Effect of Basalt Fiber on Unconfined Compressive Strength of Cement Stabilized Clay, an Experimental Approach

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Abstract
This research explores the influence of basalt fiber reinforcement on the unconfined compressive strength (UCS) of cement-stabilized clay, with the aim of improving its geotechnical viability. A suite of laboratory experiments was undertaken, varying the proportion of basalt fibers, cement content, and curing times to evaluate their impact on the mechanical performance of the composite. Scanning Electron Microscope (SEM) analysis was also conducted to investigate the microstructural interactions within the fiber-matrix system, particularly focusing on crack resistance and the quality of interfacial bonding. The findings reveal that the inclusion of 6 mm basalt fibers, notably at a 1.2% concentration, substantially enhances UCS by 71% and improves ductility. Prolonged curing durations were found to further augment strength by fostering advanced cement hydration and stronger fiber-matrix cohesion. SEM images substantiate these outcomes, indicating a reduction in crack formation and an increase in material resilience. The study proposes that the incorporation of basalt fibers could significantly bolster the strength of cement-stabilized clay, positioning it as a fitting candidate for applications such as road foundations and slope reinforcement.

Keywords: Basalt Fiber, Unconfined Compressive Strength, Cement-Stabilized Clay, Soil Reinforcement, Curing Duration.

1. Introduction

Infrastructure development is essential for fostering economic growth and social progress. In recent years, China has achieved remarkable advancements in infrastructure, with projects such as Beijing Daxing Airport and the Shanghai Yangshan Port Automation Terminal exemplifying the country's commitment to innovative construction [1], [2], [3]. However, large-scale construction projects often face challenges related to soil quality. Soil is a fundamental component in construction, and its properties significantly influence the type of structures that can be built. Pre-construction soil testing is essential to assess these properties [4], [5], [6]. Historically, clay, silt, and organic soils have been considered unsuitable for construction due to their poor technical qualities [7], [8], [9]. However, recent engineering advancements have introduced new methods to stabilize these soils, enhancing their viability for construction. Clay soils, characterized by fine particles and plasticity, are common and pose significant engineering challenges due to their high compressibility and low shear strength [10], [11]. These properties can lead to structural failures such as settlement and sliding [12]. Additionally, clay soils are susceptible to moisture changes, which can cause swelling or shrinking, further

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Basalt fibers exhibit high tensile strength (up to 4840 MPa) and are non-reactive in alkaline environments, making them ideal for geotechnical use.

compromising structural integrity [13]. Traditional stabilization methods, such as adding cement or lime, improve load-bearing capacity but can alter soil chemistry and have environmental impacts [11], [14],[15], [16]. Soil reinforcement is a critical aspect of geotechnical engineering, enhancing soil mechanical properties and improving stability for construction applications [15], [16]. Techniques like soil stabilization and reinforcement are essential for preventing soil-related failures and ensuring the longevity of infrastructure projects [17], [18], [19]. Effective reinforcement can mitigate risks such as landslides and foundation settlements [20], [21]. Basalt fibers, derived from igneous basalt rocks, offer significant advantages over traditional reinforcement materials. They are strong, resistant to chemical and thermal degradation, and environmentally friendly [22], [23], [24]. Preliminary studies indicate that basalt fibers can enhance the strength, stiffness, and durability of clay soils, potentially reducing issues like erosion and settlement [25], [26]. Further research is needed to explore the mechanisms and potential of basalt fibers in soil reinforcement, including their impact on soil hydraulic properties and optimal configurations for different soil types. This research is essential for developing standardized guidelines for soil stabilization projects [27]. Figure 1. Illustration of fiber reinforcement effects in cement-soil matrices. This diagram elucidates the role of fibers in bolstering shear resistance, mitigating crack propagation, and facilitating load distribution across the composite material.

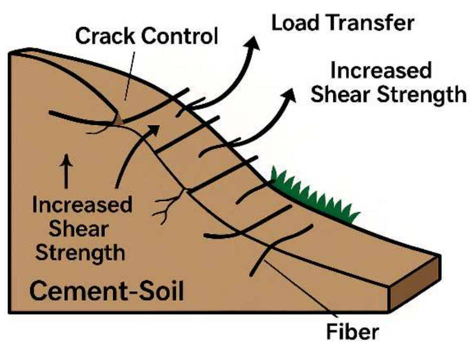

Figure 1: Fiber reinforcement effects in cement-soil matrices

1.1 Problem statement and novelty

In geotechnical engineering, soft and weak soils pose significant challenges due to their limited load-bearing capacity and susceptibility to deformation [28], [29], [30], [31], [32]. Traditional cement stabilization methods, while effective at enhancing soil strength, often lead to brittleness, which can compromise the durability and performance of geotechnical structures. Recent advancements suggest that incorporating fibers into stabilized soils can mitigate brittleness and improve mechanical properties [33], [34], [35], [36]. Among various fiber types, basalt fibers are particularly promising due to their superior mechanical properties, eco-friendliness, and resistance to chemical degradation [25], [37], [38], [39], [40]. However, existing research on fiber-reinforced soil stabilization primarily focuses on synthetic fibers and often lacks detailed mechanical characterization, particularly with regard to curing time, failure mode transitions, and residual strength [41], [42], [43], [44]. This study aims to fill this gap by conducting a comprehensive assessment of basalt fiber reinforcement in cement-stabilized clay, focusing on strength improvement, failure mode transformation, crack resistance, and fiber-matrix interactions. By integrating Unconfined Compressive Strength (UCS) testing with Scanning Electron Microscopy (SEM) analysis, this research provides valuable insights into the long-term performance and durability of fiber-reinforced soil. The findings contribute to the development of sustainable soil stabilization techniques, with practical applications in road subgrades, embankment reinforcement, and slope stabilization projects.

1.2 Aim and scope

This study aims to evaluate the impact of basalt fiber reinforcement on the mechanical properties of cement-stabilized

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clay, with a focus on optimizing fiber content and curing duration. The research involves a detailed experimental program that examines different cement dosages (4%, 8%, and 12%) and basalt fiber contents (0%, 0.4%, 0.8%, and 1.2%). Unconfined Compressive Strength (UCS) tests are conducted over curing periods of 7, 14, and 28 days to analyze the evolution of strength. Additionally, Scanning Electron Microscopy (SEM) analysis is used to investigate the microstructural interactions within the fiber-matrix system. The findings from this study are expected to provide practical recommendations for the use of basalt fibers in soil stabilization, offering a sustainable approach for geotechnical applications such as road subgrades, embankment reinforcement, and slope stabilization.

2. Test Materials and Methods

2.1. Test Materials

2.1.1. Clay Soil

The clay soil used in this study was sourced from Jiangsu University, China, at a depth of approximately 3 meters below the surface. The physical and mechanical properties of the soil were determined under the JTG 3430-2020 [45] standard. A particle size distribution analysis was performed to classify the soil, and key properties, including liquid limit, plastic limit, plasticity index, optimum moisture content, and maximum dry density, were recorded in Figure 1(a), Figure 2, and Table 1.

