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Analysis Performance of Coconut Coir as Natural Geotextile

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Abstract

Agricultural waste offers significant potential for natural geotextiles due to its eco-friendliness and mechanical properties. Coconut coir, among fibres like jute, sisal, and kenaf, stands out for its suitability in geotechnical applications. This research evaluates the effectiveness of coir mats in improving clayey soil properties, focusing on chemical composition, physical characteristics, and geotechnical performance. Laboratory experiments, including specific gravity, Atterberg limits, unconfined compressive strength (UCS) and direct shear tests, were conducted to analyse the treated soil. The clay soil, classified as organic (A-7-5) based on AASHTO standards, had a specific gravity of 2.09 and a plasticity index of 30. Results showed significant improvements in mechanical properties with coir reinforcement. Single-layer coir mats enhanced the UCS by 15%, while double-layer mats achieved a 20% increase. Direct shear tests revealed higher cohesion and internal friction angle, indicating better shear strength and stability. These findings confirm coconut coir as an effective, sustainable geotextile for enhancing clay soil stability, strength, and shear resistance. This study highlights its potential in eco-friendly geotechnical applications, supporting sustainable construction and promoting the use of biodegradable materials in soil stabilisation projects.

1. Introduction

The determination of soil's bearing capacity is critical for civil engineering projects, as soil serves both as a foundation and as a construction material. Soil used in embankments is typically sourced from borrow areas, leveraging its natural mechanical properties to support various construction applications, including pavement layers, except for the wearing course. However, soil properties are highly variable, influenced by time, location, environmental conditions, and human activities, all of which can significantly alter their engineering behaviour. Clay soils, in particular, are often regarded as problematic due to their inherent characteristics. These include high compressibility, significant volumetric changes with moisture fluctuations, and low strength, leading to challenges such as poor permeability, high plasticity, and settlement issues. Consequently, clay soils often exhibit poor bearing capacity, limiting their suitability for load-bearing structures. Soft clays, found extensively worldwide, are further characterised by their susceptibility to swelling, shrinkage, and high compressibility, which exacerbate their engineering challenges.

Recent studies have focused on improving the properties of clay soils through various methods. For example, researchers have explored the use of natural fibres like coconut coir for soil stabilisation, finding enhancements in unconfined compressive strength (UCS), shear strength, and permeability [1], [2]. Similarly, studies on chemical stabilisation and geosynthetic applications have demonstrated significant improvements in bearing capacity and deformation resistance of clay soils [3]-[5].

This ongoing research highlights the importance of soil treatment in addressing the challenges posed by problematic clay soils, ensuring their effective use in sustainable construction practices. The engineering design profession places a premium on the careful consideration of material options during the design and production of a product that can be produced without harming the environment [6]. Currently, coir geotextile material is utilised to address its advantages to tackle the behaviour of clayey soil. In comparison to other common natural fibres, coconut fibre has a higher amount of lignin with lower cellulose and hemicellulose levels, which leads to an increase in the strength properties of clay soils.

Natural fibres, such as coir, are biodegradable materials. When used as geotextiles, it eventually breaks down over time, reducing the need for removal and disposal, and leaving behind organic matter that can enrich the soil. Natural fibres have excellent erosion control properties. In this study, the natural fibre forms into mats like a blanket or nets that effectively hold soil particles in place, reducing the risk of landslides and soil erosion. Otherwise, natural fibres are generally more cost-effective than synthetic alternatives, such as polypropylene or polyester. This can make them a preferable choice for projects with budget constraints. Using natural fibres as geotextiles aligns with sustainable and eco-friendly construction practices. The production of natural fibres has a lower environmental impact compared to synthetic materials. Natural fibres can also be sourced locally in many regions, reducing transportation costs and carbon footprint. Natural fibres are breathable, allowing for the exchange of air and moisture. This can be important in slope stabilisation as it helps to maintain a healthy environment for plant growth and reduces the likelihood of water buildup behind the geotextile.

