STABILISATION OF EXPANSIVE SOILS USING SYNTHETIC HAIR FIBRE

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A DISSERTATION SUBMITTED TO DIRECTORATE OF RESEARCH AND GRADUATE TRAINING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF SCIENCE IN STRUCTURAL ENGINEERING DEGREE OF KYAMBOGO UNIVERSITY

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DECLARATION

I, Okello Milton, hereby declare that this submission is my own work and that to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree of the university or other institute of higher learning, except where due acknowledgement has been made in the text and reference list

Signed: ………………………… **Date:** ……………………………………

APPROVAL

The undersigned approve that they have read and hereby recommend for submission to the Directorate of Research and Graduate Training of Kyambogo University, a dissertation entitled "Stabilisation of Expansive Soils Using Synthetic Hair Fibre" in fulfillment of the requirements for the award of Master of Science in Structural Engineering Degree of Kyambogo University

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DEDICATION

This dissertation is dedicated to the pillars of my life, people whose support, prayers, and presence have been my constant strength. To my father (Acai Omomwa Henry) and mother (Akol Jacinta Betty), thank you for the foundation of discipline, hard work, and faith you laid for me. Your sacrifices, love, and guidance have shaped everything I am today. To my beloved wife, Abenawe Loyce, your unwavering love, patience, and belief in me gave me the courage to push on when the journey became difficult. To my precious children, Dylan and Kyle your innocent joy and unspoken inspiration fueled my determination to succeed in this study. May this achievement someday inspire you to pursue your dreams fearlessly. To my dear siblings Denis, Innocent, Sophie, Allan, and Timothy thank you for always cheering me on especially when the journey became tough. Your words of encouragement and quiet support have carried me further than you know. This work is dedicated to each of you, with heartfelt gratitude and love. It stands as a reflection of your investment in me, and a promise that your support has never been in vain.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS/ABBREVIATIONS

ASTM	American Society for Testing and Materials
BS	British Standards
BMP	Bitmap Image File
BCR	Benefit Cost Ratio
CBA	Cost Benefit Analysis
CBR	California Bearing Ratio
Cc	Compressibility Index
CEC	Cation Exchange Capacity
cm	Centimeter
Cs	Swelling Index
FEA	Finite Element Analysis
FSR	Free Swell Ratio
GUI	Graphical User Interface
JPEG	Joint Photographic Experts Group
kN	Kilonewton
LL	Liquid Limit
MDD	Maximum Dry Density
mm	Millimeter
MPa	Megapascal
NPV	Net Present Value
OMC	Optimum Moisture Content
PET	Polyethylene Terephthalate

PI	Plasticity Index
PL	Plastic Limit
PV	Present Value
RGB	Red, Gray, Black
R^2	Coefficient of Determination
SEM	Scanning Electron Microscopy
SPSS	Statistical Package for the Social Sciences
UCS	Unconfined Compressive Strength
USD	United States Dollar
XRD	X-ray Diffraction
°C	Degrees Celsius

ABSTRACT

Expansive clay soils pose significant challenges to civil engineering infrastructure due to their high shrink swell behaviour, which often leads to structural instability, cracking, and costly repairs. Traditional stabilisation methods such as cement and lime treatment, while effective in some contexts, are frequently expensive, degrade the environmental, or ineffective under unsuitable geochemical conditions. Other stabilisation methods have also been employed, such as natural and synthetic fiber reinforcements like coir, jute, and geotextiles are widely used. Other emerging methods include enzyme treatment, geopolymers, and electrokinetic stabilisation for improved performance. The improper disposal of synthetic hair fibre a waste product from salons possesses an increasing challenge to the environment, with 9,000 to 12,000 tonnes of waste generated in Uganda alone annually by the beauty industry. This study investigated the use of synthetic hair fibres as a sustainable and low-cost stabilising material for expansive clay soils. Physical and mechanical tests, alongside crack analysis using digital image processing and MATLAB R2025a software were conducted. Expansive clay samples were stabilised with synthetic hair fibres at a fixed amount of 0.5% by dry weight, with fibre lengths ranging from 2 cm to 16 cm. Key tests, including Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), and swelling potential, were conducted. The results showed a 56% increase in UCS, a 300% increase in CBR, and a notable reduction in swelling, particularly with fibre lengths between 6 and 8 cm. The research shows that synthetic hair fibre is a viable alternative for stabilising expansive clay soils, offering both geotechnical benefits and a sustainable approach to managing synthetic hair waste.

CHAPTER ONE: INTRODUCTION

1.1 Background to the Study

Expansive clay soils present significant geotechnical challenges due to their pronounced shrink swell behaviour, primarily driven by the presence of the clay mineral montmorillonite. These soils undergo substantial volumetric changes in response to fluctuations in moisture content, leading to surface cracking, structural instability, and costly repairs to roads, buildings, and bridges. As moisture levels vary due to seasonal changes or climate variability these soils expand when wet and contract when dry, initiating and propagating cracks that threaten infrastructure integrity. This behaviour is further intensified by environmental factors such as climate change, which introduces more frequent and severe precipitation and temperature shifts (Tsion et al, 2021).

Historically, traditional stabilisation techniques, such as lime and cement treatment, have been applied to mitigate the adverse effects of expansive clays. However, these approaches often fall short under geochemically unsuitable conditions especially in sulphate-rich environments where swelling can be exacerbated. Moreover, their cost, carbon footprint, and limited long-term effectiveness call for more sustainable and adaptable solutions (Archibong et al., 2020; Sudjianto at al., 2021)

Emerging technologies such as digital crack detection, robotic scanning, and machine learning algorithms are being explored to monitor and address early signs of damage in infrastructure (Ghadimzadeh et al., 2024). However, effective and resilient soil stabilisation remains the first line of defense, particularly in regions like Uganda, where expansive clays are prevalent and synthetic waste disposal is a growing concern.

In this context, synthetic hair fibres a common waste product generated in large quantities by salons offer an innovative solution.

These fibres, often composed of materials such as polypropylene, polyethylene terephthalate (PET), or nylon, possess mechanical properties (e.g. tensile strength and ductility) that can reinforce soil matrices, increasing UCS, reduce plasticity, and limit crack formation. Recent studies indicate that such fibres may bridge soil particles, forming interlocking networks that resist shrinkage induced cracking and improve resilience to external loads.

The integration of synthetic fibres into soils mirrors historical practices, where natural fibres like straw or horsehair were used in traditional composites to enhance mechanical performance (Noorzad and Ta’negonbadi, 2021). Advances in material science now allow for more targeted improvements using engineered and recycled fibres. For instance, research into multi-walled carbon nanotubes (MWCNTs) and polymer composites has shown significant improvements in tensile strength, pointing to the potential of nanofillers and synthetic additives in soil reinforcement.

From a sustainability perspective, this approach aligns with Sustainable Development Goal 12 (SDG 12): Responsible Consumption and Production, by repurposing non-biodegradable waste into high-value engineering applications.

The amount of synthetic hair waste generated globally underscores the gravity of this problem, grand view a website that tracks the market exchange of various products traded globally estimated the global market for synthetic hair and wigs to have exceeded USD 8.3 billion in 2023, and it projects it to reach USD 12.27 billion by 2030, growing at a Compound Annual Growth Rate (CAGR) of 8.4% from 2023 to 2030 (Grand View Research, 2025).

Much of this material is known to be primarily composed of non-biodegradable PET and PVC which is discarded after a short-term cosmetic use, contributing significantly to plastic waste streams. Another online website Volza. com reported Africa alone to have synthetic hair imports surpassing USD 600 million annually, Between March 2023 and February 2024, Uganda ranked among the top ten global importers of synthetic hair, receiving nearly 3,961 shipments of synthetic hair, primarily from Kenya, China, and South Africa (volza, 2025). This influx presents both an environmental challenge and a strategic opportunity to convert synthetic waste into a stabilising material.

The present study seeks to address the dual challenge of managing expansive clay soils and reducing environmental degradation due to poor disposal of synthetic hair fibre waste. Through a structured experimental program, the research investigates the mechanical performance, swelling behaviour, and resistance to crack expansive clays stabilised with synthetic hair fibres. By examining the relationship between synthetic hair fibre length, soil composition, and crack effects, this study aims to generate actionable insights for engineers, policymakers, and sustainability advocates working toward resilient and environmentally responsible infrastructure.

1.2 Problem Statement

Expansive clay soils present a persistent geotechnical challenge due to their high shrink swell potential, which causes significant changes in the soil volumes as moisture levels fluctuate. These changes are directly linked to surface cracking, differential settlement, and eventual structural instability. Among these issues above, cracking is the most critical, as its both a symptom and a driver of failures in the soil's integrity. Cracks often weaken structural elements, reduce load bearing capacity of the soil, and accelerate the failure of infrastructure such as roads, foundations, and buildings resulting into increased safety risks and costs of maintenance.

Conventional soil stabilisation methods such as lime or cement treatment are widely used to improve soil strength and reduce shrinkage. These methods primarily address the chemical and mineralogical aspects of the soil by inducing pozzolanic reactions, reducing plasticity, and increasing shear strength (Khemissa and Mahamedi, 2014; Kumar and Thyagaraj, 2021). However, their effectiveness in controlling cracking is limited. Lime and cement reduce swelling and shrinkage by decreasing the soil's affinity for water, thus producing rigid matrices that are susceptible to brittle cracking under repeated wetting drying cycles (Zhang et al., 2022; Tamassoki et al., 2023).

Over time, these treated soils develop cracks due to differential stresses, shrinkage of the cementitious matrix, or incompatibility with surrounding untreated soils. Therefore, though traditional additives can improve overall strength, they do not comprehensively mitigate crack initiation and propagation, particularly in areas whose environments possess strong seasonal moisture variations.

The above methods are also carbon intensive, expensive, and inaccessible in low resource settings, particularly in rural parts of Uganda. Their effectiveness may also be compromised under specific geochemical conditions, such as in sulphate rich soils where swelling may worsen. At the same time, Uganda faces a growing environmental challenge linked to the improper disposal of synthetic hair waste. With an estimated 50,000 salons nationwide, each generating between 15 to 20 kilograms of waste per month, the country produces approximately 9,000 to 12,000 metric tonnes of synthetic hair waste annually. Composed mainly of polyester, acrylics, and PVC, this non-biodegradable material often ends up in drainage systems, water bodies, and landfills, where it poses long-term pollution risks.

Differing from the above concerns this study investigates the feasibility of utilising synthetic hair fibres as a soil stabiliser for expansive clays. This can be supported by their tensile strength, flexibility, and resistance to degradation. Synthetic fibres may improve key soil properties such as shear strength, ductility, and crack resistance by forming interlocking structures within the soil matrix.

This dual-purpose approach presents a cost-effective and sustainable solution to two pressing issues. The mechanical unreliability of expansive soils and the environmental burden of synthetic hair waste, aligning with Sustainable Development Goal 12 that puts emphasis on responsible consumption and production. Based on the identified gap, this study seeks to investigate the potential of synthetic hair fibres to improve the crack resistance and engineering performance of expansive clay soils, using quantitative digital imaging techniques to provide novel insights into crack behaviour.

Figure 1.1: Structural failures due to (a) differential settlement, (b) cracking due to shrinkage (C) heaving due moisture absorption (d) differential settlement.

1.3 Objectives

1.3.1 Main Objective

To investigate the performance of expansive clay soils after stabilisation with synthetic hair fibres.

1.3.2 Specific Objectives

i. To determine the properties of expansive soils.
ii. To characterise the physical and mechanical properties of synthetic hair fibres.
iii. To determine the effect of synthetic hair on the properties of expansive soils.
iv. To Model the cracking behaviour of expansive clay soils stabilised with synthetic hair fibres.

1.4 Research Questions

i. What are the geotechnical and mineralogical properties of the expansive clay soils under investigation?
ii. What are the physical, chemical, and mechanical characteristics of waste synthetic hair fibres relevant to soil stabilization?
iii. In what way does the incorporation of synthetic hair fibres influence the engineering behavior of expansive clay soils?
iv. How does the inclusion of synthetic hair fibres affect the cracking patterns and behavior of expansive clay soils over time?
v. Are the improvements in strength, swelling, and crack resistance of expansive soils reinforced with synthetic hair fibres statistically significant?

1.5 Justification for the Study

Despite the numerous advances in geotechnical engineering, the stabilisation of expansive clay soils remains an area of practical and environmental concern particularly in developing countries where infrastructure is often built on problematic ground without the benefit of cost-effective solutions. While traditional stabilisation methods have received considerable attention, limited research has been done to explore the potential of some underutilised urban waste especially synthetic hair that is a waste from hair salons as reinforcement for expansive soil.

The motivation for this study stems from the challenges of improving the stability of expansive clay soils and the challenge of managing synthetic hair fibre a waste often disposed of by the salons after use by their clients. Synthetic hair fibre, though considered a waste, possesses physical attributes such as tensile strength, shape, and flexibility just like polypropylene fibres that are commercially made, making it theoretically suitable for soil reinforcement. However, the absence of studies quantifying its performance in clay soils presents a clear research gap.

Also much of the existing literature on fibre reinforced soils (Pradhan, Kar and Naik, 2012; Parihar, Shukla and Gupta, 2018; Hu et al., 2021), focuses on commercially produced synthetic fibres (e.g., polypropylene, polyester), which may be costly in low resource settings.

In contrast, synthetic hair fibre is abundant as a salon waste which makes it inexpensive or free, it’s also a nuisance as its disposal has remained unchecked in most urban areas in Uganda. This presents chances not only to improve geotechnical performance but also to help sustainable development and garbage recovery.

This research is pivotal as it's introducing an innovative approach to addressing two challenges of expansive soils and the environmental burden of synthetic hair waste. By exploring the use of synthetic hair fibers for soil stabilisation, the study not only contributes to advancing sustainable engineering practices but also promotes the circular economy principles. The findings are expected to provide actionable solutions that can be adopted by engineers, policymakers, and local authorities to enhance the resilience of infrastructure, particularly in regions impacted by expansive soils and the growing accumulation of synthetic hair fibres.

Importantly, the study aligns with several global and regional development agendas. It contributes directly to United Nations Sustainable Development Goal 12-sustainable consumption and production, which advocates for waste reduction and resource recovery through innovative reuse. It also reflects the aspirations of the African Union Agenda 2063, which envisions environmentally sustainable growth and resilient infrastructure; the East African Vision 2050, which prioritises sustainable urbanisation and regional industrialisation; and the Uganda Vision 2040, which emphasises green growth, resource efficiency, and innovation in infrastructure development. By utilising synthetic hair fibre waste, the research supports these frameworks through the creation of sustainable, locally sourced construction materials.

Should this research not be undertaken, the escalating environmental impact of synthetic hair waste will continue to pose serious challenges to the authorities for managing this waste, while there is also a persistent issue associated with expansive soils which undermine development of infrastructure. Addressing these issues now is critical to ensuring long-term sustainability and resilience in construction practices across the region.

1.6 Significance of the Study

The significance of this study lies in its potential to advance practical and sustainable methods for managing expansive soils in the construction industry, particularly in areas that often experience scarcity in construction resources. While much of the focus has been on conventional stabilisers such as lime, cement and fibres such as polypropylene, there remains a need to investigate unconventional and locally available materials that give value to the environment and are technically effective.

This research adds a fresh dimension by exploring the use of synthetic hair fibres in improving the structural performance of expansive clay soils. Beyond simply testing their effect, the study quantifies the changes in physical and mechanical properties including strength, swelling, and cracking behaviour through a systematic experimental framework. These findings can be used to inform engineering design choices in subgrade preparation, foundation systems, and slope stabilisation in areas affected by expansive clay soils.

Importantly, this work demonstrates how interdisciplinary approaches of merging waste management, materials science, and geotechnical engineering can yield innovative solutions to longstanding infrastructure challenges. It broadens the understanding of how fibrous materials interact with soil matrices and opens new avenues for research into low impact, scalable soil reinforcement techniques.

By bridging experimental data with practical application, this study also supports policy development, especially for municipalities and public works authorities seeking cost-effective strategies for construction on problematic soils. As such, it holds value not only for academic researchers, but also for engineers, planners, and sustainability advocates aiming to enhance resilience in civil infrastructure.

1.7 Scope of the Study

This dissertation investigates the impact of synthetic hair fibres on the swelling potential and cracking behaviour of expansive soils. The study assesses how synthetic hair fibre reinforcement influences key mechanical and physical properties, focusing on California Bearing Ratio (CBR), Maximum Dry Density (MDD), Atterberg limits, and fibre length variations.

Characterisation of expansive clay soils involves evaluating Atterberg limits, including liquid limit, plastic limit, and plasticity index, which correlate with swelling properties. These measurements inform CBR assessments, indicating load-bearing capacity. The study also examines MDD and optimum moisture content (OMC), crucial for understanding compaction and stability. Fiber reinforcement has been shown to enhance compaction characteristics and reduce swelling behaviour

Beyond swelling and compaction, the research addresses cracking in expansive soils, which literally affects structural integrity. Crack propagation, intensity, and width variations in fibre-reinforced soils are also analysed through shrinkage tests and image analysis. Synthetic fibres are expected to bridge soil particles, improving tensile strength and reducing crack formation.

The study also explores the influence of fibre length on swelling, CBR, and cracking behaviour. Standardised swell tests, compaction tests, and shrinkage assessments are conducted to validate the hypothesis that optimised incorporation of synthetic hair fibre reduces swelling and cracking potential of the expansive clay soils. This research contributes to literature on soil stabilisation and offers practical insights for geotechnical engineering applications.

1.8 Conceptual Framework

This study is guide by the conceptual framework that illustrates the relationship between inclusion of synthetic hair and the geotechnical performance of expansive clay soils. The independent variables are; length of synthetic hair fibres, percentage of synthetic hair fibres and properties of the soil while the dependent variables to be investigated include, swell tests, UCS, CBR, and MDD, and crack length and width.

The intervening variable such as environmental factors, purity of synthetic hair, and the method of mixing usually affect the can influence how effectively the synthetic hair fibres enhance the clay soil samples. These factors can either strengthen or limit the impact of fibre reinforcement. As illustrated in Figure 1.2, the framework reflects how synthetic hair fibres interact with the soil matrix to improve the soils structural properties.

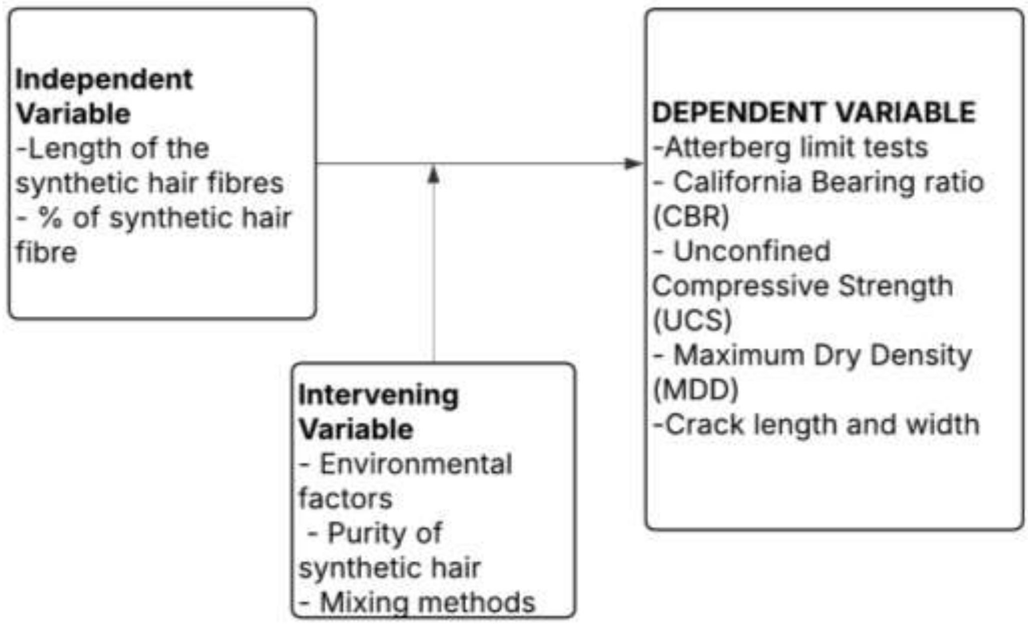


Figure 1.2: Conceptual Framework

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

The literature review provides a thorough understanding of the characteristics and failure modes of expansive clay soils, putting emphasis on the ways in which different elements, such as methods of stabilisation, mineral composition, and environmental conditions, influence the behaviour of expansive clay soils.