(a) (b) (c)

Figure 2: Materials; (a) Clay; (b) Cement; (c) Basalt Fiber

TABLE 1: Clay Soil Properties

Liquid limit Wl/%	Plastic limit Wp/%	Plasticity index Ip/%	Optimal moisture content w%	Maximum dry density ρ_d/(g cm^{-3})
41.1	21.6	19.5	18.35	1.816

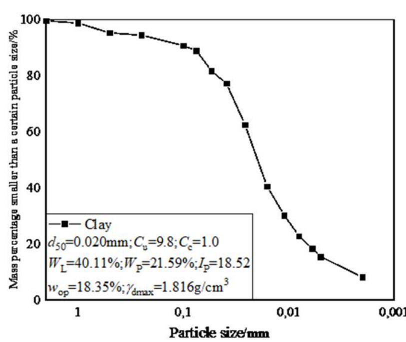

Figure 3: The grading curve for the particle size

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2.1.2. Basalt Fiber (BF) and Cement

The basalt fibers used in this research were procured from Hunan Changsha Ningxiang Building Materials Co., Ltd shown in Figure 1(c) and 3. These fibers had an average length of 6 mm and were characterized by high tensile strength, durability, and resistance to chemical and thermal degradation Table 2. The cement utilized in the stabilization process was PSA32.5 slag Portland cement, a commonly used binder for soil improvement Figure 1(b).

TABLE 2: Basalt Fibers' Physical Properties

Properties	Density(g/cm^3)	Elastic modulus (GPa)	Tensile strength (MPa)	Length (mm)	Filament diameter/μm	Tensile strength under heat treatment (%)		
						20°c	200°c	400°c
Performance	2.63-2.65	91~110	3000~4800	6	7~15	100	95	82

2.1.3 Conceptual Framework of the Fiber–Soil–Cement Interaction

Figure 4**.** Conceptual illustration of the internal load transfer and reinforcement mechanisms in basalt fiber-reinforced cemented soil. This schematic illustrates the synergistic interaction among soil particles, the cementitious matrix, and discrete basalt fibers. The cement component binds adjacent soil particles through hydration products, forming a rigid network responsible for the initial strength gain. Embedded basalt fibers contribute to mechanical enhancement by acting as crack arresters, interrupting microcrack development and delaying their growth under applied loads [46]. These fibers facilitate load redistribution within the matrix, allowing stress to be more evenly transferred and absorbed, particularly after peak stress is reached. Moreover, the fiber–matrix interface plays a critical role in toughness and ductility enhancement, promoting strain-hardening behavior and residual strength retention [47]. The conceptual framework supports the experimental findings of this study, where increased fiber content improved both peak and post-peak performance. This framework reinforces the applicability of fiber-reinforced cemented soils in geotechnical contexts requiring higher energy dissipation, crack resistance, and long-term mechanical stability.

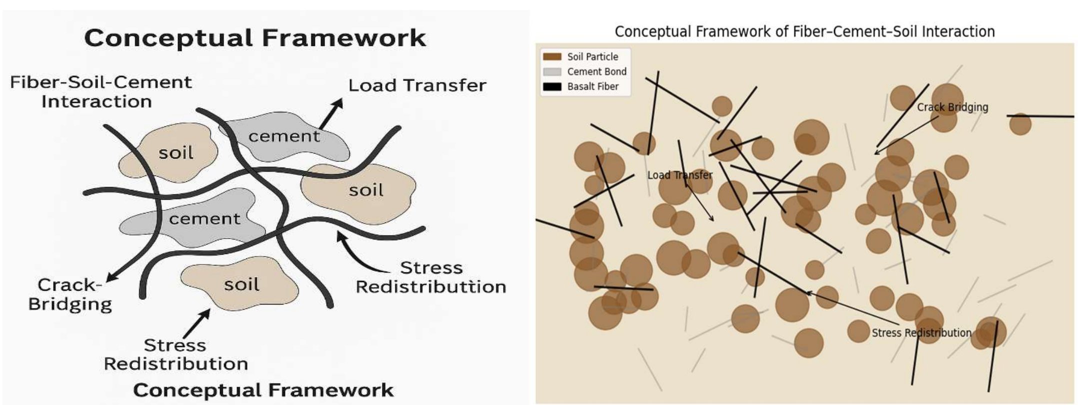

Figure 4: Conceptual Framework of Fiber-Cement-Soil

2.2. Test Methods

2.2.1. Index and Compaction Properties

The basic geotechnical characterization of the clay soil was performed through Atterberg limit and compaction tests. The liquid and plastic limits were determined following the BS 1377 [48] procedure using the cone penetration method. The liquid limit corresponded to a 20 mm cone penetration, while the plastic limit was identified as the moisture content at which soil threads begin to crumble when rolled. The plasticity index (PI), calculated as the difference between LL

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and PL, ranged from 31.5 to 33, indicating a medium to high plastic clay. Notably, the liquid limit remained constant at 52%, while the plastic limit decreased slightly with increased cement content. The test outcomes are summarized in Table 3**.**

Compaction behavior was assessed using the Standard Proctor method (ASTM D698) [49]. The test yielded an optimum moisture content (OMC) of 18.35% and a maximum dry density (MDD) of 1.816 g/cm³. These results reflect a moderately compacted soil, suitable for stabilization with cement and fiber additives. The compaction curve are illustrated in Figure 3.

TABLE 3: Results of the Liquid Limit Test

Cement-Soil%	Liquid limit W_l/%	Plastic limit W_p/%	Plasticity index I_p
4-96	52	20.5	31.5
8-92	52	19.5	32.5
12-88	52	19	33

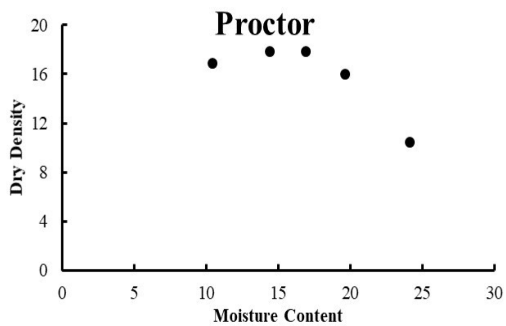

Figure 5: Compaction curve

3. Unconfined Compressive Strength (Peak and Post-Peak calculation process)

3.1 Unconfined Compressive Strength

UCS tests were conducted in accordance with BS 1377-7 to evaluate the strength development of cemented clay specimens. Cylindrical samples (38 mm in diameter and 76 mm in height) were prepared, cured under controlled moisture conditions for 7, 14, or 28 days, and tested at a constant axial strain rate of 1 mm/min. The peak load was recorded to determine UCS, and the post-peak behavior was also observed for residual strength analysis explained in Figure 6 (a) and (b).

The unconfined compressive strength (UCS) test was conducted by ASTM D2166 [50], a standard method for evaluating the compressive behavior of cohesive soils. This test provides essential data on load-bearing capacity, stress-strain behavior, and failure characteristics**,** making it highly relevant for assessing the impact of fiber reinforcement and cement stabilization on soil strength.

The UCS was determined using the equation:

$$\mathrm{UCS(qu)} = \frac{\mathrm{Pmax}}{\mathrm{A}} \tag{1}$$

Where:

P_{max}= Maximum axial load before failure peak (N)

A = Initial cross-sectional area of the specimen (mm²), computed as:

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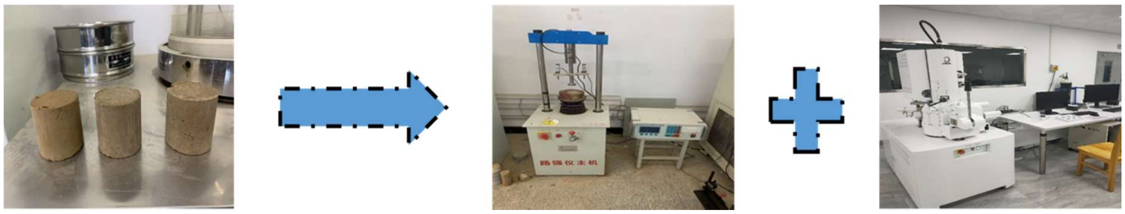
$$A = \frac{\pi D^2}{4} \tag{2}$$

Where D is the specimen diameter.