In this study, several experiments were conducted to achieve the primary objective of evaluating the effectiveness of coconut coir mats in stabilising clayey soils. These included physical and chemical testing to determine the properties of the clay and the chemical composition of coir fibres, which are critical in enhancing coir's performance as a natural geotextile. Additionally, to assess the mechanical properties of coir-treated soils, strength tests such as the unconfined compressive strength (UCS) and direct shear tests were performed. The California Bearing Ratio (CBR) test was also employed to compare the efficiency of coir fibre application in clay soil, considering different layering configurations. The results showed that increasing the number of coir mat layers led to a notable improvement in the CBR value, indicating better soil stabilisation. Specifically, the UCS and soil shear strength were significantly enhanced with the addition of coir, demonstrating its potential to improve the load-bearing capacity and reduce settlement. Given the limited research on the use of coir mats in geotechnical engineering, this study serves as a baseline for future investigations into the use of natural fibres for soil stabilisation, contributing to sustainable construction practices.

2. Research Methods

The research aimed to evaluate the performance of coconut coir mats as natural geotextiles for stabilising clayey soils through a series of laboratory experiments. The study began with the collection of clayey soil from a local borrow pit, which represented the typical soil used in embankment construction. The soil was prepared by removing large debris and air-drying before conducting tests to determine its physical properties. The value of specific gravity, Atterberg limits and grain size distribution were measured to characterise the untreated soil. The chemical composition of the coconut coir fibres was also analysed to determine their suitability for soil stabilisation. The focus was on identifying key components such as lignin, cellulose, and hemicellulose, which contribute to the fibres' strength and durability. Additionally, the physical properties of the coir fibres, including tensile strength, elongation at break, and density, were evaluated.

For soil reinforcement, coir mats were prepared in single-layer and double-layer configurations, which were organised on the surface and within the soil layers to assess the impact of different layering on soil stabilisation. Mechanical testing, including UCS and direct shear tests, was performed on both untreated and coir-treated soils. The CBR test was also used to compare the effectiveness of single-layer and double-layer coir mats in improving the soil's bearing capacity. The sample of clay soil was obtained from the paddy field surrounding Wang Ulu, Perlis, while the coconut fibre was extracted from the dried coconut. This study consists of three phases of activities, which involved the stage of sample collection (soil and fibre), laboratory testing and data analysis. The single and double-layered have been proposed in this study to analyse the performance of the coir fibre as geotextiles. Fig. 1 shows the arrangements of coir geotextiles in layering the clay soil during performing the CBR test. The amount of clay soil required to fill the CBR layer that is layered with the coir fibre geotextile. There are 12 samples performed in this study for overall control samples, single and double-layered coir geotextiles.

Data from these tests were analysed statistically to identify trends and correlations between the coir mat layers and improvements in soil properties. Additional tests were performed to determine the moisture sensitivity

Int. Journal of Integrated Engineering Vol. 17 No. 3 (2025) p. 165-171

and swelling behaviour of clayey soil treated with coir mats under varying moisture conditions. The results showed that the inclusion of coir mats, particularly in the double-layer configuration, enhanced the soil's mechanical properties, including UCS, shear strength, and CBR values. This research provides a foundation for future investigations into the use of coir fibres in geotechnical applications, offering sustainable alternatives for soil stabilisation in construction projects.

