Reinforcing Cement-Stabilized Clay with Basalt Fibers: A Literature Review of Strength Enhancement Mechanisms

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Abstract

This research investigates the potential of using basalt fibers to reinforce clay treated with cement, aiming to enhance its mechanical performance for construction and geotechnical applications. Known for their exceptional tensile strength and long-term durability, basalt fibers have notably improved the unconfined compressive strength (UCS) of cement-treated clay. This improvement is primarily due to the fibers' capacity to limit micro-crack formation, boost tensile capacity, and promote more uniform stress distribution within the soil structure. The study evaluates several parameters that affect UCS, such as fiber content, orientation, curing conditions, and the intrinsic properties of the soil. Experimental findings reveal considerable gains in both strength and durability, while also highlighting issues related to achieving uniform fiber dispersion. Future investigations are encouraged to examine combined reinforcement techniques and to assess long-term field performance. Overall, the findings support the use of basalt fiber-reinforced cemented clay as a durable and eco-friendly option for contemporary engineering projects.

Keywords: Basalt Fibers, Cement-Stabilized Clay, Mechanical Strength, Soil Reinforcement, Compressive Strength

I. Introduction

Infrastructure development is fundamental to both economic growth and societal advancement, serving as a cornerstone for the strategic progress of modern nations. Over the last ten years, countries such as China have made significant strides in developing both conventional and advanced infrastructure systems. Projects like the Beijing Daxing International Airport and the automated terminal at Shanghai's Yangshan Port exemplify their global leadership in construction and engineering innovation [1][2]. Despite these achievements, large-scale infrastructure construction continues to face obstacles, particularly those linked to subgrade soil conditions. As one of the most ancient and widely used natural construction materials, soil must undergo thorough evaluation prior to use, since its physical and mechanical properties directly influence the integrity and feasibility of any structure [3]. Clay soils, in particular, are often problematic due to their high compressibility, low shear strength, and sensitivity to moisture-

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induced volume changes. These characteristics can cause settlement issues, instability, and structural damage, posing serious engineering challenges [4], [5], [6], [7].
To address these challenges, various soil stabilization techniques have been developed, with chemical methods such as lime and cement treatment being among the most commonly applied [8]. Although effective, these treatments can alter the natural properties of soil and may lead to environmental concerns, such as increased alkalinity and potential soil contamination [9]. In response, more sustainable alternatives are being explored, with basalt fibers emerging as a viable reinforcement material. Derived from volcanic rock through an environmentally friendly manufacturing process, basalt fibers are characterized by their high tensile strength, resistance to thermal and chemical degradation, and long service life [10], [11]. These qualities make them suitable for soil reinforcement, where they help minimize crack formation, enhance tensile resistance, and promote better stress distribution within the soil matrix [10], [12]. Additionally, basalt fibers are non-toxic and chemically inert, offering a more eco-conscious alternative to synthetic materials like fiberglass.
The application of basalt fibers in cement-treated clay is an emerging area of study with encouraging preliminary outcomes. Research indicates that incorporating basalt fibers can significantly enhance the mechanical behavior of clay soils, increasing their strength, stiffness, and long-term durability while reducing risks such as erosion and settlement [13], [14]. Nonetheless, a more detailed understanding of the interaction mechanisms between basalt fibers and clay is required. This study seeks to analyze how basalt fibers influence the performance of cement-stabilized clay, focusing on strength development, microstructural modifications, and the roles played by different influencing factors. By compiling and critically analyzing existing research, the study aims to pinpoint existing knowledge gaps, emphasize the ecological and technical benefits of using basalt fibers, and suggest future research directions. Ultimately, this work supports the advancement of effective, sustainable methods for soil improvement.

1.1 Literature Gap

Although notable progress has been made in the field of soil stabilization, several critical gaps remain in current research, which this study aims to address. While many investigations have assessed the effectiveness of different reinforcement materials in cement-treated clay, the precise mechanisms through which basalt fibers improve the mechanical performance of such soils are not yet fully clarified. Most existing studies emphasize overall enhancements in strength and durability but offer limited insights into the underlying microstructural transformations and the specific interactions between the fibers and the soil matrix.
In addition, much of the current knowledge is derived from laboratory experiments, with relatively little data available on how basalt fiber-reinforced soils behave in field settings over extended periods. This lack of real-world performance data is particularly important considering the diverse environmental conditions and soil types encountered in actual engineering applications. Assessing the behavior of basalt fibers under varying environmental stresses such as freeze-thaw cycles, fluctuations in moisture content, and chemical exposure is essential to broaden their practical implementation in geotechnical projects.
Furthermore, although the structural benefits of basalt fibers are widely recognized, further studies are needed to determine the most effective fiber content, orientation, and distribution patterns within the soil. Ensuring uniform fiber dispersion and maintaining alignment during mixing and curing stages remain significant technical hurdles, which must be overcome to achieve consistent reinforcement results.
The potential advantages of combining basalt fibers with other reinforcement materials—referred to as hybrid strategies also remain largely unexplored. Such combinations may offer synergistic effects, capitalizing on the strengths of each component to enhance soil stability and performance beyond what is possible with a single reinforcement material.

This research aims to bridge these knowledge gaps by conducting an in-depth analysis of the microstructural changes caused by basalt fiber inclusion, examining long-term performance under diverse environmental conditions, and investigating the feasibility and effectiveness of hybrid reinforcement systems. Through these efforts, the study contributes to advancing sustainable and efficient techniques for soil stabilization.

II. Literature Review

2.1. Characteristics of Cement-Stabilized Clay

Cement treatment is a common and effective technique for enhancing the geotechnical properties of clay soils, making them more appropriate for construction and infrastructure development. When cement is blended with clay, both chemical and physical transformations occur, leading to improved soil behavior, as illustrated in Figure 1. The key chemical process involved is cement hydration, which produces calcium silicate hydrate (C-S-H) and calcium hydroxide through its reaction with water. These compounds act as binding agents, linking soil particles together and resulting in a more compact and cohesive soil structure. The development of C-S-H is particularly critical, as it substantially increases the soil's compressive strength, improving its ability to bear structural loads (Buckner et al., 2016)(Owino & Hossain, 2023).

In addition to strength enhancement, cement treatment lowers the plasticity of clay soils by reducing their capacity for large-scale deformation under loading. This is important for controlling problematic behaviors such as swelling and shrinkage, which can cause damage to built structures [17]. On the physical level, cement-stabilized clay becomes more compact and rigid, contributing to greater durability and resistance against environmental degradation like erosion and weathering. Shear strength is also improved, increasing the soil's resistance to failure from external forces such as sliding or pressure. These benefits make cement-stabilized clay a favored material for use in the construction of road subgrades, embankments, and structural foundations [17].

However, the performance of cement-stabilized clay depends on multiple factors, such as the type of clay being treated, the cement dosage, and the curing conditions. These variables can significantly influence the final strength, durability, and long-term stability of the improved soil [17].

Figure 1: Cement-Soil

2.2. Limitations of Cement Stabilization Alone

Although cement stabilization offers several engineering benefits, it also presents some limitations that can affect the long-term reliability of the treated soils. One of the main concerns is the inherent brittleness of cement-treated clay. Once stabilized, the material tends to become stiff and inflexible, which limits its ability to adapt to natural ground shifts. This inflexibility makes the soil prone to cracking when subjected to external stress or fluctuating environmental conditions, such as thermal changes or seismic events. In regions with such environmental challenges, these cracks can compromise structural safety [18].

Another significant limitation is shrinkage cracking, which typically occurs during the curing stage as the soil loses moisture. These shrinkage-induced fractures can reduce the overall strength of the stabilized soil and create voids that allow water to penetrate. Over time, water infiltration can worsen structural degradation, as outlined in Table 1 [18].

In addition, the durability of cement-stabilized soils can decline when exposed to aggressive environments. Conditions such as sulfate-rich soils or cycles of freezing and thawing can accelerate the deterioration of the material. Specifically, the leaching of calcium hydroxide a hydration byproduct of cement can cause strength loss and increased vulnerability to erosion [19].

These drawbacks highlight the importance of supplementary reinforcement strategies to enhance the long-term performance and resilience of cement-treated clay. One promising solution involves incorporating fibers, such as basalt fibers, which have been shown to enhance tensile strength, minimize shrinkage cracking, and provide improved flexibility to better accommodate soil movement [15], [20].