The UCS values were recorded for all test specimens, and comparative analyses were conducted to evaluate the effects of varying fiber and cement contents on compressive strength. Additionally, stress-strain relationships were examined to assess the ductility, toughness, and failure mechanisms of the stabilized soil under compressive loading.



(a) (b) (c)

Figure 6: UCS Test ; (a) Samples; (b) UCS Equipment; (c) Scanning Electron Microscopic

The research was structured to examine the impact of basalt fibers, each with a uniform length of 6mm, on the mechanical behavior of clayey soil across a range of fiber concentrations. A total of samples were prepared and divided into two main testing groups summarized in Table 4:

- Group 1: Unconfined Compression Tests (UCS) on Cement-treated soil

These tests, conducted at 7, 14, and 28 days, measured the compressive strength of Cement-treated soil samples to provide control data for comparison with fiber-reinforced samples.

- Group 2: Unconfined Compression Tests (UCS) on Cement-fiber-treated soil

Conducted under the same periods as cement-treated soil samples, these tests evaluated how the addition of basalt fibers affected the soil's compressive strength.

TABLE 4: Test Procedure

Tests.	Group	Mixture	Content (% by weight)			Length of basalt Fiber(mm)	Curing-days		
			Soil	cement	Basalt Fiber				
Unconfined compressive strength	1	96%S-4%C-0%F	96	4	0	6	7	14	28
		92%S-8%C-0%F	92	8	0	6	7	14	28
		88%S-12%C-0%F	88	12	0	6	7	14	28
	2	96%S-4%C-0.4%F	96	4	0.4	6	7	14	28
		92%S-8%C-0.4%F	92	8	0.4	6	7	14	28
		88%S-12%C-0.4%F	88	12	0.4	6	7	14	28
		96%S-4%C-0.8%F	96	4	0.8	6	7	14	28
		92%S-8%C-0.8%F	92	8	0.8	6	7	14	28
		88%S-12%C-0.8%F	88	12	0.8	6	7	14	28
		96%S-4%C-1.2%F	96	4	1.2	6	7	14	28
		92%S-8%C-1.2%F	92	8	1.2	6	7	14	28
		88%S-12%C-1.2%F	88	12	1.2	6	7	14	28

2.2.4. Scanning Electron Microscope SEM

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A Scanning Electron Microscope (SEM) image provides a highly detailed, grayscale visualization of a sample's surface, revealing its microscopic features with remarkable clarity [51]. Scanning Electron Microscope (SEM) analysis was performed on specimens cured for 28 days to examine the microstructural characteristics of the cement-stabilized clay and its interaction with basalt fibers. The primary objective was to investigate the fiber-matrix bonding, crack propagation, and interfacial transition zone (ITZ), which are crucial in strength development and durability.

Small fragments of the tested specimens were carefully extracted and coated with a thin layer of conductive material to prevent electron charging during imaging. The samples were then placed in an SEM chamber, where a focused electron beam scanned the surface to generate high-resolution images of the fiber-matrix interface. These images provided insights into the distribution of cement hydration products, fiber bridging mechanisms, and structural integrity of the composite material. The SEM machine used for this study is shown in Figure 6 (c).

3. Results and Discussion

3.1 Unconfined Compressive Strength (UCS) Test Results

The stress-strain responses of cement-stabilized clay specimens reinforced with varying basalt fiber contents (0%, 0.4%, 0.8%, and 1.2%) were analyzed over 7, 14, and 28 days curing periods. The influence of fiber addition, cement content, and curing duration on the mechanical behavior of the composite was systematically assessed. Furthermore, the samples were subjected to a one-day soaking period before UCS testing, which likely influenced the observed strength characteristics.

The mixtures consist of soil (S) and 12% cement (C), 8% cement (C), and 4% cement (C). The control mixtures (Soil-12% Cement 0% Fiber, Soil-8 % Cement-0 % Fiber, and Soil-4 % Cement-0 % Fiber) display a brittle failure pattern, marked by a sharp peak in axial stress followed by a rapid decline, indicating low ductility shown in Figure 7. This observation is consistent with R. and G. (2001) [52], who noted that unreinforced soil-cement mixtures often fail abruptly due to their limited tensile strength. At 28 days, the control mixtures show a slight increase in peak stress compared to earlier curing periods, reflecting the ongoing hydration of cement, as highlighted by L. Wang et al. (2018)[53].

The addition of fiber significantly alters the stress-strain response. In Figures 7 fiber content increases, the curves reveal higher peak stresses and more gradual post-peak softening, indicating improved ductility. For instance, the 12% Cement-0.4% Fiber, 8% Cement-0.4% Fiber, and 4% Cement-0.4% Fiber mixtures show a moderate rise in peak stress and strain at failure compared to the control, as fibers bridge micro cracks and delay failure. This aligns with findings from J. Zhao et al. (2024)[54], who demonstrated that fibers enhance soil-cement mixtures' energy absorption capacity and toughness. 0.8% Fiber mixtures achieve a notable increase in both strength and strain at failure, with a flatter post-peak curve, indicating enhanced toughness. This is consistent with V. Sharma, Vinayak, and Marwaha (2015)[55] , who found that fiber reinforcement improves the energy absorption capacity of soil-cement composites. 1.2% Fiber mixtures exhibit the highest peak stress and strain at failure, suggesting that fiber content up to 1.2% optimizes strength and ductility. However, additional fiber may lead to diminishing returns beyond this threshold, as observed by Ahmad et al. (2024)[56].

The 28-day curves generally display higher peak stresses and improved ductility compared to the 7- and 14-day curves, reflecting the continued hydration of cement and the development of stronger bonds between soil particles and fibers. This is consistent with Shengnian Wang et al. (2021)[57], who reported that longer curing periods enhance the mechanical properties of fiber-reinforced soil-cement mixtures. The results suggest that fiber reinforcement effectively improves the strength and ductility of soil-cement mixtures, making them more suitable for applications such as road subgrades, slope stabilization, and embankments.

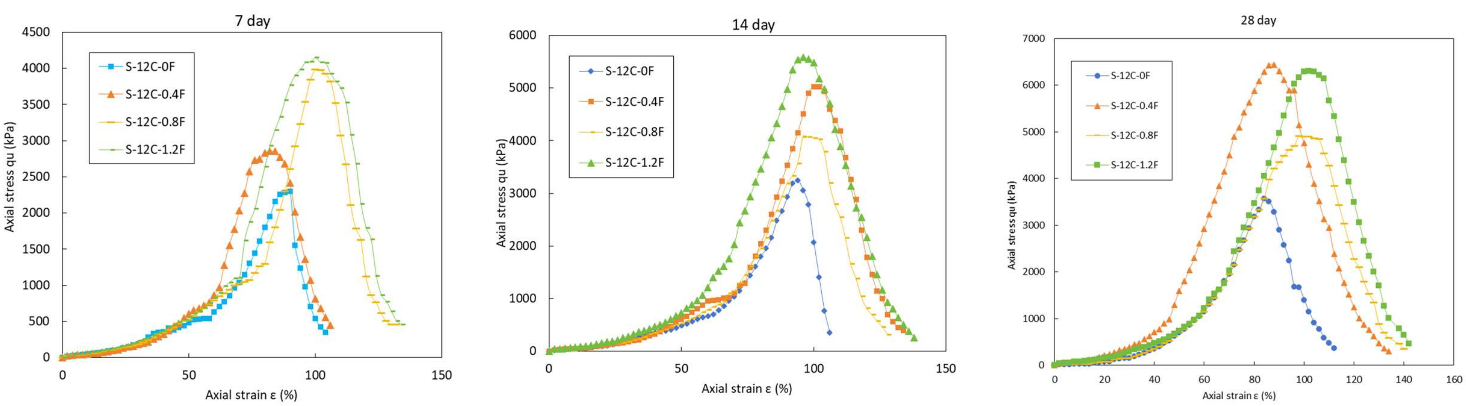
Basalt fibers exhibit high tensile strength (up to 4840 MPa) and are non-reactive in alkaline environments, making them ideal for geotechnical use.

