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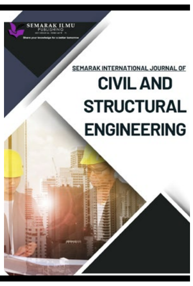

The Use of Monofilament Fibre Reinforcement Concrete in Improving Soil-Cement Columns

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ABSTRACT

This study examines the improvement of soil characteristics through the incorporation of fibre-reinforced concrete (FRC) into soil-cement columns. The study involves a detailed examination of the physical and mechanical properties of soil, highlighting the influence of different compositions of FRC and cement and clay combinations on soil stability. The approach comprises two categories of tests: physical property testing to ascertain the natural characteristics and behaviour of soil, and mechanical property testing, which primarily evaluates the impact of FRC on soil-cement columns. The shear box test and the unconfined compression test (UCT) were performed to achieve these aims. A series of mixtures was conducted to examine the behaviour of the FRC-cement column with varying cement and fibre contents. This study employs two stabilisers: cement and FRC. Cement compositions of 10%, 15%, 20%, and 25% were utilised. Each mixture was subsequently amalgamated with differing proportions of FRC to enhance the composite's characteristics: the 90% clay and 10% cement mixture was integrated with 0.5% FRC; the 85% clay and 15% cement mixture with 1.0% FRC; the 80% clay and 20% cement mixture with 1.5% FRC; and the 75% clay and 25% cement mixture with 2.0% FRC. The shear box test and UCT test were performed on the cement column samples both with and without FRC inclusions after 14 and 28 days of cure. The findings demonstrated that the incorporation of FRC in both uncemented and cement-stabilised soil enhanced the unconfined compressive strength and axial strain at failure, transforming the brittle behaviour of cement-stabilised soil into a more ductile behaviour. The UCT test indicates that a mixture of 20% cement and 1.5% FRC can enhance compression strength to 3005.00 kPa after a 28-day curing period. The shear strength similarly increased, with the identical mixture yielding a measured value of 2065.3 kPa after a 28-day curing time. The mechanical properties of the soil-cement-fibre combinations were enhanced through the utilisation of FRC.

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1. Introduction

In geotechnical engineering and construction, addressing soil stabilisation and ground improvement difficulties is essential for the sustainability and safety of infrastructure projects. Conventional techniques, including the use of soil-cement columns, have proved fundamental in improving the engineering characteristics of soft and problematic soils. These approaches use the hydraulic binding characteristics of cement to enhance soil strength and rigidity. A study by Xue *et al.,* [1] revealed that soil-cement columns can markedly decrease soil compressibility and improve load-bearing capacity, representing a crucial improvement in geotechnical stabilisation methods. Traditional soil stabilisation technologies, while efficient, exhibit limitations regarding longevity, tensile stress performance, and environmental degradation resistance.

This has prompted the investigation of novel solutions, particularly the integration of fibre-reinforced concrete technology. The integration of fibres in the concrete matrix enhances tensile strength, crack resistance, and toughness, addressing the inherent deficiencies of traditional soil-cement columns. Huang *et al.,* [2] indicated that including fibres can enhance the flexural strength of cemented soils by as much as 25%, demonstrating the efficacy of fibre reinforcement in prolonging the lifespan and durability of stabilised soils. Fibre-reinforced concrete (FRC) technology provides a comprehensive enhancement compared to conventional soil-cement stabilization [3,4]. The synergistic interaction between cementitious bindings and fibres boosts mechanical characteristics and provides flexibility to accommodate variability in soil and environmental conditions. Ribeiro *et al.,* [5] conducted a study that emphasised the environmental benefits of fibre-reinforced solutions, demonstrating a carbon footprint reduction of about 15% relative to traditional methods, attributed to the optimal utilisation of cement and the integration of recovered fibres.

This corresponds with the worldwide construction sector's objective of reconciling infrastructure advancement with environmental conservation. The economic ramifications of implementing FRC in soil stabilisation initiatives are significant [6]. The long-term savings in maintenance, repair, and replacement significantly offset the initial material prices. Kim *et al.,* [7] performed a cost-benefit study, demonstrating that the implementation of FRC soil-cement columns may result in a 20% decrease in overall project expenses over a 30-year period due to improved durability and diminished intervention requirements.