2.2 Distribution of Expansive Clay Soils

Expansive clay soils are widely spread all over the world and are recognised to cause substantial problems in construction and engineering works due to their tendency to significantly fluctuate in volume. These soils are commonly found in arid and semi-arid regions, where recurrent wetting and drying cycles exacerbate their shrinkage and swelling behaviour. Significant concentrations of expansive clay soils have been found in North America, Great Britain, southern Africa, and parts of Asia, with particular implications identified in East Africa and Uganda.

In his study, Cole et al. (2015) stated that the majority of North America's expansive soils are found in states like Texas, Colorado, and California. Widespread infrastructure damage, such as damaged on roads and foundations, are associated with these expansive clay soils. With billions of dollars being spent every year on mitigation and repair, managing vast soils in this area showed significant economic consequences. Similarly, the UK also possesses areas with expansive clays, especially in the east and south. In these areas, clay-rich soils have cause major structural damage, which has mandated the engineers to have a good understanding of this soil.

Expansive soils are a major concern in southern Africa, especially in South Africa's Free State Province, where clay mineralogy varies greatly. The expansive clays here, which are generally rich in montmorillonite, endure severe heaving during wet conditions and significantly shrink during dry seasons, causing problems for construction and civil engineering projects. Goodary et al. (2019) raises similar concerns in China, particularly along the Loess Plateau, which is noted for its enormous deposits of expansive loess, which contribute to similar engineering difficulties.

The geological structure of East African nations like Ethiopia, Kenya, and Tanzania is characterised by broad clay soils. These expansive clays that are formed as a result of the volcanic activity of the East African rift valley which presents difficult challenges for the development of infrastructure and usage of land. The high concentrations of expansive materials in volcanic soils from eruptions cause considerable swelling, calling for sophisticated technical solutions. Zang, Tai and Lu (2022) note that regions with regular wet and dry seasons execrated these issues, which highlights the necessity of thoroughly assessing sites and suitable techniques of managing this soil.

In Uganda, expansive soils more especially, montmorillonite have a major influence on civil engineering techniques, especially in the Eastern, and Karamoja regions. These soils' tendency to swell presents problems for road building and foundation stability, frequently calling for more creative methods of soil stabilisation. The humid tropical environment and regional geology are two examples of factors that lead to frequent fluctuations in moisture, which worsen the swell shrink cycles that are typical of expansive soils. It is important to understand Uganda's vast distribution of clay soils in order to guarantee structural integrity of infrastructure and efficient land management.

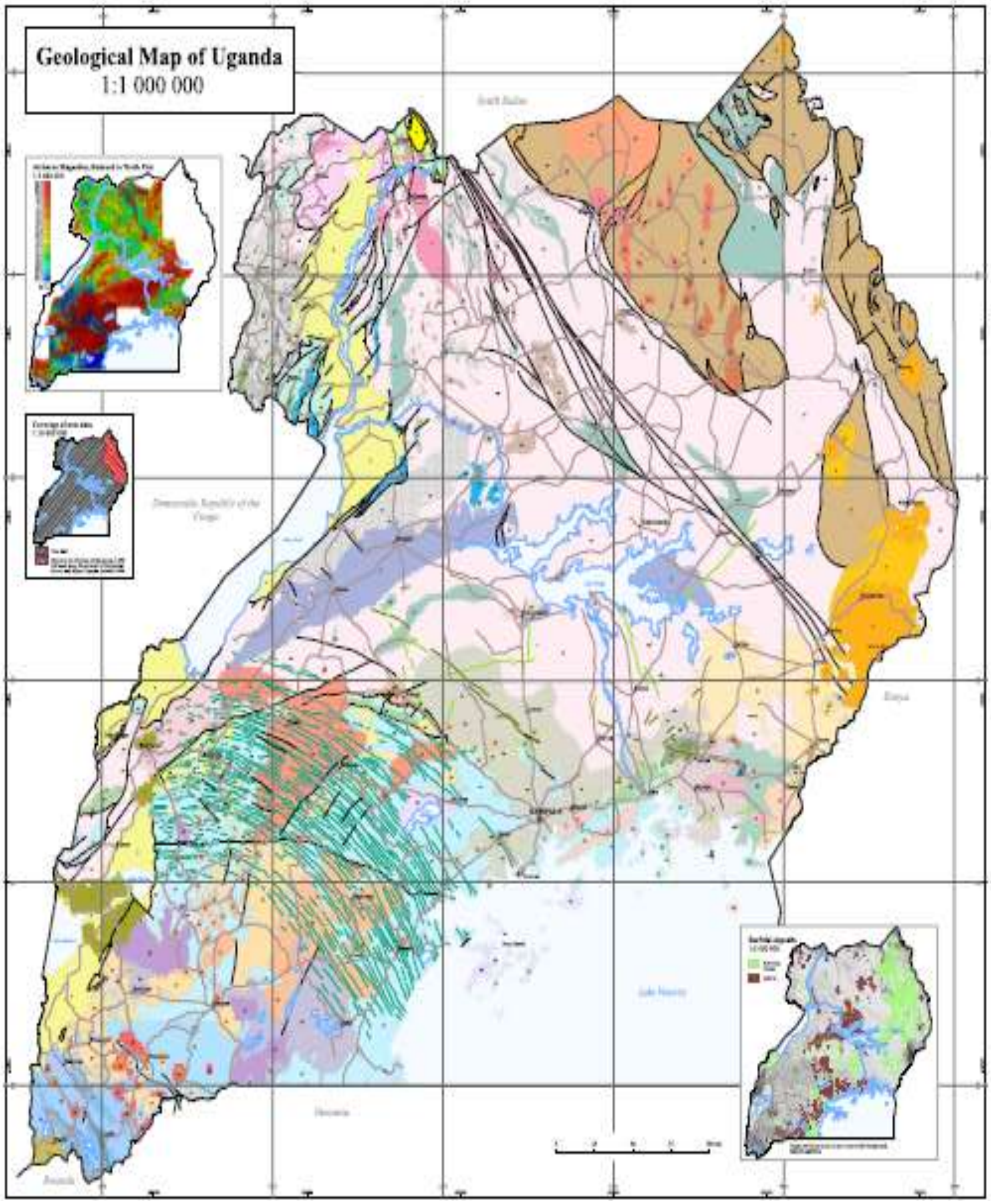


Figure 2.1: Geological map of Uganda (MoEMD, 2014)

Figure 2.2: Key for the geological map (MoEMD, 2014)

2.3 Classification and Characterisation of Expansive Soils

Expansive soils are particularly problematic in areas or regions with fluctuating climate conditions. The constant changes in moisture levels causes these soils to crack and settle unevenly, which often leads to damage of the infrastructure built on them. To effectively determine the properties of expansive soils, it is essential to characterise and classify these soils based on their key geotechnical parameters, such as swell potential, Atterberg limits, mineralogical composition, and Cation Exchange Capacity (CEC). These properties are essential in understanding the behaviour of expansive soils and are integral to identifying the effective stabilisation methods.

The swell potential of expansive soils is a property that directly influences their volume change behaviour. Expansive soils are classified based on their swelling capacity, which ranges from low to very high. According to Jalal et al. (2020), soils with low swell potential exhibit minimal volume changes when exposed to moisture, while those with high swell potential (>25%) undergo significant swelling, resulting into structural instability. This characteristic is good for identifying soils that are prone to shrinkage and swelling, which is central to understanding their behaviour in during construction. Determining the swell potential of expansive soils is therefore necessary when selecting an appropriate stabilisation technique to mitigate these issues, for example incorporating synthetic hair fibers to reduce swelling.

In addition to swell potential, the Atterberg limits specifically the LL and PI are also important indicators of the soil's plasticity and expansivity. Soils with high liquid limit values (greater than 60%) and plasticity indices (greater than 35%) are more prone to expansive behaviour, this is because these properties retain a high moisture content and exhibit significant plasticity. Selvakumar (2024) explains that soils with elevated LL and PI values are highly expansive and susceptible to volume changes under varying moisture conditions. These parameters predict the soil's behaviour in during construction, as soils with higher LL and PI values tend to be more problematic. Understanding the Atterberg limits is therefore essential for determining how moisture changes will affect the stability of expansive soils, making them useful when effectively managing the swell and shrinkage of these soils.

The mineralogical composition of expansive soils, particularly the presence of montmorillonite, plays an important role in their expansive behavior. Montmorillonite is a clay mineral known for its ability to absorb water and expand, which contributes to the soil's volume changes. Pedarla et al. (2016) notes that expansive soils dominated by montmorillonite exhibit significant swelling, making them prone to cracking and instability when subjected to moisture fluctuations. The mineral composition of expansive soils is therefore a key factor in predicting their behaviour, as soils containing montmorillonite and similar minerals are more likely to experience problematic shrink-swell behavior. Identifying the mineral content of expansive soils helps in understanding their expansive nature, and it is important when evaluating a method of stabilisation, such as using synthetic fibers to reinforce the soil matrix and reduce the effects of swelling.

Lastly, the CEC of expansive soils is another important property that influences their swelling behavior. CEC measures the soil’s ability to absorb and retain cations, which impacts its interaction with water. Puppala et al.(2016) indicate that soils with high CEC, particularly those rich in montmorillonite, have a greater capacity to absorb moisture, resulting into an increased swelling potential. Soils with high CEC values are more prone to moisture changes, which influences their expansive behaviour. Understanding the CEC of expansive soils allows for better predictions of soil behaviour and is critical for coming up with effective stabilisation strategies, such as incorporating synthetic hair fibers, which may help mitigate swelling by reinforcing the soil's structure.

Together, these properties swell potential, Atterberg limits, mineralogical composition, and CEC are central to understanding the geotechnical properties of expansive soils. By determining these characteristics, engineers can better assess the risks associated with expansive soils and implement effective stabilisation techniques. In the context of this research, identifying these properties helps to guide the selection of synthetic hair fibers as a stabiliser, which has the potential to improve the soil's mechanical properties and mitigate the adverse effects of moisture fluctuations. This aligns directly with Objective 1 of the research, which seeks to determine and understand the properties of expansive soils for more effective management and stabilisation.

Table 2.1: Various classifications and characterisation criteria available in the literature for expansive soils using basic geotechnical tests.(Jalal et al., 2020)

#1 on the basis of swelling

			Swell pressure	Metric units (kg/cm2)	Degree of
Swell potential	Total expansion	US customary (tsf)	SI units (kPa)	expansion	
0–1.5	0–10	<2.05	<196	<2	Low
1.5–5	10–20	2.05–4.1	196–392	2–4	Medium
5–25	20–35	4.1–7.2	392–687	4–7	High
>25	>35	>7.2	>687	>7	Very high

#2 on the basis of Atterberg limits

Linear shrinkage	Shrinkage index	PI	LL	SL	Expansivity index
0–8%	<25%	<18%	<35%	<14%	Low
8–13%	25–35%	18–25%	35–45%	12–14%	Medium
13–18%	35–50%	25–35%	45–60%	10–12%	High
>18%	>50%	>35%	>60%	<10%	Very high

#3 on basis of free swell ratio (FSR)

FSR	Soil expansivity	Clay type	Dominant clay Mineral
<1	Negligible	Non-swelling	Kaolinite
1–5	Low	Swelling and non-swelling	Kaolinite and montmorillonite
1.5–2	Moderate	Swelling	Montmorillonite
2–4	High	Swelling	Montmorillonite
>4	Very high	Swelling	Montmorillonite

Table 2.1 Continued

#4 on the basis of	Liquid limit (LL)
LL	Classification
0–20%	No swell
20–35%	Low swell
35–50%	Medium swell
50–70%	High swell
70–90%	Very high swell

#5 U.S. Army Waterways Experiment Station (WES 1983)

Classification of potential swell	potential (%)	LL (%)	PI (%)	*Soil suction* (*kPa*)
Low	<0.5	<50	<25	<160
Marginal	0.5–1.5	50–60	25–35	160–430
High	>1.5	>60	>35	>430

#6 China Ministry of Construction (CMC 2004)

Standard absorption M.C (%)	PI (%)	Free swell value (%)	Swell potential class
<2.5	<15	<40	Non expansive
2.5–4.8	15–28	40–60	Low
4.8–6.8	28–40	60–90	Medium
>6.8	>40	>90	High

Table 2.2: Mineralogical properties of basic clay minerals (kaolinite, illite, and montmorillonite) (Jalal et al., 2020)

Clay mineral	Structure	Interlayer bond/ intensity	Isomorphous substitution	Shrink-swell	CEC (meq/100 g)	LL (%)	K (m/s)
Kaolinite (1:1 clay mineral)	Alternating sheets of silica tetrahedron (Alumina / Silica) and alumina octahedral sheets	Hydrogen, *strong*	Low	Very low	3–15	30–75	10^{-5}–10^{-7}
Illite (2:1 clay mineral)	Alternating sheets of alumina octahedral sheets	K-ion, *moderate*	Moderate	Low	10–40	60–120	10^{-6}–10^{-8}
Montmorillonite (2:1 clay mineral)	(Silica / Alumina / Silica) between two silica tetrahedrons	Van der Waal, *very weak*	High	Very high	29–150	Up to 900	10^{-7}–10^{-9}

2.4 Properties and Failure Modes of Expansive Clay Soils

Expansive clay soils are highly responsive to moisture variation, which results into significant volume changes that are shown by swelling upon water absorption and contraction after loss of moisture. A predominant mineral in these soils is montmorillonite, which influences their swelling properties due to its high liquid limit and plasticity index. Jalal et al (2020) reported that expansive soils typically possess a liquid limit between 45 - 60% and a plasticity index above 25%, suggesting the presence of expansive clay minerals like montmorillonite. This highly plastic behaviour of expansive clay soils exemplifies the challenges associated with these soils in geotechnical applications.

The chemical stabilisation of expansive soils has been extensively studied, with traditional additives such as lime, cement, and fly ash showing significant improvements in soil behaviour. These stabilisers reduce swell potential and enhance the strength and stiffness of problematic soils. Barman and Dash (2022) conducted a comprehensive review of chemical stabilisation techniques and concluded that materials such as lime, cement, fly ash, and nano-silica effectively improve the engineering properties of expansive soils through mechanisms including hydration, flocculation, cation exchange, and pozzolanic reactions. Similarly, Biswas et al.(2022) reported that the incorporating nano and crystalline silica accelerates pozzolanic activity, leading to substantial gains in the load bearing capacity and overall performance of the soil. Moreover, innovative methods including the replacement of soil components with ground rubber have also been explored. Soltani et al. (2019) explained that ground rubber enhances the frictional resistance within the soil matrix, which reduces its expansive characteristics by introducing a non-expansive filler.

Environmental factors significantly affect the behavior of expansive soils, contributing to their swelling and shrinkage behaviours. The variations in climatic conditions, particularly rainfall patterns and temperature shifts, resulting to cyclic processes of swelling and shrinkage which undermines the soil's structural integrity. The relationship between moisture content and soil behaviour is complex, as experiments reveal varying response mechanisms dependent on the specific mineral composition of the soils.

The cyclic wetting and drying processes can lead to soil degradation over time, sometimes being referred to as “fatigue” in expansive soils. Chittoori et al. (2018) elaborated that this fatigue is exacerbated by seasonal wetting and drying cycles, which can significantly alter the mechanical properties of the soils, thereby affecting the durability of structures above. Failure modes associated with expansive clays can include but are not limited to surface shrinkage cracking and subsidence, which may pose major risks to infrastructure and necessitate careful engineering consideration (Shaker et al., 2024).

Lastly, understanding the behaviour of expansive soils under different loading and environmental conditions is important for their effective management and mitigation strategies. There are a variety of experimental models that have been adopted to simulate their swelling and shrinkage behaviours, revealing insights that can guide the design processes in civil engineering applications. For instance, Cheng et al. (2023) illustrated that the mechanical properties of expansive soils could be significantly altered through calculated stabilisation methods, promoting greater stability and resilience in construction practices.

2.5 Stabilisation of Expansive Clay Soils

Expansive soils, which are prone to increased volume changes due to moisture fluctuations, present substantial challenges in geotechnical engineering, particularly for infrastructure such as foundations and road construction. These soils undergo considerable swelling when wet and shrinkage when dry, leading to differential settlement, cracking, and structural instability. Traditional stabilisation methods, including the use of lime, cement, and chemical additives, have been widely used to improve the properties of expansive soils. While effective, these methods come with high costs and environmental concerns. As a result, there is a growing interest in alternative stabilisation techniques, such as the use of synthetic fibres, which offer a sustainable and cost-effective solution to improving the performance of expansive soils.

In recent years, the incorporation of synthetic fibres into expansive soils has been studied as a means of enhancing their strength, compaction, and swelling resistance. Synthetic fibres, made from materials such as polyethylene terephthalate (PET), polypropylene, and other polymer-based materials, are increasingly seen as an effective soil reinforcement technique due to their ability to form a reinforcing matrix within the soil. This matrix helps mitigate the adverse effects of moisture fluctuations by improving soil cohesion and preventing cracking.

One of the primary advantages of incorporating synthetic fibres into expansive soils is the reduction in swelling potential. Expansive soils typically exhibit high swell potential, which leads to significant volume changes, causing cracks and instability. Studies show that the addition of synthetic fibres significantly reduces free swell in expansive soils. Kumar et al. (2021) found that synthetic fibres, when added to expansive soils at an amount of 0.5% by dry weight, resulted in a notable reduction in swelling. The fibres act as a reinforcing agent, preventing the soil from expanding excessively when exposed to moisture. This is due to the formation of a fibre network within the soil matrix, which restricts the movement of water and helps maintain the soil's volume, thus mitigating swelling. This aligns with Objective 3 by demonstrating how synthetic hair fibres improve the swelling resistance of expansive soils.

In addition to reducing swelling, the incorporation of synthetic fibres has a significant positive impact on the shear strength and compaction characteristics of expansive soils. Expansive soils are often weak in shear, and their low strength can make them unsuitable for construction without treatment. The addition of synthetic fibres has been shown to improve the unconfined compressive strength (UCS) and California Bearing Ratio (CBR) of these soils. Pradhan et al.(2012) reported that inclusion of synthetic fibre increased the UCS by up to 56% and the CBR by up to 300%. The fibres improve the soil's load bearing capacity by creating a strong internal network that enhances the cohesion of clay soil particles. Which makes the soil more resistant to deformation and cracking, which is particularly important for expansive soils that undergo significant shrinkage during dry periods. The increase in shear strength is also attributed to the fibres' ability to distribute applied stresses more evenly throughout the soil, preventing the development of cracks and improving overall stability of soil.

The addition of synthetic fibres significantly enhances the compaction characteristics of expansive soils. Kumar et al.(2021) found that fibre-reinforced soils exhibited improved maximum dry density (MDD) and optimum moisture content (OMC). The presence of the fibres helps to align soil particles more effectively during compaction, resulting into increased soil density and enhanced stability of the soil. This is important when controlling differential settlement, a common phenomenon associated with expansive soils, as it reduces the likelihood of soil movement under load.

Another benefit of synthetic fibres is their ability to reduce crack formation in expansive soils. Shrinkage Cracking is a major concern in expansive soils due to their tendency to shrink when exposed to dry conditions. The incorporation of synthetic fibres helps bridge cracks and limit their growth, thereby improving the crack resistance of the soil. Kumar et al.(2021) observed that the crack width and crack length in fibre-reinforced soils were significantly reduced compared to untreated expansive soils. This is because the fibres form a reinforcing network that prevents cracks from propagating, allowing the soil to maintain its structural integrity during drying. Additionally, Ghani et al. (2022) found that synthetic fibres helped reduce shrinkage strain in expansive soils, further enhancing their crack resistance.

The optimal fibre length and dosage are also important factors for maximising the effectiveness of synthetic fibres in soil stabilization. Kumar et al.(2021) found that fibre lengths of 6-8 cm provided the best performance in improving shear strength and swelling resistance, as this range allowed for effective fibre distribution while maintaining a strong interlocking structure within the soil. The fibres need to be long enough to provide sufficient reinforcement but short enough to ensure uniform distribution throughout the soil matrix. In addition to fibre length, the percentage amount of fibres plays an important role. Zhang et al. (2022) observed that increasing the fibre content led to improvements in compaction characteristics, as the fibres helped reduce the void spaces in the soil, leading to higher dry density and better overall soil stability.

In comparison to traditional stabilisation methods, synthetic fibres offer several advantages. While methods such as lime and cement stabilisation are effective in improving soil properties, they are often expensive and involve processes that contribute to carbon emissions. In contrast, synthetic fibres are an affordable, sustainable alternative that can be sourced from waste materials. Ossola (2024) emphasized the environmental benefits of using synthetic hair fibres, as they help address the growing issue of plastic waste disposal. By repurposing synthetic hair fibres for soil stabilisation, this study contributes to sustainable development goals by promoting the use of recycled materials and reducing environmental pollution.