The findings of this study, with a compressive strength of approximately 6000 kPa, position it among the highest values reported, particularly following the work of Chen et al. (2024)[42], who explored the role of basalt fiber (BF) in improving the strength of cement-stabilized expansive soil. Their research focused on the effect of incorporating 0-1% BF in soil stabilized with 6% cement, revealing a substantial improvement in unconfined compressive strength (UCS) when 0.4% Basalt Fiber was added. The study also highlighted the enhanced performance under both normal conditions and after exposure to multiple dry-wet cycles, demonstrating Basalt Fiber is potential to increase soil stability and durability.

This study surpasses several others in terms of compressive strength, such as those Pavithra and Moorthy (2021)[58], Ghanbari et al. (2022)[41] , and X. Zhang et al. (2023)[59], whose results ranged approximatively from 4 to 8 MPa. Numerous studies have examined the efficacy of basalt fiber in improving UCS under different conditions and material compositions, including its application in peat-soil reinforcement and nano-SiO2 concrete mixtures. These studies consistently show that basalt fiber enhances mechanical properties, durability, and cracking resistance, underscoring its versatility as a reinforcing agent in both geotechnical and structural engineering.

In summary, this study's findings reveal a notable enhancement in compressive strength, surpassing much of the existing research in the field. The results underscore the effectiveness of the chosen methodology in achieving higher compressive strength, demonstrating its potential for use in applications that require improved material durability. This strong performance serves as a testament to the innovative approach taken, laying a solid foundation for future research and development and positioning this study as a significant contribution to advancing the field.

Additionally, the results emphasize the potential of basalt fiber reinforcement in stabilizing clay soils for geotechnical applications. The optimal fiber content of 1.2% strikes a balance between improving strength and maintaining workability, while prolonged curing contributes to enhanced long-term durability. Furthermore, the impact of pre-soaking suggests that moisture conditioning may play a crucial role in further optimizing the interactions between soil, cement, and fiber.



(a) (b) (c)

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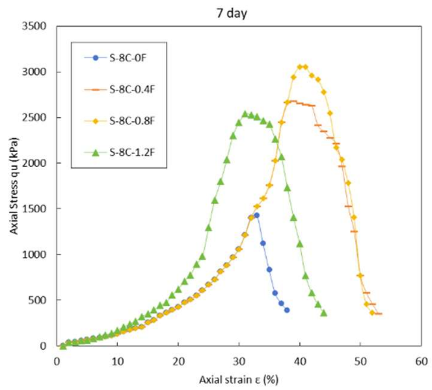

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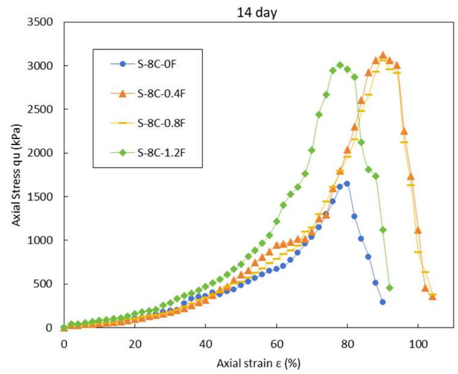

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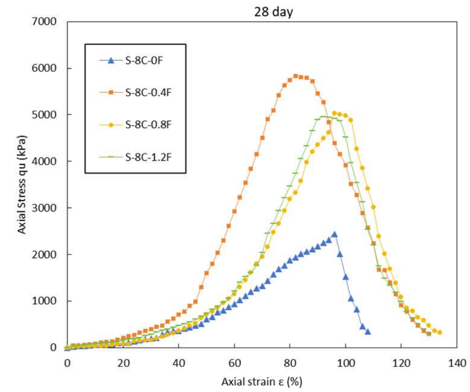

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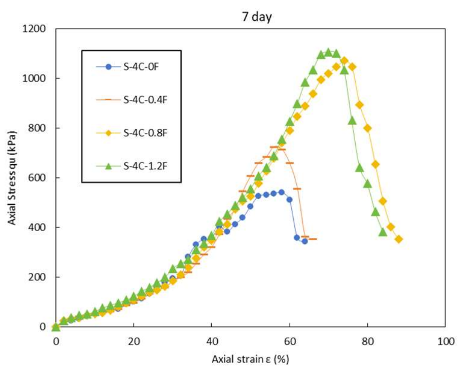

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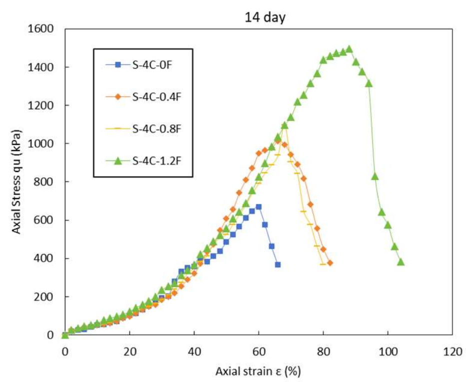

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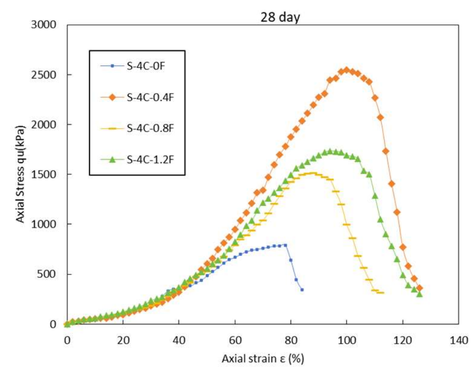

(i)

Figure 7: UCS Curves ;(a, d, g) At 7 Days ;(b, e, h) At 14 Days ;(c, f, i) At 28 Days

3.1.1 Influence of Basalt Fiber Content

The UCS curves for various cement-clay ratios (S-C) illustrate the transition from brittle failure in unreinforced samples to a more ductile response when fibers are incorporated. Control samples without fibers exhibited a distinct peak stress followed by a rapid decline, characteristic of brittle failure. The strength improvement in these specimens primarily resulted from cement hydration, which continued over 28 days.

Figure 8, fiber reinforcement; the stress-strain curves gradually declined after reaching peak stress, indicating enhanced ductility and energy absorption. At 0.4% fiber content, a moderate increase in peak stress was observed, highlighting the role of fibers in crack bridging. A further increase in stress at failure was recorded at 0.8%, suggesting improved load resistance and deformation capacity. The highest strength improvement occurred at 1.2% fiber addition, beyond which diminishing returns could arise due to fiber clustering, as reported in previous research Ahmad et al. (2024)[56].

A closer analysis of the stress-strain curves reveals that peak stress values increased with fiber content, with the maximum peak observed for the 1.2% fiber-reinforced mix. Control specimens (0% fiber) displayed sharp peak stress values followed by sudden failure, indicative of brittle behavior. Conversely, fiber-reinforced samples exhibited a more progressive post-peak softening, reflecting improved ductility. The stress-strain behavior suggests that fiber inclusion promotes a more uniform stress distribution, reducing the likelihood of sudden failure and enhancing load-bearing capacity.

The influence of pre-soaking before testing was particularly evident in fiber-reinforced samples, as moisture redistribution may have impacted fiber-matrix interactions. Pre-saturation likely enhanced the effectiveness of fiber

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reinforcement at higher dosages, facilitating improved stress transfer and delaying crack propagation. These findings emphasize the importance of optimizing fiber content to achieve a balance between strength and workability.