Table 1:Performance of Portland Cement-Modified Soils (CMS)[18]

Soil description and classification	Cement content used (volume %)	Test specimen	Plasticity index	Shrinkage limit	Shrinkage ratio
Brown silty clay A-6	9.0	Original soil	29.6	12.1	2.01
		1938 CMS	12.7	28.9	1.5
		1983 CMS	11.0	19.3	1.57
Brown Silty clay Sand A-2-4	9.5	Original soil	40.8	10.2	2.12
		1938 CMS	18.0	27.4	1.55
		1983 CMS	3.0	21.1	1,4
Reddish brown clay A-4	6.0	Original soil	21.5	15.0	1,9
		1938 CMS	6.6	28.2	1.5
		1983 CMS	3.0	15.9	1.61
Brown Sandy silty clay A-2-4	16.0	Original Soil	50.5	10.5	2.1
		1938 CMS	15.0	34.7	1.42
		1938 CMS	4.0	22.3	1.42

2.3. Role and Properties of Basalt Fibers in Soil Reinforcement

Basalt fibers, produced from natural volcanic basalt rock, offer a sustainable and eco-friendly option for reinforcing soil, as depicted in Figure 2(a). The production process involves heating the basalt rock to a high temperature and extruding it into thin fibers, illustrated in Figure 3. These fibers have several desirable properties for geotechnical applications. One of their main strengths is their exceptional tensile strength, comparable to that of steel, which enhances the load-bearing capacity of soil mixtures and mitigates structural failure risks, as demonstrated in Table 2 [21]. Furthermore, their high elastic modulus contributes to the stiffness of the reinforced matrix, maintaining structural integrity under stress [22].

Basalt fibers are also notably resistant to thermal changes and environmental damage, which makes them suitable for use in challenging conditions such as coastal zones and industrial sites [23]. They are chemically inert, which prevents adverse reactions with surrounding soil and eliminates concerns about environmental contamination. This chemical stability, coupled with their non-toxic nature, positions basalt fibers as a more environmentally responsible alternative to many synthetic reinforcements.

The combination of tensile strength, chemical resistance, and environmental durability makes basalt fibers particularly suitable for reinforcing cement-treated soils. Unlike synthetic options like polypropylene, which may degrade due to UV radiation or chemical exposure, basalt fibers maintain their structural properties over time, ensuring consistent reinforcement performance, as shown in Figure 4.

When incorporated into cement-stabilized soil mixtures, basalt fibers enhance both compressive and tensile strength by forming an internal mesh that redistributes applied stresses. This stress dispersion helps prevent localized failures and cracking. Research indicates that even a fiber content as low as 0.1% by weight can significantly boost soil strength, as the fibers serve as micro-bridges that bind particles and enhance the cohesion of the material [24].

Economically, basalt fibers present a cost-effective solution. As they are derived from natural raw materials and require relatively low energy for processing, their environmental impact is reduced compared to that of synthetic fibers. These advantages make basalt fibers an attractive choice for large-scale soil improvement projects where performance, sustainability, and cost are all important factors [24].

In comparison to other fiber types such as polypropylene and glass, basalt fibers stand out for their superior durability and environmental performance. They show high resistance to chemical attack and UV radiation, which allows them to retain strength and flexibility even in harsh conditions. In contrast, polypropylene fibers can deteriorate under sunlight or chemical exposure, and glass fibers, while strong, are typically more brittle and less effective in dynamic or flexible applications [25], [26], [27].

From an environmental standpoint, basalt fibers are advantageous due to their low carbon footprint during production. Their manufacturing process requires less energy than that of glass fibers and avoids the use of toxic chemicals. Basalt is currently the only mineral fiber considered entirely "green," producing no environmental pollution. Its composition is detailed in Figure 5 and Tables 3 and 4 [10]. While glass fibers can also enhance soil strength, their fragility under stress limits their effectiveness compared to the flexible, resilient nature of basalt fibers. Additionally, basalt fibers offer an optimal balance between mechanical performance and environmental safety, making them a practical and sustainable option for soil reinforcement in civil and geotechnical engineering [24], [27], [28].

Figure 2: Different forms of basalt fiber, (a) basalt rock, (b, and c) chopped basalt fiber of varying length

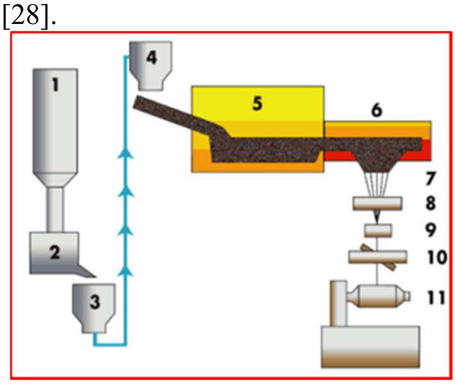

Figure 3:Diagram of basalt fiber spinning: 1) Crushed stone Silo, 2) Loading station, 3) Transport system, 4) batch charging station, 5) Initial melt zone, 6) Secondary controlled heat zone, 7) Filament forming, 8) Sizing applicator, 9) Strand formation, 10) Fiber tensioning, 11) Winding

Table 2: Basalt fiber properties [29]

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Property	Value Range	Source
Tensile Strength (MPa)	**2.800 – 4.800**	[30]
Young's Modulus (GPa)	**86 – 90**	[30]
Elongation at Break (%)	**3.1**	**Basalt Fibertec GmbH**
Density (g/cm³)	**2.63**	**Basalt Fibertec GmbH**
Softening Point	**1.05**	**Basalt Fibertec GmbH**
Maximum Operating Temperature	**-260 to 650**	**Basalt Fibertec GmbH**
Short-term Maximum Temperature	**1.1**	**Basalt Fibertec GmbH**

Table 3:Physical properties of fibers [10]

Physical properties	Steel	Basalt	E-Glass	S-Glass	PP	Carbon	Aramid
Spec density (g/cm³)	7.8	2.63	2.54	2.54	0.91	1.78	1.45
Tensile Strength (Mpa)	600-900	3800-4000	2600-2800	3200-4100	420	3500-6000	2900-3400
Modulus of elasticity (Gpa)	250	89-93	72	86	3.5	230-430	70-140
Elongation of break (%)	25	3.1	4.7	5.3	10	1.5-2.0	1.8-3.6
Softening Point (°c)	800	1050	850	850	100	-	250
Max. Operating temp (°c)	500	-	380	380	60	500	250
Short-term Max. temp (°c)	950	1100	1000	950	100	800	250

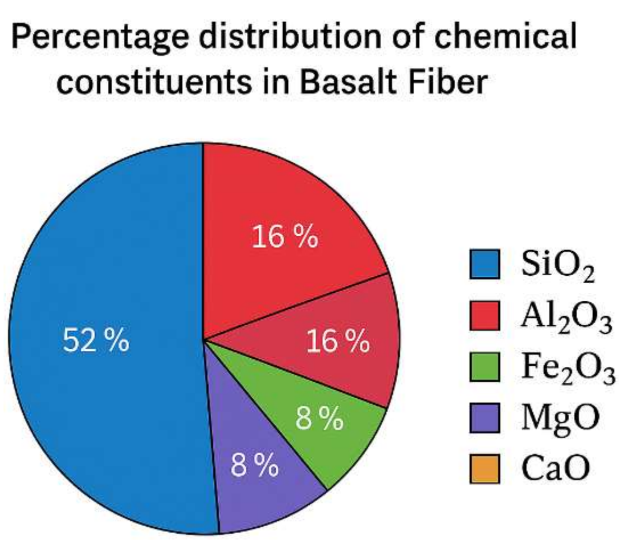

Figure 4 : Percentage distribution of chemical constituents in Basalt Fiber

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Table 4 :Physical properties of fibers [10]

Type	Diameter (μm)	Density (g/cm3)	Tensile strength (MPa)	Elastic modulus (GPa)	Ultimate elongation (%)
Asbestos fiber [31]	0.02–30	2.5	200–1800	164	2.0–3.0
Aramid fiber [32]	12	1.39–1.44	2900–3400	74–124	3–4.5
Acrylic fiber [33]	–	1.18	500–600	7–9	20–26
Polyethylene fiber [34]	20	0.97	2900	116	2.42
Polyvinyl alcohol fiber [35]	40	1.3	1600	42	7
Glass fiber [36]	13	2.68	1500	71	2.5
Carbon fiber [37]	7	1.76	>3000	200	1.5
BF [38]	15	2.65	3300–4500	80–100	2.4–3.0
Steel fiber [39]	250–1000	7.8	280–2800	200–250	0.5–4.0

Figure 5: Different types of fibers (a) Steel fibers; (b) Basalt fibers; (c) E-Glass fiber; (d) S-Glass fibers; (e) Polypropylene fibers; (f) Carbon fibers; (g) Aramid fibers

The inclusion of basalt fibers in cement-stabilized clay promotes significant improvements in structural strength and stability through processes such as microstructural modifications, improved tensile strength and flexibility, and effective crack mitigation and stress distribution.