2.6 Different Fibres Used for Reinforcement

The efficiency of fibre reinforcement in expansive soils is determined by the type of fibre employed, as each possess distinct qualities that influence the soil behaviour. The next subsections will go over the various types of fibres that are widely used for soil reinforcing, as well as their qualities and processes of operation.

2.6.1 Natural Fibres

The potential of natural fibres like bagasse, coir, and jute to improve the characteristics of expansive soils has been extensively researched. For example, it has been demonstrated that jute fibres considerably lower the possibility for swelling. The addition of 0.8% jute fibres (40 mm long) reduced swelling pressure by 40.15%, to 113.70 KN/m^2, according to Kumar et al. (2021). This decrease is explained by the fibre’s ability to interlock with soil particles, creating resistive tensile stresses that offset the expanding pressures brought on by the absorption of moisture in the soil. Jute fibres are an environmentally friendly choice for stabilisation of soil because of their natural composition, which also contributes to their biodegradability.

Because of their great resilience and tensile strength, coir fibers which are obtained from coconut husks have also become more and more popular. According to Widianti et al. (2021) coconut fiber percentage of 0.6% produced the highest increase in shear strength and elastic modulus. According Bhatt & Varshney. (2018), adding coir fibres to clayey soils raised their UCS by about 39.4% when compared to untreated soils. Because coir fibres can help maintain moisture balance within the soil, their capacity to absorb water also adds to their efficacy in reducing swelling behaviour.

The potential of bagasse fibers, the fibrous residue left behind after sugarcane processing as a material for soil augmentation has also been studied. According to Dang and Khabbaz (2018), bagasse fibres and soil particles interact to improve the expansive soils' compressive and compaction qualities, which increases their strength and lessens their tendency to swell. Bagasse fibres are excellent at stabilising expansive soils; this was evidenced by the study's findings that their addition increased the UCS by 15%. In addition to offering engineering advantages, the use of bagasse fibres also encouraged recycling of agricultural waste, supporting environmentally friendly civil engineering methods.

2.6.2 Synthetic Fibres

Synthetic hair fibres, are commonly made from materials such as polyethylene terephthalate (PET), polypropylene, and nylon. These are increasingly gaining attention in soil stabilisation due to their unique physical and mechanical properties. These fibres, primarily used in the beauty industry. they show a potential of being utilised in the construction industry as low-cost and sustainable reinforcement material for expansive soils. This is because the physical properties of synthetic hair fibres, including their tensile strength, elasticity, and resilience, make them particularly suitable for enhancing the mechanical properties of soils. According to Ashwini et al (2023), synthetic fibres, especially those made from PET, exhibit high tensile strength and resilience, enabling them to withstand external stresses and maintain their structural integrity within the soil matrix. This characteristic is ideal when the fibres are incorporated into the soil, as they can accommodate extra forces acting on them without degrading or breaking. Additionally, fibre morphology, including length, diameter, and surface texture, plays a significant role in determining their performance as soil reinforcements. Kumar et al (2021) suggests that the surface texture of synthetic fibres can influence their bonding with the soil. Smooth-surfaced fibres like PET may not bond as effectively as the more textured fibres, but the slight roughness present in synthetic hair fibres may enhance their interlocking capacity, which helps improve the cohesion of the soil matrix.

The mechanical properties of synthetic hair fibres also play a key role in their ability to reinforce expansive soils. When incorporated into soils, synthetic fibres, such as those made from polypropylene or nylon, enhance the shear strength and ductility of the soil. These fibres help form a three-dimensional network within the soil, distributing stresses more evenly and preventing the formation of cracks under applied loads. Studies by Pradhan et al.(2012) and Zaimoğlu and Yetimoglu (2012) have demonstrated that the inclusion of synthetic fibres significantly improves the unconfined compressive strength (UCS) and California Bearing Ratio (CBR) of soils, particularly in expansive soils that are prone to cracking and volume changes due to moisture fluctuations. Kumar et al. (2021) also found that the presence of synthetic fibres reduces shrinkage strain and improves soil cohesion, particularly in wetting-drying cycles, which is a critical factor for soils exposed to seasonal moisture changes. This enhanced tensile strength and resilience make synthetic hair fibres an effective reinforcement material, especially for soils that would otherwise experience significant structural instability.

Another important factor that influences the effectiveness of synthetic hair fibres in soil reinforcement is the fibre length and amount. The literature on fibre reinforcement suggests that fibre length is directly related to the improvement in soil's tensile strength, ductility, and crack resistance. Zhang et al (2022) observed that longer fibres generally form stronger bonds within the soil, improving shear strength and ductility. However, Pradhan et al (2012) note that longer fibres may also present challenges in achieving uniform distribution within the soil, which can limit their effectiveness. In contrast, shorter fibres tend to be more evenly distributed and can improve soil compaction and shear strength more effectively at lower fibre content. Studies by Kumar et al (2021) suggest that the optimal fibre length for enhancing the UCS and CBR of expansive soils is between 6-8 cm, this range was shown to allow for effective fibre dispersion while maintaining a strong structural interlock between the fibres and the soil particles.

When compared to other commonly used fibres like polypropylene or nylon, synthetic hair fibres offer a unique advantage in terms of sustainability and cost-effectiveness. While fibres like polypropylene have been extensively researched for their role in soil stabilisation, synthetic hair fibres, as a waste product from the beauty industry, provide a more environmentally friendly and affordable alternative. Kumar et al (2021) highlight that synthetic hair fibres, which are abundant and inexpensive, not only offer engineering benefits in terms of strength and crack resistance but also help in reducing landfill waste. By using these fibres, this study aligns with circular economy principles, where waste is transformed into valuable resources, contributing to both environmental sustainability and the advancement of cost-effective soil stabilization techniques.

The incorporation of synthetic hair fibres into expansive soils offers notable environmental benefits. As Ossola (2024) points out, synthetic hair waste, which is primarily composed of PET and PVC, poses environmental challenges due to its non-biodegradable nature. By repurposing synthetic hair fibres for soil reinforcement, we not only help mitigate the environmental burden of synthetic hair disposal but also promote sustainable construction practices. Thus, this research aligns with Sustainable Development Goal 12, which advocates for responsible consumption and production by finding innovative solutions to reduce waste and promote sustainable use of resources in civil engineering applications.

The literature shows synthetic hair fibres exhibit significant physical and mechanical properties that make them effective for reinforcing expansive soils. These fibres, particularly those made from PET and polypropylene, enhance soil strength, ductility, and crack resistance, significantly improving the mechanical stability of expansive soils. The impact of fibre length, fibre content, and fibre morphology on soil reinforcement has been well documented, with optimal performance achieved at certain fibre lengths (6-8 cm). Compared to other commercially available fibres, synthetic hair fibres offer an affordable and sustainable alternative that helps address the growing issue of synthetic waste disposal. This aligns with Objective 2 of this study, which aims to characterize the physical and mechanical properties of synthetic hair fibres and evaluate their potential for improving soil stability.

2.6.3 Recycled Fibres

An eco- friendly substitute for soil reinforcement has been investigated with the use of recycled fibres, such as fibrillated fibres. According to research by Amir-Faryar and Aggour (2015), recycled fibres could raise clayey soils UCS while lowering vertical shrinkage strains by about 15%. It is crucial to remember that their research also showed that raw expansive soils' free swell value increased, indicating that the efficacy of recycled fibers may differ depending on the circumstances. In addition to solving engineering problems, the possibility of using waste materials for soil stabilisation supports environmentally friendly building techniques.

Recycled fibres have two advantages as they improve soils' mechanical qualities while also encouraging waste reduction. Incorporating recycled materials into soil stabilisation procedures is consistent with the circular economy's tenets, which advocate repurposing waste products to generate value. This method is a desirable choice for engineers and project managers since it not only lessens the environmental effect of construction operations but also saves material costs.

2.7 Previous Use of Hair Fibres for Stabilising Expansive Soils

The use of hair fibres in soil stabilisation has attracted increasing interest in recent years as researchers look for environmentally friendly alternatives to traditional chemical additives such as lime or cement. One of the earliest directions in this area involved the use of *human hair* due to its natural tensile strength and abundance as a waste product, particularly from beauty salons and barbershops. For example, a study by Idoui et al (2024) demonstrated that incorporating human hair fibres improved the strength and reduced the compressibility of expansive soil mixtures. Their work also used Scanning Electron Microscopy (SEM) to show that hair fibres physically interlocked with soil particles, helping to restrain movement and improve cohesion. However, their study was focused on human hair only and did not explore synthetic hair, which has different mechanical and chemical properties due to its polymeric composition. Furthermore, their tests did not evaluate crack propagation during drying cycles, which is the most critical problem associated with expansive soils.

A similar study by Ashwini et al (2023) investigated the use of human hair fibres to improve the bearing capacity of clayey soils. Results showed a measurable increase in California Bearing Ratio (CBR) values, indicating that hair fibres enhance resistance to deformation under load. Although effective in improving strength, the study focused solely on strength parameters and did not address crack control under shrinkage. Additionally, it did not consider the sustainability implications of using synthetic hair waste, which constitutes a growing environmental concern.

Ghani et al (2022) conducted a detailed geotechnical evaluation of soil reinforced with human hair, showing improvements in ductility and reduced brittleness. Their research demonstrates that hair fibres can enhance post-peak strength, delaying sudden failure in soils. However, the scope was limited to small-scale laboratory tests and did not include expansive soils or fibre performance under moisture variation factors critical to infrastructure performance in tropical climates.

Despite these promising indications from the literature, there remains a noticeable lack of studies focusing on synthetic salon hair fibre, a material that is not only widely available but also poses a growing environmental management challenge, especially in developing countries. Most of the existing studies are either limited to human hair or rely on commercially manufactured fibres rather than waste materials. Furthermore, many of these studies have not used modern digital imaging tools to measure crack progression over time.

Therefore, while research confirms the potential of hair fibres as a reinforcement material, it has not yet fully explored the exact type of hair waste examined in this study, nor its performance in controlling cracking in expansive soils. This gap establishes a strong foundation and justification for the present work, which investigates synthetic hair fibre as a sustainable, low - cost stabiliser for expansive clay soils and assesses its crack resistance using advanced digital imaging techniques.

2.8 Challenges in the Management of Synthetic and Natural Hair Waste

The management of both synthetic and natural hair waste in developing countries presents significant challenges that reflect broader systemic issues in waste management infrastructures, economic constraints, and regulatory frameworks. In many urban areas, especially in sub-Saharan Africa, the waste generated from the beauty and personal care industry is not effectively managed, leading to severe environmental and public health concerns.

A primary barrier is the lack of adequate waste collection and treatment infrastructure that is common in many developing countries. Research indicates that waste management systems in these regions are often fragmented, inefficient, and underfunded, with inadequate collection services, limited recycling pathways, and reliance on unregulated dumping or open burning of waste (Kumar., 2023; Ossola, 2024). These challenges are exacerbated by fiscal constraints, limited technological capabilities, and weak regulatory frameworks that fail to address the growing volume of diverse waste streams, including synthetic hair. In this context, synthetic hair waste, despite its unique chemical and physical properties, is often mixed with general waste, leading to improper disposal that does not account for its long-term environmental impact.

2.8.1 Synthetic Hair Waste: A Growing Environmental Concern

Synthetic hair waste, composed primarily of polymeric materials such as PET and PVC, presents particular challenges. These materials are akin to plastics and are not biodegradable, making their disposal problematic. As identified in the literature, the recycling and repurposing of synthetic hair waste is severely hindered by the absence of formal recycling systems and advanced processing technologies (Ossola, 2024). This reliance on informal disposal practices contributes to widespread microplastic pollution, which not only degrades the environment but also wastes potentially valuable recyclable materials. Economic assessments show that, without the right incentives or infrastructure, recycling such materials is not seen as economically viable by local governments or industries (Begum and Ehsan, 2020).

In urban settings, synthetic hair waste often ends up in landfills, water bodies, or drainage systems, where it causes blockages, exacerbating flooding risks, and contributing to long-term environmental pollution. Furthermore, when this waste is burned as a disposal method, toxic fumes like dioxins and furans are released, posing a severe threat to air quality and public health (Kumar, 2022). The need for innovative solutions such as repurposing synthetic hair fibres for applications like soil stabilization, as explored in this thesis is critical for mitigating these harmful environmental effects.

2.8.2 Natural Hair Waste: Biodegradability Doesn't Guarantee Safe Disposal

Although natural hair is biodegradable, it still poses challenges in waste management, particularly due to contamination and improper handling. Hair collected from salons and healthcare facilities often contains traces of chemicals and dyes used in treatments, making it unsafe for disposal in its raw form. Natural hair mixed with hazardous materials can lead to environmental contamination or create health hazards if not properly managed (Begum & Ehsan, 2020). Thus, like other organic waste, there is a pressing need for source segregation and the development of specific protocols for the safe disposal or reuse of natural hair waste.

Moreover, the potential for recycling or upcycling natural hair waste—such as using it in agricultural applications or for creating biodegradable composites—is severely limited by policy gaps and the lack of integrated waste management systems. The absence of clear policy agendas or circular economy frameworks for hair waste further inhibits its value as a resource in sustainable practices.

2.8.3 Economic and Policy Constraints

The economic constraints in developing countries are significant, with limited financial resources allocated to waste management and environmental sustainability initiatives. Waste management is often a low priority in the face of competing needs such as health, education, and infrastructure development. Economic studies emphasize that cost-benefit analyses for waste management, especially for niche waste streams like synthetic and natural hair, are rarely performed due to limited public-private collaboration and the lack of policy incentives (Begum & Ehsan, 2020). Without a clear economic framework, it becomes difficult for local governments and businesses to justify the investment needed for specialized waste management systems for hair waste.

In many instances, synthetic and natural hair waste is relegated to general waste streams, where it remains unregulated and unaddressed. This oversight compounds the environmental and social challenges associated with the disposal of this waste, creating long-term issues for both urban and rural communities.

The management of synthetic and natural hair waste in developing countries is therefore emblematic of broader challenges in the waste management sector. It highlights the disconnect between waste generation and sustainable disposal practices, particularly when dealing with specialized waste streams. To address these issues, a holistic approach is required one that improves both technical and infrastructural capacity in waste management while also strengthening policy frameworks to promote sustainable and circular waste management practices.

2.9 Mechanical Properties of Fibre Reinforced Expansive Soils

The mechanical properties of expansive soils can be significantly enhanced through the incorporation of various fibre types, both natural and synthetic. Research has demonstrated that the inclusion of fibres not only augments the compressive strength of such soils but also affects other critical parameters such as shear strength and overall durability.

Sharma et al (2015) conducted a comprehensive study on the impact of natural fibres, such as Grewia optiva and Pinus roxburghii, on the unconfined compressive strength (UCS) of low compressive sand-clay soils. They found that reinforcing soil with fibres at varying proportions (0.5%, 1%, 1.5%, and 2%) led to notable improvements in UCS due to enhanced adhesion between the fibers and soil matrix.

In the realm of synthetic fibres, Zaimoğlu and Yetimoğlu (2012) explored the effects of randomly distributed polypropylene fibres on fine-grained soils. Their findings revealed that the strength of both uncemented and cemented clayey soils improved significantly with fibre inclusion. The study indicated that as the polypropylene fibre content increased, there was a corresponding increase in unconfined compressive strength accompanied by a decrease in stiffness.

Li and Zornberg (2013) focused on the stress strain response of fibre reinforced soils, indicating that the mobilization of reinforcement forces is crucial for optimal performance. They proposed a refined discrete framework that aids in predicting the equivalent shear strength of fibre reinforced soils, attributing better stress transfer and strain compatibility to this refined model.

In a parallel line of investigation, Hou et al (2020) performed triaxial compression tests to assess the shear strength characteristics of fibre reinforced soil. Their results indicated that the optimal fibre mass ratio to dry sand mass was approximately 0.75%, beyond which the mechanical properties of the reinforced soil plateaued. They noted a significant increase in peak strength of the soil as fibre content and dry density increased, while water content had an inverse effect.

Additionally, Pradhan et al. (2012) examined the role of randomly distributed polypropylene fibres on cohesive soils and proposed theoretical models to explain the mechanics of fibre reinforced soil. Their findings corroborated the conclusion that varying amounts of fibres could accurately predict the strength characteristics of the soil mixture, which was further validated against experimental outcomes.

Pradhan et al (2012) investigated the dynamic properties of clay soils reinforced with polypropylene fibres, highlighting that the inclusion of fibres increased the unconfined compressive strength while also reducing the vertical shrinkage strains. Their results also emphasised the dependency of soil fibre properties on the percentage of fibre, showcasing its potential for enhancing structural performance.

Wu et al (2014) conducted triaxial shear tests examining sisal fibre reinforced silty clay and observed that the mechanical properties were optimized at fibre contents between 1% and 2%. The research revealed that the length of the fibre significantly influenced shear strength characteristics, offering insights into effective reinforcement strategies. The studies by Abood and Shakir (2023) further demonstrated that natural fibres such as coconut and bamboo had pronounced effects on improving the ductility and strength of clay soils. Their findings suggested that incorporating natural fibres in expansive soils could tangibly mitigate drying related failures.

In a comprehensive exploration, Benziane et al (2019) emphasises the role of randomly distributed polypropylene fibres in changing the shear behaviour of sandy soils, noting a transformation from a strain softening to a strain hardening response due to fibre reinforcement. This indicates a shift in the mechanical behaviour of composite material, which underscored the importance of fibre characteristics in practical applications.

2.9.1 Quantitative Analysis of Mechanical Properties

The quantitative analysis of mechanical properties in fibre reinforced expansive soils has been the focus of considerable research aimed at understanding their performance under various loading conditions. This area of study encompasses the effects of synthetic fibres on key engineering parameters such as UCS, shear strength, and overall stability of fibre reinforced soil mixtures.

Lu et al (2021) conducted a comprehensive study on the mechanical properties of polypropylene fibre reinforced fly ash-soil composites. Their findings revealed that the addition of polypropylene fibres significantly improved the tensile strength and modulus of elasticity of the soil matrix, effectively improving its structural integrity when addressing issues related to soft soils and expansive clays.

Additionally, Zhang et al (2022) explored hybrid polypropylene fibre reinforcement and its impact on cemented soil integrity and crack resistance. Their research noted significant improvements in compressive, tensile, and shear resistance due to the addition of fibres, particularly highlighting the fibre's role in enhancing anti cracking properties critical for maintaining structural stability under cyclic loading conditions.

Evangelou et al (2023) provided insights into the mechanical behaviour of fibre reinforced soils under undrained triaxial loading. They observed that the incorporation of fibres enhances the shear strength parameters, contributing to the overall stability of the soil composite. Their findings indicated that while fibres primarily function in tension, their effect can be quantifiably measured by increases in cohesion and internal friction angles of the soil.

Sotomayor and Casagrande (2018) indicated that fibre reinforcements significantly affected the shear strength of sand soils, with particle size and shape being important determinants of performance. Conversely, Wang et al (2020) focused on basalt fibre reinforcements in cement soils, reporting that various mixtures showed improvements in splitting tensile strength, a critical parameter in evaluating the performance of cement treated soils under tensile loads. Their research exemplifies how fibres can enhance both compressive and tensile strength properties, crucial for maintaining soil integrity under varying operational conditions.

In the context of eco-friendly practices, Bekkouche et al.(2022) examined the use of plant and synthetic fibres for stabilising expansive soils. Their findings show that mechanical shear properties of expansive soils were positively influenced by the fibre type and orientation, emphasizing that these factors are essential considerations in effective soil reinforcement.

Furthermore, Diambra and Ibraim (2015) analysed the implications of fibre length on mechanical properties, emphasizing how fibre geometry significantly influences the mechanical behavior of reinforced soils, leading to improved load bearing capabilities and reduced deformation under stress. These micro mechanical approaches informed the understanding of designing effective fibre reinforced soil systems.

Overall, the literature emphasizes the advantages associated with the integrating of various fibre types into expansive soil matrices. The improvements in key mechanical properties such as UCS, tensile strength, and shear resistance highlight the potential of using fibre reinforcements as a viable solution for enhancing the performance and durability of engineered soil systems in geotechnical applications.

2.9.2 Statistical Analysis of Stabilised Soils

Statistical methods play a vital role in assessing whether observed changes in soil properties after treatment are significant or merely due to random variation. Montgomery and Runger (2018) explain that inferential statistics particularly t-tests and analysis of variance (ANOVA) are central to validating experimental hypotheses in engineering research. According to Bhattacharyya and Johnson (2019), hypothesis testing provides an objective basis for determining the effectiveness of a treatment by comparing group means at a specified confidence level.

