; inspect materials/mixture; verify compaction, permeability; adhere to standards.

Figure 3: Construction method for BF-asphalt concrete.

3.2.6 Potential Challenges in Construction

Fiber dispersion is a primary concern, as inadequate mixing can lead to clumping, reducing uniformity and weakening the mixture's reinforcement. This may result from high BF dosages or insufficient dry mixing time, potentially increasing voids and susceptibility to moisture damage. Other issues involve higher initial viscosity requiring adjusted mixing temperatures (up to 5°C–10°C higher), which could elevate energy use, and storage sensitivity to moisture, risking degradation. Field trials and quality checks are recommended to mitigate these, ensuring optimal performance.

3.3 Advantages and Disadvantages of Different Fibers in Asphalt Mixtures

When chopped fibers are added to asphalt concrete (AC), the discontinuity of the fibers creates complex interactions between the fibers themselves and between the fibers and the surrounding matrix. These interactions significantly affect the toughness and failure process of the composite material, contributing to increased elasticity, viscosity, strength, and toughness. Fibers commonly added to asphalt concrete both domestically and internationally include lignin fibers, polymer fibers, and inorganic mineral fibers, each of which has its own unique performance characteristics. A comparison of the advantages and disadvantages of several types of fibers for asphalt is shown in Table 2.

Table 2: Comparison of various asphalt pavement fibers [28].

Fiber type	Advantages	Disadvantages
Lignin fiber	- Enhances toughness and viscosity - Improves aging resistance and water stability of the mixture	- Easily absorbs moisture, forming water films between aggregates and asphalt binder - Less effective in large-void hot-mix asphalt - Less effectiveness in porous structures - Poor durability
Polymer fiber	- High-temperature stability - High resistance to cracking - Resistance to freezing/water damage - Low density	- Lower oil absorption compared to lignin fibers - Low high-temperature resistance
Inorganic mineral fiber	- Increasing asphalt thickness and improving oxidation and aging resistance - High tensile strength and toughness of asphalt mixtures - Non-absorbent and moisture-resistant - Good high-temperature resistance	- Brittle due to crystalline particles in fibers, easily breaking during mixing and paving, altering fiber aspect ratio and making control difficult - Complex production process with low efficiency and insufficient domestic production capacity, leading to high costs and limited application

3.4 Comparison of Test Data for Basalt Fiber

This section highlights the benefits of incorporating BF into asphalt mixtures compared to ordinary asphalt and other fiber-modified mixtures. Table 3 shows that AC-16 BF-asphalt mixtures outperform ordinary AC-16 asphalt mixtures in key properties, such as stability (19.2 vs. 14 kN), dynamic stability at 60°C (2310 vs. 1210 cycles/mm), and residual strength ratio (81.7% vs. 76.8%), with zero water permeability, meeting or exceeding standard requirements. Table 4 compares asphalt mixtures with varying fiber contents and asphalt-aggregate ratios. The AC-16 BF mixture (0.3% fiber) achieves superior dynamic stability (6282 cycles/mm) with the lowest coefficient of variation (2.5%), indicating improved consistency. SMA-13 mixtures with BF (0.4%) also outperform lignin fiber, with higher dynamic stability (6441 vs. 5403 cycles/mm). These results demonstrate that BF enhances asphalt mixtures durability, stability, and resistance to deformation, making it a superior additive for high-performance pavements. Test results indicate that adding BF to asphalt concrete significantly improves the performance of asphalt mixtures, with performance enhancements of approximately 30%–45%, thereby extending the service life of pavements. Furthermore, adding basalt fiber to SMA asphalt concrete significantly reduces the asphalt-aggregate ratio, decreasing oil consumption and offering a high cost-performance ratio, resulting in notable social and economic benefits.

Table 3: Comparison of test results: BF asphalt mixture vs. ordinary asphalt mixture.

Test Item	AC-16 BF Asphalt Mixture	AC-16 Asphalt Mixture	Standard Requirement
Bulk Volume Density (g/cm^3)	2.419	2.406	–
Optimal Asphalt-Aggregate Ratio (%)	4.9	4.8	–
Stability (kN)	19.2	14	≥8
Flow Value (mm)	3.1	3.5	2–4
Dynamic Stability at 60°C (cycles/mm)	2310	1210	≥800
Residual Strength Ratio (RSR) (%)	81.7	76.8	≥70
Permeability Coefficient (mL/min)	0	37	≤120

Table 4: AC modified asphalt vs. SMA.