Despite the theoretical promise of FRC in cement soil columns for addressing soft soil conditions and cost optimisation, there is a notable gap in research and practical application, particularly in the context of Malaysia. There is a lack of comprehensive studies that systematically investigate the feasibility, cost-effectiveness, and engineering performance of this innovative technique in local soft soil conditions. Furthermore, the specific combinations of fibre types, dosage levels, and construction methods that optimise both engineering outcomes and cost savings remain largely unexplored [8].

To fill in these important gaps in knowledge, this study looks at how adding FRC to cement-soil columns can help improve the conditions of soft soil in Malaysia while also lowering the cost of building. It aims to investigate the mechanical properties, structural performance, and environmental implications of this novel approach in a manner that provides actionable insights for engineers, contractors, and stakeholders involved in geotechnical projects in Malaysia's challenging soft soil environments. By doing so, this research strives to contribute to sustainable and cost-efficient ground improvement practices that align with the specific needs and constraints of the Malaysian construction industry [9,10].

1.1 Monofilament Fibre (Sika Fibre)

This study employed sika fibre as a monofilament fibre as shown in Figure 1. The field of advanced material science has led to the creation of Sika fibre, a synthetic reinforcement product that improves the structural integrity of concrete. This idea arises from the urgent demand in the construction sector for more resilient, adaptable, and sustainable building materials. The distinctive composition and characteristics of Sika fibre enhance the mechanical performance and longevity of concrete buildings considerably [11,12].

Fig. 1. Sika Fiber

The mechanical and physical characteristics of Sika fibres render them exceptionally useful for strengthening soil cement columns, a technique widely used in contemporary geotechnical engineering projects to improve ground stabilisation and load-bearing capacity. Sika fibres possess a specific gravity of 0.91 g/cm^3, rendering them lightweight and contributing negligibly to the weight of the soil-cement combination while markedly improving its strength. The fibres have an average length of 12 mm, sufficient to establish a network within the cement matrix, enhance stress distribution, and augment resistance to cracking. It is demonstrating a tensile strength ranging from 300 to 400 N/mm^2, essential for enduring the loads and strains imposed on soil cement columns. The modulus of elasticity is approximately 4000 N/mm^2, ensuring the requisite stiffness to sustain structural integrity under load. Hydrophobic properties of the fibres ensure the preservation of their strength and structural integrity in humid or water-saturated situations, which is crucial for applications exposed to fluctuating moisture levels [13-15].

Sika fibres have high-temperature resistance, with a melting point of 160°C and an ignition point of 365°C, rendering them appropriate for areas susceptible to elevated temperatures or fire hazards [16,17]. The fibres' minimal thermal and electrical conductivity ensures that the soil cement columns don't interfere with adjacent electrical systems and don't experience significant heat loss, thereby maintaining their performance and longevity [18-20]. These attributes jointly enhance the durability, robustness, and efficacy of soil cement columns reinforced with Sika fibres. It is stopping cracks from forming, protect against environmental stresses, and provide strong mechanical support. They are a reliable choice for complex geotechnical applications, making sure that reinforced structures can withstand tough conditions and stay stable over time [21].

The use of Sika fibres in soil-cement columns provides a range of environmental benefits that align with the growing demand for eco-friendly construction techniques. Using Sika fibres in soil-cement column formulations significantly reduces the cement required for soil strengthening. Based on study conducted by Hammodi *et al.,* [22], it was claimed that the sika fibres can increase the undrained unconsolidated strength (UUS) of weak clay soil. Apart from the Sika fibre, which had adverse effects, the UUS increased as the percentage of additions increased. As Table 1 shows, the Sika fibre content has great tensile strength and modulus of elasticity, which can assist in strengthening soil. One effective additive for strengthening the soil and soil-cement column will be Sika fibre [23].