3. Result

3.1 Unconfined Compressive Strength (UCS) Test

The Unconfined Compressive Strength (UCS) test is a standard procedure for evaluating the compressive capacity of soils and construction materials, especially those modified with additives such as basalt fibers. A typical specimen preparation setup is illustrated in Figure 6. This test measures how well a material can withstand axial compressive loads in the absence of lateral confinement, offering valuable insights into its load-bearing potential. The UCS test is particularly important in the analysis of composite materials commonly used in construction and geotechnical engineering, as it helps understand their deformation behavior under stress.

When applied to cement-stabilized clay enhanced with basalt fibers, the UCS test is instrumental in assessing how fiber reinforcement improves the mechanical properties of the soil. Basalt fibers are known for their excellent tensile strength, durability under extreme temperatures, and resistance to chemical deterioration, making them a suitable reinforcement material. Incorporating basalt fibers into cement-treated soils improves strength, ductility, and overall resilience, as supported by studies such as those by [27][40]. These enhanced composites are increasingly being considered for infrastructure applications including pavement bases, foundation improvements, and general earthworks.

A key advantage of the UCS test lies in its ability to help determine the optimal fiber dosage for performance enhancement. By systematically varying fiber content, engineers can evaluate the corresponding changes in compressive strength, enabling the development of formulations that are both effective and economically viable [27].

Numerous studies have explored how basalt fiber inclusion affects the strength and behavior of cement-treated soils. For instance, Ghanbari et al. (2022) found that while both cement and basalt fibers individually increase the UCS of peat soil, cement-stabilized samples achieved higher strength than fiber-only samples. However, the fiber-reinforced specimens displayed better ductility. Moreover, when both cement and basalt fibers were combined, the increase in UCS was greater than when either was used alone, indicating a synergistic effect.

Similarly[40] explored the effectiveness of basalt fibers with diameters of 10–20 μm and lengths of 12–20 mm at an optimal volume content of about 1%. Their findings demonstrated substantial improvements in mechanical properties such as fracture toughness, fracture energy, and deflection capacity. The addition of basalt fibers also enhanced resistance to chloride penetration and sulfate attack, offering greater durability. Their study also emphasized advancements in numerical modeling for evaluating these improvements.

Chen et al. (2024) investigated how combining basalt fibers (0–1%) with 6% cement improves the properties of expansive soil. Their UCS tests revealed that incorporating 0.4% basalt fibers increased strength by 24.8% under normal conditions and by 38.87% after 16 dry–wet cycles. The study highlighted that both basalt fibers and environmental cycling significantly influenced strength and introduced a multivariate predictive model to estimate these effects.

Further support comes from Weiwei et al. (2024), who conducted UCS tests on cement-stabilized soils reinforced with basalt fibers following freeze–thaw cycles. Their results showed that a 0.5% basalt fiber content provided the best strength performance and was most effective in minimizing damage from freeze–thaw effects. This dosage is recommended for improving the durability of subgrade fills in cold climates.

Overall, the UCS test is an indispensable method for evaluating the compressive behavior of basalt fiber-reinforced cemented soils. Findings from researchers such as Weiwei et al. (2024), Chen et al. (2024), Zheng et al. (2022) and Ghanbari et al. (2022) consistently demonstrate the benefits of basalt fiber reinforcement in improving compressive strength, ductility, and environmental resistance of treated soils. These results, summarized in Table 5 and illustrated in Figure 7, support the conclusion that basalt fibers are an effective and sustainable enhancement for geotechnical applications.

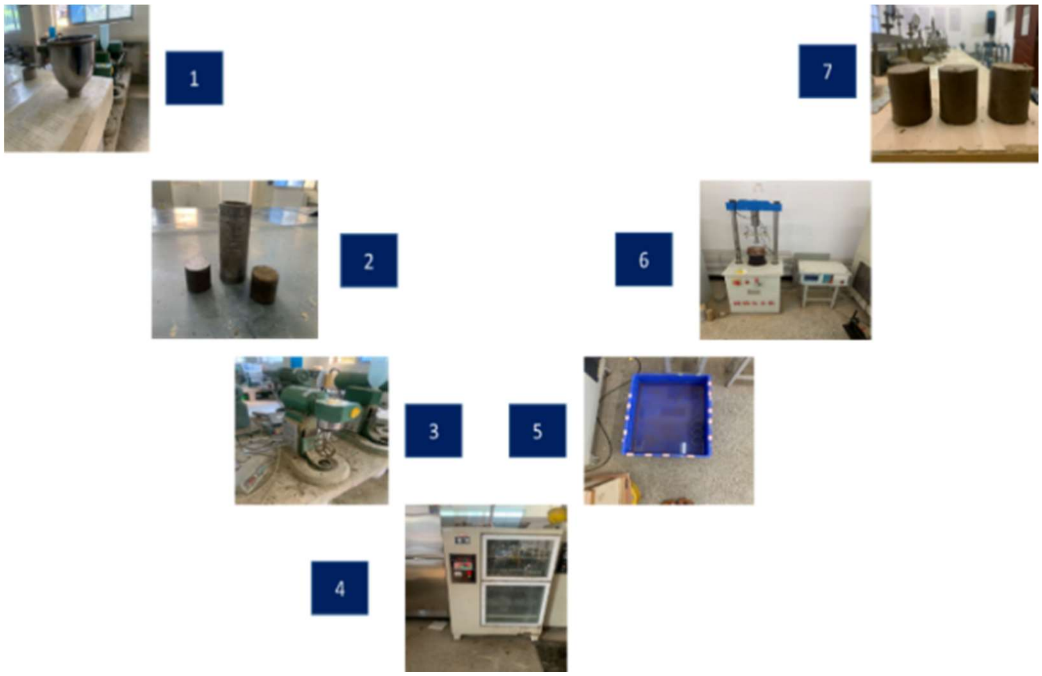

Figure 6 : Samples Preparation Each Process (1-7)

Table 5: Authors name with different fiber content at different curing time

Authors/years	References	Fiber percentages	Fiber length (mm)	Curing	Compressive strength
S.Sun et al (2023)	[43]	0.2%	12	28	1.8Mpa
Ghanbari et al. (2022)	[41]	1%	18	28	8Mpa
Zheng et al. (2022)	[40]	1%	18	-	2.5Mpa
Dehong Wang et al. (2019)	[44]	0.15%	12	24	11Mpa
Kizilkanat et al. (2015)	[45]	0.5%	12	28	6.7Mpa
Sahim et al. (2021)	[46]	1.2%	12	56	8.8Mpa
Cao et al. (2022)	[47]	-	12	-	5Mpa
Pavithra and Moorthy (2021)	[29]	0.35%	-	28	4.8Mpa
Sun et al. (2024)	[48]	0.4	6	28	2.1Mpa
G.Sun et al. (2018)	[49]	-	-	-	3.22Mpa
Zhang et al. (2023)	[50]	0.3%	12	-	8.5Mpa
Chen et al. (2024)	[25]	0.4%	6	-	17MPa
Boz et al. (2024)	[51]	0.75%	19	90	11MPa

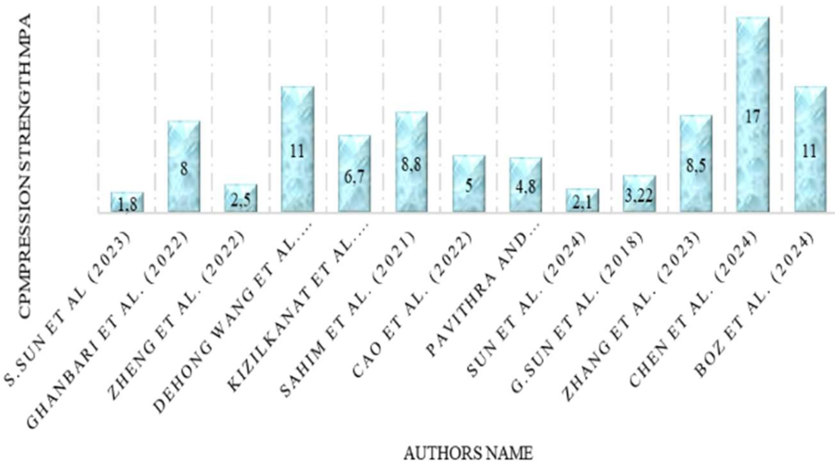

Figure 7: compressive strength results based on different authors

3.2 Flexural Strength Test

The Flexural Strength Test assesses a material's capacity to resist bending or flexural loads and is frequently used in evaluating concrete, fiber-reinforced composites, and cement-treated soils. The procedure involves applying a load to a beam or slab specimen until it bends and fractures, with flexural strength calculated based on the peak stress experienced before failure. In geotechnical applications, this test is essential for analyzing the performance of fiber-reinforced soils such as cement-stabilized clay enhanced with basalt fibers under bending forces. The integration of basalt fibers enhances crack resistance and fracture toughness, making the material more suitable for infrastructure applications that demand high flexural durability and load resistance, such as roadbeds and pavements.