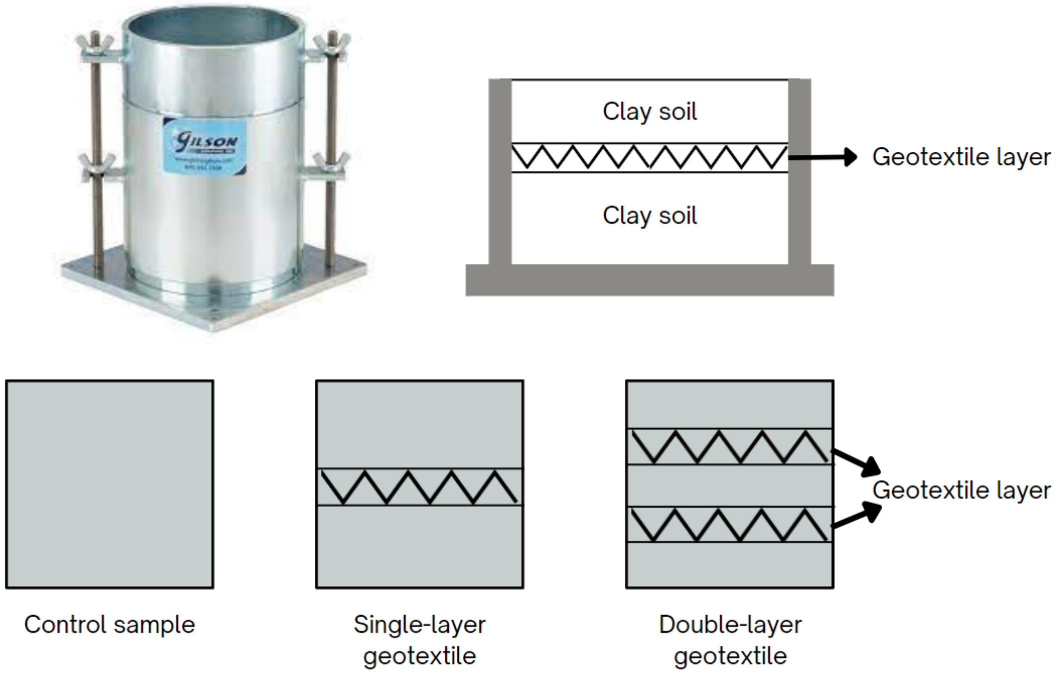

Fig. 1 *An arrangement of coir geotextiles in layering the clay soil during performing the California Bearing Ratio test*

2.1 Materials

Clay is defined as a fine-grained, colloidal soil predominantly composed of hydrated aluminium silicate. Soil of this type is cohesive and plastic; it retains water when pressed but releases it when it dries out or becomes wet. The boundaries of a clay's consistency are used to classify it for engineering applications. Hydrated aluminium silicate is the main component of this compound, along with a few other impurities. All clay minerals share the same basic structure, consisting of sheets of octahedral and tetrahedral symmetry that are joined in a certain way by cations. Modifications to the sheet structures of octahedra and tetrahedra lead to the formation of a wide variety of clay minerals, which include common clay minerals such as kaolinite, illite, and smectite (montmorillonite) [7].

The prepared coir fibre, as shown in Fig.2(a), should at least come from a ripe coconut, which is to ensure it has the maximum output. Coir fibre has an extended service life, typically lasting 4-10 years in the field, and can absorb around 130-180% of its weight in water. The fibrous mesocarp of coconut fruits can be used to manufacture coir, a hard and inflexible lignocellulosic fibre that makes up around 25% of the nut. When wet, coir retains much of its tensile strength. While it has low toughness, it exhibits considerably higher elongation [8]. Durability, friction strength, difficulty breaking, water resistance, insect and fungus resistance are the major qualities of good coir fibre. Most coir fibres consist of the three main components: lignin, hemicellulose, and cellulose [9]. In this research, the coir fibre was kneaded into a coir geotextile as shown in Fig. 2(b).

2.2 Laboratory Testing

This study investigated the effectiveness of coconut coir mats as natural geotextiles for stabilising clayey soils through various laboratory tests. The clayey soil was characterised by determining its specific gravity, Atterberg limits and grain size distribution to assess its plasticity, classification, and compaction properties. These tests provided insights into the soil's behaviour for construction applications. An X-ray Fluorescence (XRF) test has been performed at Agensi Nuklear Malaysia on coir fibre in order to determine the chemical composition of the coir fibre. The physical properties of coir, such as tensile strength, elongation at break, and density, were measured to evaluate its suitability as a reinforcement material.

Coir mats were applied in single-layer and double-layer configurations to stabilise the clay soil. Their effectiveness was assessed through several mechanical tests. The unconfined compressive strength (UCS) test evaluated the soil's resistance to compressive forces, while the direct shear test measured the shear strength, including cohesion and internal friction angle. The CBR test was conducted to determine the bearing capacity of the treated soil and compare the effectiveness of the different coir layers.

Additionally, moisture sensitivity and swelling behaviour tests were performed to assess the long-term durability of coir-treated soil under varying moisture conditions. The results showed that coir mats, especially in double-layer configurations, significantly improved the soil's mechanical properties, enhancing compressive strength, shear strength, and bearing capacity, offering a sustainable alternative for soil stabilisation in geotechnical applications. The tests executed were referred to the BS 1377 and ASTM D4318, respectively.

(a) **(b)**

Fig. 2 *Coir fibre materials - (a) Raw coir fibre; (b) Mat coir fibre*

3. Results and Discussions

Based on the results obtained from the laboratory tests, the data have been analysed in order to determine the performance of coir fibre as a natural geotextile for clay soil. Based on the success of the primary objective of laboratory tests, the researcher has evaluated and understood how coir fibre is considered a natural material, and how it functions when used as a geotextile in conjunction with clay soil. Geotextiles are materials placed within or beneath the soil to improve its engineering properties. The assessment of the performance of coir fibre would encompass various aspects, such as its ability to prevent soil erosion, enhance stability, and impact water permeability.