Table 1
Mechanical/Physical Properties of Sika Fiber [22]

Index	Value
Specific Gravity (g/cm^3)	0.91
Average Length (mm)	12
Tensile strength (N/mm^2)	300-400
Modulus elasticity (N/mm^2)	4000
Water absorption	Nil
Melt Point	160°C
Ignition Point	365°C
Thenn al conductivity	Low
Electrical conductivity	Low

The application of Sika fibres in soil significantly improves its resistance to cracking and shrinkage. This property enhancement reduces waste generation during the construction phase and extends the material's service life. Preventing premature deterioration reduces the need for early repairs and replacements, leading to a reduction in waste production and disposal over time. This aspect was highlighted in a study that documented a 20% reduction in crack-related waste when Sika fibres were used in road construction projects. The thermal properties of Sika fibre-reinforced concrete contribute to better insulation of buildings. This improvement in thermal efficiency can reduce the energy required for heating and cooling, thus lowering the energy consumption of buildings. Data from a research project indicated that buildings constructed with Sika fibre-reinforced concrete showed a 5-7% improvement in energy efficiency compared to those built with traditional concrete. This enhancement is particularly significant in the context of reducing energy usage and associated emissions from the building sector [24,25].

2. Methodology

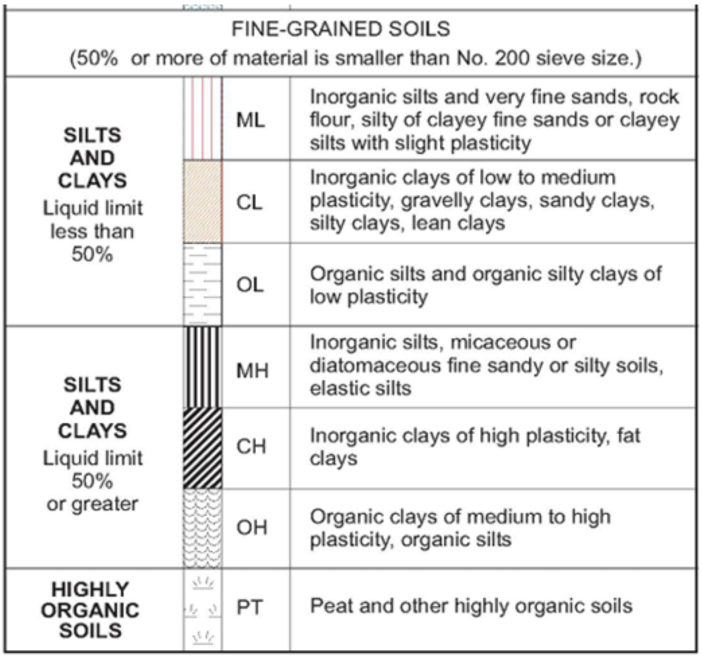
2.1 Study Area and Soil Collection

This study specifically examines the western coastal region, which, according to a study conducted by Abdullah *et al.,* [26] and Badrolhisham *et al.,* [27], indicates that the majority of the coastal area is characterised by the presence of soft soil and similiar. Based on a study conducted by Lim and Shakri [28], it was mentioned that 70% of the peninsular Malaysian area is covered by soft clay soil, with the highest percentage found in the Klang Valley area. Thus, for this study, the soft soil sample has been collected from one of the under-progress projects, which is the Project Rapid Transit System Link site in Johor Bahru, Malaysia. The location is shown in Figure 2. The clay soil, characterised by its high plasticity and significant compressibility, presented challenges typical of soft soils, including low bearing capacity and high moisture content. Table 2 provides an overview of the physical and chemical features of the employed soil. With a composition of gravel (0.65%), sand (48.41%), silt, and clay (59%), the soil was identified as CL based on the Unified Soil Classification System (USCS) as shown in Figure 3.