Figures 8 illustrate the effect of fiber content on compressive strength and stress across different curing durations and densities. The results confirm that fiber incorporation significantly improves the material's mechanical properties. As shown in these figures, compressive strength (q_u) (in kPa) increases with fiber addition, particularly at 1.20% content. This pattern is consistent across curing durations of 7, 14, and 28 days. Notably, at 28 days, mechanical performance is significantly enhanced, underscoring the combined benefits of prolonged curing and fiber reinforcement.

At 7 days (Figure 8a), stress values remain relatively low and exhibit irregular trends, especially for 4% and 8% hydration. Early curing appears insufficient for strong fiber-matrix bonding, and incomplete hydration further limits strength development. These results suggest that both time and hydration are crucial for achieving effective strength improvement at this stage. By 14 days (Figure 8b), stress values increase, and trends become more consistent. Higher fiber content contributes significantly to strength, with 12% hydration yielding the best results. The extended curing period strengthens fiber-matrix interaction, leading to better load distribution and enhanced material performance. At 28 days (Figure 8c), stress reaches its peak levels, with consistent trends across all hydration levels. The prolonged curing duration ensures optimal fiber-matrix bonding, with 1.2% fiber content and (8%, 12%) hydration demonstrating superior mechanical performance. These findings highlight the essential role of curing time and hydration in maximizing material strength.

Figure 8(d) presents the variation of stress with fiber content for samples containing 4%, 8%, and 12% cement, cured over 7, 14, and 28 days. The data show that increasing cement content significantly enhances stress capacity, with 12% cement yielding the highest strength across all curing periods. This improvement is attributed to increased cementitious bonding within the soil matrix, promoting better load transfer [60]. Fiber addition also contributes to stress improvement, particularly at intermediate contents (0.4–0.8%), beyond which the strength either plateaus or slightly decreases. This behavior suggests a threshold beyond which excess fiber may hinder uniform dispersion or compaction, limiting further gains a trend reported in earlier fiber-soil studies [61].

The study further indicates that fiber content exerts a more significant effect in lower-density matrices (e.g., 12% hydration). In such cases, fibers likely enhance stress transfer and mitigate micro-crack propagation by serving as structural bridges, resulting in greater strength improvements compared to higher-density materials. This observation aligns with previous research by Y. Zhou, Fan, and Chen (2016)[62]; Ding, Guo, and Chen (2019)[63]; and Mohit and Arul Mozhi Selvan (2018)[64], which suggested that less dense matrices facilitate better fiber dispersion and bonding, thereby maximizing the reinforcing potential of fibers.

Moreover, the findings demonstrate that mechanical properties peak at 1.20% fiber content, supporting the conclusions of Wei, Teng, and Khayat (2024)[65], who identified an optimal fiber range of 1.0–1.5% for maximizing strength without compromising workability. The observed trend of increasing strength up to this optimal fiber level is consistent with the findings of C. Zhou et al. (2024)[66]; Yoo, Lee, and Yoon (2013)[67]; J. Zhang, Leung, and Gao (2011)[68], who reported enhanced mechanical behavior due to improved crack bridging and stress distribution at higher fiber contents. However, exceeding this range may lead to fiber clustering, potentially diminishing performance, though such effects were not observed in the current study.

Additionally, the trends in stress presented in the figures align with (Abdulmajeed et al. (2011)[69] , who found that fiber-reinforced composites exhibit superior mechanical performance in lower-density materials. The results also support the observations of Zijl and Slowik (2017)[70], who demonstrated that fibers enhance material ductility and reduce crack propagation, particularly in long-cured systems, as evidenced by the 28-day findings.

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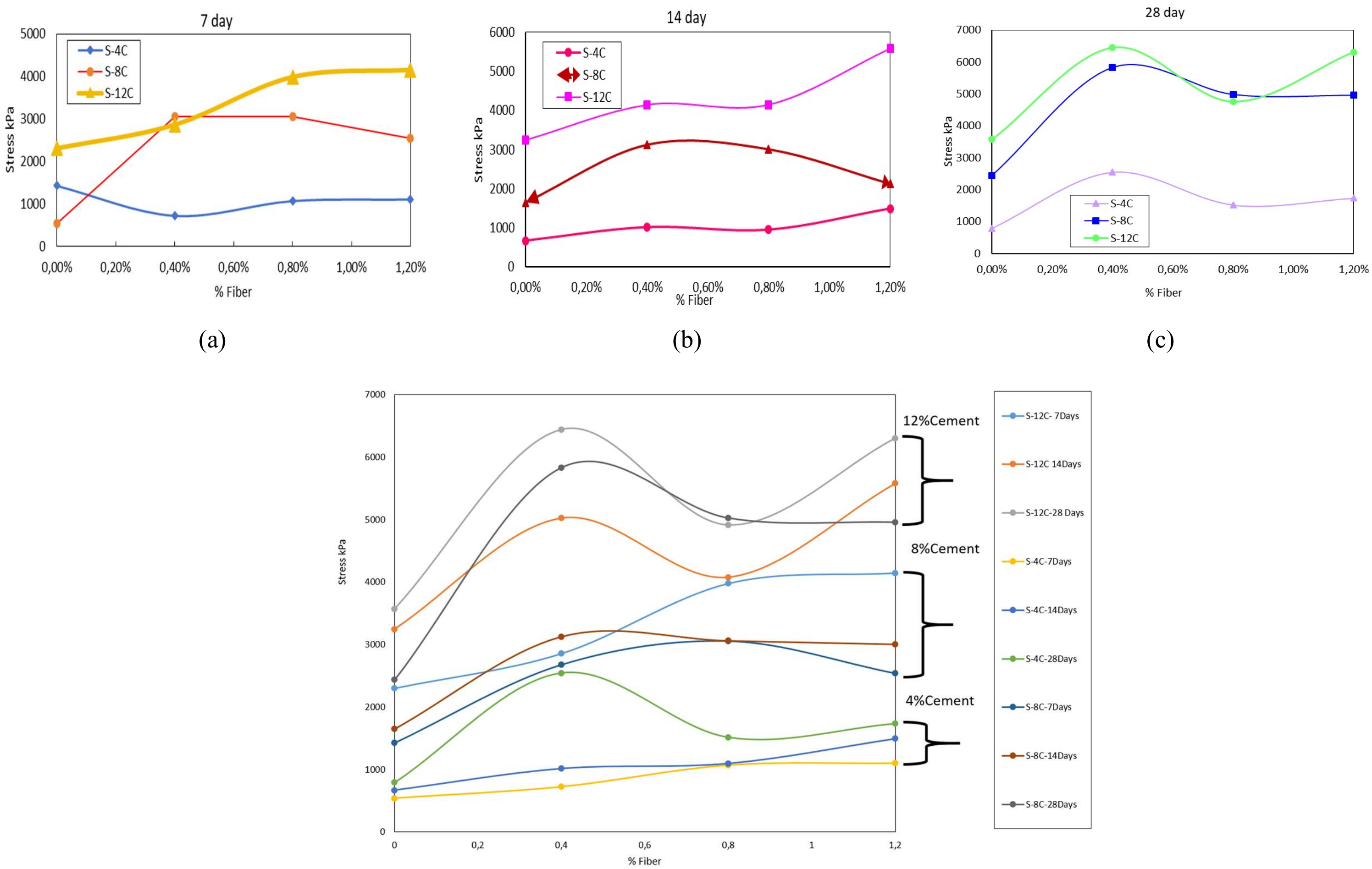

(a) (b) (c)

(d)

Figure 8: Fiber Content; (a) 7 Days; (b) 14 Days ; (c) 28 Days ; (d) Fiber Evolution Based On Each Cement

3.1.2 Effect of Curing Duration

The curing period plays a crucial role in determining the unconfined compressive strength (UCS) of the examined mixtures. At 7 days, the UCS values remained relatively low, particularly in the control samples, due to incomplete cement hydration. While fiber inclusion provided a minor advantage at this early stage, its reinforcing effects became more pronounced as the curing period progressed to 14 and 28 days Figure 9.