Numerous studies have examined how basalt fiber influences the flexural strength of cement-based composites and treated soils. For example, Hu et al. (2024) observed a significant improvement in flexural strength over time in basalt fiber-reinforced specimens compared to unreinforced ones, as depicted in Figure 8. However, the study also reported that excessively long fibers or high fiber content could negatively affect flexural strength. Optimal performance was achieved with 3 mm fiber length, 0.1% fiber content, and a water-to-cement ratio of 0.38, which contributed to improved toughness and crack resistance within the cement matrix.

In a similar investigation, Zheng et al. (2019) explored the flexural performance of cement composites reinforced with basalt fibers. Their results indicated that basalt fibers significantly enhanced the flexural strength of cement-stabilized macadam. The strength increased non-linearly with fiber content, achieving optimal results at 3 kg/m³ for low cement content mixtures and 6 kg/m³ for high cement content mixtures. However, excessive fiber content led to diminished performance due to poor fiber dispersion. The fibers acted as stress bridges across fracture zones, improving tensile ductility, delaying crack propagation, and ultimately enhancing the mechanical performance of pavement materials especially in preventing shrinkage-related cracking.

Another important study by Cao et al. (2022) examined the flexural behavior of cement composites reinforced with various fibers, including basalt. The study focused on how temperature and fiber type affect the flexural strength of steel-basalt fiber-reinforced cement composites (SBFRCC). From room temperature to 400°C, the strength either slightly increased or declined slowly. However, above 800°C, a sharp reduction in strength was observed. Interestingly, at 900°C, the residual strength improved with increased basalt fiber content from 12.4% (no basalt) to 36.0% (100% basalt fiber). While steel fibers were more effective at temperatures below 600°C, basalt fibers outperformed them above 800°C. Between 400°C and 600°C, basalt fiber effectiveness decreased due to reduced flexibility and weakened fiber-matrix bonding. These findings, illustrated in *Figure 9*, were used to develop a predictive model showing a strong correlation with test results ($R^2 = 0.91115$), highlighting the complementary strengths of steel and basalt fibers at different temperature ranges.

Ramesh and Eswari (2020) also contributed to this field by examining the impact of basalt fibers on the flexural strength of cement-treated soils. Their results showed that incorporating basalt fibers into concrete significantly increased flexural strength (measured as modulus of rupture), with the highest improvement 57% achieved at a fiber content of 1.5%. Beyond this concentration, strength began to decline due to inadequate fiber dispersion. Fiber-reinforced concrete also exhibited more ductile failure behavior, as the fibers effectively bridged cracks and delayed their spread, unlike the brittle failure observed in conventional concrete. This enhanced ductility and crack resistance underline the role of basalt fibers in improving structural integrity under flexural stress.

Overall, the Flexural Strength Test is a critical tool for evaluating how well materials withstand bending forces. It offers essential insights into a material's ability to maintain structural performance under flexural loading. For cement-treated soils reinforced with basalt fibers, the test reveals the degree to which fiber addition mitigates cracking and improves bending resistance. Results from multiple researchers, including Hu et al. (2024), Zheng et al. (2019), Cao et al. (2022), and Ramesh and Eswari (2020) support the effectiveness of basalt fiber reinforcement under varied conditions. The findings, summarized in Table 6 and visualized in Figure 10, emphasize basalt fibers' potential in enhancing the flexural performance of soil composites across a range of environmental and loading scenarios.

Table 6: Flexural Strength based on different authors

Authors/years	References	Fiber percentages	Fiber length (mm)	Curing time	Flexural Strength
Hu et al.(2024)	[52]	**0.1**	**3**	**28**	**8.6Mpa**
Dehong Wang et al. (2019)	[44]	**0.15**	**12**	**24**	**10.49Mpa**
Jiang et al. (2014)	[55]	**0.3**	**22**	**90**	**8.28Mpa**
M.Li,Gong, and Wu (2020)	[56]	**0.1**	**20**	**28**	**7.5Mpa**
Katkhuda and Shatarat (2017)	[57]	**1.5**	**18**	**28**	**4.9Mpa**
Ramesh and Eswari '2020)	[54]	**1.5**	**36-50**	**28**	**4Mpa**
Cao et al. (2022)	[58]	**2**	**12**	**°c**	**3.5Mpa**

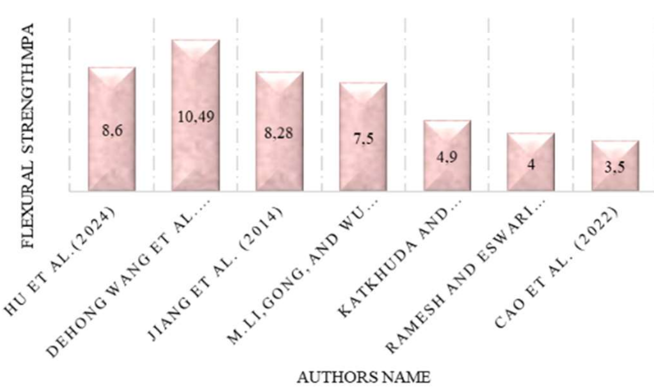

Figure 8: Flexural Strength Result based on Authors

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3.3 Triaxial Test

The Triaxial Test is a fundamental laboratory technique in geotechnical engineering designed to measure the shear strength of soils and construction materials by applying both axial and confining stresses to a cylindrical specimen. This method replicates the stress conditions encountered in the field, providing insight into soil behavior under load and contributing to the design of stable structures such as foundations, embankments, and roadways. The use of basalt fibers in cement-treated soils has been evaluated through this test, as fiber inclusion enhances shear resistance by improving cohesion, limiting deformation, and increasing overall stability under stress. Numerous studies have focused on the influence of basalt fibers on the shear performance of such composites using the Triaxial Shear Test.

For instance, J. Xu et al. (2021b) utilized the unconsolidated-undrained (UU) triaxial test to assess the shear strength of loess reinforced with basalt fibers of varying lengths and contents. Their results indicated that shear strength increased with the incorporation of fibers, following an inverted U-shaped trend. The highest strength was observed at 0.6% fiber content and a fiber length of 12 mm. Digital imaging techniques were employed to monitor surface strain and damage evolution during loading. The unreinforced samples exhibited brittle failure with prominent shear bands, whereas fiber-reinforced specimens showed plastic deformation and bulging, reflecting enhanced mechanical behavior. A statistical damage model developed in the study accurately predicted stress-strain responses, validating the experimental data.

Similarly, Weiwei et al. (2024) examined the mechanical and durability performance of basalt fiber-reinforced cemented soils under triaxial compression conditions. Their research aimed at improving both strength characteristics and resistance to freeze–thaw (FT) cycles, especially in cold climate applications. The tests revealed that incorporating basalt fibers led to higher peak strength, improved shear modulus, and greater resistance to degradation from FT cycles. An optimal fiber content of 0.5% was identified, coupled with 6% cement, as the most effective combination for enhancing the performance of silty clay subgrades. The presence of fibers minimized microcrack development and preserved structural integrity after repeated FT exposure.

Lv et al. (2019) also investigated how basalt fibers influence the shear response of cemented sandy soils. Their triaxial tests demonstrated that the addition of basalt fibers substantially boosted both peak and residual shear strength, while also reducing the material's brittleness and increasing ductility. At an ideal fiber content of 0.75%, cohesion increased to 406.1 kPa, a 74.6% improvement, while residual cohesion reached 145.4 kPa, a 148% gain. The stress-strain curves showed higher peak strains and less post-peak stress drop, indicating improved energy absorption. SEM analysis revealed mechanisms such as fiber sliding and pull-out at the microstructure level, which helped resist deformation and delay crack propagation. These behaviors illustrate the transformation from brittle to ductile failure, highlighting basalt fiber's potential in improving cemented soil for engineering applications.

Overall, the Triaxial Shear Test is essential for analyzing the shear resistance and deformation properties of soils and reinforced composites. Simulating realistic loading scenarios it provides critical data for the safe design of infrastructure. In the context of basalt fiber-reinforced cement-treated soils, this test confirms that fibers significantly improve material performance by enhancing cohesion, minimizing deformation, and delaying failure. These enhancements are summarized in Table 7 and illustrated in Figure 11, which compiles findings from various studies under different test conditions.