Fig. 2. Location of Construction Site for Soil Sample Collection: Project Rapid Transit System Link (RTS)

Table 2
Properties of the soil sample

Parameters	Standard	Value
Natural moisture content (%)	ASTM D 2216	23.55
Atterberg Limits		
Liquid limit (%)	ASTM D 4318	53.33
Plastic limit (%)	ASTM D 4318	23.33
Plasticity index (%)	ASTM D 4318	20.0
Particle Size Distribution		
Gravel (%)	ASTM D 422	0.65
Sand (%)	ASTM D 422	48.41
Silt & Clay (%)	ASTM D 422	50.94



FINE-GRAINED SOILS (50% or more of material is smaller than No. 200 sieve size.)			
SILTS AND CLAYS Liquid limit less than 50%		ML	Inorganic silts and very fine sands, rock flour, silty of clayey fine sands or clayey silts with slight plasticity
		CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
		OL	Organic silts and organic silty clays of low plasticity
SILTS AND CLAYS Liquid limit 50% or greater		MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
		CH	Inorganic clays of high plasticity, fat clays
		OH	Organic clays of medium to high plasticity, organic silts
HIGHLY ORGANIC SOILS		PT	Peat and other highly organic soils

Fig. 3. Unified Soil Classification System (USCS) Guide

The steel tube sampler has been utilised for the purpose of gathering undisturbed samples. The specimens were enclosed within steel cylinders, and it is important to avoid undue disruption during the sampling process. Ten (10) steel thin wallet samplers, measuring 50 mm in diameter and 1 m in length, were used to collect the samples. The land was initially excavated to a depth of over 2 m from the surface using a backhoe, with the purpose of removing the topsoil. Subsequently, the slender samplers are inserted gradually into the soil and subsequently extracted using a backhoe. The samplers were thereafter encased in transparent plastic wrap to prevent any loss of moisture content within the samples.

2.2 Sample Preparation

Two fundamental geotechnical tests the Unconfined Compression Test (UCT) and the Shear Box Test were conducted to evaluate the shear strength and compressive strength of soil-cement column strengthening by varying concentrations of Sika fibre. These tests provided critical data on the performance characteristics of the FRC soil-cement composites under different curing periods (14 and 28 days), highlighting the enhancement of mechanical properties through the addition of fibres and cement.

Table 3
Total Amount of Samples for UCT and Direct Shear Test

Sample Labelling	Stabilizers			No. of Samples (UCT)	No. of Samples (Direct Shear Test)
	Cement (%)	Sika Fibre (%)	Curing Period (days)		
UC	-	-	-	4	6
SCP1	10%	0.5%	14 & 28	4	6
SCP2	15%	1.0%	14 & 28	4	6
SCP3	20%	1.5%	14 & 28	4	6
SCP4	25%	2.0%	14 & 28	4	6
			Total	50	

The samples in this study were created using different ratios as shown in Table 3, which summarises the sample design for this study. These ratios were used based on previous studies that mentioned that the optimum percentage of Sika fibre that can strengthen the soft soil is between 0.5% and 2% [22-23]. The sample preparation technique involves combining soft clay soil with a designed combination of cement and Sika fibre as stated in Table 3. The water is added according to the measured natural water content percentage obtained from the natural water content determination test mentioned in Table 2, which is 23.55%. This is to ensure that the soft clay sample is in its natural state, similar to the site condition. Prior to curing, the sample will be manually compacted to guarantee a consistent density.

2.3 Unconfined Compressive Test (UCT) and Shear Box Test

The Unconfined Compressive Test (UCT) as shown in Figure 4 was conducted to determine the Unconfined Compressive Strength (UCS) which the stress at a cylindrical soil specimen fails when subjected to axial compression in an unconfined state. The test was conducted on both treated and untreated clay soil to assess the enhancement in strength of the remolded samples, following the protocol specified in ASTM D 2166: Standard Test Method for Unconfined Compressive Strength of Cohesive Soil.