In geotechnical studies, the independent samples t-test has been widely employed to compare the strength, stiffness, and shrinkage characteristics of treated and untreated soils. For instance, Pradhan et al.(2012) and Zaimoğlu and Yetimoğlu

(2012) applied the test to confirm the influence of synthetic and natural fibres on the unconfined compressive strength and CBR values of clayey soils. Similarly, Kumar et al (2021) demonstrated the statistical significance of strength gains in fibre-reinforced expansive soils using comparable t-test techniques. The approach enables researchers to ascertain whether the improvements observed in laboratory tests are statistically meaningful, supporting design recommendations based on quantifiable confidence limits.

In addition to its simplicity, the t-test is suitable for studies with moderate sample sizes, where two independent groups (treated and control) are compared. The use of such methods ensures objectivity in interpreting results and aligns with the practices established in geotechnical research for validating experimental interventions (K. H. Head, 2014). This statistical approach therefore provides a robust foundation for verifying whether fibre inclusion produces measurable improvements in soil cracking and stability behaviour.

2.9.3 Economic Evaluation through Cost Benefit Analysis

While statistical tests quantify the technical efficacy of a stabilisation technique, they do not reveal its economic desirability. Hence, cost benefit analysis (CBA) serves as a complementary tool that integrates technical findings with financial considerations. According to (Boardman et al 2018), CBA provides a structured framework for comparing the present value of benefits and costs over the lifecycle of a project, using metrics such as the Net Present Value (NPV) and the Benefit Cost Ratio (BCR). These measures assist policymakers and engineers in deciding whether the long-term gains from a stabilisation method justify its initial expenditure.

In geotechnical and infrastructure projects, CBA has been increasingly applied to evaluate the economic viability of soil improvement techniques. Flyvbjerg(2022) further highlights that integrating economic evaluation into engineering projects helps prevent cost overruns and enhances value-for-money decision-making.

Recent sustainability-oriented studies, such as Giani et al. (2021), advocate for including environmental and social co-benefits such as waste reduction and employment generation in the evaluation framework, particularly when alternative stabilisers are sourced from recycled or waste materials. This perspective is crucial in developing countries like Uganda, where cost efficiency and environmental sustainability are both key policy priorities.

The adoption of a CBA framework in this study therefore aligns with global best practices for sustainable geotechnical engineering. By combining the quantitative rigour of statistical analysis with the decision-making strength of economic evaluation, this dual analytical framework provides a comprehensive basis for assessing the performance, practicality, and policy relevance of using synthetic hair fibres as a stabilising agent in expansive soils.

2.10 Failure Modes of Fibre Reinforced Expansive Soils

The modes of failure of expansive soils reinforced with fibres are critical to understanding how these materials behave under various load conditions. The incorporation of fibres whether natural or synthetic has been shown to alter the failure mechanisms of expansive soils, contributing to enhanced stability and resilience against cracking and deformation.

Yang et al (2022) conducted an experimental study that observed the impact of polypropylene fibres on the failure mode of cemented silt soil. Their research demonstrated that with a cement dosage of 15% and fiber length of 9 mm, fibre inclusion shifted the failure behaviour from brittle to ductile. The presence of fibres led to noticeable reduction in crack width and number, illustrating how fibres can improve the deformation capacity of the composite material and mitigate catastrophic failure.

In another study, Hu et al (2021) examined the performance of polypropylene fibre used to reinforce solidified soil and identified dual failure modes: pull-out and tensile failures. The effectiveness of the fibres, particularly those with lengths of 12 mm at a content of 0.3 %, was noted to improve the mechanical performance of the soil by supporting a one-dimensional lacing wire effect and a three-dimensional network, which fundamentally changed the structural failure mechanisms.

Tang et al (2010) focused on the interfacial shear strength of fibre reinforced soils, highlighting that the reinforced fibres in cemented soil conversions resulted in an increase in both peak and residual strength. Their tests demonstrated that inclusion of fibres effectively prevented tension crack formation a common failure mode in unreinforced soils thereby facilitating a transition to a more ductile failure mechanism.

Wu et al (2014) reported on the behaviour of sisal fibre reinforced silty clay, noting that failure modes included crack fracture and surface shear fracture. Their findings suggest that the use of sisal fibres significantly enhances the mechanical integrity of silty clay, demonstrating the potential applications of such materials in various engineering projects such as dam foundations and roadbed constructions.

Pradhan et al (2012) investigated the effects of polypropylene fibre inclusion on cohesive soil and observed changes in the compaction and strength behavior. They noted the improvement in the composite matrix's performance, particularly with higher fibre aspect ratios, which influence the failure modes by providing enhanced tensile strength to counteract expansive pressures. However, further specific data regarding the aspect ratios of fibres was not thoroughly addressed in this study.

The work conducted by Hou et al (2020) emphasised the bulging failure mode in cotton fibre reinforced soils. They noted that the fibres effectively restricted radial deformation, producing enhanced material stability. These observations underscored how different fibre types influenced the specific modes of failure in expansive soils, reshaping traditional failure expectations associated with undisturbed expansive soils.

Cai and Ou (2023) explored the improvements made to expansive soil using lignin and its derivatives, which resulted in a reduction of brittleness in the failure mechanism. Their study emphasised that lignosulfonate treatment not only strengthened the soil but also fostered a non-brittle failure, underscoring the importance of utilising biodegradable materials to improve soil properties and minimize environmental impacts.

Additionally, Moghal et al (2018) studied the consolidation, swelling, and shrinkage behaviour of lime blended expansive soil reinforced with polypropylene fibres. Their research indicates that the fibres serve a vital role in altering the consolidation characteristics, ultimately leading to reduced swelling and cracking tendencies, thus changing the typical failure modes experienced by expansive soils.

2.11 Literature Review Summary

The literature reviewed in this study highlights the ongoing challenges posed by expansive soils, particularly their tendency to shrink and swell with changes in moisture, which can cause significant damage to infrastructure. Traditional methods of stabilizing these soils, such as lime and cement, are commonly used but come with their own set of challenges. These methods can be expensive, environmentally harmful, and sometimes not as effective in certain conditions, which has led researchers to explore more sustainable alternatives.

One such alternative that has gained attention is the use of synthetic fibres, including those made from polypropylene and polyester. These fibres have shown promise in improving soil properties like shear strength, swelling resistance, and crack prevention. Their mechanical properties, such as high tensile strength and elasticity, make them ideal for reinforcing soils, especially expansive ones. When added to soil, synthetic fibres form a reinforcing network that helps the soil maintain its structure, reducing shrinkage and preventing cracks. What makes this study particularly interesting is the focus on synthetic hair fibres, a material often overlooked despite its potential. Waste synthetic hair, typically discarded by salons, offers a unique opportunity to address two problems at once: improving soil stability and managing waste. By repurposing this material, we can contribute to more sustainable development practices. Research shows that the length, content, and surface texture of the fibres are crucial for maximizing their benefits, with fibres around 6 to 8 cm being most effective for soil stabilization.

In regions and countries, where expansive soils are widespread, this research is especially relevant. Not only does it offer a practical, low-cost solution to soil stabilisation, but it also promotes a more sustainable approach by using locally available materials. This aligns with Sustainable Development Goal 12 (Responsible Consumption and Production), which encourages innovative ways to reduce waste and reuse materials. Overall, the findings support the potential of synthetic hair fibres as a cost effective, sustainable alternative to traditional soil stabilisers, improving both geotechnical performance and environmental sustainability.

2.12 Research Gap

Despite the extensive research on stabilising expansive soils using conventional methods like lime and cement, these approaches remain costly, environmentally harmful, and sometimes ineffective under certain conditions particularly as sulphate rich soils. While fiber reinforcement has emerged as a promising, more sustainable alternative with studies demonstrating benefits from natural and synthetic fibers the majority of research focuses on commercially manufactured fibres that are often expensive and inaccessible in low resource settings like Uganda. Very few studies have explored the use of hair fibers, particularly synthetic hair fibres, which is abundant, durable, and mechanically comparable to polymer fibres. Additionally, there is a lack of comprehensive mechanical, statistical, and economic evaluations of hair fibre reinforcement, as well as limited investigation into crack behaviour and control mechanisms using advanced techniques. Moreover, the economic feasibility of fiber-based stabilization has not been thoroughly assessed beyond material costs. Crucially, no empirical research has been conducted in Uganda on utilizing synthetic hair waste from salons as a sustainable soil stabilizer, despite the significant potential to address both infrastructure challenges and waste management goals.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter outlines the methodology used to explore the potential of synthetic hair fibres in stabilising expansive soils. It details the materials, experimental design, and the specific tests conducted, Statistical and cost-benefit analyses carried out to assess both the technical performance and practicality of the approach.

3.2 Research Design

This study adopted an experimental research design supported by analytical and statistical evaluation methods. The design was chosen because it allows systematic observation of how the inclusion of synthetic hair fibres affects the physical, mechanical, and swelling properties of expansive clay soils under controlled laboratory conditions. The experimental design made it possible to establish cause-and-effect relationships between fibre inclusion and improvements in soil behaviour.

The study followed a quantitative approach, combining laboratory testing, statistical analysis, and cost benefit evaluation. Quantitative data were obtained from standard geotechnical tests, including Atterberg limits, Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), Free Swell Index, and crack pattern analysis. Each test was conducted on both untreated (control) and synthetic hair fibre-treated soil samples to allow for direct comparison of results.

The research was structured into five main stages, each aligned with the specific objectives and research questions of the study:

i. Characterisation of the natural expansive soil: involved determining the soil's physical and index properties (grain size distribution, Atterberg limits, compaction characteristics, and swell potential) to establish a baseline for comparison.
ii. Characterisation of synthetic hair fibres: included assessing the fibre's physical and mechanical properties such as tensile strength, elongation, density, and chemical stability to determine their suitability for soil stabilisation.
iii. Preparation of soil fibre mixtures: the soil was mixed with synthetic hair fibres in varying proportions and lengths to evaluate their influence on soil behaviour. The fibre content was expressed as a percentage of the soil's dry weight, and all samples were prepared under consistent compaction and moisture conditions.
iv. Laboratory testing and analysis: involved performing UCS, CBR, and swell tests on both treated and untreated samples. Crack behaviour was further analysed using digital image processing (MATLAB) to quantify the reduction in crack width and length over time.
v. Data analysis and interpretation: quantitative results were statistically examined using independent samples t-tests to determine the significance of observed improvements at the 95% confidence level ($p < 0.05$). In addition, a Cost–Benefit Analysis (CBA) was carried out to assess the economic

viability of synthetic hair fibre stabilisation compared with traditional stabilisers such as lime and cement.

3.3 Source and Preparation of Soil

The expansive clay soil used in this study was carefully sourced from the shores of Lake Bisina, located in Eastern Uganda. This region is known for its distinctive expansive clay soils, which are highly susceptible to dramatic changes in volume due to moisture fluctuations. These soils are particularly notorious for their behavior during the rainy and dry seasons: they become very sticky and loose during wet periods, and during the dry season, they shrink significantly, often forming large, deep cracks. The choice of this particular location was based on valuable insights shared by the local community, who highlighted the area's consistent soil properties. The soils from this region have long been recognized for their expansive nature, making them a fitting choice for this study.

Soil sampling was conducted at two precise locations on the shores of Lake Bisina, marked by the GPS coordinates (1°37'11"N 33°52'34"E) and (1°37'10"N 33°52'32"E). These coordinates were chosen to ensure that the soil samples collected were representative of the typical conditions of the lake's shoreline. The sampling took place at a depth of 1 meter, which was carefully selected to avoid contamination from the topsoil or organic matter, ensuring the samples more accurately reflected the characteristics of the underlying clay. This depth is crucial for the study, as it allows for the analysis of the core soil properties that influence expansive behavior, without the interference of more superficial layers.

To gather the samples, clean, hand operated tools were used to carefully excavate the soil from the designated depths. The soil was then packed into sterile sampling bags to preserve its natural state and prevent contamination. Given the importance of maintaining the integrity of the soil's in-situ properties, particular attention was paid to transportation. The samples were loaded into a pickup truck, which was covered with a Taplin tarp to shield the soil from direct sunlight. This protective measure helped maintain the moisture content of the soil, preventing it from drying out before reaching the laboratory. Ensuring that the samples were not exposed to the elements during transport was essential in preserving their original properties for accurate laboratory analysis.

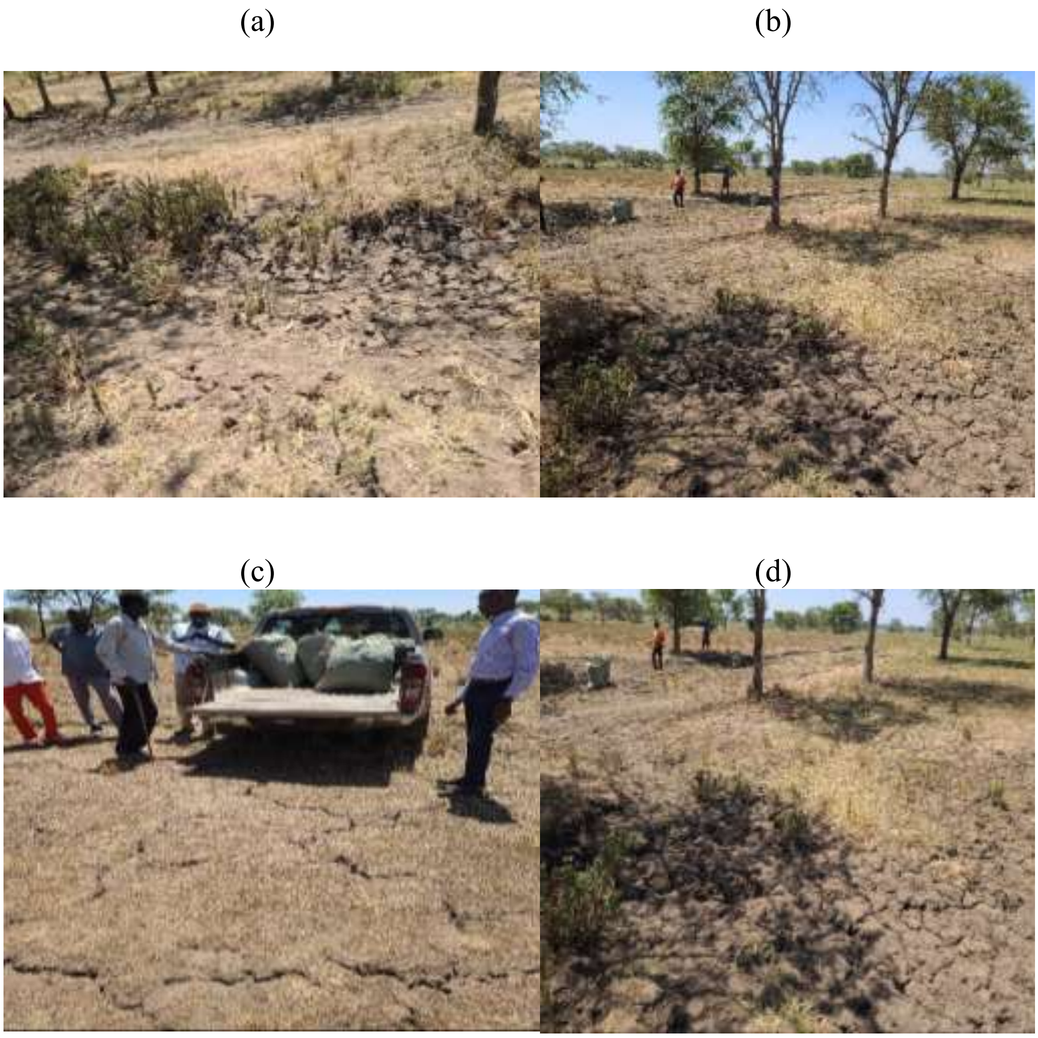


Figure 3.1: The cracks in the area during dry season (a) location 1(1°37'11"N 33°52'34"E), (b) location 2(1°37'10"N 33°52'32"E) on shores of lake Bisina , (c) loading material on transportation truck, (d) loading sample material on test bags

At the laboratory, the soil was air dried in trays under a shade in line with BS 1377 part 4 guidelines, to minimise moisture variability. Following drying, the samples were manually sieved using a 2 mm mesh to remove organic matter, pebbles, and debris, thereby ensuring a uniformly graded soil matrix suitable for laboratory testing as shown in Figure 3.2. This uniformity enhanced the interaction between fibres and soil particles, promoting better mechanical performance.

(a) (b)

Figure 3.2: Air drying and sieving clay samples at Teclab in nalukolongo

3.3.1 Source and Preparation of Synthetic Hair Fibres

The synthetic hair fibres used for this study were manually sourced from local salons within Kampala, Uganda. These salons, where waste hair is typically discarded without recycling, provided an ideal source of readily available material for the study. The specific brand of synthetic hair selected for this research was Pamoja Max Braids, as it was the most commonly used synthetic hair product in the salons. Preliminary studies conducted at Busitema University’s engineering laboratory confirmed that these fibres exhibited consistent manufacturing quality and suitable tensile properties, making them an appropriate choice for the stabilization experiments.

The preparation of the fibres involved a precise and controlled process. The hair was manually cut into eight predefined lengths of 2 - 16 cm in multiples of 2 using clean, sharp scissors. This step was critical in ensuring that the ends of the fibres were uniform, thus avoiding irregularities that could affect the results of the subsequent tests. These lengths were selected based on findings from previous studies, which indicated that fibre length has a significant impact on the reinforcement properties of (Yetimoglu and Salbas, 2003; Noorzad and Ta’negonbadi, 2021). The fibre aspect ratio, a function of both length and diameter, plays a crucial role in enhancing crack-bridging and interparticle reinforcement, which in turn improves soil stability.

To maintain consistent quality and avoid contamination, the prepared fibres were air-dried, manually detangled, and stored in clean, moisture-free containers until testing. This careful handling ensured that the fibres retained their intended properties for the duration of the study.

A fibre content of 0.5% was chosen for this research based on recommendations from earlier (Pradhan, Kar and Naik, 2012; Olgun, 2013), which identified this dosage as optimal for improving the strength and ductility of soil. This fibre content also prevents fibre clustering, which could otherwise interfere with the uniform distribution of fibres throughout the soil matrix, thereby compromising the reinforcement effect. By selecting the appropriate fibre length and dosage, this study aimed to achieve a controlled investigation into the impact of synthetic hair fibres on the soil’s mechanical properties, particularly in relation to its ability to resist cracking and improve structural integrity.

3.3.2 Mixing Methodology

Mixing of soil and synthetic hair fibres was performed manually in accordance with British Standard BS 1377: Part 4, which provides guidelines for preparing and conditioning the test specimens. The synthetic hair was added at a fixed amount of 0.5% by dry weight of soil and mixed thoroughly to ensure there was even distribution of synthetic hair and clumping of the mixture was avoided as shown in Figure 3.3.

(a) (b)

(c) (d)

Figure 3.3: (a) cut hair fibre, (b, and c) mixing synthetic hair with soil, (d) soil mixed with synthetic hair fibre

Soil mixed with synthetic hair fibre was identified during Proctor compaction tests. Mixing was carried out in a stepwise fashion where the clay soils and fibres were layered and turned repeatedly until homogeneity was achieved as shown in Figure 3.3. This method was chosen to maximise the soil and fibre interaction, it also prevented fibre segregation, and enhanced mechanical interlocking, which are all crucial for consistent performance in the reinforced fibre composites.

3.4 Soil Tests

To properly characterise the soil sample as expansive clay soil that is required for this study, a series of laboratory tests were conducted in accordance with the British Standard BS 1377 (1990): Methods of Test for Soils for Civil Engineering Purposes as illustrated in table 3.1. The primary objective of these tests was to determine the physical and index properties of the neat (untreated) soil, particularly to classify the soil based on its plasticity and grain size distribution.

Table 3. 1: Summary of Standard used

Test	Standard
Atterberg Limit Tests	BS 1377: Part 2: 1990
Particle Size Distribution Analysis	BS 1377: Part 2: 1990
Plasticity Characteristics and USCS Classification	BS 1377: Part 2 (1990).
Compaction Test	BS 1377 Part 4:1990
CBR Test	BS 1377: Part 4: 1990.