Asphalt Mixture Type	Asphalt-Aggregate Ratio (%)	Dynamic Stability (cycles/mm)	Coefficient of Variation (%)
AC-16 Modified Asphalt Mixture	4.9	5915	8.5
AC-16 Basalt Fiber Modified Asphalt Mixture (0.3% fiber)	5.0	6282	2.5
SMA-13 Asphalt Mixture with Lignin Fiber (0.3% fiber)	5.9	5403	8.3
SMA-13 Asphalt Mixture with Basalt Fiber (0.4% fiber)	5.6	6441	5.5

3.5 Advantages of BF in Asphalt Mixtures

BF has excellent surface affinity with asphalt, making it an ideal oil-absorbing fiber. It increases asphalt content, enhances the thickness of the asphalt film, and improves the oxidation resistance of asphalt mixtures. With high strength and elastic modulus, BF is an exceptional reinforcing material based on composite material reinforcement principles. It significantly enhances the tensile strength and toughness of asphalt mixtures, which improves the asphalt pavement's resistance to low-temperature cracking and fatigue durability. It also helps improve deformation resistance at high temperatures, reducing rutting. BF is non-absorbent and resistant to moisture, making it easy to transport and store. It also helps prevent oxidation aging of the asphalt film and improves adhesion between the asphalt film and aggregates, thereby reducing water damage to the pavement. Its high-temperature resistance makes it suitable for hot-mix asphalt environments. Being 100% natural, BF does not harm the environment or human health. Its high-temperature resistance ensures that BF-asphalt concrete can be recycled, reducing maintenance costs significantly. Tests conducted on municipal roads in Taiyuan City showed that compared to ordinary asphalt, basalt fiber asphalt can reduce road noise by 5 db, lowering noise pollution along the roads. Additionally, it improves pavement adhesion in rainy and snowy weather, enhancing anti-slip performance.

3.6 Mechanism of BF in Asphalt Mixtures

While mechanisms like adsorption and reinforcement are common across fiber types in asphalt mixtures, BF offers distinct advantages due to its volcanic origin, providing superior tensile strength and thermal stability compared to glass or polypropylene (Fig. 4). Experimental data demonstrates BF's higher viscosity enhancement in mixtures, reducing aging more effectively than synthetics, underscoring its unique role in sustainable pavements [29,30].

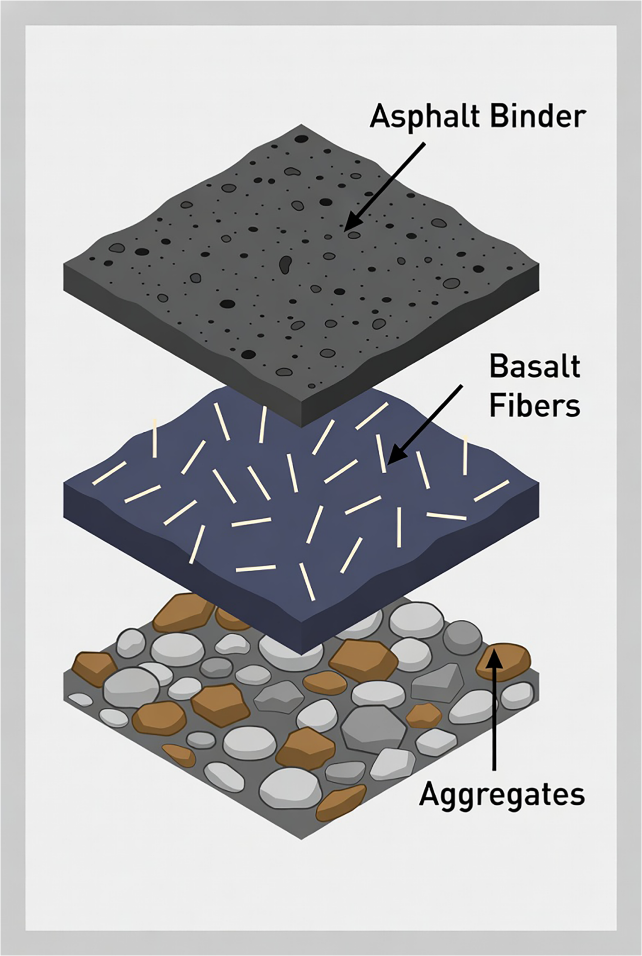


Figure 4: Schematic of basalt fiber mixed with asphalt binder and aggregates.