A detailed examination of the UCS curves over different curing durations reveals that at 7 days, peak stress values remained relatively low, reflecting incomplete cement hydration. By 14 days, a notable increase in peak stress was evident, particularly in fiber-reinforced specimens. At 28 days, the stress-curing time curves exhibited the highest peak stress values, along with extended strain hardening, indicative of enhanced fiber-matrix interaction and improved crack-bridging capabilities.

The combination of fiber reinforcement and extended curing also influenced the failure mechanisms of the material. While control samples exhibited abrupt failures, fiber-reinforced specimens demonstrated strain-hardening characteristics, suggesting improved load redistribution. This underscores the long-term benefits of fiber incorporation in enhancing both the strength and durability of the composite material.

Figures 9 highlight the effect of curing time on axial stress and fiber content within the material, a crucial aspect in construction and material science. Curing time significantly influences the mechanical properties of materials,

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particularly composites or fiber-reinforced cementitious systems. The data indicates that axial stress varies with different curing durations such as 14 and 28 days and is further modulated by fiber content.

Figures 9 (a) and (b) illustrate the relationship between curing duration, fiber content, and axial stress. In the early curing phase (0–7 days), axial stress remains relatively low across all fiber contents, likely due to incomplete hydration and weak fiber-matrix bonding. As curing progresses (7-14 days), axial stress increases significantly, particularly in specimens with fiber contents of 0.8% and 1.2%, indicating improved hydration and enhanced fiber-matrix interaction. During the extended curing phase (14-28 days), stress values either stabilize or peak, with the 1.2% fiber content yielding the optimum strength. This suggests that prolonged curing optimizes hydration and maximizes the reinforcing effects of fibers.

Figure 9 (a and c) presents distinct variations in axial stress across different fiber contents. Unreinforced samples (0%) consistently exhibit the lowest axial stress at all curing stages, confirming the absence of mechanical reinforcement. The incorporation of 0.4% fibers leads to a notable increase in axial stress across all curing periods compared to the control specimens (Figure 9). At 14 days, specimens with 0.8% fiber content exhibit a moderate rise in stress (Figure 15a, c), likely due to enhanced fiber-matrix bonding. The highest axial stress is observed in samples containing 1.2% fibers, with peak strength achieved at 28 days. These findings underscore the critical role of optimal fiber reinforcement and extended curing duration in enhancing the mechanical performance of the material.

Figures 9 (a, b, and c) further illustrate that axial stress stabilizes or increases with prolonged curing, confirming that extended hydration periods contribute to improved material strength. These findings align with previous research indicating that extended curing times enhance hydration and matrix bonding, thereby improving mechanical performance [71][72]. Additionally, the presence of fibers, particularly at higher dosages, amplifies this effect, as fibers aid in stress redistribution and reinforcement.

Figure 9 (d) shows the variation in unconfined compressive strength (qu) with curing time and fiber content. Strength increases with both longer curing periods and the inclusion of fibers, confirming that cement hydration and fiber reinforcement jointly improve mechanical performance [73].

The most notable strength gains occur at 0.4% and 0.8% fiber, especially at 28 days, suggesting effective crack-bridging and stress transfer. However, performance slightly declines at 1.2% fiber in some cases, likely due to poor fiber dispersion or reduced mix workability.

The data also demonstrates the varying impact of fiber percentages (e.g., 0%, 0.4%, 0.8%, and 1.2%) on axial stress. Higher fiber content generally corresponds with increased axial stress, consistent with studies highlighting fiber reinforcement's role in enhancing tensile strength and crack resistance [74]. However, the relationship between fiber content and curing duration remains complex, requiring an optimal balance between these factors to maximize performance.

The results indicate that curing time significantly influences axial stress, with longer durations and higher fiber content generally leading to superior mechanical performance. These findings align with existing literature, reinforcing the importance of both extended curing and fiber reinforcement in material design and application.

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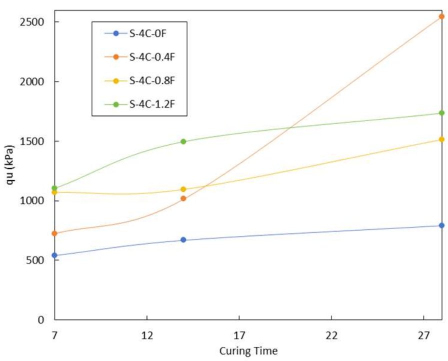
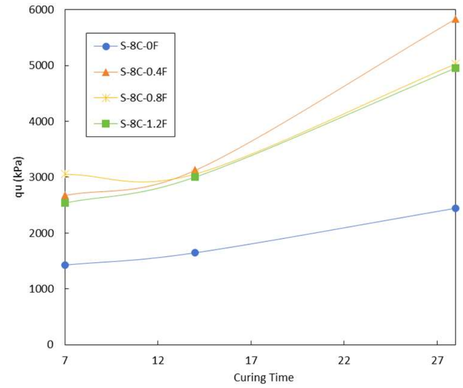
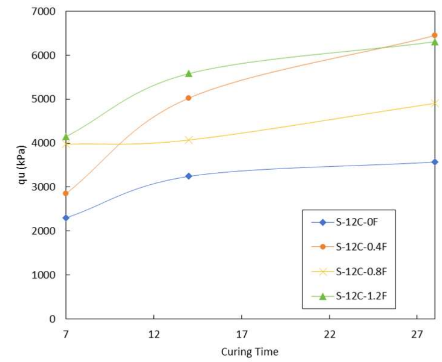


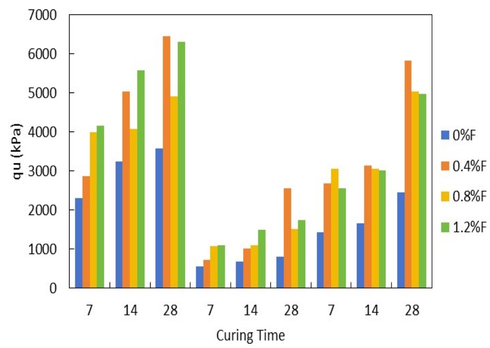
(a)



(b)



(c)



(d)

Figure 9: Strength ;(a) 4%Cement ;(b) 8%Cement ;(c) 12%Cement ;(d) Curing Time at Different Fiber Content

3.2 Failure Mechanism

Figure 10 compares the surface cracking behavior of cylindrical specimens with and without fiber reinforcement, highlighting the influence of fiber inclusion on shrinkage-induced damage.

The fiber-reinforced specimens exhibit finer, more distributed micro-cracks, while those without fibers show prominent shrinkage cracks and visible edge damage. In the fiber-reinforced samples, the cracks appear less severe and more dispersed, suggesting that the fibers effectively control crack propagation by bridging micro-fractures and redistributing internal stresses. This aligns with previous findings that fibers improve the tensile resistance and energy absorption capacity of cemented composites, thereby mitigating crack growth during drying or loading phases[75].

In contrast, the specimens without fibers display larger and more concentrated shrinkage cracks, with some samples showing edge damage. These defects are typical of brittle failure modes in unreinforced cemented materials, where shrinkage strains exceed the material's tensile capacity. The lack of fiber bridging allows cracks to develop unimpeded, leading to surface separation and localized deterioration[76].