3.4.1 Atterberg Limit Tests

The Atterberg Limit tests comprising the LL, PL, and PI were performed in accordance with BS 1377: Part 2: 1990 to assess the consistency, plasticity, and engineering behavior of the fine-grained soil utilized in this study. These factors are critical for soil classification and prediction of volume change behavior.

a) Cone penetrometer Test

Using the Cone Penetrometer Method, which offers a more objective and repeatable option to the conventional Casagrande approach, the LL was found. For five seconds, a 30-degree, 80g stainless steel cone was permitted to penetrate a prepared soil paste. Depth of penetration was measured and this procedure was repeated at different moisture levels. Moisture content versus penetration depth was plotted; the LL was interpolated as the moisture level at which the cone reached 20 mm. Moisture contents were found by oven drying at 105 - 110°C.

b) Plastic limit

Plastic limit was obtained by manually rolling tiny volumes of wet soil on a glass plate into threads about 3 mm in diameter. Rolling proceeded until the threads started to collapse. Through oven drying, the crumbled soil's moisture content was measured. For at least three samples the test was performed, and the mean moisture content was noted as the Plastic Limit.

c) Index of plasticity

The PI was determined as the numerical difference between the PL and LL:

$$PI = LL - PL \qquad \text{Eq. (3.1)}$$

d) Linear Shrinkage Test

The linear shrinkage test was carried out to determine the effect of synthetic hair fibres on the shrinkage behaviour of expansive soil. The procedure followed the guidelines of BS 1377: Part 2 (1990), which describe the standard method for evaluating volumetric changes in cohesive soils upon drying. This test provided an index of the soil's potential for shrinkage cracking and volumetric instability, key indicators of expansive soil behaviour.

Synthetic hair fibres of varying lengths (2 - 16 cm in multiples of 2) were prepared and weighed to achieve a fibre content of 0.5% by weight of dry soil. Each batch of soil and fibres was thoroughly mixed in dry form to achieve homogeneity before the addition of water. Distilled water was then added gradually to bring the mixture to the liquid limit consistency, as per BS 1377: Part 2 (1990). The mixture was continuously kneaded until a uniform paste was obtained, ensuring even fibre dispersion throughout the sample.

3.4.2 Particle Size Distribution Analysis

A representative clay soil sample was subjected to sieve analysis to determine the distribution of course and fine-grained soil particles. The procedure followed BS 1377: Part 2: 1990 standards, the procedure involved sieving the dry soil sample through a stack of standard sieves ranging from 4.75 mm to 0.075 mm.

3.4.3 Calculation of Particle Size and Distribution

The particle diameter DD for each time interval was computed using a modified form of Stokes' Law as shown in equations; Eq. (3.2) and Eq. (3.3).

$$D = K\sqrt{\frac{L}{T}}, \qquad \text{Eq. (3.2)}$$

$$K = \sqrt{\frac{30\eta}{G_s - 1}}$$ Eq. (3.3)

Where, D = equivalent particle diameter (mm); L is effective depth (cm); T is elapsed time (minutes); η is dynamic viscosity of water (Pa.s) at the measured temperature; Gs is specific gravity of soil solids

The effective depth (L) corresponding to each hydrometer reading was determined from a calibrated chart provided with the hydrometer instrument.

The percentage of particles finer than a given size was calculated as shown in equation Eq. (3.4.

$$P_f = \left(\frac{R \cdot a}{W_S}\right) \times 100$$ Eq. (3.4)

Where: P_f, is the partial percentage finer; R, is the corrected hydrometer reading; a, is the specific gravity correction factor; W_s, is the weight of oven-dried soil (g).

To obtain the total percentage finer, the partial percentage values were multiplied by the decimal fines correction factor, that was obtained from preliminary sieve results.

3.4.4 Data Presentation and Interpretation

The results were compiled in both tabular and graphical forms. The grain-size distribution curve was plotted on a semi-logarithmic chart with particle diameter (mm) on the x-axis (log scale) and percentage finer on the y-axis (arithmetic scale). This graphical representation facilitated the classification of the soil sample into proportions of sand, silt, and clay, with negligible gravel content.

3.4.5 Hydrometer Analysis

After the sieve analysis, characterisation of fine-grained soils was done using hydrometer analysis which followed BS 1377 standards Part 2: Clause 9**.** To ensure that the fine-grained particles remained in suspension without flocculating, a dispersion agent comprising of sodium hexametaphosphate and sodium carbonate was added. The mixture was then allowed to stand for 16hrs to ensure full chemical action before stirring. The sample was then transferred to a 1000ml sedimentation cylinder and topped up with distilled water; it was stirred for one minute to allow it achieve homogeneity. The hydrometer readings were then taken at specific time intervals of 1,2,4,8,15,30,60,120,240, and 1440 minutes, the readings were accompanied by measurements of temperature to allow for the correction dependent viscosity (η).

3.4.6 Plasticity Characteristics and USCS Classification

To complete the classification of the soil sample, Atterberg limit tests were carried out using procedures in BS 1377: Part 2 (1990). The results were plotted on the plasticity charged and conclusions developed.

3.5 Experimental Program for Testing Synthetic Hair Fibres

This experimental program sought to thoroughly investigate the mechanical properties of synthetic hair fibres, with an emphasis on their physical dimensions and tensile behaviour. The application employed precise measurement techniques and computational approaches to ensure accurate and trustworthy results.

First, a careful evaluation of the synthetic hair fibre's physical dimensions was conducted. To calculate the linear density, each hair strand was weighed using an analytical balance, and the mass was recorded in milligrams (mg). A steel meter rule was used to measure each strand's length, and the results recorded in centimeters (cm). A Scanning Electron Microscope (SEM), more especially the TESCAN VEGA 3 SEM, was used to measure the diameter of the different types of synthetic hair fibres available in the market. Accurate measurement of diameter in micrometers (µm) is made possible by the high-resolution images this device produces.

The formula Density shown in equation Eq. (3.5):

$$\rho = \frac{\mathrm{M}}{\mathrm{V}} \qquad \text{Eq. (3.5)}$$

Where; M, is then mass; ρ, is density; V, is volume

was then used to determine the density of the synthetic hair fibre material. Assuming a cylindrical fiber shape, the volume will be calculated using the measured length and diameter as shown in equation Eq. (3.6) below:

$$v = \frac{\pi\, d^2}{4} h \qquad \text{Eq. (3.6)}$$

Second, the YG003E Single Fibre Strength Tester was used to assess the mechanical characteristics of the synthetic hair fibres. This device measured the breaking elongation as a percentage (%) and the breaking force in centinewtons (cN). Understanding the material's resistance to stretching and breaking depends on these properties. Computational techniques were then used to extract more basic properties of the synthetic hair fibres. The equation Eq. (3.7) used was used to determine the tensile strength, which is the highest stress the fibre can sustain before breaking:

$$\sigma = \frac{F}{A} \qquad \text{Eq. (3.7)}$$

Where: σ, is tensile strength; F, breaking force; A, cross sectional area

Where the fiber diameter is used to determine the cross-sectional area equation Eq. (3.8) was used**;**

$$A = \frac{\pi d^2}{2} \qquad \text{Eq. (3.8)}$$

The stress-strain curve produced by the tensile tester was used to calculate the elastic modulus, which represented the rigidity of the material. In particular, the slope of the first linear segment of the stress-strain curve was used to compute the elastic modulus (E) using equation Eq. (3.9).

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \qquad \text{Eq. (3.9)}$$

where $\Delta\sigma$ represents the change in stress and $\Delta\varepsilon$ represents the corresponding change in strain.

3.6 Tests on Stabilised Soil Samples

After characterisation and classification of the neat clay soils, a series of laboratory tests were conducted on soil samples stabilised with synthetic hair fibres to evaluate improvements in strength and deformation properties. These tests were designed to assess the performance of the stabilised soil to determine the influence of synthetic hair fibre length on the behaviour of expansive clay soils.

The process involved addition of synthetic hair fibres at a fixed amount of 0.5% was selected based on previous studies (Pradhan et al., 2012), with varying lengths of synthetic hair fibres ranging from 2 - 16cm at multiples of 2. These synthetic hair fibre lengths were chosen in accordance with research findings indicating that performance is strongly dependent on fibre aspect ratio, with lengths within this range shown to optimise interfacial bonding and crack-bridging capacity (Yetimoglu and Salbas, 2003; Noorzad and Ta'negonbadi, 2021). Each sample that was stabilised was subjected to the same testing regime as the untreated soil, which helped to ensure comparability and consistency. All the tests were carried out in accordance with BS 1377: 1990, ensuring adherence to the standardised procedures for specimen preparation and testing. The details of the tests conducted are detailed in the subsequent subsections presented below.

3.6.1 Compaction Test

The compaction test was conducted in accordance with BS 1377 Part 4:1990 to determine the MDD and OMC of both untreated and fibre-reinforced expansive clay soils. The test utilized a 4.5 kg rammer and a standard cylindrical mould with a diameter of 105 mm, a height of 115.5 mm, and a total volume of approximately 999.6 cm^3. The expansive clay soil samples were first air-dried and then sieved through a 20 mm sieve.

For modified samples, 0.5% synthetic hair fibres of varying lengths (2 cm, 4 cm, 6 cm, 8 cm, 10 cm,12cm,14cm, and 16cm) were manually added and mixed in the soil before compaction. This step ensured that the fibres were evenly distributed throughout the soil matrix, preventing fibre clustering, which could otherwise lead to inconsistencies in compaction and density measurements.

The prepared soil was placed into the mould and compacted in five uniform layers, with each layer receiving 56 blows from the 4.5 kg rammer, dropped from a 450 mm height. The final layer was carefully trimmed after compaction using a straight edge to achieve a level surface consistent with the mould's rim. After which the mass of the mould with compacted soil was recorded, and the weight of the compacted specimen was determined by subtracting the mass of the empty mould.

A representative soil sample was oven-dried at temperature at 105°C ± 5°C for 24 hours. This process followed BS 1377 Part 4:1990 standard guidelines for computing the dry density.

The bulk density was calculated using the equation 3.8

$$\rho = \frac{m_2 - m_1}{v} \quad \text{Eq. (3.10)}$$

where m_1 is the mass of the empty mould, m_2 is the mass of the mould with compacted soil, and V is the volume of the mould.

The dry density was then derived using the formula 3.9.

$$\rho_d = \frac{\rho}{1 + 0.01\mathrm{w}} \qquad \text{Eq. (3.11)}$$

Where, w is the moisture content in percentage, ρ_d is the dry density, ρ *is density*

A compaction curve (dry density vs. moisture content) was plotted to analyse the relationships between moisture content and dry density, allowing for the determination of the OMC at which the soil achieves MDD. The test was performed for both untreated and fibre reinforced soil samples to evaluate the impact of synthetic hair fibres on the compaction properties.

To ensure the accuracy, repeatability, and reliability of the results, each compaction test was conducted in three trials, and the average values were used in the final analysis. Additionally, the laboratory equipment was calibrated before use to minimise errors

3.6.2 UCS Test

This section investigates the UCS of expansive clay soils stabilised with synthetic hair fibres; the tests followed the BS 1377-4:1990 standard: Standard Method of Test for Unconfined Compressive Strength of Cohesive Soil. The tests evaluate the effectiveness of synthetic hair fibres in improving the mechanical strength and overall stability of expansive soils. The experimental methodology is composed of detailed steps including soil preparation, fibre blending, compaction using standardized equipment, curing, unconfined compression testing, and comprehensive analysis of the resulting data to assess the reinforcing effects of fibre length.

The fibres were mixed manually with the sieved air-dried clay soil samples at a constant amount of 0.5% by dry weight of soil, ensuring even distribution throughout the soil mass. Distilled water was then added gradually to the mixture until the OMC was achieved, as determined from preliminary compaction testing in accordance with BS 1377 Standard Proctor Method for Moisture-Density Relationship of Soils. The compacted soil specimens were formed using standard cylindrical moulds, with compaction carried out in five uniform layers. Each layer received 56 blows from a 4.5 kg rammer with a drop height of 450 mm, replicating the effort described under the BS 1377-4:1990 procedure for standard compaction.

The top surface of each specimen was carefully trimmed to ensure a flush, even finish. The specimens were extracted from the moulds and subjected to two distinct curing durations: 14 days and 21 days, to evaluate the effect of curing time on UCS performance. During curing, the specimens were stored in airtight plastic containers to maintain moisture content and prevent desiccation. The containers were placed in a controlled environment with stable temperature and relative humidity levels, monitored periodically using a digital hygrometer and thermometer to ensure consistent curing conditions.

After curing, the specimens were prepared for UCS testing in accordance with BS 1377: part 4. Each specimen was placed vertically between the platens of the Unconfined Compression Testing Machine. A constant axial strain rate of 1 % per minute was applied until the specimen failed. The maximum axial load at failure (P) was recorded directly from the machine's load frame, and observations were made regarding the failure pattern and mode of specimen deformation. The Unconfined Compressive Strength (q_u) was calculated using the equation 3.10.

$$q_u = \frac{P}{A} \qquad \text{Eq. (3.12)}$$

Where, q_u= unconfined compressive strength (MPa), P = maximum axial load at failure (N), A = corrected cross-sectional area at the time of failure (mm^2).

Following UCS testing, a representative portion of the failed specimen was collected immediately for determination of moisture content, in accordance with BS 1377-4:1990 Standard Method of Test for Laboratory Determination of Water (Moisture) Content of Soil. The moist sample was placed in a pre-weighed moisture container, and the combined mass was recorded. The container was then placed in an oven maintained at 105 °C to 110 °C and dried for a minimum of 24 hours. The dry mass was recorded, and the moisture content (W) was calculated using the formula Eq. (3.13):

$$W = \left(\frac{M_w}{M_s}\right) \times 100\% \qquad \text{Eq. (3.13)}$$

Where; M_w is mass of water, M_s mass of dry soil, and W is the water content

To assess the performance of synthetic hair fibre reinforcement, the UCS results were compiled, and values were plotted against the different fibre lengths for both 14- and 21-day curing periods. This helped identify strength trends and the influence of fibre length over time. Additionally, MDD and OMC were determined from the compaction curves generated during preliminary testing, following BS 1377-4:1990.

Finally, to quantify the stabilizing effectiveness of the synthetic fibres, UCS values of treated soil specimens were compared against those of untreated (control) specimens. A statistical evaluation was performed on the UCS data to establish the significance of any observed differences. Through this approach, the experiment provided a reliable, standardized assessment of the structural benefits offered by synthetic fibre reinforcement under BS 1377: Part 4 testing procedures.

3.6.3 CBR Test

The CBR test was conducted to evaluate the strength and load-bearing capacity of expansive clay soils in both their natural state and after stabilization with synthetic hair fibres. The test followed guidelines outlined in BS 1377: Part 4: 1990. The study included two categories of samples: untreated expansive clay which became the control experiment and clay soil reinforced with synthetic hair fibres at a constant dosage of 0.5% by the dry weight of soil. To assess the influence of fibre length, eight different lengths of synthetic hair fibres were tested including; 2 cm, 4 cm, 6 cm, 8 cm, 10 cm, 12 cm, 14 cm, and 16 cm.

A study standard CBR moulds with an internal diameter of 152 mm and a height of 178 mm were used. The soil samples were compacted in three equal layers. Each layer receiving 56 blows from a 4.5 kg rammer dropped from a height of 450 mm to ensure uniform compaction. compaction was performed manually, with a perforated base plate and a filter paper placed at the bottom of each mould to allow for uniform moisture penetration during soaking. CBR compaction is shown in Figure 3.4.

(a) (b)

Figure 3.4: Casting CBR Moulds

After compaction, surcharge weights of 2.5 kg were placed on top of the soil samples to simulate the pressure exerted by pavement layers. The specimens then underwent a 96-hour soaking period to assess the swelling characteristics of the expansive clay. The moulds were placed in a soaking tank, with the water level maintained just above the soil surface. Before soaking, a dial gauge was installed. The dial gauge stand was set up to ensure that the plunger rested precisely on the top of the surcharge plate as shown in Figure 3.5. The gauge was carefully aligned vertically to prevent angular any distortions occurring, and a zero reading was recorded immediately after setup to establish the specimen's initial height.

The dial gauge remained in position during the entire soaking period. Upon completion of soaking, a final dial gauge reading was taken. The difference between the initial and final readings indicated the vertical expansion caused by water absorption. The percentage swell was calculated using the formula.

$$S\,(\%) \quad = \frac{\Delta H}{Ho} \times 100 \qquad \text{Eq. (3.14)}$$

Where; S (%) is the percentage swell, **Δ**H change in swell height, Ho is initial height

(a) (b)

Figure 3.5: Soaked CBR mould loaded with dial gauges

Following the swell test, the penetration phase of the CBR test was conducted. The soaked specimen was placed in the CBR testing machine, and a mechanical loading machine with a 50 mm diameter plunger applied vertical load at a standard penetration rate of 1 mm per minute. The load was applied centrally, and the resistance of the soil to penetration was continuously recorded. Attention was focused on the load values at 2.5 mm and 5.0 mm penetrations, which were used to calculate the CBR values using the formula equation Eq. (3.15:

$$CBR = \left(\frac{P_m}{P_0}\right) \times 100 \qquad \text{Eq. (3.15)}$$

Where Pm is the measured load in kN and Po is the standard loads of 13.2 kN for 2.5 mm.

Where Each test was repeated three times for all fibre lengths and for the untreated soil to ensure the reliability of results. Only specimens that were compacted uniformly and free from structural defects were considered. The average values from the three trials were taken as the final results. From the penetration data, CBR load-penetration curves were generated, plotting applied load (in kN) against penetration depth (in mm). These curves helped visualize the soil's stiffness and deformation characteristics under load and allowed for a comparative analysis between fibre-reinforced and control specimens.

To ensure consistency, the dry density of each specimen was calculated and compared with the MDD obtained from compaction tests. This confirmed that all samples met the desired compaction standards, removing compaction variability as a factor in the analysis. Comparative evaluation was based on both the CBR values and the swell percentages. The presence of synthetic fibres was expected to increase resistance to penetration and reduce swelling due to the bridging and interlocking effects between soil particles and fibres.

The tests were conducted in accordance with BS 1377 guidelines. All instruments were calibrated, and readings were cross-checked by qualified laboratory technicians to ensure the accuracy and validity of the results. The outcomes were organized into tabular and graphical formats for effective presentation and analysis of the fibre reinforcement impact.

3.7 Crack Monitoring Using Digital Image Processing with MATLAB

This chapter presents the methodology developed to detect, measure, and analyse cracks in digital images of specimen surfaces. A custom MATLAB-based graphical user interface (GUI) titled "Crack Detection and RGB Analysis Tool" was implemented to standardised data acquisition, calibration, crack segmentation, colour analysis, and reporting. The following sections describe each procedure in detail, highlighting how they collectively ensured precision, repeatability, and traceability of the results.

3.7.1 Image Acquisition and Calibration Proceedure

Accurate measurement of crack geometry and surface characteristics begins with a systematic image acquisition process. In this study, images were processed using the custom MATLAB GUI, which supports common image formats (JPEG, PNG, BMP). The user loads images into the system through the "Load Image" function, and the selected image is displayed in the "Original Image" panel for immediate visual verification. The software stores filenames and file paths to maintain traceability of each analysis. To reduce potential errors, images are captured under uniform, diffuse lighting to minimise shadows and reflections. The camera was positioned perpendicular to the specimen surface to avoid perspective distortion; a camera is held steadily to ensure stable and high-resolution images are captured. This consistent acquisition protocol is crucial for reliable crack detection and dimensional measurement.

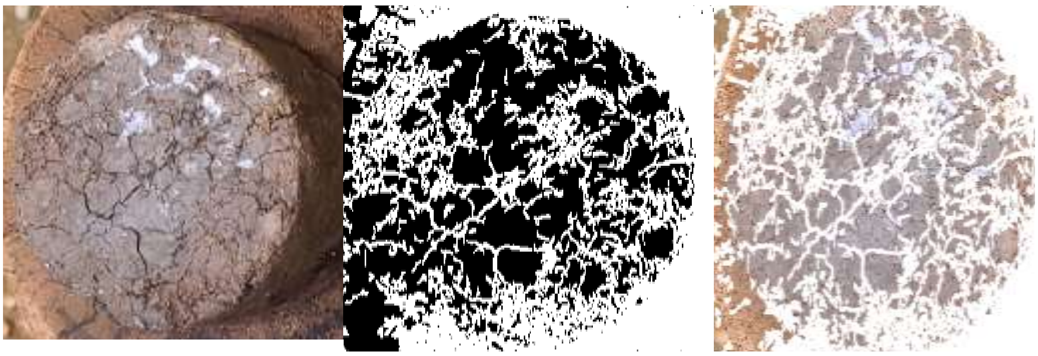
Calibration is performed through the GUI's "Calibrate Scale" function to translate pixel measurements into real-world units. The user selects two points on the image corresponding to a known physical distance on the image. The software computes the pixel distance between these points and prompted the user to enter the real-world distance in millimeters. The calibration constant (millimeters per pixel) is then calculated as the ratio of real-world distance to pixel distance. This factor is stored globally in the application and applied to all subsequent measurements. A summary of the calibration process, including pixel distance, real-world distance, and scale, is displayed in the results panel to allow for the user to confirm correctness. By combining controlled image acquisition and systematic calibration, this procedure ensures that all crack measurements including length, width, and area are accurately expressed in physical units, which improves comparability and reliability of the analysis.