Fig. 4. Unconfined Compression Test

Specimens were methodically prepared by compacting the soil in several uniform layers within a cylindrical mold measuring 36 mm in diameter and 76 mm in height. The UCT was performed after the specimens had undergone curing periods of 14 days and 28 days. During the test, the load was applied at a consistent rate of 0.5% per minute, while the deformation of each specimen was closely monitored. Deformation was recorded every two seconds using a dial gauge to ensure precise measurement intervals. The collected data from these tests were used to construct stress-strain curves, allowing for the determination of optimal axial stress and strain for the soil specimens, thus providing valuable insights into the soil's behavior under compression. The compressive strength (σc) is calculated using the Eq. (1). The σc is compressive strength, P is applied load and A is cross-sectional area of the specimen.

$$\sigma c = P/A \tag{1}$$

Direct Shear Test as shown in Figure 5 assesses the shear strength parameters of soil, particularly cohesion and the internal friction angle (φ). It involves applying horizontal shear stress to a soil sample within a controlled box setup until shear failure occurs along a predefined plane. This is according to the linear soil shear strength modeling developed by Terzaghi [29] where the shear strength (τ) was determined by the Eq. (2) below. Where τ is shear strength, C’ is the cohesion based on effective stress analysis, Σ is total stress and Ø’ is soil internal angle of friction based on effective stress analysis.

$$\tau = C' + (\sigma)\ tan\ \emptyset' \tag{2}$$

Fig. 5. Direct Shear Test

3. Results

3.1 Unconfined Compression Strength Test (UCT)

Table 4 tabulated the results of unconfined compression tests conducted after different curing periods for all the soil specimens. Figure 6 examines the details of the impact of the curing period on the mechanical properties of clay soil treated with Sika fibre and cement, focusing on UCS across two curing periods: 14 days and 28 days. The untreated control (UC) displayed minimal strength gains, while the fibre-reinforced samples, especially SCP3, showed the most substantial improvements in UCS, highlighting the efficacy of Sika fibre and cement in soil stabilization. SCP3 emerged as the optimum mix, achieving the highest UCS values of 2250 kPa and 3005 kPa at 14 days and 28 days, respectively, suggesting an ideal fibre-cement ratio that maximises strength gains. This finding underscores the importance of precise mix design and adequate curing time in optimising the mechanical properties and durability of fibre-reinforced soil, supporting the use of optimal percentages of fibres and cement for effective soil stabilisation.

Table 4
Unconfined Compression Test Result

Sample Labelling	Unconfined Compressive Strength (kPa)	
	14 Days	28 Days
US	495	531
SCP1	813	1490
SCP2	1369	1982
SCP3	2250	3005
SCP4	1734	2593