3.6.1 Adsorption Effect

Dispersed fibers in asphalt, with their large surface area, form a wetting interface that absorbs asphalt, increasing the thickness of the asphalt film on aggregate surfaces. This helps slow down asphalt aging.

3.6.2 Stabilizing Effect

In asphalt mixtures, the crisscross fibers absorb asphalt, increasing the proportion of structural asphalt and enhancing the viscosity of the mixture. This raises the softening point of the asphalt, improving high-temperature stability. During high-temperature seasons, when asphalt expands under heat, the voids within the fibers act as buffers, preventing free asphalt from bleeding, further contributing to high-temperature stability.

3.6.3 Reinforcing Effect

The fibers are randomly distributed in a three-dimensional structure within the mixture. Due to their high strength and large quantity, they provide widespread reinforcement, hindering the development of cracks. This increases the strength of the asphalt pavement and its ability to self-heal cracks, reducing their occurrence. Without fibers, large quantities of asphalt and mineral powder may form clumps that cannot evenly disperse among aggregates. Fibers ensure proper dispersion of these clumps.

3.6.4 Adhesion Enhancement Effect

By absorbing asphalt, fibers improve the wrapping force of asphalt on aggregate particles. This strengthens the bond between aggregates through the asphalt film, ensuring the overall cohesion of the asphalt pavement and reducing looseness. This leads to improved road construction quality.

3.7 Economic Analysis of BF in Asphalt Concrete

For a two-way four-lane road with a width of 15 m and an asphalt layer thickness of 0.04 m and based on the national construction standards specified chopped BF addition rate of 0.4% of the asphalt mixture mass, the consumption of chopped BF per km is 6 t, at a cost of 138,000 RMB as follows:

15 m (road width) × 1000 m × 0.04 m (asphalt thickness) × 2500 kg/m^3 (asphalt mixture density) × 0.4% × 23 RMB/kg (unit price of chopped fiber) = 138,000 RMB.

4 Application of Basalt Fiber in Cement Concrete

Chopped BF for cement is an inorganic mineral fiber, made by chopping continuous BF into lengths less than 50 mm (Fig. 5). BF for cement can replace cellulose and glass fibers mixed in cement mortar, or polypropylene, polyacrylonitrile, and steel fibers mixed in cement concrete. It effectively enhances the impact resistance, wear resistance, crack resistance, impermeability, and workability of cement mortar or concrete. As a typical silicate fiber, BF mixes easily with cement concrete and mortar, ensuring good dispersion. Concrete mixed with BF exhibits excellent volume stability, workability, durability, reinforcement, toughening, impermeability, crack resistance, and impact resistance. The cost of adding short-cut BF to cement concrete is significantly lower than using steel or carbon fibers.


(a) (b)

Figure 5: BF reinforcement in cement and shield tunnel segments (**a**) Short-cut BF for cement, (**b**) Basalt shield tunnel segments.

4.1 Performance Indicators of Basalt Fibers for Cement

The performance indicators of short-cut basalt fiber for cement must meet the requirements of "*Highway Engineering, Basalt Fiber Products*" (JT/T776.1-2010) and short-cut BF for cement concrete and mortar (GB/T 23265-2009), as shown in Table 5.

Table 5: Performance indicators of short-cut BF and cement concrete and mortar mixed with BF.