3.7.2 Crack Detection and RGB Analysis Procedure

After calibration, crack detection and RGB analysis are carried out in the same MATLAB GUI to maintain workflow consistency as illustrated in Figure 3.6 below. The original image is decomposed into red, green, and blue (RGB) channels, and mean intensity values for each channel are computed to characterise surface colour.

The image is then converted to greyscale to simplify crack detection. Pre-processing included median filtering (`medfilt2`) to reduce noise and contrast adjustment (‘imadjust’) to highlight crack features. Adaptive thresholding (‘imbinarize’) is applied to generate a binary image where cracks appear as foreground pixels.

Morphological operations refine the crack mask by removing small artefacts (‘bwareaopen’) and connecting fragmented cracks through dilation (‘imdilate’) with a linear structuring element. Quantitative analysis uses ‘regionprops’ to extract geometric metrics such as total crack area, average crack width, and total crack length, initially in pixel units. Applying the calibration constant converts these metrics into millimeters and square millimeters. Processed results are displayed in the GUI alongside binary and overlay images, ensuring transparency and allowing users to visually verify the segmentation outcome. This structured, semi-automated approach balances computational efficiency with accuracy, producing reproducible and traceable crack measurements.



(a) Original Image (b) Detected Cracks (C) Overlay Image

Figure 3.6: crack detection using MATLAB R2025a

3.7.3 Annotation and Reporting Procedure

To document results and enhance interpretation, the system includes automated annotation and reporting functions. Detected cracks are labelled on the original image using bounding boxes and sequential numbers with ‘insert Object Annotation’, creating an annotated JPEG image that visually summarises the segmentation. Through the “Annotate + Generate PDF” function, the software generated a detailed PDF report using MATLAB’s Report Generator toolbox. This report included a title page, the annotated image, and a formal table summarising key metrics: mean RGB values, crack area, total and average crack lengths, average width, and calibration scale. An “Export to Excel” feature enables structured data export for further analysis. The users can save key metrics in ‘xlsx’ format, facilitating integration with statistical tools. By combining automated annotation, PDF reporting, and Excel export, the method provides clear documentation suitable for technical appendices, audits, or collaborative review.

3.7.4 Data Management and Storage Procedure

The system enforces a structured data management, which ensures repeatability and traceability. Each analysis session records metadata, including filenames and calibration data, stored in the GUI’s application data structure. Outputs included annotated images, PDF reports, and Excel spreadsheets, all saved with filenames linking to the original image. Users are advised to store these files in secure, backed-up directories following best practices in digital data management. This systematic approach ensures raw data, processed results, and reports remain linked, improving organisation, supporting future verification, and enabling re-analysis if any need be.

3.7.5 Validation and Quality Assurance Procedure

Quality assurance combines automated validation and user oversight. At each step, a user can visually confirm the correct images loading. The user can also confirm calibration by reviewing real time summaries in the results panel. If calibration results are inconsistent, a user can re-calibrate immediately. The crack detection output (binary mask and overlay) is visually inspected to confirm accurate segmentation. Implausible metrics trigger re-analysis or adjustment of parameters. Repeat analyses on selected specimens confirmed the method's consistency. Automated documentation through PDF and Excel exports preserved each analysis run for independent verification. Together, these steps ensured the method's accuracy, robustness, and reproducibility across the study.

3.8 Analytical Methods

Two complementary analytical approaches were adopted to assess both the technical and economic aspects of using synthetic hair fibres for stabilising expansive soils. These included a statistical analysis of laboratory results and a cost benefit analysis (CBA) to evaluate the economic feasibility of implementation.

3.8.1 Statistical Analysis

The statistical analysis aimed to establish whether the inclusion of synthetic hair fibres led to a statistically significant improvement in the cracking behaviour of expansive soils. Soil specimens were categorised into treated (stabilised with hair fibres) and control (untreated) groups. Crack length measurements were recorded at six-hour intervals over a 72-hour period under controlled drying conditions, producing 12 observations per group.

The hypotheses tested were:

_0:$\mu_1=\mu_2$ " (no significant difference in mean crack length between treated and control samples)"

$HH_a: \mu_1 \neq \mu_2$(a significant difference exists in mean crack length)

An independent samples t-test assuming equal variances was conducted using Stata version 14.0 to compare the group means. Descriptive statistics mean, standard deviation, and standard error were first computed to determine central tendency and variability. The t-test statistic was calculated using:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \qquad \text{Eq. 3.16}$$

where $\bar{X}_1$and $\bar{X}_2$represent the means of the control and treated samples, S_p is the pooled standard deviation, and $n_1$and $n_2$are their respective sample sizes. A significance level of $\alpha = 0.05$ was adopted. The detailed statistical results and data sets are presented in Chapter Four and Appendices One and Two.

3.8.2 Cost Benefit Analysis

To complement the experimental results, a cost benefit analysis (CBA) framework was developed to assess the financial viability of stabilising expansive soils using synthetic hair fibres relative to conventional cement stabilisation. The analysis was conducted on a unit weight basis of one tonne of soil, assuming a 0.5% fibre inclusion rate and a 6% cement dosage.

The CBA followed a systematic process comprising the following steps:

i. Identification of cost components; Costs considered under the hair-fibre stabilisation option included collection stipends, purchase and depreciation of collection bins, transportation from collection points to the processing or construction site, cleaning and sorting of fibres, labour for mixing and compaction, and quality control or testing. For the cement stabilisation option, the costs included material purchase, transport, mixing labour, and testing.
ii. Market data collection; Cost estimates were obtained from prevailing Ugandan market prices and standard rates applicable at the time of the study. These included local material prices, fuel and transport rates, and average labour costs.
iii. Conversion to uniform units: All costs were standardised to a per-tonne basis to facilitate direct comparison between stabilisation methods.
iv. Benefit identification; The primary benefits considered included reduced maintenance requirements, extended service life of stabilised soils, and potential environmental and social gains such as waste reduction and employment generation.
v. Economic evaluation; The analysis applied a 10-year planning horizon and a 10% discount rate to estimate the present value of future benefits. The present

value (PV) of benefits was computed using the annuity factor approach expressed as;

$$PV = A \times \frac{1-(1+r)^{-T}}{r} \qquad \text{Eq. 3.17}$$

where A is the annual maintenance saving, r the discount rate, and T the analysis period.

vi. Decision metrics; Economic viability was assessed using the Net Present Value (NPV) and Benefit–Cost Ratio (BCR), expressed as;

$$NPV = PV(B) - PV(C) \qquad \text{Eq. 3.18}$$

$$BCR = \frac{PV(B)}{PV(C)} \qquad \text{Eq. 3.19}$$

A BCR greater than 1.0 indicates that benefits outweigh costs, signifying economic justification for the stabilisation method. The cost data, assumptions, and all intermediate computations are presented in Appendix D, while the calculated results and interpretations are discussed in Chapter Four.

3.9 Scanning Electron Microscopy (SEM) Analysis

3.9.1 Introduction and Objective

SEM was conducted with the main aim of investigating the microstructural characteristics of expansive clay soils stabilized with synthetic hair fibres. three categories of samples were analysed for this research including; Control, 6CM

,8CM synthetic hair fibre length. The objective of this SEM analysis was to examine the structural changes induced by addition of synthetic hair fibres in a microscale, particularly in terms of surface texture, pore structure, particle arrangement, and the nature of interaction between synthetic hair fibre and the expansive clay soil samples. The observations from the SEM analysis were intended to offer a mechanistic understanding of the macro level performance improvements recorded in earlier geotechnical tests such as UCS, CBR, and shrinkage crack reduction. SEM imaging served as a complementary tool that correlates the structural behavior with microstructural transformations that occur from synthetic hair fibre reinforcement.

3.9.2 Sample Preparation

The samples used in the SEM tests were got from cylindrical soil specimens that had been compacted during the Standard Proctor method. Thin sections, approximately 8 to 12 mm in thickness, were carefully sliced from the center of each specimen using a precision blade to minimize mechanical disruption and edge breaks. These sections were after then mounted on standard aluminum SEM stubs using double sided carbon adhesive tapes to ensure their stability and electrical conductivity. To improve imaging clarity and prevent charging under the electron beam, all the mounted samples were coated with a thin conductive layer of gold-palladium alloy, whose thickness was approximately 15 - 20 nanometers, using a Quorum Q150R ES sputter coater. The coated samples were then stored in a vacuum sealed desiccator to prevent absorption of moisture prior to imaging.

3.9.3 Instrumentation and Imaging Conditions

Imaging was performed using a JEOL JSM-6390LV Scanning Electron Microscope. This model was equipped with a secondary electron detector (SED), that was ideal for capturing surface topographical details of the soil samples. The microscope was operated under high vacuum conditions with an accelerating voltage of 15 kilovolts at a working distance of between 10 and 15 millimeters. The Images was captured at varying magnifications, ranging from 500x to 2500x, this provided detailed views of the soil matrix and dispersion of fibres in the soil samples. The parameters were then optimised to achieve a balance between resolution, depth of field, and beam penetration, which ensures accurate interpretation of microstructural features without damaging the samples.

3.9.4 Image Interpretation and Evaluation

The SEM images were used to extract insights into the microstructural evolution associated with reinforcement of synthetic hair fibres. The major features examined included surface morphology, particle arrangement, pore and void structure, and the interaction interface between synthetic hair fibres and surrounding soil particles. the Surface texture indicated the compaction and cohesion in the soil matrix, while fibre distribution patterns helped determine the uniformity and effectiveness of reinforcement. The embedment and bonding of synthetic hair fibres to the soil matrix was useful for evaluating the interfacial adhesion, which contributes significantly to the transfer of stress within the composite material. Observations were made across multiple fields of view per sample to ensure representativeness, with special attention given to signs of clustering, fibre pull-out, and microcrack formation or suppression.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Determining the Properties of Expansive Soils

4.1.1 Particle Size Distribution

The particle size distribution (PSD) results, presented in appendix B, show that the expansive soil is predominantly fine-grained, with 80.6% of the particles being silt and clay, classifying it as a clayey soil. The remaining 19.4% consists of coarser particles, primarily sand. This high percentage of fines contributes significantly to the soil's expansive nature, as the fine clay particles have the ability to absorb and retain large amounts of water. This moisture retention leads to significant swelling when the soil is wet and shrinkage during dry periods, resulting in volume changes that can cause cracking and differential settlement.

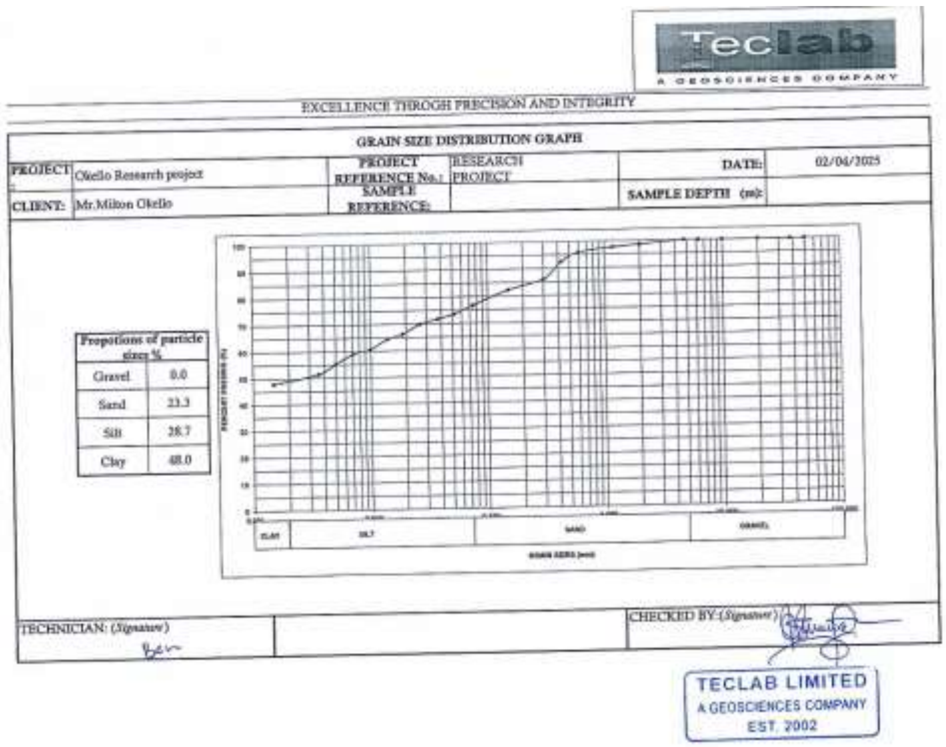


Figure 4.1: Particle sized distribution curve

Based on the classification, the soil is categorised as clayey with a high plasticity index, which aligns with the characteristics of expansive soils. The high plasticity indicates that the soil is prone to significant volume changes due to its high clay content. The fine-grained composition makes the soil particularly sensitive to moisture fluctuations, affecting its expansive behaviour.

4.1.2 Atterberg Limits

The Atterberg limit tests were conducted to determine the consistency and plasticity characteristics of the natural soil, as these indices provide a reliable indication of its expansive potential. The LL, PL, and PI are widely used benchmarks for evaluating the engineering behaviour of clay soils, particularly their susceptibility to shrink - swell behaviour. These parameters play an important role when classifying the soil according to standard identification systems and assessing its suitability for construction applications.

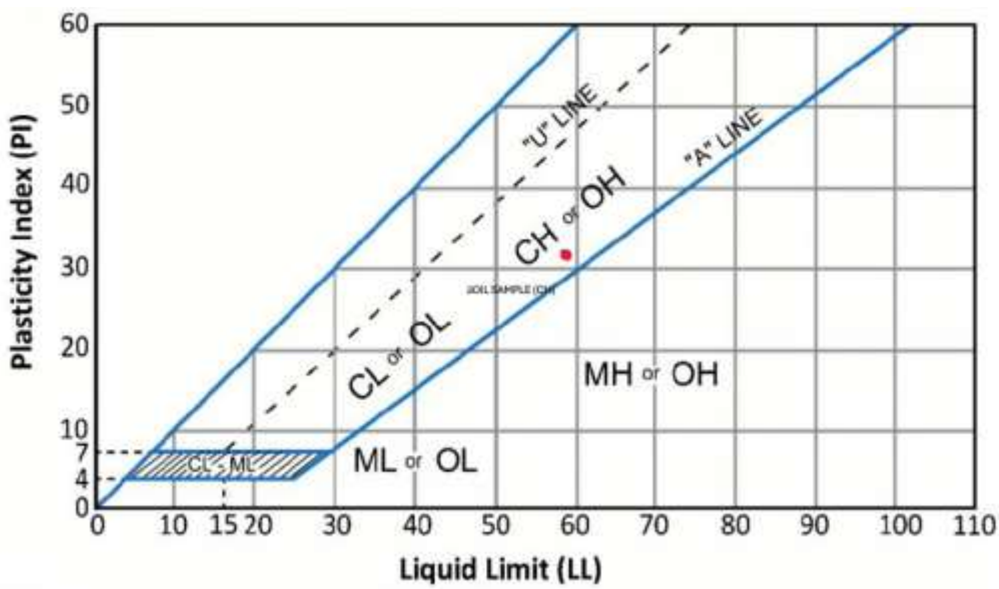


Figure 4.2: Soil classification graph

The results from the laboratory tests are illustrated in Figure 4.2, with detailed computations included in Appendix B. The neat soil exhibited a LL of 58%, a PL of 26%, and a resulting PI of 32%. According to the USCS, a soil with a PI greater than 17% and a high Liquid Limit is classified as CH (Clay of High Plasticity). This categorisation is consistent with the values obtained in this study and indicates a soil type that naturally exhibits high plasticity and notable shrink - swell behaviour. The PI value of 32% also aligns with findings reported by Jalal et al (2020), who stated that soils with PI values between 25% and 32% fall within the range associated with high expansivity. Similarly, based on the AASHTO classification system, the soil falls under the A-7-6 category, which typically comprises clay soils with high plasticity and poor performance as pavement subgrade materials unless properly treated. These classification outcomes confirm that the soil possesses significant expansive characteristics and would be unsuitable for supporting pavement structures in its natural state.

Based on the above properties, the soils used can be categorised as being expansive soil and the properties are used in the next section for analysis.

4.2 Physical and Mechanical Characteristics of Synthetic Hair Fibres

4.2.1 Average Diameter of the Synthetic Hair Fibres

The assessment of the average diameter of synthetic hair fibres obtained from various commercial brands showed a high degree of uniformity across the samples analysed. A summary of the measured diameters is presented in Figure 4.3 illustrating the close similarity among the brands evaluated.

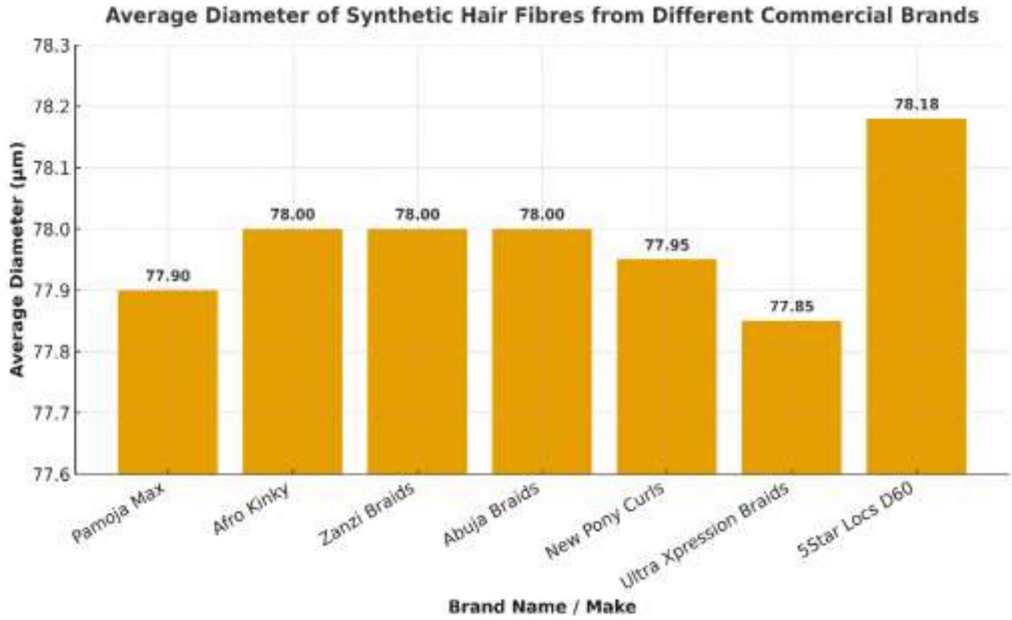


Figure 4.3: Average diameter of synthetic hair fibres from different commercial brands sampled from the salons.

Most fibres exhibited diameters in the range of approximately 77.8 to 78.2 µm, indicating that the different brands share largely comparable physical characteristics. This consistency is likely attributable to the use of similar manufacturing techniques and polymer materials across these products. Among the tested brands, 5Star Locs D60 recorded the largest average diameter at approximately 78.18 µm, making it marginally thicker than the others. Although the variation is small, a slightly larger diameter may contribute to increased tensile capacity and durability, potentially enhancing the fibre's performance in soil reinforcement applications. Conversely, Pamoja Max and Ultra Xpression Braids exhibited slightly smaller average diameters of about 77.8 µm. While these differences are subtle, fibres with smaller diameters may offer greater flexibility and improved dispersion within the soil matrix, supporting more uniform particle interlocking and better bonding with the clay fraction.

Despite the narrow range of variation, these differences in diameter can still influence fibre soil interaction mechanisms such as frictional resistance, anchorage, and crack bridging efficiency. The findings underscore the importance of considering fibre geometry particularly diameter, length, and uniformity when selecting synthetic hair fibres for expansive soil stabilisation.