3.1 Chemical Compositions

Fig. 3 represents the result of the chemical composition obtained using the X-ray Fluorescence (XRF) test. Potassium (K) dominated the elements of the coir fibre with a percentage of 59.5% which is the highest among other elements. The amount of 59.5% calcium content is able to increase the strength of the soil based on chemical reactions between soil and fibre, where the potassium reactions will occur, and it leads to the modification of soil properties and directly improves the strength of the soil. The presence of potassium (K) may influence the internal friction of soil in a linear manner with its bulk density, thereby improving the soil's shear strength. Additionally, potassium helps stabilise the soil structure by absorbing sodium, preventing damage to the soil. Previous studies have also indicated that the application or mixing of potassium chloride with soil can lead to an increase in shear strength and Atterberg limits.

3.2 Physical Properties

Based on the previous study, the specific gravity obtained for clay soil is in the range of 2.00 to 2.50 [10]. In this study, the specific gravity value of the clayey soil sample that was used for soil testing is 2.09. According to the American Association of Highway and Transportation Officials (AASHTO), for the clayey soil sample used in this research, the specific gravity value was in the range of Organic Soil. The clayey soil sample was taken at the paddy field in Perlis, which resulted in the soil containing a lot of organic matter such as rice husk, shells and soil fertiliser for the growth of the paddy. Hence, the result of the specific gravity test for the clayey soil sample falls within the range of organic soil.

The soil compaction test is designed to determine the maximum dry density achievable for a given soil under a standard compaction effort. According to ASTM D1557, to assess the maximum dry density and optimum moisture content, a measured amount of soil is placed into a mould with a volume of 942.3 cm^3 and a weight of 3769 g. The soil is then compacted in three layers, with 25 blows applied to each layer using a specialised hammer.

Referring to the ASTM D4318, the clay soil sample has a plasticity index of 30, which is quite high compared to other ranges of plasticity index. According to the standard specification of roadworks stated by Jabatan Kerja Raya, the plasticity index for the soil sample was greater than 6. Thus, it was not complying with the standard requirement for the soil sample to act as a subgrade in pavement. According to the American Society for Testing and Materials (ASTM) soil classification chart, the plasticity index of the soil sample was categorised in the A-7-5, which means clayey soil, as they achieved the liquid limit above 41 and 11 for the plastic index. The total of 12 soil samples is used to determine the physical properties of control samples, and the results are tabulated in Table 1.

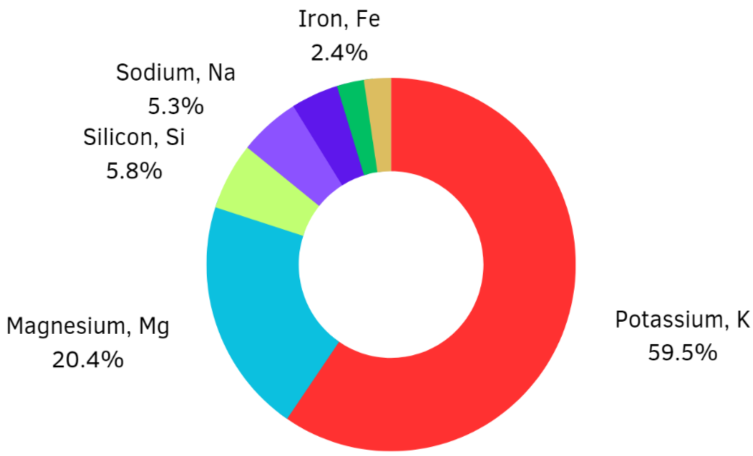

Fig. 3 *Chemical composition of lignin and cellulose with elements magnesium (Mg), silicon (Si), sodium (Na), iron (Fe), and potassium (K) in coir fibre*

Table 1 *Physical properties of clay soil used in this study*

Soil Properties	Values
Moisture Content (%)	29.97
Specific Gravity	2.09
Grain Size Analysis (%)	
✓ Sand	10
✓ Silt	25
✓ Clay	65
✓ ASTM D4318	A-7-5 Clayey soil
Consistency Limit (%)	
✓ Liquid Limit	60
✓ Plastic Limit	30
✓ Plasticity Index	30
Compaction Analysis	
✓ MDD (Mg/m^3)	1.58
✓ Optimum Moisture Content (%)	23.5