Test Item	**Short-Cut BF for Concrete**		**Short-Cut BF for Mortar**
Crack-Resistant of Fiber	**Crack Resistant**	**Toughening and Reinforcing Fiber**	**Crack Resistant**
Tensile strength (MPa) ≥	1050	1250	1050
Elastic modulus (GPa) ≥	75	80	75
Elongation at break (%) ≤	3.0	3.0	3.0
Alkali resistance, Single fiber strength retention rate (%) ≥	75	75	75
Cement Concrete and Mortar Mixed with BF			
Dispersion relative error (%)	−10 to +10	−10 to +10	−10 to +10
Reduction in concrete/mortar cracks (%)	55	55	55
Concrete compressive strength ratio (%)	95	100	_
Mortar compressive strength ratio (%)	_	_	95
Improvement in concrete impermeability (%)	30	30	_
Mortar water permeability pressure ratio (%)	_	_	120
Toughness index (I_5)	_	3	_
Concrete impact resistance (%)	160	300	_

4.2 Characteristics of BF-Concrete

According to a series of tests conducted by the Highway Research Institute of the Ministry of Transport, Southwest Jiaotong University, Harbin Institute of Technology's School of Transportation, Northeastern

University's School of Civil Engineering, and Southeast University, it has been determined that chopped basalt fibers for cement mortar/concrete can effectively enhance the impact resistance of mortar/concrete. Additionally, they improve wear resistance, resistance to thermal shrinkage, and freeze-thaw durability. They also enhance crack resistance, impermeability, workability, construction efficiency, and economic benefits in construction projects. The performance advantages of cement concrete mixed with short-cut BF are shown in Table 6. Based on experimental and empirical data, adding 3–5 kg/m^3 of short-cut BF to cement concrete significantly improves its shear resistance, crack resistance, impermeability, impact resistance, freeze-thaw resistance, and corrosion resistance.

Table 6: Advantages of cement concrete mixed with short-cut BF.

Performance	Advantages
Basic Mechanical Properties	Compressive strength increased by 10%–20%, shear strength by 20%–50%, and flexural strength by 20%
Impermeability	Both BF-concrete achieve an impermeability grade of P12
Toughness	Toughness indicators are rated as good to excellent
Shotcrete Performance	BF significantly improve the rebound effect of steel fibers
Freeze-Thaw Resistance	BF-concrete satisfies the requirement of 300 rapid freeze-thaw cycles

4.3 Cost Benefit Analysis of BF-Concrete

The economic analysis shows that BF offers significant cost advantages over steel fiber and comparable costs to polypropylene fiber in cement concrete, with a dosage of 4 kg/m^3 and a cost of 13.8 RMB/km, compared to 40 kg/m^3 for steel fiber (48 RMB/km) and 2 kg/m^3 for polypropylene fiber (3.6 RMB/km). BF also excels due to its adherence to national and transportation standards, such as GB/T 23265-2009 and JT/T 776.1-2010, and requires careful quality control during construction, including material inspection, mixing, and pouring under temperatures between −5°C and 25°C.

5 Application of BF Composite Rebars

Basalt fiber composite rebars address challenges in reinforced concrete structures, such as corrosion resistance and durability in harsh environments, including northern, humid southern, and acidic/alkaline regions. They simplify reinforced concrete pavement construction (Fig. 6), reduce bridge self-weight while enhancing load capacity and lifespan, eliminate the need for welding in reinforcement, and provide permanent anchoring solutions for infrastructure like tunnels and slopes. Additionally, they streamline construction, improve efficiency, reduce timelines, and lower overall project and maintenance costs.

These rebars are produced using high-strength BFs and vinyl resin (or epoxy resin) through processes such as continuous pultrusion, winding, surface coating, and composite molding. In corrosive environments, reinforced concrete structures, such as road bridges exposed to de-icing salts, coastal infrastructure, chemical plants, and sewage treatment facilities, are vulnerable to the infiltration of carbonates and chlorides. Over time, these infiltrations lead to the gradual neutralization of concrete, causing the passive protective film on steel reinforcement to break down, initiating corrosion. Corroded steel expands in volume compared to its original state, generating significant internal expansion forces that result in cracking and spalling of the concrete, and ultimately structural failure.

Figure 6: BF rebars for pavement.