Notably, the bottom-left image labeled "crack reduced fiber effect" visually reinforces the role of fibers in suppressing major crack formation. In this case, crack networks appear less defined, and no significant spalling or edge chipping is evident, further indicating that fiber addition contributes to improved structural integrity and dimensional stability during curing and drying.

Overall, this visual comparison confirms that fiber reinforcement substantially improves the post-curing crack resistance of cemented sand composites by altering crack patterns from dominant, open shrinkage cracks to more

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controlled and dispersed micro-cracks. These observations support the use of fibers as an effective crack-mitigating additive in cement-treated geomaterials.

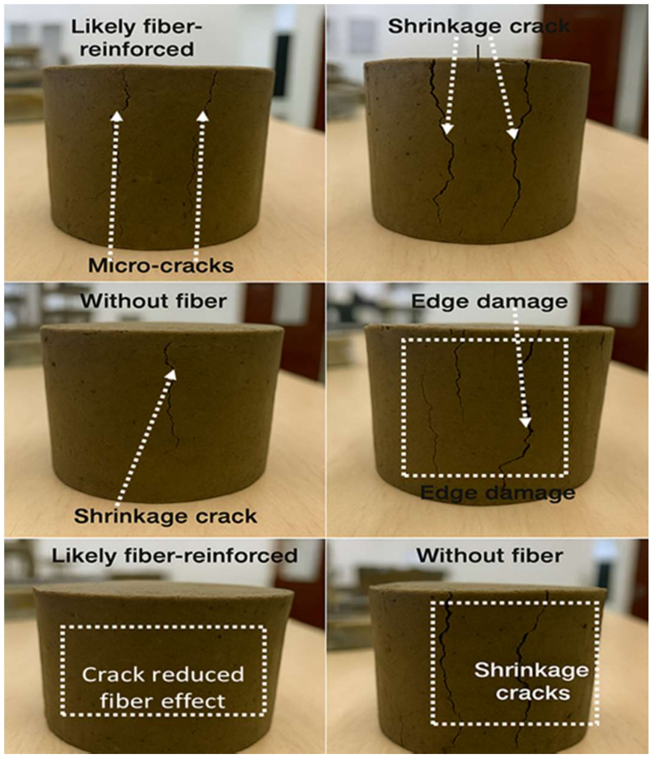

Figure 10: Crack Failure Mode

4. Scanning Electron Microscope (SEM) Analysis

The SEM micrographs clearly illustrate the microstructural evolution and reinforcing mechanisms within basalt fiber-reinforced cemented clay. The images (Figure11) reveal that basalt fibers play a pivotal role in bridging microcracks, thereby enhancing the material's post-peak load-bearing capacity. This crack-bridging effect, observable in several micrographs, contributes to the redistribution of stress across the matrix and effectively improves residual strength. Additionally, a dense matrix can be observed around the fibers, which results from ongoing cement hydration and the progressive formation of calcium silicate hydrate (C–S–H) gels. The presence of these hydration products around the fibers enhances bonding and reinforces the interface, facilitating better stress transfer within the composite. Notably, the interface between the fibers and cementitious matrix is seen developing as curing progresses, with the bond still maturing at 14 days, indicating the importance of curing time in achieving a robust fiber–matrix interlock.

Despite these improvements, microvoids and microcracks are still visible, particularly in early-age samples. However, their detrimental effect appears mitigated by the fiber network, which arrests crack propagation and helps retain structural integrity. Furthermore, the internal pore structure visible in the images reflects the porosity of the matrix. The inclusion of fibers, along with cement hydration, seems to refine the pore network, thus improving the overall durability and reducing permeability. The combined presence of a dense matrix, strong fiber–matrix bonding, and active crack bridging by fibers is consistent with the observed increases in unconfined compressive strength and residual strength at later curing stages. These microstructural characteristics support the mechanical enhancements observed at the macroscopic level and align with findings from similar studies in fiber-reinforced cemented soils [77], [78].

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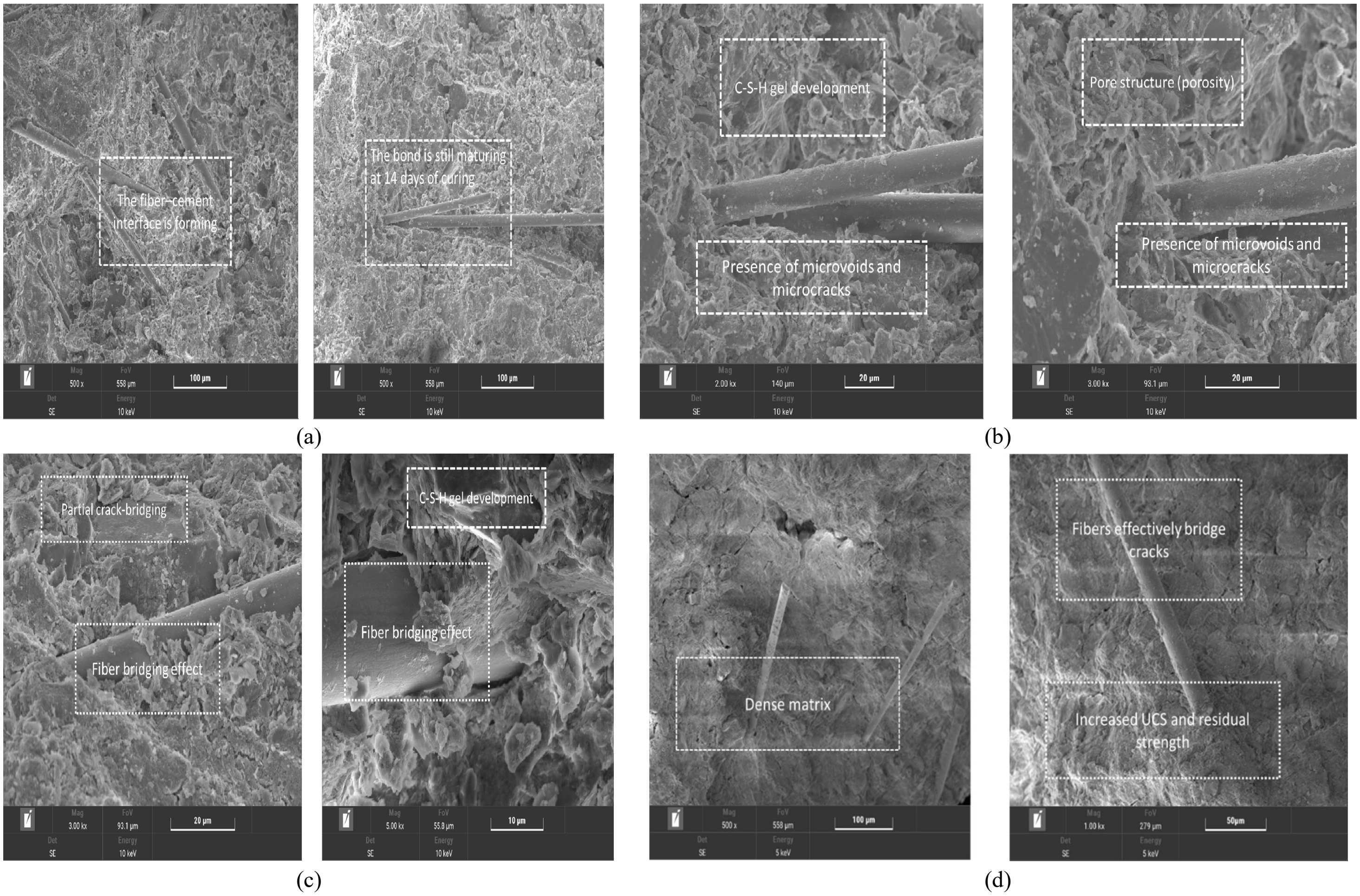

Figure 11: SEM Images Basalt Fiber-Cement Clay Matrix

5. Discussion

The outcomes of this research into basalt fiber reinforcement in cement-stabilized clay are in harmony with the broader scientific literature, particularly aligning with the findings reported by S. Wang et al., (2020)[79] and Gao et al., (2020)[80], Both studies underscore the beneficial impact of basalt fibers on the mechanical properties of cement soil. This research indicates a notable enhancement in unconfined compressive strength (UCS) due to the addition of basalt fibers, with peak performance observed at a fiber content of 1.2% and a length of 6 mm. This aligns with the conclusions from S. Wang et al., (2020)[79]who also found that basalt fibers significantly bolster the tensile strength of cement soil.