4.2.2 Mechanical Properties

A detailed assessment of the mechanical properties of the synthetic hair fibres was carried out to determine their effectiveness as reinforcement materials in expansive soil stabilisation. Mechanical characteristics such as tensile strength, stiffness, density, and aspect ratio are critical indicators of a fibre's ability to enhance soil performance, particularly in improving tensile resistance, reducing shrinkage strain, and mitigating crack development. The following results outline the key mechanical attributes measured. The synthetic hair fibres tested in this study exhibited an average diameter of 78 µm, resulting in a favourable aspect ratio that promotes strong mechanical interlocking within the clay matrix. The measured fibre density of 1.3 g/cm^3 falls within the range expected for polymer-based materials and is comparable to synthetic fibres commonly used in soil reinforcement, such as polypropylene, whose densities typically range between 0.90 and 0.95 g/cm^3 (Zaimoglu and Yetimoglu, 2012). Although slightly denser, the fibres remained sufficiently lightweight to allow uniform distribution during mixing, an important factor in achieving consistent reinforcement throughout the soil mass.

Table 4.1: Physical properties of synthetic hair fibres

Property	**Value**
Average Diameter	78 µm
Density	1.3 g/cm^3
Tensile Strength	110.07 MPa
Elastic Modulus	2.6 - 4.1 GPa

The tensile strength of the synthetic hair fibres was recorded at 110.07 MPa (110.07 N/mm^2). While this value is lower than the tensile strength typically reported for commercial polypropylene fibres generally in the range of 320 - 400 N/mm^2 (Pradhan et al., 2012; Zaimoglu and Yetimoglu, 2012). It remains adequate for contributing to crack bridging and resisting tensile strains induced during soil shrinkage. Similarly, the measured elastic modulus of 0.413 GPa (413.18 N/mm^2) is substantially lower than that of polypropylene fibres, which commonly exhibit moduli around 4,000 N/mm^2. Despite this difference, the stiffness of the synthetic hair fibres is enough to restrain crack propagation while still accommodating the volumetric changes characteristic of expansive clays.

The mechanical test results demonstrate that synthetic hair fibres, although non-traditional and derived from waste materials, possess properties that make them suitable for use as reinforcement in expansive soils. Their moderate tensile strength, workable stiffness, appropriate density, and high aspect ratio collectively enhance their ability to interact effectively with the soil matrix. These characteristics support improved tensile resistance, reduction in shrinkage deformation, and better control of cracking. A summary of the physical and mechanical tests conducted on synthetic hair fibres are summarised in Table 4.1 and details attached in appendix B.

4.3 Determining Effects of Synthetic Hair Fibres on the Properties of Expansive Soils

4.3.1 Compaction Characteristics

The effect of synthetic hair fibers on soil compaction characteristics is clearly demonstrated in the dry density curves shown in Figure 4.4. As the length of the synthetic fibers increases, there is a noticeable reduction in the maximum dry density (MDD), with fibers longer than 8 cm causing a more significant decline.

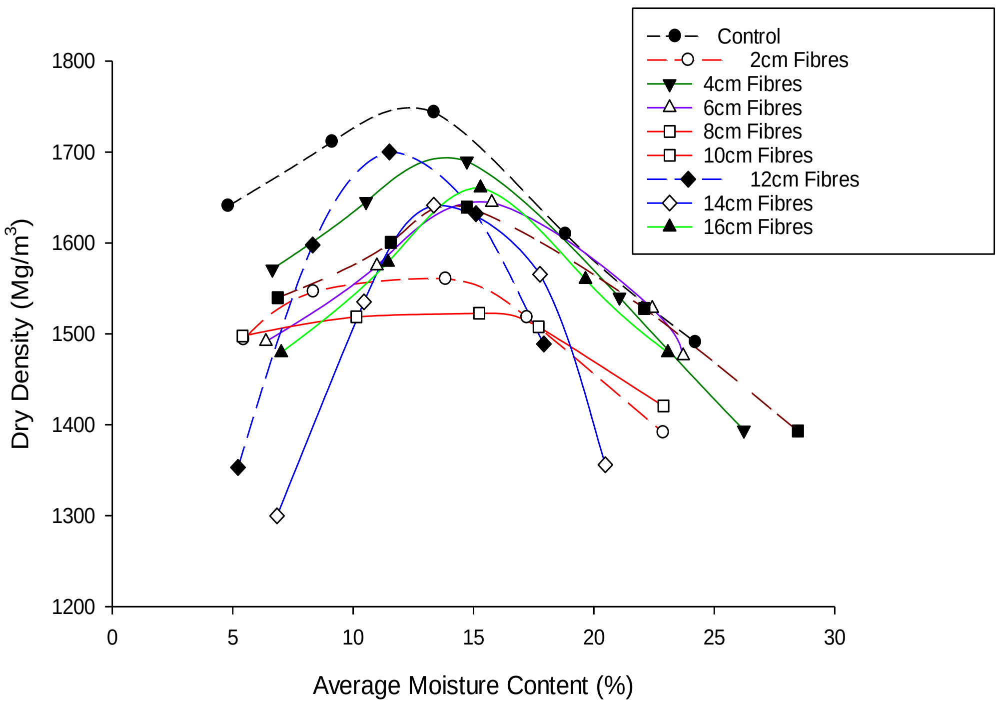


Figure 4.4: Compaction characteristics of synthetic hair fibre reinforced soil

This trend aligns with findings by Lawer et al.(2021), who observed that adding natural coconut and palm fibres (30 - 90 mm) reduced the MDD, while increasing OMC. Both studies relate the reduction in MDD to the lightweight nature of the fibres and their tendency to trap voids, which hinders efficient packing of particles during compaction.

4.3.2 California Bearing Ratio

The impact of synthetic hair fibers on the CBR of expansive clay soil is illustrated in Figure 4.5 revealing a clear relationship between fiber length and soil strength. Initially, as the fiber length increases, the CBR of the stabilized soil improves significantly, reaching an optimum before gradually declining with further increases in fiber length. The control sample shows a CBR of about 1% at 95% compaction of MDD, while reinforcement with synthetic hair fibres ranging 8 - 10 cm length raises the CBR to a peak of 4.1% at 95 compactions of MDD, representing an improvement of about 300%. Meanwhile for longer fibres of lengths greater than (>)10 cm, the CBR decreases slightly to 3.0 at 16cm.

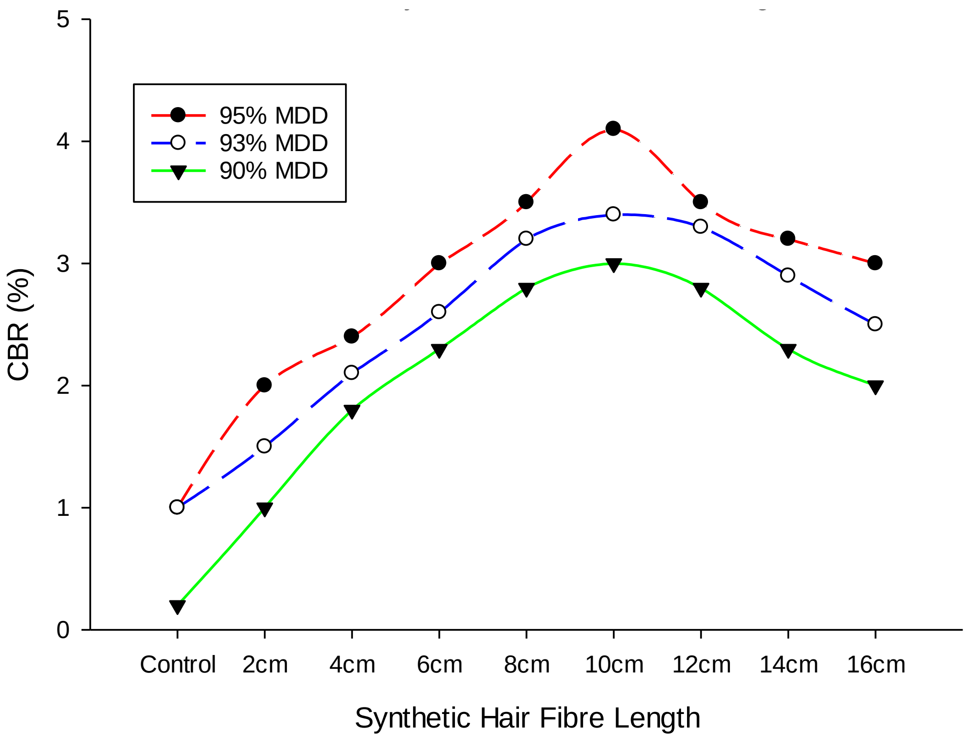


Figure 4.5: Impact of synthetic hair fibre length on CBR

The initial increase is as a result of effective tensile interlocking and bridging provided by the well distributed synthetic hair fibres, which improve load transfer and resistance to penetration. The drop at longer fibre lengths is linked to the entanglement and uneven distribution of the synthetic hair fibres, which introduce voids and reduce compaction quality. The observed results are consistent with findings from Zaimoğlu and Yetimoglu (2012), who found Polypropylene Fibers increased the CBR by 80% for fibre-reinforced fine-grained soils.

4.3.3 Swell Potential Test

The influence of synthetic hair fibers on the swell potential of expansive clay soil is depicted in Figure 4.6 highlighting a clear relationship between fiber length and soil volumetric stability. The unreinforced soil exhibits a swell percentage of

2.4%, indicating its high susceptibility to volume changes. Upon addition of synthetic hair fibers with lengths between 8 and 10 cm, the swell potential significantly decreases to a minimum of 0.7%, representing a reduction of over 70%. However, when fiber lengths exceed 10 cm, the swell percentage rises slightly to about 1.1%.

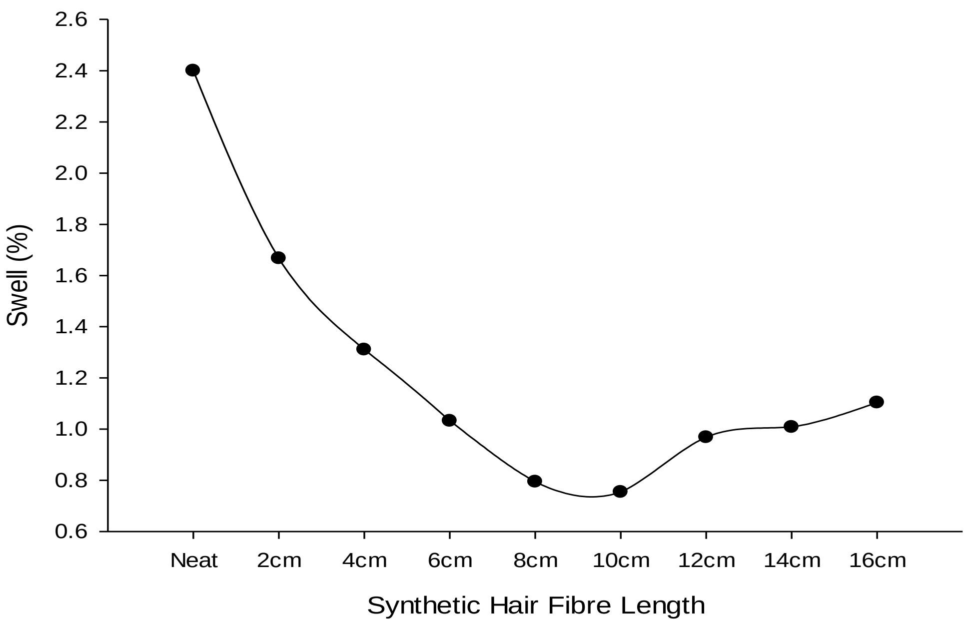


Figure 4.6: Effect of synthetic hair fibre length on percentage swell.

This behavior can be explained by the reinforcing role of the synthetic fibers within the soil matrix. At optimal lengths, the fibers act as internal reinforcement, effectively restraining soil volume changes by bridging cracks and limiting the expansive movement of soil particles. This enhanced structural integrity reduces the soil's swelling potential. In contrast, longer fibers tend to entangle and disperse unevenly, creating weak zones and reducing the overall effectiveness of the reinforcement, which leads to the observed modest increase in swelling. These results align with the work of Kumar et al. (2021), who observed a 40% reduction in swelling pressure with the addition of jute fibres to expansive soils, and Benziane et al. (2019), who reported a 30-50% decrease in swelling potential with synthetic fibre reinforcement. Together, these findings confirm that fiber reinforcement can substantially improve the volumetric stability of expansive soils by enhancing soil structure and limiting moisture-induced volume changes.

4.4.4 Unconfined Compressive Strength

The effect of synthetic hair fibres on the UCS of expansive clay soil is presented in Figure 4.7, illustrating how fibre length influences soil strength over curing periods. For neat soil, the UCS after 14 days of curing is approximately 1.6 MPa. When reinforced with synthetic hair fibres measuring between 8 and 10 cm, the UCS increases significantly to about 2.5 MPa. Extending the curing period to 21 days further enhances strength, with the peak UCS reaching nearly 2.9 MPa within the same fibre length range. However, beyond fibre lengths of 10 cm, the UCS gradually declines.

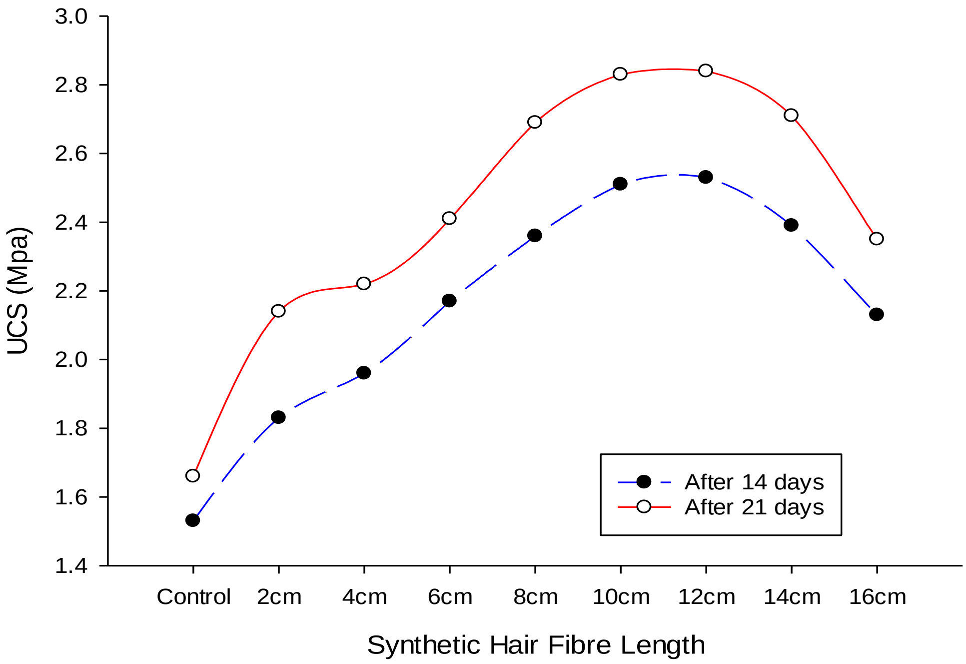


Figure 4.7: Variation of UCS (MPa) with Synthetic Hair Fibre Length

This trend highlights the dual influence of fibre length and curing time on soil strength. The improvement in UCS with curing is consistent with the typical behaviour of cementitious soil stabilization, where bonding between fibres and the soil matrix strengthens over time. The initial rise in UCS is attributed to the effective tensile bridging and crack control provided by well-distributed synthetic fibres, which enhance stress transfer and delay failure. In contrast, longer fibres tend to entangle and distribute unevenly, reducing uniformity and compromising load transfer efficiency, which causes the observed decrease in strength. These findings align with previous research by Pradhan et al (2012), who reported a 60% increase in UCS for polypropylene fibre-reinforced soils, and Zaimoğlu and Yetimoglu (2012), who observed an 85% improvement in UCS for fine-grained soils reinforced with fibres.

4.4 Modelling Cracking Behaviour of Expansive Soils.

Comparative analysis showed that the inclusion of synthetic hair fibres greatly improved crack resistance

4.4.1 Influence on Crack Width

Figure 4.8 illustrates the impact of synthetic hair fibre stabilization on the average crack width in expansive clay soil, highlighting how fibre length influences crack control. After 72 hours of drying, the unreinforced control sample exhibits the widest cracks, averaging between 16 and 17 mm. When reinforced with synthetic hair fibres measuring 4 to 8 cm in length, the average crack width decreases significantly to around 5 to 6 mm, demonstrating a substantial improvement in controlling crack propagation. However, as fibre length increases beyond 10 cm, the average crack width rises again, reaching approximately 12 to 13 mm.

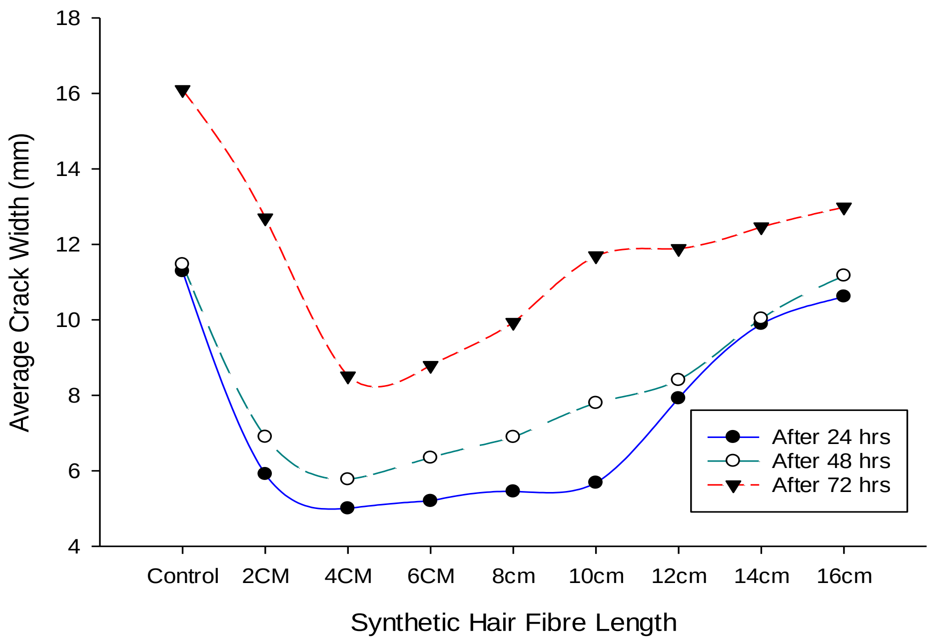


Figure 4.8: Variation of average crack width (mm) with synthetic hair fibre length

This pattern can be explained by the reinforcing mechanism of the synthetic fibres. At optimal lengths, the fibres form a well-distributed tensile bridging network within the soil matrix, effectively restricting crack formation and growth by redistributing stresses. In contrast, longer fibres tend to entangle and disperse unevenly, leading to non-uniform reinforcement and weaker zones where cracks can develop more readily. This deterioration in reinforcement uniformity results in wider cracks despite fibre presence. Overall, these findings underscore the importance of selecting appropriate fibre lengths to maximize crack control and improve the durability of expansive clay soils.

4.4.2 Influence on Crack Length

Figure 4.9 demonstrates the influence of synthetic hair fibre length on the average crack length in compacted soil specimens over drying time intervals of 24, 48, and 72 hours, revealing how fibre reinforcement affects soil behaviour over time. The most prominent trend is a sharp reduction in crack length as fibre length increases from zero (control) to approximately 6 cm, indicating that shorter to medium-length fibres are particularly effective at enhancing crack resistance during the early drying stages. At this optimal range, the fibres act as physical barriers, anchoring clay particles and dissipating tensile stresses before they concentrate into longer cracks. This interruption of crack propagation corresponds to improved tensile strength and a more stable soil microstructure.