Table 7: Triaxial test result based on different authors

Authors/years	References	Fiber percentages	Fiber length (mm)	Curing time	Triaxial
Lv et al. (2019)	[60]	0.75	6	14	28Mpa

12

J.Xu et al. (2021)	**[61]**	**0.6**	**12**	**-**	**5Mpa**
J.Xu et al. (2021a)	**[61]**	**0.6**	**12**	**-**	**2.58MPa**
F.Chen et al. (2021)	**[62]**	**3**	**-**	**-**	**52.57Mpa**
Boz et al. (2018)	[51]	**0.75**	**19**	**90**	**11MPa**
C.Kun Chen et al. (2023)	**[63]**	**0.8**	**16**	**-**	**0.17Mpa**
Fu et al. (2021)	**[64]**	**0.3**	**12**	**-**	**68Mpa**

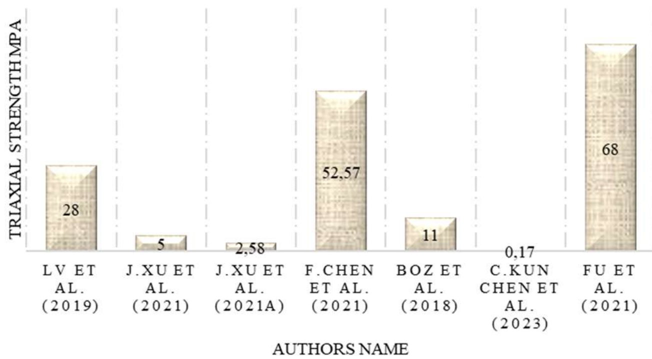

Figure 9: Triaxial Strength Result based on Authors

3.4 Microstructural Changes

Basalt fibers induce significant microstructural transformations within cement-stabilized soils by bridging cracks, filling voids, and enhancing fiber-to-matrix bonding. According to [25], Scanning Electron Microscope (SEM) images show that basalt fibers form a tightly interconnected network within the soil matrix, improving cohesion and reducing porosity. This densification strengthens the material's ability to sustain external loads and reduces the likelihood of long-term degradation and cracking. The microstructure illustrated in *Figure 6* emphasizes how basalt fibers bridge microcracks and occupy voids, enhancing the overall stability of the material [24], [25].

SEM and other analytical techniques, such as X-ray diffraction (XRD), provide insights into internal structural features like particle packing, bonding, pore distribution, and fiber-matrix interactions. In cement-treated soils, these fibers enhance bonding with soil particles and hydration products, contributing to a more compact structure. The presence of hydration products such as calcium-silicate-hydrate (C-S-H) fills the inter-particle spaces, while basalt fibers contribute tensile strength by resisting crack initiation and propagation. These changes improve both the mechanical strength and durability of the material in challenging environments.

Several studies have demonstrated the importance of such microstructural improvements in enhancing the performance of fiber-reinforced soils. For instance, Cao et al. (2022) examined the thermal stability and microstructure of basalt and hybrid (basalt-steel) fiber-reinforced cement composites under different temperature exposures using SEM analysis. Their results showed that basalt fibers maintained structural integrity up to 600°C and remained effective in bridging cracks even at 900°C. Steel fibers, though initially well-bonded, began to rust and lose bonding strength around 600°C, while the matrix showed loosening above 800°C. Basalt fibers, on the other hand, continued to improve the composite's toughness, supporting a multi-stage crack-resisting mechanism.

In another study, J. Xu et al. (2021) analyzed the microstructure of basalt fiber-reinforced loess by varying fiber contents and lengths. SEM images demonstrated that increased fiber content led to a more uniform fiber distribution. However, longer fibers showed a tendency to bend and entangle, which could reduce their reinforcing efficiency. These observations underscore that not only the presence but also the geometry and arrangement of fibers critically influence the effectiveness of soil reinforcement.

Ma, Cao, and Yuan (2018) also explored the microstructural behavior of expansive soils stabilized with different additives, including fly ash, sand, and basalt fibers. Their SEM observations revealed that fly ash enhanced particle bonding through the generation of hydration products like C-S-H and AFt, while sand filled gaps and improved the soil's compactness. Basalt fibers significantly increased the interlocking between the soil particles and the matrix, thereby boosting overall strength. The study confirmed that effective fiber-soil interactions are key to achieving stable, high-performance stabilized soils.

Additionally, Deng et al. (2022) investigated the influence of fiber distribution and surface treatment on performance. Basalt fibers were modified using hydrochloric acid (HCl), which increased their surface roughness and thereby improved dispersion within the cement paste. After 15 hours of treatment with a 4 mol/L HCl solution at 50°C, fiber dispersion in the paste reached 84%, with a dispersion coefficient of 0.9 in the hardened matrix. These improvements led to higher splitting tensile and flexural strengths in the fiber-reinforced concrete. SEM images confirmed that surface-treated fibers bonded more effectively with the matrix, contributing to better mechanical performance.

Lastly, S. Wang et al. (2021) used SEM to observe the microstructural evolution of clay soil (CS) stabilized with alkali-activated binder (AAB) composed of CaO, Na_2SiO_3, and metakaolin (MK), along with basalt fibers. Initially, the untreated clay had a loose and flaky structure. After one day of curing, CaO hydration led to the formation of ettringite and C-S-H gels that began bonding with basalt fibers. By day three, the soil matrix exhibited cementitious networks that replaced the initial flaky structure. After seven days, the gels had enveloped the clay particles, forming dense aggregates with stronger bonds and lower porosity. Residual pores were gradually filled as the reaction progressed, resulting in a more compact and mechanically robust matrix.

These studies collectively highlight how microstructural modifications brought by basalt fibers—particularly through pore filling, crack bridging, and improved fiber-matrix bonding—are fundamental to enhancing the strength, durability, and environmental resistance of cement-treated soils.

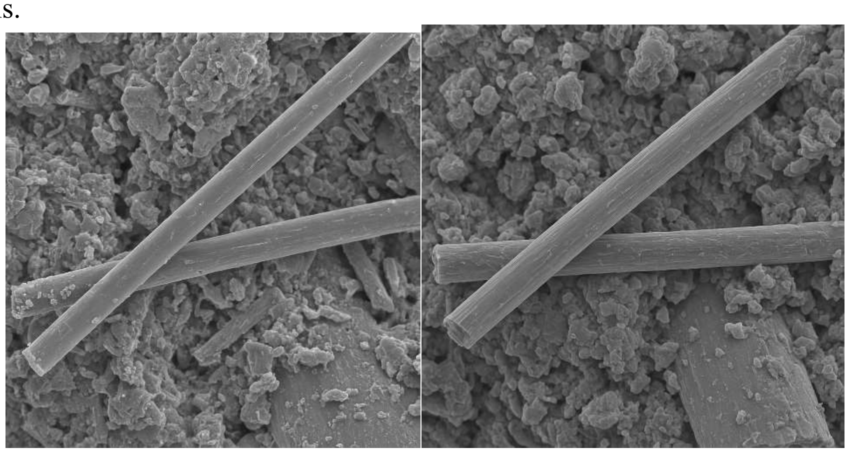

Figure 10: Scanning electron microscopy (SEM) images of basalt fibers reinforced cement-based composites exposed to various temperatures

3.4 Tensile Strength and Flexibility

Basalt fibers play a pivotal role in enhancing the tensile strength and flexibility of cement-stabilized clay, enabling the material to better absorb stress and deformation without failure.

Due to their high tensile strength and elastic modulus, basalt fibers reinforce the cemented matrix by limiting crack propagation and reducing the likelihood of brittle failure. Research by [28] demonstrates that even at low inclusion rates (0.4–0.5%), basalt fibers significantly enhance both the unconfined compressive strength (UCS) and flexural strength of the composite. This increase in ductility contributes to better performance under environmental stressors such as thermal expansion and moisture-induced shrinkage, reducing the risk of cracking and material degradation.

Further studies support these findings. Wang et al. (2020) observed that the addition of basalt fibers to cement-treated soils led to notable gains in tensile strength compared to non-reinforced samples. Likewise, Chowdhury, Pemberton, and Summerscales (2022) reported improvements in bending resistance and flexibility when basalt fibers were introduced, particularly under elevated temperature conditions. These enhancements make basalt fiber-reinforced soils more suitable for infrastructure projects subjected to variable environmental conditions.

In a comparative study, Lv et al. (2019) examined the mechanical response of clayey soils stabilized with cement and reinforced using both polypropylene fibers (PPF) and basalt fibers (BF). The results revealed that while both fiber types improved tensile strength and flexibility, PPF showed superior performance in terms of strength. However, the combination of fibers with cement yielded better UCS values than using fibers alone. Moreover, optimal moisture content and curing time further enhanced the material's strength, although higher cement content was associated with reduced axial strain at failure, indicating a trade-off between strength and ductility. A regression model developed in the study was able to predict UCS with over 95% accuracy, underscoring the consistency of these enhancements.

Ghanbari et al. (2022) explored the reinforcing effect of basalt fibers in cement-treated peat soil, a weak and highly compressible substrate. Their findings revealed that the combined use of cement and basalt fibers significantly improved UCS and ductility. While cement alone provided higher compressive strength than fibers, the inclusion of basalt fibers improved the soil’s deformability and resistance to cracking. The synergy between the two materials resulted in a composite with enhanced strength and flexibility—attributes that are especially important in reinforcing soft or problematic soils prone to settlement and cracking.