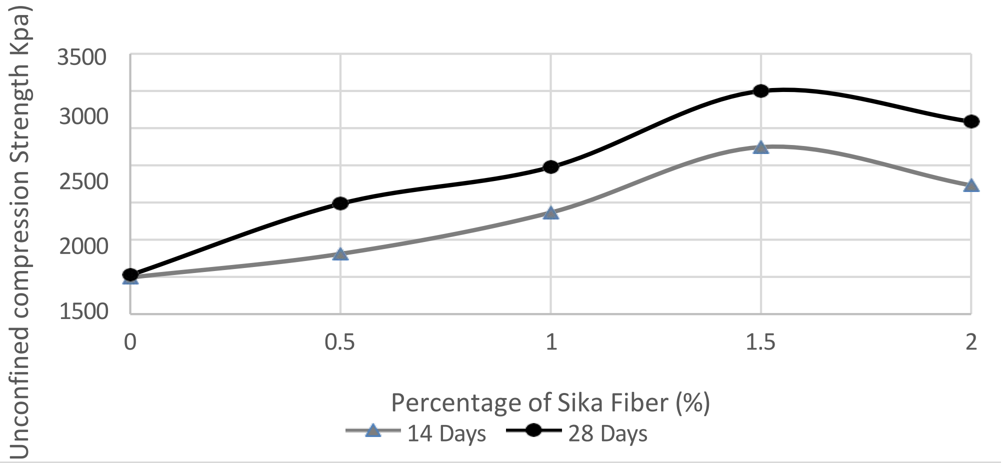
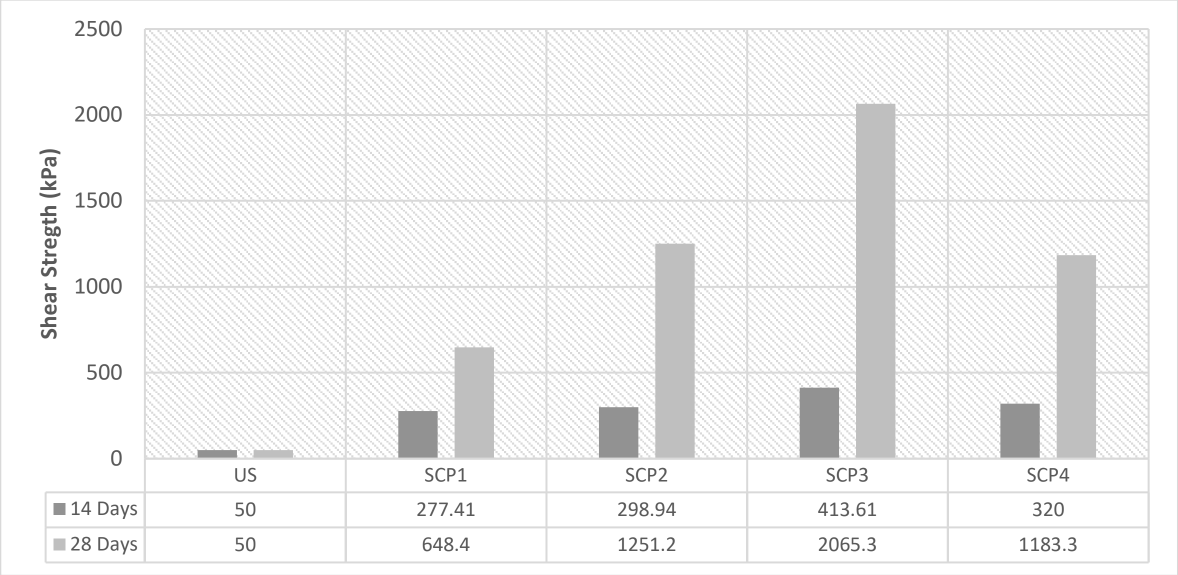


Fig. 6. UCS vs. Percentage of Sika fibre graph

Figure 6 also indicates the influence of the curing period on the mechanical properties of clay soil, particularly focusing on the UCS of samples treated with Sika fibre and cement over 14 and 28 days. SCP3 showed the highest UCS increases, peaking at both 14 and 28 days (2250 kPa and 3005 kPa, respectively), suggesting an optimal fibre-cement ratio that maximises structural integrity without the diminishing returns observed in other compositions like SCP4. Enhanced hydration and pozzolanic reactions facilitated by optimal curing conditions and fibre-cement ratios were key to these results, underscoring the importance of precise mix design and adequate curing in achieving superior soil stabilization. This analysis confirms the pivotal role of curing periods in enhancing the ductility and load-bearing capacity of fibre-reinforced soil, advocating for strategic engineering practices to optimise soil mechanical properties for improved durability and performance in geotechnical applications.

3.1 Shear Box Test

From Figure 7, during the initial 14-day curing period, the shear box test revealed progressive increases in shear strength with the addition of Sika fibre, up to a certain point. Starting with a baseline peak shear stress of 277.41 kPa at 0.5% fibre content, a slight increase was observed when the fibre content was raised to 1%, reaching 298.94 kPa. This indicates a modest improvement in the soil's resistance to shear forces, likely due to enhanced cohesion provided by the fibres. The most significant improvement occurred at 1.5% fibre content, where the peak shear stress surged to 413.61 kPa. This suggests that this fibre percentage optimally enhances the interaction between the soil particles and the fibres, providing increased stability and resistance to shearing forces. However, an increase in fibre content to 2% resulted in a reduction in peak shear stress to 320 kPa, indicating that excessive fibre may disrupt the soil matrix and reduce overall effectiveness, potentially due to over-saturation or poor distribution of fibres within the soil.