The optimal fiber content and length identified in this study mirror those identified by S. Wang et al., (2020)[79] who determined that 0.4% basalt fibers and a length of 12 mm were most effective for enhancing tensile strength. The consistency in these findings across different studies suggests that there is an optimal range for fiber content and length that maximizes the benefits of basalt fiber reinforcement without causing fiber clustering or other adverse effects.

Regarding the influence of curing duration, our study's emphasis on the impact of extended curing periods on strength gains is supported by the findings of S. Wang et al., (2020)[79]. Their research also indicates that longer curing times lead to improved mechanical properties, underscoring the crucial role of adequate hydration periods in realizing the full potential of basalt fiber-reinforced cement soil.

The microstructural analysis from this study, which revealed dense matrix formation and reduced microcracking, is corroborated by the microstructural observations of S. Wang et al., (2020)[79]. Both studies point to enhanced interfacial

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bonding and toughening mechanisms facilitated by basalt fibers, including effective bridging and crack deflection. These mechanisms are crucial for improving the overall performance of cement soil, especially in geotechnical applications where crack resistance is paramount.

The linear relationship between splitting tensile strength and compressive strength identified in this study is consistent with previous research. This relationship is pivotal for predicting the mechanical behavior of fiber-reinforced cement soil and optimizing its use in engineering applications.

Additionally, the research by Gao et al., (2020)[80], provides further context to the discussion. Their study investigated the effects of freeze-thaw cycles on the static and dynamic behaviors of plain cement-soil (PCS) and basalt fiber reinforced cement-soil (BRCS). The findings from Gao et al., (2020)[80]suggest that the incorporation of basalt fibers improves the wave velocity, UCS, and dynamic compression strength (DCS) of cement-soil samples after freeze-thaw cycles. This aligns with this study's findings on UCS and suggests that basalt fibers also contribute to the dynamic mechanical properties of cement soil, which is an important consideration for geotechnical engineering applications.

This study's outcomes are well-aligned with the existing literature, particularly with the work of S. Wang et al., (2020)and Gao et al., (2020) Both studies emphasize the significant benefits of basalt fibers in enhancing the mechanical properties of cement soil, including UCS, tensile strength, and resistance to freeze-thaw cycles. The optimal fiber content and length, the influence of curing time, and the microstructural improvements due to fiber inclusion are key findings that are consistent across both studies. These comparisons not only validate these findings but also highlight the generalizability of basalt fiber reinforcement in improving the performance of cement soil across different studies. This consistency across studies reinforces the potential of basalt fiber reinforcement as a reliable strategy for enhancing the durability and strength of cement soil in various geotechnical applications. The findings from both studies suggest that basalt fiber reinforcement could be a promising method to improve the mechanical properties of cement-stabilized clay, making it suitable for applications such as road subgrades, slope stabilization, and embankment reinforcement.

6. Conclusion

This study establishes that incorporating basalt fibers into cement-stabilized clay significantly enhances both unconfined compressive strength (UCS) and ductility. The reinforcing effect of the fibers contributes to crack bridging and improved stress resistance, with the highest mechanical performance observed at an optimal fiber content of 1.2%.

(1) **Optimal Fiber Content:** The findings indicate that 1.2% fiber content yields the greatest improvement in strength and ductility. Beyond this threshold, the benefits tend to stabilize or diminish due to potential fiber agglomeration, which may interfere with efficient stress transfer.

(2) **Influence of Curing Duration:** The role of extended curing, particularly up to 28 days, is critical in facilitating cement hydration and strengthening the bonds between soil particles, cement, and fibers. This prolonged hydration process leads to significant improvements in mechanical stability and load-bearing capacity.

(3) **Effect of Pre-Soaking:** Pre-soaking before UCS testing appears to enhance fiber-matrix interaction and promote more uniform hydration. This process likely contributes to improved mechanical behavior by facilitating better fiber dispersion and increasing resistance to crack initiation and propagation.

(4) **Transition in Failure Mechanism:** A shift from brittle to ductile failure was evident in the stress-strain response of fiber-reinforced samples. This behavior highlights the ability of basalt fibers to improve energy absorption and stress redistribution, thereby enhancing the material's toughness and post-peak load-bearing capacity.

(5) **Microstructural Evidence:** SEM analysis confirms the effectiveness of basalt fibers in enhancing fiber-matrix bonding and reducing microcracking. The presence of hydration products surrounding the fibers suggests improved load transfer mechanisms, which correspond to the observed enhancements in UCS and ductility.

(6) **Practical Applications:** The enhanced mechanical performance of fiber-reinforced cement-stabilized clay underscores its potential for geotechnical applications such as road subgrades, slope stabilization, and embankment

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construction. These improvements make it a viable material for infrastructure projects in regions with problematic soil conditions.

(7) Combined Effects of Fiber Reinforcement and Curing: The findings emphasize the interactive effects of fiber reinforcement, extended curing, and pre-soaking. The synergy between these factors contributes to optimal material performance, highlighting the need to carefully balance fiber dosage and curing conditions in engineering applications.

Overall, this study reinforces the viability of basalt fiber reinforcement as a means of improving the strength, durability, and ductility of cement-stabilized clay, offering a practical and effective approach for geotechnical and construction applications.

7. Future Research Directions

While this study provides valuable insights, further research is needed to assess the long-term durability of basalt fiber-reinforced soils under varying environmental conditions, including freeze-thaw cycles, moisture fluctuations, and chemical exposure. Investigating the impact of fiber degradation over time and its implications for mechanical performance would also be beneficial. Moreover, a comprehensive life-cycle assessment should be conducted to evaluate the environmental footprint and economic feasibility of large-scale basalt fiber applications. Future studies could also explore the influence of different fiber lengths, orientations, and hybrid fiber combinations to optimize reinforcement efficiency. Additionally, advanced numerical modeling and field-scale experiments should be pursued to validate laboratory findings and facilitate the practical implementation of basalt fiber-reinforced soil stabilization techniques.

The findings of this research have significant practical implications for civil engineering and construction industries. Incorporating basalt fibers into soil stabilization strategies can enhance infrastructure durability and resilience, particularly in regions prone to weak or expansive soils. Further investigations into construction methodologies, quality control measures, and performance monitoring in real-world conditions will be essential for advancing the widespread adoption of this technology.

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. Liu Ping and 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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The authors declare no potential conflict of interests.

Data Availability:

The data that support the findings of this study are available from the corresponding author upon reasonable request

Competing interest:

The authors confirm that there are no conflicts of interest associated with this study

Nomenclature

UCS: Unconfined Compressive Strength

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OPC: A commonly used hydraulic cement widely employed in construction and soil stabilization
SEM: Scanning Electron Microscope
ASTM: An international standards organization that develops and publishes technical standards
ITZ: Interfacial Transition Zone.

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