5.1 Mechanical Properties of BF Composite Rebars

BF composite rebars exhibit superior mechanical, physical, and chemical properties compared to traditional steel reinforcement, significantly enhancing the durability and service life of cement concrete structures in corrosive environments [31]. BF composite rebars adhere to established Chinese and international standards and specifications to ensure their performance, reliability, and applicability in various construction environments (JT/T776.4 [24]-2010, GB 50608-2010 [32], ACI 440.1R-15 [33]). The key performance characteristics of BF composite rebars include:

- **High tensile strength:** The tensile strength of BF composite rebars exceeds three times that of conventional steel rebars of the same specification.
- **Thermal expansion coefficient:** The thermal expansion coefficient of BF composite rebars closely matches that of concrete, minimizing temperature-induced stresses between the two materials.
- **Exceptional corrosion resistance:** BF composite rebars demonstrate superior resistance to corrosion, surpassing all other fiber-based material products.
- **Wave transmission properties:** BF composite rebars are non-shielding, non-conductive, and non-thermal conductive, which makes them suitable for applications where electromagnetic neutrality or insulation is required.
- **Customizability:** These rebars can be prefabricated into standard bends or other customized shapes to accommodate diverse structural requirements.

Table 7 presents the mechanical properties of the BF composite rebars, with JT/T 776.4-2010 serving as the benchmark for their use in road and bridge construction.

Table 7: Mechanical properties of BF composite rebars.

Property	Value
Density (g/cm^3)	1.9–2.1
Tensile strength (MPa)	≥750
Tensile elastic modulus (MPa)	$\geq 4.0 \times 10^4$
Bending strength (MPa)	≥650
Elastic modulus (GPa)	≥50
Relative density (g/cm^3)	1.9–2.1
Elongation at break (%)	≥1.8
Thermal expansion coefficient ($\times 10^{-6}/°C$)	Longitudinal: 9–12
Transverse: 21–22	
Alkali resistance (strength retention rate, %)	≥85

(Continued)

Table 7 (continued)

Property	Value
Magnetic susceptibility (1×10^{-5} CGSM)	$\leq 5 \times 10^{-7}$
Barcol hardness	≥65
Service life	≥60 years in 13 pH alkaline environment
Creep	No creep failure occurs when sustained load is ≤60% of short-term load
Forming and bending	Strength after bending remains ≥40% of ultimate strength

5.2 Construction Methods for BF Composite Rebar Road and Bridge

The construction of pavement layers using basalt fiber composite rebars requires adherence to relevant technical standards, such as JTGF30-2003 [34]. In addition to these standards, the following procedures and considerations are essential for ensuring successful implementation.

5.2.1 Preliminary Preparation

Prior to construction a comprehensive site assessment should be conducted, including a review of rebar arrangements in the design drawings and the construction schedule, to plan the required quantity of BF composite rebars, appropriate roll lengths, and personnel allocation. Also the positions of rebar meshes, beams, and joints should be accurately marked as per the design drawings. Parameters such as rebar diameter, spacing, positioning, dimensions, and the number of layers should be complied with design specifications.

5.2.2 Cutting

BF composite rebars, supplied in continuous coils, must be cut on-site to the required lengths specified in the construction drawings. The cutting process should consider site conditions and design requirements, to ensure proper placement and tying in subsequent steps. Bent rebars should be straightened to enable accurate placement and maintain correct spacing of the rebar mesh. Additionally, dragging rebars on the ground should be avoided to prevent surface abrasion, which may compromise their bonding strength with concrete.

5.2.3 Rebar Mesh Placement

When placing BF composite rebar meshes, construction drawings must be followed strictly, ensuring a minimum concrete thickness of 80 mm above the mesh in bridge decks. At joints, areas of negative bending moment, and sections with structural variations, additional reinforcement with steel rebars may be required, taking care to avoid damage to the composite rebars during steel welding. Rebars should be positioned accurately and spaced according to design specifications; for single-layer meshes, longitudinal rebars must be placed within 1/2 to 1/3 of the surface layer's thickness from the top, with transverse rebars positioned below. The center of the outermost rebars should be at least 100 mm from joints or free edges. For double-layer meshes, longitudinal rebars in the upper layer should be installed at the top, while those in the lower layer should be placed at the bottom. To maintain spacing between layers, 4–6 welded brackets or circular tying stirrups per square meter should be used, and the bottom layer should be supported by welded upright rebars or 30 mm-thick concrete blocks, with at least 4–6 supports per square meter. A protective layer of at least 30 mm must be provided between the lower mesh and the surface of the base layer, while a wear-resistant protective layer of at least 50 mm is required between the top of the mesh and the surface of the concrete panel. Stainless steel wires should be used for tying to ensure secure connections, with rebars straightened during placement and spacing adjusted to meet design requirements. Overlap lengths for longitudinal and transverse rebars must be at least 35 times the rebar diameter (35d), and overlap joints in adjacent rebars should be staggered by at least 500 mm, ensuring no two joints occur on the same vertical section.