	US	SCP1	SCP2	SCP3	SCP4
■ 14 Days	50	277.41	298.94	413.61	320
■ 28 Days	50	648.4	1251.2	2065.3	1183.3

Fig. 7. Shear strength for 14 days and 28 days curing period

From Figure 7 also, the 28-day curing results show even more pronounced increases in shear strength across most fibre percentages. For the specimens with 0.5% fibre, the peak shear stress more than doubled from the 7-day results, reaching 648.4 kPa. This dramatic increase highlights the continuing hydration and bonding processes that strengthen the soil- fibre matrix over time. A remarkable peak stress of 1251.2 kPa was recorded for the 1% fibre specimens, more than quadrupling the 7-day peak stress and illustrating the substantial impact of both fibre content and curing duration. The peak shear stress reached its zenith at 2065.3 kPa for the 1.5% fibre content, confirming this as the optimal fibre percentage for maximizing shear strength over longer curing periods. In contrast, the 2% fibre specimens, while also showing increased strength to 1183.3 kPa compared to their 14-day counterparts, did not achieve the levels seen at 1.5%, reinforcing the notion that there is an optimal threshold for fibre content beyond which additional fibres may not contribute to, or may even detract from, desired mechanical properties. In the evaluation of FRC soil subjected to direct shear tests, the 1.5% fibre content consistently demonstrated superior performance in terms of shear strength across all applied loads when compared to lower (0.5% and 1.0%) and higher (2.0%) fibre percentages. This optimal performance can be attributed to several factors related to the physical and mechanical interactions between the fibre s and the clay matrix.

4. Conclusions

This research aimed to explore the effectiveness of FRC (Sika fibre) as the binder used for improving the mechanical properties of clay cement columns, focusing on soil stabilisation in geotechnical engineering applications. The investigation centred around a series of laboratory tests to assess the impact of various percentages of Sika fibre and curing periods on the compressive and shear strength of clay soils. The study's findings underscore the potential of Sika fibre s to significantly enhance soil stability, providing a viable alternative to traditional soil stabilisation methods.

There are substantial benefits to integrating Sika fibres into clay soils, particularly in enhancing the mechanical properties necessary for effective soil stabilization. The integration of these fibres has been shown to markedly improve both the compressive and shear strength of the treated soils. It was found that the optimal fibre content is 1.5%, at which point the soil specimens exhibited the highest resistance to shear forces and the most significant increase in compressive strength. This finding highlights the effectiveness of fibre reinforcement in increasing soil stability and strength, providing a robust solution for geotechnical engineering challenges.

The influence of the curing period on the performance of fibre-reinforced soils was also a significant aspect of this study. Extended curing times have allowed for more comprehensive chemical reactions and bonding within the soil-fibre matrix, which are crucial for the development of stronger and more durable soil structures. Notably, the specimens that were cured for 28 days displayed superior mechanical properties compared to those that were cured for only 14 days, emphasising the importance of allowing sufficient time for the curing process to maximise the benefits of fibre reinforcement.

Furthermore, the study explored the cost and environmental benefits associated with the use of Sika fibres in soil stabilization. While the initial costs of using Sika fibre are higher than traditional methods, the long-term benefits—such as reduced maintenance and repair costs—offer a compelling economic advantage. Additionally, the reduced reliance on cement for stabilisation contributes to lower carbon emissions, which is increasingly important in today's construction industry. This alignment with sustainable practices not only helps in reducing the environmental footprint of construction projects but also supports broader goals of sustainability in the construction sector.

In conclusion, the integration of Sika fibres into clay soil for stabilisation purposes presents a viable and effective solution that enhances mechanical properties, optimises load-bearing capacities, and supports environmental sustainability. The findings from this project provide valuable insights for the construction industry, especially in regions with challenging soil conditions, and contribute to the advancement of more sustainable and cost-effective geotechnical engineering practices.

Future research should focus on increasing the number of ratios of Sika fibre and cement to examine the diverse effects of these materials on soil enhancement. The implementation of an on-site experiment is recommended, as this research is limited to laboratory trials involving soil samples collected and transported to the laboratory; hence, it does not represent the complete soil structure and nature at the site.

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