Collectively, these studies confirm that basalt fibers are effective in enhancing not only the tensile and compressive strength but also the flexibility and durability of cement-stabilized soils. Their ability to delay or prevent crack formation under stress, combined with improved bending resistance, positions them as valuable additives in geotechnical applications where both strength and deformation control are essential.

Table 8: Tensile test result based on different authors

Authors/years	References	Fiber Content	Fiber Length	Curing Time	Tensile Strength
Jiang et al. (2014)	[55]	**0.3**	**22**	**90**	**25Mpa**
Katkhuda and Shatarat (2017)	[57]	**1.5**	**18**	**28**	**3.5Mpa**
Cao et al. (2022)	[47]	**2**	**12**	**°c**	**1.5Mpa**
S.Wang et al. (2021)	**[67]**	**-**	**12**	**-**	**5.48MPa**
Z.Cao,Ma, and Wang (2019)	**[69]**	**1.5**	**9**	**28**	**1.78Mpa**
H.Zhang et al. (2016)	**[70]**	**0.21**	**12**	**°c**	**4.84Mpa**
Meng et al. (2021)	**[71]**	**-**	**-**	**°c for10h**	**41.11Mpa**
Xie et al. (2022)	**[72]**	**0.2**	**6**	**28**	**-**

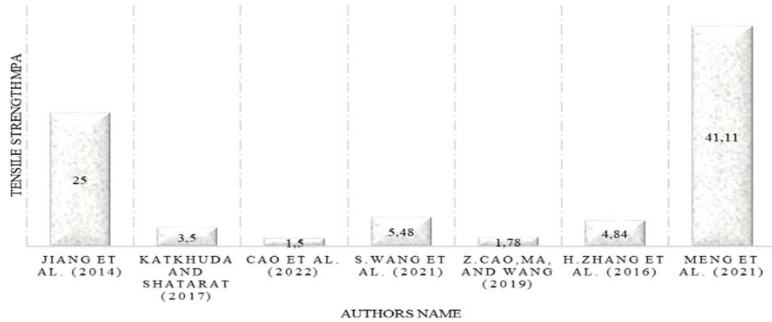

Figure 11: Tensile test result based on different authors

3.5 Crack Mitigation and Stress Distribution

Basalt fibers play a crucial role in minimizing crack formation and propagation by promoting a uniform distribution of stress throughout the cement-treated soil matrix. Unlike rigid reinforcement alternatives that can create stress concentration zones, basalt fibers disperse forces more evenly, mitigating areas of high stress that typically lead to failure. This uniform stress distribution enhances the overall load-bearing capacity and reduces the likelihood of localized structural damage. Findings from S. Sun et al. (2023), as shown in Figure 12, demonstrate this effect by illustrating a more balanced stress-strain response in basalt fiber-reinforced composites. This behavior helps prevent excessive strain in weaker regions of the matrix, thereby improving crack resistance and material longevity [25], [27].

The core mechanism behind this improvement lies in the fibers' ability to bridge microcracks as they develop, thereby halting their spread and enhancing both tensile and flexural performance. This mechanism ensures stress redistribution across a broader area, which is particularly beneficial under fluctuating or cyclic load conditions. Chen et al. (2024) confirmed the efficiency of basalt fibers in controlling crack growth in cement-treated expansive soils. Their SEM observations showed that fibers acted as physical barriers within the matrix, reducing crack width and arresting further propagation, leading to a more durable material.

A foundational study by Dilandro, Dibenedetto, and Groeger (1988) also highlighted basalt fibers' capacity to redistribute stress uniformly across soil matrices, preventing localized failures and improving deformation resistance. Similarly, Guo et al. (2023) reported enhanced fatigue resistance in basalt fiber-reinforced composites exposed to repeated loading, such as in pavement layers, due to the fibers' ability to absorb and transfer dynamic stresses.

Zheng et al. (2019b) examined basalt fiber performance in bending scenarios, revealing that fibers significantly improved flexural behavior by preventing early-stage crack initiation and enhancing toughness. Meanwhile, Lu et al. (2017) investigated the long-term behavior of basalt fiber-reinforced composites under environmental cycles such as freeze-thaw and wet-dry conditions. Their results showed that the crack-bridging properties of basalt fibers remained effective even under these harsh exposures, preserving the structural integrity over time.

In comparative analyses by Jagadeesh, Rangappa, and Siengchin (2024)**;** Jamshaid and Mishra (2016), basalt fibers outperformed synthetic fibers like polypropylene and glass in terms of controlling crack formation and distributing stress. This superiority was largely attributed to basalt fibers' high tensile strength and stiffness, which provide effective crack arresting and enhanced energy absorption under stress.

Collectively, these findings underscore the value of basalt fiber reinforcement in cement-stabilized clays. The material not only gains improved crack resistance and mechanical performance but also benefits from enhanced resilience against environmental stressors. As a result, basalt fiber-reinforced soil presents itself as a durable, sustainable solution in geotechnical applications, offering significant advantages over traditional soil stabilization techniques [24], [25], [28].

4. Discussion

4.1 Overview of Performance Enhancements

Across multiple studies, the integration of basalt fibers into cement-treated clay consistently results in improved mechanical behavior, particularly in unconfined compressive strength (UCS), tensile strength, and flexural performance. These improvements are largely attributed to the fiber's ability to bridge microcracks, redistribute stress, and enhance internal cohesion within the soil-cement matrix. For example, Ghanbari et al. (2022) and Chen et al. (2024) observed that combining cement with basalt fibers produced synergistic effects, yielding higher strength and ductility than using either component alone [25][42]. These outcomes underscore basalt fiber's suitability for applications requiring both load resistance and deformation capacity.

4.2 Durability and Environmental Resistance

Several studies have explored the long-term durability of basalt fiber–reinforced soils, especially under freeze–thaw cycles, moisture fluctuations, and chemical exposure. Weiwei et al. (2024) and Chen et al. (2024) reported that moderate fiber contents (around 0.4%–0.5%) significantly enhanced strength retention following repeated environmental cycling [25]. The chemical inertness and high-temperature resistance of basalt fibers further contribute to the resilience of the composite in aggressive environments, outperforming conventional reinforcements such as polypropylene and glass fibers in terms of durability [10][22][27].

4.3 Microstructural Improvements

Microstructural investigations using SEM and XRD have revealed that basalt fibers improve internal bonding, reduce porosity, and fill voids within the cement-soil matrix. The fibers act as physical barriers that delay crack initiation and propagation while promoting denser packing of soil particles. Studies by Xu et al. (2023) and Cao et al. (2022) showed that fiber-treated specimens exhibited reduced brittleness and increased matrix continuity, particularly when fiber alignment was optimized [24][48]. These microstructural changes underpin the observed mechanical enhancements and highlight the role of fiber–matrix interaction in reinforcing effectiveness.

4.4 Influence of Key Parameters

Fiber content**,** length**, and** distribution play crucial roles in determining the mechanical response of reinforced soils. Most studies agree that fiber contents between 0.1% and 0.3% yield optimal results for UCS and tensile strength [27][44]. Exceeding this range can lead to fiber clumping and non-uniform stress transfer, diminishing overall performance. Additionally, curing duration significantly affects strength gain. A 28-day curing period is commonly reported as optimal, allowing sufficient hydration and strong interfacial bonding between fibers and the cement matrix [27][44]. Furthermore, soils with fine particles and high silica content exhibit better compatibility with basalt fibers, enhancing bond quality and structural integration [10][28].

4.5 Limitations and Practical Constraints

Despite these promising outcomes, several challenges remain. Achieving uniform fiber dispersion during mixing is a recurring issue, particularly at higher dosages. Uneven distribution leads to localized weak zones that undermine the composite's strength. Moreover, maintaining consistent curing conditions and fiber orientation in field settings is difficult, especially under varying environmental conditions. These technical limitations must be addressed through standardized mixing procedures and field-scale validation studies [26][44].

4.6 Research Gaps and Future Needs

Although laboratory results demonstrate the efficacy of basalt fibers in cement-stabilized soils, real-world data remain scarce. Long-term field studies are urgently needed to evaluate durability under natural weathering, traffic loads, and soil variability. Additionally, there is limited research on **hybrid reinforcement strategies**, where basalt fibers are combined with other materials like steel or polypropylene to enhance multidimensional performance. Another emerging gap lies in the **digital modeling of behavior** — few studies have applied finite element or machine learning–based models to predict performance outcomes under varying field conditions [24][28].

4.7 Practical Implications and Sustainability

The use of basalt fibers aligns well with sustainable construction practices. Compared to synthetic alternatives, basalt fibers are derived from abundant natural resources, require minimal energy for processing, and are chemically inert and non-toxic [10][22]. Their integration into soil stabilization practices offers not only enhanced structural performance but also a reduction in the environmental footprint of infrastructure projects. Economically, their long service life and low maintenance potential make them a cost-effective solution in geotechnical design.