5.2.4 Concrete Pouring

Fix the rebar mesh on brackets or elevate it with concrete blocks before pouring, ensuring that the height from the top of the beam aligns with the thickness of the concrete layer, typically no less than 30 mm. During the process, ensure the mesh does not touch the ground, deform, shift, or loosen. Inspect and approve the rebar mesh prior to pouring concrete, and continuously monitor it during the pouring process to identify and address any breakages by overlapping and tying the rebars as needed. For any unspecified details, adhere to standard practices for rebar mesh installation.

6 Energy Consumption Analysis of Basalt Fiber

The sustainability of BF extends beyond its natural origin and superior performance to its notably low energy footprint during production and application, positioning it as an environmentally preferable alternative to synthetic fibers and traditional reinforcements. Life-cycle assessments consistently highlight BF's advantages, including reduced embodied energy and greenhouse gas emissions compared to carbon fiber, glass fiber, and steel. To further emphasize BF's eco-friendliness, a direct comparison with glass fiber reveals substantial environmental benefits. While glass fiber production generates 3.14 kg CO_2 equivalent per kg of fiber and requires 99.2 m^3 of water per ton, BF production emits 0.06 kg CO_2 eq/kg (98% less) and uses 14.4 m^3/t (85% less water), owing to its single-stage melting process without chemical additives [35]. Additionally, BF's volcanic origin results in minimal waste and no harmful emissions during manufacturing, as potential greenhouse gases were released during ancient eruptions, making it more inert and non-toxic than glass fiber. Life Cycle Assessment (LCA) studies confirm BF outperforms glass in key impact categories, including global warming potential and resource depletion.

As stated by Ma et al. [36], the comprehensive energy consumption for carbon fiber per unit product is 8603 kgce/t, while that for domestic advanced basalt continuous fiber is 737 kgce/t. The comprehensive energy consumption per unit product for carbon fiber is 11.7 times that of basalt continuous fiber. On the other hand, based on DB37/746-2007 standard, the comprehensive energy consumption limit for steel rebars is approximately 705 kgce/t. In comparison, the comprehensive energy consumption per unit product of BF composite rebars is 1078 kgce/t. However, since the density of BF composite rebars is 25% of steel rebars, under the same reinforcement rate conditions, replacing steel rebars with BF composite rebars reduces the comprehensive energy consumption per unit product to 323 kgce/t, which is only 46% of that for steel rebars.

7 Conclusion

This review underscores basalt fiber's (BF) transformative role in China's pavement engineering, leveraging its natural abundance and eco-friendly production to enhance infrastructure resilience and sustainability. Key properties, including exceptional tensile strength, thermal and chemical resistance outperform traditional fibers, enabling superior performance in asphalt and cement concrete applications. In asphalt mixtures, BF's adsorption, stabilization, and reinforcement mechanisms boost viscosity, crack resistance, and high-temperature stability, and reduce noise by 5 dB and extending service life by 30%–45%. For cement concrete, optimal dosages (3–5 kg/m^3) improve impermeability, toughness, and freeze-thaw durability, with cost benefits over steel (13.8 vs. 48 RMB/km). BF composite rebars mitigate corrosion in harsh environments, simplifying construction and lowering maintenance costs through non-conductive, customizable designs.

Energy analysis reveals BF's lower embodied impacts (323 vs. 705 kgce/t) for steel, supporting circular economy goals. China's advancements, driven by domestic resources and research from institutions like Harbin Institute of Technology, position BF as a cornerstone for high-performance pavements, aligning with ecological civilization policies. Challenges like production scalability and fiber dispersion warrant further optimization. Ongoing research, such as hybrid graphene-BF mixtures for seasonally frozen regions and AI-optimized gradations for enhanced rutting resistance, alongside technological advances like surface-modified fibers for better durability, promise to expand BF's applications. Future directions include hybrid composites, smart pavements, and expanded standards to accelerate adoption, fostering greener transportation infrastructure amid rapid urbanization.

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