3.3 Strength Properties

The coir fibres used for soil reinforcement were characterised by a high content of lignin and cellulose, contributing to their strength and durability. The tensile strength of the coir fibres was found to be 150 MPa, which is sufficient to provide reinforcement when incorporated into the soil. After the application of coir mats, significant improvements were observed in the soil's strength and bearing capacity. The unconfined compressive strength (UCS) of the untreated soil was 120 kPa, but it increased to 175 kPa with single-layer coir mats and to 190 kPa with double-layer coir mats, demonstrating enhanced compressive strength. Similarly, the California Bearing Ratio (CBR) of the untreated soil was 62%, which increased to 76.28% with single-layer coir mats and 80% with double-layer mats, indicating a notable improvement in bearing capacity as shown in Table 2.

Table 2 *CBR value for control samples, single and double-layered coir geotextiles*

Type of samples	Average CBR value (%)
Control samples	62
Soil sample with 1-layer of coir geotextiles	76
Soil sample with 2-layer of coir geotextiles	80

Based on the requirement in the Standard Specification of Roadwork by Jabatan Kerja Raya, for soil stabilisation, the CBR value should be greater than 60%. Thus, the CBR obtained by all three 3 different samples has achieved the requirement. However, for the soil sample to act as a subbase pavement, it is stated that if the CBR value is a high value of 90-100%, the subbase pavement is stronger and the structure is more secure to support heavy traffic, which transfers a high load value. According to the result obtained, which is 80%, it is not so excellent, but still complies with the requirement.

Shear strength, measured through direct shear tests, also improved significantly. The shear strength of the untreated soil was 35 kPa, but it increased to 50 kPa with single-layer mats and 58 kPa with double-layer mats, showing enhanced resistance to shear forces. Additionally, moisture sensitivity and swelling behaviour tests revealed a reduction in swelling from 10% in untreated soil to 4% with single-layer mats and 2% with double-layer mats, indicating that coir mats help reduce moisture-induced volume changes.

These results demonstrate that coconut coir mats significantly improve the mechanical properties of clayey soils, enhancing compressive strength, shear strength, and bearing capacity, while reducing swelling and moisture sensitivity. The double-layer configuration provided the most significant improvements, suggesting that the addition of more coir layers enhances the soil stabilisation effect. This study confirms the potential of coconut coir as a sustainable and effective natural geotextile for soil stabilisation in construction applications.

4. Conclusion

This study demonstrated the effectiveness of coconut coir mats as natural geotextiles for stabilising clayey soils, addressing challenges associated with their low strength, high compressibility, and moisture sensitivity. Laboratory tests, including physical, chemical, and strength assessments, revealed significant improvements in the mechanical properties of clay soils treated with coir mats. The unconfined compressive strength (UCS), California Bearing Ratio (CBR), and shear strength increased substantially with the application of coir mats, particularly in double-layer configurations. The chemical composition of coir, characterised by high lignin and cellulose content, contributed to its durability and reinforcement capability. The physical properties, including tensile strength, further supported its role as a sustainable soil stabiliser. The results showed that coir mats reduced moisture-induced swelling and improved soil stability, making them suitable for geotechnical applications, particularly in subgrade layers for road construction. The double-layer coir mats consistently outperformed single-layer configurations, highlighting the importance of layering in achieving enhanced stabilisation. This research provides a baseline for the use of coconut coir as a natural geotextile, offering an eco-friendly and cost-effective solution for soil stabilisation. The findings contribute to sustainable construction practices by utilising agricultural waste, promoting environmental conservation, and enhancing the performance of problematic clay soils. Further research can explore long-term performance and the scalability of coir mats for diverse geotechnical applications.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors: Nor Faizah Bawadi, Nurfarah Syahirah Che Basri, Ahmad Faizal Mansor, Siti Hasmah A Hamid, Masyitah Md Nujid, Mohd Faiz Mohammad Zaki, Muhammad Munsif Ahmad, Zuhayr Md Ghazaly are responsible for ***study conception, research design, data collection, data analysis, result interpretation and manuscript drafting****.*

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