4.1 Contributions to the Field

This research introduces an innovative method for reinforcing cement-stabilized clay using basalt fibers, which is a significant improvement over conventional soil treatment techniques. The use of basalt fibers markedly enhances the mechanical properties of the soil matrix, providing valuable insights into the mechanisms of soil reinforcement. This study not only offers empirical evidence of the effectiveness of basalt fibers in improving soil strength and durability but also explains the microstructural changes that contribute to these enhancements. These findings are in line with recent research on the mechanical properties and durability of basalt fiber-reinforced materials [22],[40]. Additionally, the study aligns with the comprehensive review by Hejazi et al. (2012), which highlights the effectiveness of various fibers in enhancing the mechanical properties of soil.

4.2 Advanced Analytical Techniques and Comprehensive Study Design

This research employs cutting-edge analytical methods and a thorough experimental design, which are not typically utilized in this field. These advanced techniques enable a detailed examination of the interactions between basalt fibers and the soil matrix under diverse conditions. The broad scope of this study, which includes a wide range of environmental conditions and soil types, provides an in-depth analysis of the effects of basalt fiber reinforcement. The use of advanced techniques such as Scanning Electron Microscopy (SEM) and X-ray diffraction (XRD) offers a comprehensive understanding of the microstructural changes that occur with the inclusion of basalt fibers. This detailed analysis helps in identifying the optimal conditions for fiber dispersion and alignment, which are essential for achieving consistent reinforcement result [22], [40]. The study also references the work by Hejazi et al. (2012), which provides a historical and practical perspective on the use of natural and synthetic fibers in soil reinforcement.

4.3 Enhanced Understanding of Long-Term Performance

A significant contribution of this research is the inclusion of long-term performance assessments, which are crucial for understanding the durability of basalt fiber-reinforced composites. These assessments provide valuable insights that can inform future design and application strategies, potentially leading to more sustainable and resilient infrastructure solutions. Long-term studies reveal that basalt fibers significantly reduce microcracking over time, which is critical for applications exposed to freeze-thaw cycles, high humidity, and other weathering effects [40]. Additionally, basalt fiber-reinforced concrete (BFRC) demonstrates superior resistance to chemical erosion, including acid and alkali attacks, compared to traditional reinforcements [22]. This enhanced understanding of long-term performance aligns with recent studies on the mechanical properties and durability of basalt fiber-reinforced materials [22], [40]. The study also references the work by Zhao et al. (2024), which provides detailed insights into the mechanical properties of fiber-reinforced soil cement based on kaolin.

4.4 Sustainability and Environmental Impact

This study emphasizes sustainability and environmental impact, demonstrating the reduced environmental footprint of basalt fiber-reinforced materials compared to conventional methods. The findings suggest that the use of basalt fibers could lead to more environmentally responsible infrastructure development. Basalt fibers are derived from naturally abundant volcanic rock and require minimal processing, making them an eco-friendly alternative to traditional reinforcement materials [22]. Their use in civil engineering applications not only improves performance but also reduces environmental impact. This aligns with recent studies on the mechanical properties and durability of basalt fiber-reinforced materials [22], [40]. The study also references the work by Hejazi et al. [2012], which highlights the potential of natural fibers as sustainable alternatives in soil reinforcement.

4.5 Practical Applications and Field Studies

The integration of practical applications and field studies within the research enhances the translation of laboratory findings into real-world scenarios. These applications validate the effectiveness of basalt fiber reinforcement in practical settings, highlighting its potential for broader adoption in construction and geotechnical engineering. Long-term field studies are essential to evaluate the durability of basalt fiber-reinforced composites over decades, particularly in assessing their strength retention under real-world conditions. Field trials should focus on environmental exposure factors such as freeze-thaw cycles, humidity fluctuations, and exposure to corrosive agents, which are critical for infrastructure applications [40]. This aligns with recent studies on the mechanical properties and durability of basalt fiber-reinforced materials [22], [40]. The study also references the work by Hejazi et al. (2012), which provides practical insights into the use of various fibers in soil reinforcement.

4.6 Interdisciplinary Insights

This research benefits from an interdisciplinary approach, drawing on insights from material science and environmental science to enhance the understanding of basalt fiber reinforcement. This interdisciplinary perspective opens up new avenues for research and innovation in soil stabilization techniques. The study highlights the importance of understanding the microstructural interactions between basalt fibers and various cementitious matrices, which can lead to optimized fiber-matrix interactions for improved strength and durability [22]. This aligns with recent studies on the mechanical properties and durability of basalt fiber-reinforced materials [22], [40]. The study also references the work by Hejazi et al. (2012), which provides a comprehensive review of the use of natural and synthetic fibers in soil reinforcement.

4.7 Data Analysis and Modeling

The use of innovative data analysis techniques and modeling approaches is a significant contribution of this study. These methods offer unique interpretations of the data, leading to a deeper understanding of the complex interactions within the basalt fiber-reinforced soil matrix. The development of predictive models based on experimental data allows for more accurate forecasting of the mechanical properties of reinforced soils under different conditions. This approach not only validates the experimental findings but also provides a foundation for future research and practical applications [22]. This aligns with recent studies on the mechanical properties and durability of basalt fiber-reinforced materials [22], [40]. The study also references the work by Zhao et al. (2024), which provides detailed insights into the mechanical properties of fiber-reinforced soil cement based on kaolin.

4.8. Influence of Key Parameters on Strength Enhancement

Enhancing the compressive strength, durability, and resilience of basalt fiber-reinforced, cement-stabilized clay is achieved by carefully adjusting parameters such as fiber content, curing conditions, and fiber orientation.

4.8.1. Fiber Content and Orientation

The addition of basalt fibers at optimal concentrations has been shown to significantly improve the structural properties of reinforced soils. Studies suggest that a fiber content level between 0.1% and 0.3% is most effective for enhancing unconfined compressive strength (UCS). For example, research on silty sand matrices found that a 0.2% fiber concentration yielded the best UCS results by promoting effective interaction between the basalt fibers and the cement binder [43]. However, when fiber content exceeds this optimal range, the risk of creating weak points within the matrix increases, which can compromise structural integrity [24], [27].

The fiber orientation within the matrix also impacts its mechanical behavior. Fibers aligned with the main direction of applied stress can significantly boost compressive strength, while a random orientation helps enhance tensile strength by dispersing stress throughout the structure, thereby reducing brittleness. In one study, researchers observed that random fiber placement within the matrix prevented localized crack formation, thereby improving overall ductility and tensile performance [24]. Additionally, analyses using scanning electron microscopy (SEM) have shown that aligned fibers interlock with soil particles, creating a structure that minimizes voids and promotes even load distribution [28], [43].

4.8.2. Curing Time and Conditions

Curing duration and environmental conditions are essential factors in determining the strength and durability of basalt fiber-reinforced cement-stabilized clay. Extended curing times allow for complete hydration of the cement matrix, which is crucial for achieving a strong bond between the fibers and the cementitious material. Studies show that the unconfined compressive strength (UCS) of basalt fiber-reinforced cement-stabilized clay reaches its maximum after approximately 28 days of curing. This extended period allows the fibers to integrate fully into the matrix, enhancing overall stability and load-bearing capacity[27], [43].

The curing environment, particularly the levels of humidity and temperature, also plays a critical role. Controlled humidity supports consistent hydration within the matrix, reducing the occurrence of early-age shrinkage cracks that can weaken the structure. Moderate temperatures, typically around 20°C, have been shown to promote ideal curing conditions. Under these settings, hydration occurs steadily, preventing surface cracking and resulting in stronger fiber-matrix bonds. In contrast, curing at higher temperatures often leads to rapid drying, which can cause micro-cracking on the surface and limit the reinforcement effectiveness of the basalt fibers [26], [28]. Therefore, maintaining an optimal curing environment is key to maximizing the durability and compressive strength of the reinforced matrix.

4.8.3. Soil and Cement

The composition of both the clay and cement used in the matrix significantly influences the performance of basalt fiber reinforcement. Basalt fibers bond particularly well with clay soils rich in silica and fine particles, as these materials allow for better integration within the matrix. In these soil types, the fibers form a cohesive fiber-soil-cement structure that can effectively resist compressive forces and maintain stability under stress [28].

The choice of cement type also impacts the reinforcement efficiency. Cement with high calcium silicate content fosters a stronger bond between the fibers and the matrix. This chemical compatibility helps the fibers anchor firmly within the cement-stabilized clay, improving both the modulus of elasticity and load-bearing capabilities. Research suggests that using a high-calcium silicate cement leads to enhanced structural performance, as it allows the fibers to better absorb and distribute load, which minimizes cracking and deformation under pressure [10], [27].

In addition, selecting well-graded, low-organic soils can optimize the reinforcement performance. Soils with minimal organic content provide a stable matrix where basalt fibers can distribute stress more uniformly, reducing weak points that might otherwise lead to structural failure. By carefully choosing compatible soil-cement combinations, engineers can maximize the mechanical benefits of basalt fiber reinforcement, achieving an optimal balance between compressive strength, durability, and resilience[10], [26].

5. Comparison of Experimental Findings

5.1 Strength Gains Across Studies

Numerous studies consistently demonstrate that adding basalt fibers to cement-stabilized clay significantly enhances unconfined compressive strength (UCS), with notable improvements observed across various soil types and fiber content levels. For instance, [43] identified a 0.2% fiber content as optimal for silty sand matrices, yielding substantial UCS improvements due to enhanced fiber-soil-cement bonding [43]. Similarly, [28] reported increased compressive and tensile strength at low fiber content, underscoring that higher fiber concentrations can sometimes lead to diminishing returns by creating weak zones in the matrix[28].

These findings align with other research, such as Gao et al. (2021), which showed that a fiber content of 0.1%-0.3% typically provides the best results across different cement-stabilized soils[27]. Interestingly, some studies found that soil type also plays a critical role; clay soils with high silica content, for example, appear to bond more effectively with basalt fibers, potentially due to a chemical synergy that enhances the overall strength of the composite[10], [27]. Additionally, findings by [27] suggest that fiber orientation within the soil matrix can further influence strength gains, with aligned fibers increasing load-bearing capacity and randomly oriented fibers enhancing flexibility and tensile properties [43].

5.2 Durability and Long-Term Performance

Durability studies reveal that basalt fiber-reinforced composites exhibit excellent resistance to environmental stressors such as temperature fluctuations, moisture variations, and cyclic loading. Research by Li et al. 2022) showed that basalt fibers significantly reduce microcracking over time, which is critical for applications exposed to freeze-thaw cycles, high humidity, and other weathering effects [10]. Furthermore, basalt fiber-reinforced concrete (BFRC) demonstrates superior resistance to chemical erosion, including acid and alkali attacks, compared to traditional reinforcements [26].

In addition, Bheel, (2021) conducted studies on the performance of BFRC under cyclic loading, where basalt fibers were shown to retain a high percentage of their original strength after multiple load cycles. This finding is particularly relevant for infrastructure applications where materials face repeated stresses, such as in highway foundations or retaining walls [26]. Long-term performance studies also underscore that basalt fiber reinforcement offers stable durability, outperforming traditional reinforcements in environments subject to moisture ingress and temperature-induced cracking [28].

5.3 Environmental and Economic Considerations

The environmental benefits of using basalt fibers are substantial, given that they are derived from naturally abundant basalt rock and involve minimal processing. Unlike synthetic fibers, basalt fibers do not require harmful chemicals or extensive energy inputs, making them an eco-friendly choice for sustainable construction [10]. Li et al. 2022) emphasized that basalt fibers have a lower environmental footprint than carbon or glass fibers, mainly because they are sourced from volcanic rock without added chemical agents [26].

Economically, basalt fibers are highly cost-effective. Their raw material, basalt, is widely available, which reduces production costs relative to other high-performance fibers like carbon and aramid. Furthermore, basalt's durability and resistance to environmental factors mean lower maintenance and replacement costs over the lifespan of reinforced structures [43]. This makes basalt fiber a practical choice in large-scale construction projects where both cost and environmental impact are significant considerations [27].

6. Challenges and Limitations

6.1 Technical Limitations

Despite the benefits, there are technical challenges in implementing basalt fiber reinforcement on a large scale. Achieving a uniform dispersion of basalt fibers within the cement matrix can be challenging, as non-uniform distribution can create weak points that reduce reinforcement effectiveness. Studies indicate that fiber clumping or uneven distribution may lead to reduced mechanical performance, especially in areas where load-bearing consistency is critical [28]. Additionally, maintaining fiber orientation, particularly in large-scale applications, poses a technical hurdle, as traditional mixing methods may not adequately control fiber alignment [27].

Another practical issue lies in managing the structural consistency across different soil types and environmental conditions. In large-scale applications, it is difficult to ensure uniformity in soil composition and curing conditions, which can affect the reinforcement's overall performance. As noted by Liu et al. (2022), variations in soil mineral content and environmental exposure can lead to unpredictable results, potentially undermining the benefits of basalt fiber reinforcement in certain conditions [10], [43].

6.2 Research Gaps

The field currently faces several research gaps, particularly concerning the long-term behavior of basalt fiber-reinforced soils in real-world conditions. While laboratory studies provide valuable insights, there is a limited amount of field data assessing the long-term durability and performance of basalt fiber composites in different climates and soil conditions. Research by Sun et al. (2023)indicates a need for studies examining the performance of basalt fibers under prolonged exposure to temperature fluctuations, freeze-thaw cycles, and chemical exposure [43].

Furthermore, there is a limited understanding of the microstructural interactions between basalt fibers and various cementitious matrices. This lack of knowledge hinders the ability to optimize fiber-matrix interactions for improved strength and durability. Zhu et al., (2021) noted that a more detailed examination of these interactions could reveal opportunities for enhancing the bonding characteristics of basalt fibers, thereby improving the mechanical properties of the reinforced matrix [27]. Broadening research to include a wider range of soil types and environmental exposures could also provide a more comprehensive understanding of basalt fiber reinforcement's practical applications [28].

7. Conclusion

This thorough literature review explores the use of basalt fibers to reinforce cement-stabilized clay, uncovering their capacity to substantially enhance the mechanical properties and long-term durability of these soils for a variety of construction and geotechnical applications. Collectively, the studies reviewed demonstrate that incorporating basalt fibers significantly increases the unconfined compressive strength (UCS), tensile strength, and crack resistance of these clay soils. It has been found that fiber concentrations in the range of 0.1% to 0.3% by weight are most effective in achieving these improvements. Moreover, the importance of curing conditions is highlighted, with extended curing periods and controlled environments being crucial for optimizing fiber-matrix adhesion and overall performance.

The review also highlights the environmental and economic benefits of using basalt fibers. Derived from abundant natural volcanic rock and requiring minimal processing, basalt fibers offer a sustainable and cost-effective alternative to traditional reinforcement materials. However, challenges remain in ensuring uniform fiber dispersion and maintaining fiber orientation in large-scale applications. Future research should focus on improving fiber distribution techniques and exploring hybrid reinforcement strategies that combine basalt fibers with other materials to capitalize on their complementary strengths. Additionally, long-term field studies are necessary to assess the durability of basalt fiber-reinforced composites under real-world conditions, particularly across diverse climates and soil types.

7.1. Future Directions

1. Future research should aim to develop advanced mixing methods and utilize dispersing agents to achieve uniform fiber distribution within the cement matrix. This will help maximize the mechanical benefits of basalt fiber reinforcement in large-scale applications.
2. Investigating hybrid reinforcement approaches that combine basalt fibers with other materials, such as polypropylene or steel fibers, could leverage complementary strengths. This approach may offer improved crack resistance, increased tensile strength, and enhanced flexibility, making it suitable for applications requiring multidirectional load-bearing capacity.
3. Long-term field studies are essential to evaluate the performance of basalt fiber-reinforced composites under real-world conditions. These studies should focus on environmental exposure factors such as freeze-thaw cycles, humidity fluctuations, and corrosive agents to assess the durability and strength retention of these materials over time.
4. Further research should delve into the microstructural interactions between basalt fibers and various cementitious matrices. Advanced analytical techniques, such as Scanning Electron Microscopy (SEM) and X-ray diffraction (XRD), can provide insights into fiber-matrix bonding and microstructural changes, helping to optimize reinforcement strategies.
5. Evaluating the ecological impact of basalt fiber use in construction can further affirm its suitability for sustainable infrastructure projects. This includes assessing the life cycle environmental footprint of basalt fiber-reinforced materials compared to traditional reinforcements.
6. Translating laboratory findings into practical applications through field trials is crucial. These trials should focus on infrastructure projects such as road construction, slope stabilization, and erosion control to validate the effectiveness of basalt fiber reinforcement in real-world scenarios.

In summary, reinforcing cement-stabilized clay with basalt fibers emerges as a highly promising solution for enhancing soil strength and durability in geotechnical engineering applications. The insights from this review confirm the potential of basalt fibers as a sustainable and effective reinforcement option, contributing to more resilient and environmentally friendly construction practices. Further research and practical applications are encouraged to fully harness the benefits of basalt fiber reinforcement in infrastructure projects.

Statements & Declarations

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Author Contribution:

Ichede Popina Ebonghas developed the research concept, designed the experimental framework, carried out laboratory tests, and performed data analysis. She also wrote and revised the manuscript. Laber Charles Odokonyero offered methodological guidance, supervised the research activities, and provided critical feedback on the manuscript. Both authors reviewed and approved the final version of the paper.

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