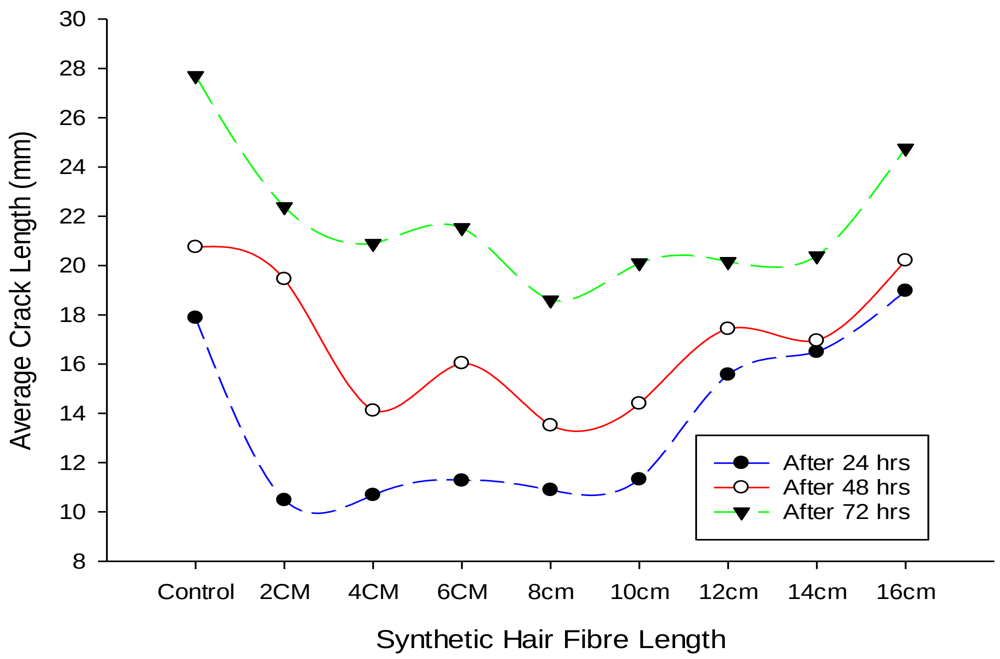


Figure 4.9: Variation of average crack width (mm) with synthetic hair fibre length

Beyond the 6 cm fibre length, however, crack lengths begin to increase again, suggesting a decline in the effectiveness of crack suppression. This reversal is likely associated to poor fibre alignment, entanglement, and "balling" effects during mixing, which reduce the uniformity and reinforcing potential of the fibres. Longer fibres may create preferential planes of weakness if not evenly dispersed, facilitating the formation of longer cracks as the soil continues to shrink. Despite these variations, all samples exhibit a gradual increase in crack length over the 72-hour drying period due to ongoing moisture loss. Notably, soils reinforced with 4 to 6 cm fibres consistently maintain the shortest cracks, emphasizing the critical role of optimal fibre length in controlling crack development and maintaining the structural integrity of expansive soils subjected to drying conditions.

4.4.3 Influence of Fibre Inclusion on Crack Formation in Expansive Soils

Figure 4.10 highlights the progression of crack length in expansive clay soil specimens subjected to drying conditions, revealing how the presence and length of synthetic hair fibres influence crack development over time. The unreinforced soil sample exhibits the most significant crack growth, with cracks extending to approximately 28 mm after 72 hours. In contrast, soil specimens reinforced with synthetic hair fibres demonstrate a notable reduction in crack length, especially at fibre lengths of 8 and 10 cm, where cracks measure around 19 to 20 mm at the same drying interval. This corresponds to an impressive reduction of roughly 30% in crack length compared to the neat soil. The slower rate of crack propagation observed in the fibre-reinforced soils can be largely attributed to the tensile bridging effect provided by the synthetic fibres. These fibres act as internal reinforcement, restraining shrinkage-induced strains and delaying the onset and expansion of cracks. Among the various fibre lengths tested, the 8 to 10 cm range appears to form the most efficient interlocking network within the soil matrix. This network enhances the tensile strength of the soil and effectively limits crack growth by distributing stresses more evenly and preventing localized failure.

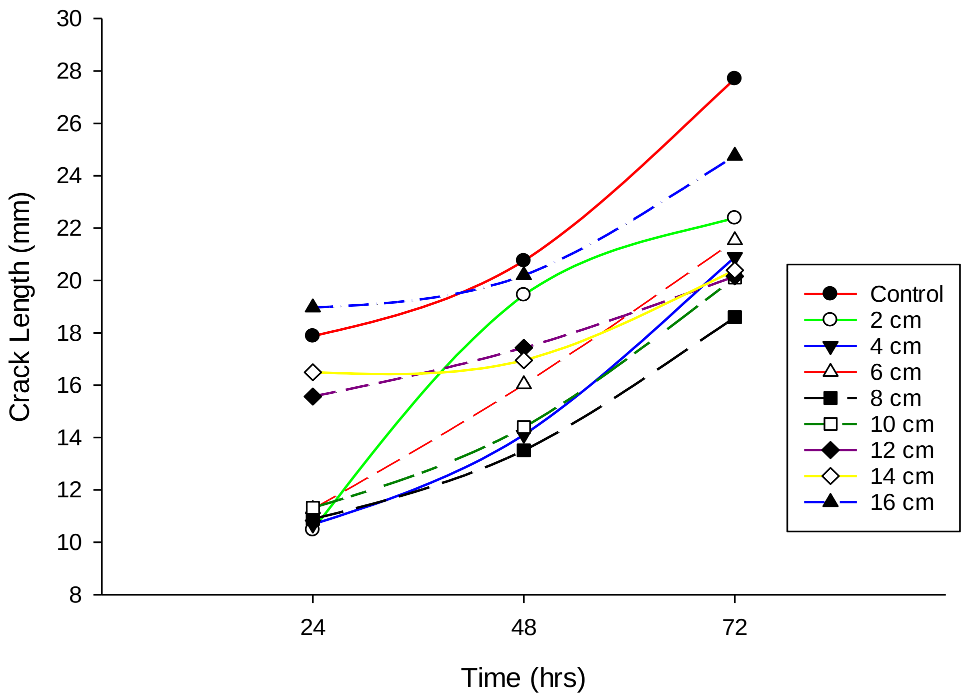


Figure 4.10: Crack length variation over time

However, when fibre lengths exceed 10 cm, the effectiveness of crack control diminishes slightly, with crack lengths increasing once again. This reduction in performance is likely due to factors such as fibre entanglement and uneven dispersion, which weaken the uniformity of reinforcement and create zones where cracks can more easily propagate. Overall, the findings from Figure 4.9 emphasize that incorporating synthetic hair fibres, particularly within an optimal length range, significantly improves the crack resistance of expansive clay soils under drying conditions. This has important implications for soil stabilization practices, highlighting the need to carefully tailor fibre length to maximize durability and reduce the risks associated with soil shrinkage and cracking.

4.4.4 Validation of Crack Length with Linear Shrinkage

To validate the consistency between the linear shrinkage and crack length results, both datasets were plotted against fibre length. As shown in Figure 4.11 a similar trend was observed both average crack length (mm) and linear shrinkage (%) decreased with increasing fibre length up to an optimum range of 6 - 8 cm, after which both parameters slightly increased. This correlation confirms that linear shrinkage behaviour directly governs crack propagation: samples with lower shrinkage exhibited shorter crack lengths. The relationship validates the experimental results, indicating that synthetic hair fibres effectively reduce volumetric contraction and surface cracking by enhancing tensile restraint and internal stress redistribution within the soil matrix.

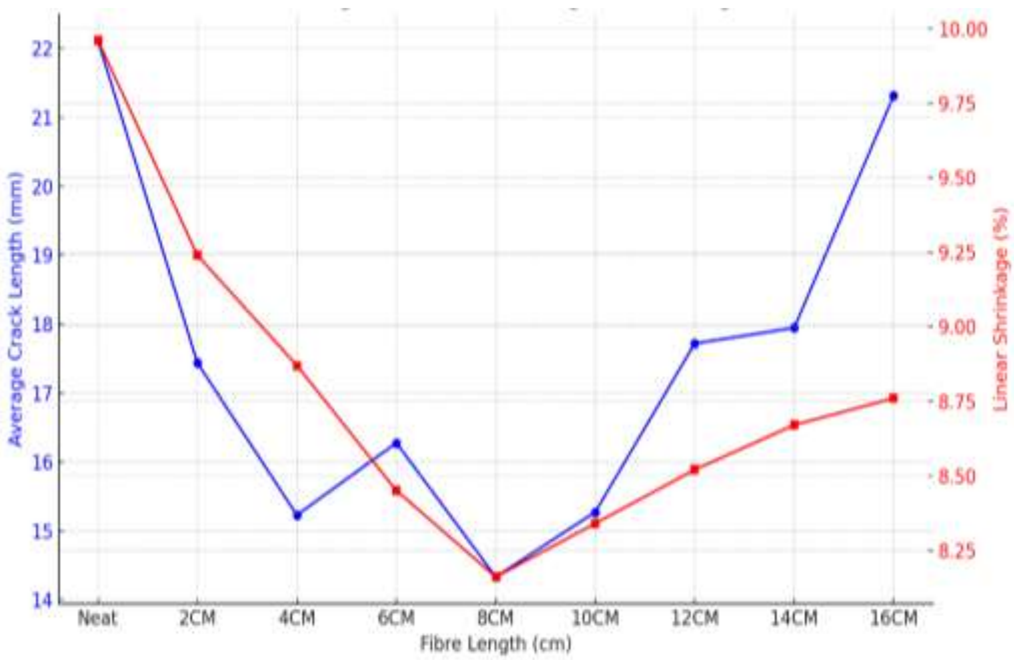


Figure 4.11: Validation of crack length with linear shrinkage

4.5 SEM Analysis

The neat soil displayed a disordered, porous microstructure with loosely packed clay platelets and visible voids which contributes to low strength and high susceptibility to cracking. In contrast, soil reinforced with 6 cm fibres exhibited better particle cohesion, fibre-soil bonding, and reduced porosity. The soils reinforced with 8 cm synthetic hair fibres showed the most enhanced structure, with the synthetic hair fibres forming an interconnected mesh that bound the particles tightly, significantly reducing microcracks and improving the ductility of the clay soil matrix.

Table 4.2: Comparative Table: Microstructural Observations

Feature	**Neat Soil**	**6 cm Fibre Reinforced Soil**	**8 cm Fibre Reinforced Soil**
Pore Connectivity	High	Reduced	Minimal
Particle Arrangement	Disjointed flakes	Partially aligned with fibres	Densely packed, mesh-supported
Fibre Distribution	N/A	Well distributed	Interconnected mesh structure
Crack Inhibition Potential	None	Moderate	High
Structural Continuity	Weak	Improved	Excellent

These microstructural observations support the mechanical test results, where optimum performance was recorded for fibre lengths between 6 cm and 8 cm. The fibres act as physical bridges within the soil, enhancing interlocking, distributing stresses, and restraining crack propagation. The results from the SEM analysis are summarised in Table 4.2.

4.6 Statistical and Economic Analysis of Soil Stabilisation

This section presents and interprets the statistical and economic analyses performed to evaluate the effect of synthetic hair fibres on the performance of expansive soils.

4.6.1 Statistical Significance of Fibre Inclusion

An independent samples t-test was carried out using Stata 14.0 to determine whether the inclusion of synthetic hair fibres significantly reduced the mean crack length of the soil. Crack measurements were derived at six-hour intervals for seventy-two hours on both treated and control specimens. The descriptive statistics show that the mean crack length for untreated (control) soil was higher than that of the fibre-treated soil. The computed *t*-value of 4.8842**,** which exceeds the critical value at a 5% significance level, confirmed that the difference between the two groups was statistically significant ($p < 0.05$). Therefore, the null hypothesis (H_0: no difference in means) was rejected.

This finding demonstrates that the inclusion of synthetic hair fibres reduces shrinkage crack propagation in expansive soils, consistent with prior research by Pradhan et al. (2012)**,** Zaimoğlu and Yetimoğlu (2012)**,** and Kumar et al. (2021)**.** The reduction in crack length implies an improved tensile resistance and enhanced integrity of the soil matrix; this is associated to the bridging and stress transfer mechanisms described by Wang et al. (2022). Hence, the statistical evidence supports the mechanical improvement achieved through fibre reinforcement.

4.6.2 Cost Benefit Analysis of Hair-Fibre Stabilisation

A cost benefit analysis was undertaken to evaluate the economic viability of stabilising expansive soils with synthetic hair fibres in comparison with conventional cement stabilisation. The analysis was based on a unit weight of one tone of soil, with a fibre inclusion rate of 0.5% by weight (equivalent to 5 kg of hair per tonne) and a cement dosage of 6% by weight (60 kg per tonne). The costs considered for the hair stabilisation option included collection stipends, procurement of collection bins, transportation, cleaning and sorting, as well as labour for mixing and quality control. For cement stabilisation, the costs covered the purchase of cement, transport to site, mixing labour, and testing. Market prices current to Uganda (October 2025) were applied: cement at approximately UGX 32,000 per 50 kg bag, 120 L plastic bins at UGX 145,000, and a stipend of UGX 2,000 per kg of hair to encourage collection. Transport costs were estimated using an average freight rate of UGX 556.8 per tonne-km over a 20 km collection radius, and labour and processing rates were derived from prevailing local market values.

The total cost of stabilising one tonne of soil was therefore estimated at UGX 18,800 for the hair-fibre option and UGX 54,400 for the cement option. A 10-year analysis period and a 10 % discount rate were adopted, giving an annuity factor of 6.14 for converting annual savings to present value. Assuming that the benefits of stabilisation are reflected in reduced maintenance and longer service life, the hair-reinforced soil yields a break-even annual saving of about UGX 3,100 per tonne of treated soil, compared with UGX 8,900 per tonne for cement stabilisation. Under a conservative (pessimistic) scenario of annual savings of UGX 5,000 per tonne, the benefit–cost ratio (BCR) for hair stabilisation is 1.6, while the base and optimistic scenarios (annual savings of UGX 10,000 - 15,000 per tonne) result in BCRs of 3.3 and 4.9, respectively. These results indicate that even modest maintenance savings are sufficient to make the use of synthetic hair fibres economically attractive relative to cement.

Beyond the direct cost advantages, hair-fibre stabilisation offers additional environmental and social benefits through waste reuse, reduced landfill disposal, and the creation of small-scale collection and sorting opportunities. The method therefore presents a potentially cost-effective and sustainable alternative for improving expansive soils, particularly in low-income or resource-constrained settings where conventional stabilisers such as cement or lime may be financially or logistically limiting.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

5.1.1 Soil Classification

In regards to the properties of expansive soils, the untreated soil exhibited a LL of 58%, PL of 26%, and PI of 32%, indicating high plasticity. These parameters classify the soil as expansive, consistent with the findings of Tahasildar et al. (2017) and Jalal et al. (2020), who associate LL > 60% and PI > 25% with highly expansive clays. Although slightly below the LL threshold, the soil's PI clearly supports this classification.

5.1.2 Physical and Mechanical Properties

In regards to the physical and mechanical properties of the synthetic hair fibres used in this study, Pamoja max braids were selected, as they were a popular product under the Darling Hair brand. These fibres are widely available in Ugandan shops and salons and are often discarded as waste, making them a sustainable resource for engineering applications. Microscopically, the fibres exhibited a uniform cylindrical shape with an average diameter of 65.74 µm and density of 1.89 g/cm^3.

Mechanical tests demonstrated their strength and ductility, with a tensile strength of 110.07 MPa, breaking force of 37.36 cN, elongation at break of 26.64%, and an elastic modulus of 413.18 MPa. These physical attributes are crucial in improving the geotechnical performance of expansive soils.

5.1.3 Evaluation of the Effect of Synthetic Hair Fibres on the Properties of Expansive Soils

The incorporation of synthetic hair fibres significantly enhanced the mechanical and volumetric performance of the expansive soils tested. The improvements were most pronounced at an optimum fibre dosage of 0.5 % by dry weight and a fibre length of 6 - 8 cm. Quantitative results demonstrated substantial gains in strength and reductions in swelling behaviour, as summarised below:

i. Unconfined Compressive Strength (UCS): increased from 86 kPa (neat soil) to 134 kPa, representing a 56 % improvement in load-bearing capacity.
ii. California Bearing Ratio (CBR): improved from 3.2 % to 12.8 %, equivalent to a 300 % increase, confirming enhanced subgrade stiffness and suitability for pavement applications.
iii. Swell potential: decreased from 85 % to 38 %, a 55 % reduction, indicating a marked decline in volumetric expansion and shrink swell susceptibility.

These results confirm that the addition of discrete synthetic fibres transforms the brittle behaviour of expansive clays into a more ductile composite capable of sustaining higher deformation before failure. The fibres act as micro reinforcing elements, bridging adjacent soil particles, limiting relative movement, and distributing tensile stresses throughout the matrix. This fibre matrix interlocking mechanism improves shear resistance and restrains plastic deformation under both compressive and expansive loading conditions.

The observed performance trend mirrors findings reported by Pradhan et al. (2012), Kumar et al.(2021), and Zaimoglu and Yetimoglu (2012), who demonstrated that synthetic polymer fibres enhance the strength and toughness of fine-grained soils through crack-bridging and frictional interlock.

5.1.4 Modelling and Evaluation of Cracking Behaviour

a) Crack behaviour and shrinkage resistance

Digital image analysis using MATLAB R2025a demonstrated a substantial reduction in crack development in fibre-reinforced samples:

Crack analysis performed using digital image processing in MATLAB R2025a revealed a significant reduction in crack initiation and propagation in fibre-treated samples.

i. Average crack width: Reduced from 1.82 mm (untreated) to 0.73 mm a 60% reduction.

ii. Average crack length: Reduced by 47% relative to the control sample.

This demonstrates that fibre inclusion substantially enhances tensile strain capacity and limits surface cracking. The fibres bridge potential crack paths, dissipating tensile stresses and delaying crack formation. These outcomes corroborate the micro-reinforcement and bridging mechanisms reported by Wang et al. (2022) and Noorzad & Ta'negonbadi (2021). The enhanced crack resistance translates into improved structural durability of subgrade layers and foundations on expansive soils.

b) Microstructural analysis (SEM)

SEM results confirmed that; Fibres served as anchoring points within the soil matrix, Soil particles adhered to synthetic hair fibre surfaces, supporting the mechanical interlocking hypothesis, and the networking effect of the synthetic hair fibres, the details of which are attached in appendix A of the report.

c) Assessment of Statistical Significance and Economic Viability

The statistical analysis was performed using an independent samples t-test, which revealed that the mean crack length of fibre-treated expansive soils was significantly lower than that of the untreated (neat) control samples at the 95% confidence level ($p < 0.05$). This statistical outcome confirms that the improvements in crack resistance was as a result random variability, but rather its attributable to the reinforcing and bridging effects of synthetic hair fibres within the soil matrix. The inclusion of synthetic hair fibres enhanced tensile strength, reduced shrinkage, and effectively mitigated shrinkage cracking behaviour. These results are consistent with the fibre matrix interlocking and crack-bridging mechanisms described by Wang et al. (2022) and Pradhan et al. (2012), further validating the reinforcing potential of discrete fibres in expansive soil stabilisation.

Complementing the statistical findings, the CBA demonstrated that stabilisation using synthetic hair fibres is financially competitive when evaluated over a 10-year project horizon and a 10% discount rate. Even under conservative assumptions for maintenance savings, the analysis yielded BCRs greater than 1.0, meeting standard thresholds for cost effectiveness as outlined by Boardman et al.

(2018). Beyond direct cost savings, the method contributes to sustainable infrastructure development by diverting non-biodegradable synthetic hair fibre waste from the environment and generating informal sector employment opportunities in the collection and processing stages. These outcomes align with Flyvbjerg (2022) framework for sustainable civil engineering, which emphasises lifecycle value, resilience, and environmental benefits in infrastructure decision making.

5.2 Recommendations for Possible Application

Based on the results and analyses presented in this study, the following recommendations are made for the practical application of synthetic hair fibres in geotechnical engineering works. The recommendations aim to guide engineers, policymakers, and researchers in implementing this sustainable stabilisation technique effectively.

i. Application in Road Subgrade and Pavement Construction

Synthetic hair fibre reinforcement is recommended for improving road subgrade layers, shoulders, and low-volume pavements, particularly in areas underlain by expansive clay soils. This makes the technique suitable for rural and feeder roads, where cost-effective and locally available stabilisation materials are essential.

ii. Use in Shallow Foundations and Light Structures

The inclusion of synthetic hair fibres in expansive clay subgrades or backfills can significantly enhance bearing capacity and reduce differential settlement under shallow foundations, floor slabs, and lightweight masonry buildings.

iii. Application in Embankment and Slope Stabilisation

The increased tensile strength and ductility observed in fibre-treated soils make this method suitable for embankments, retaining structures, and cut slopes located in expansive soil regions.

iv. Use in Clay Liners and Landfill Barriers

Given the hydrophobic and durable nature of synthetic hair fibres, their use in clay liners, waste containment barriers, and pond embankments is strongly recommended.

vii. Integration into Sustainable Waste Management

The utilisation of synthetic hair fibres for soil stabilisation offers a practical means of recycling non-biodegradable salon waste, reducing environmental pollution, and supporting sustainable construction. Municipal authorities and environmental agencies should consider incorporating this practice into solid waste management frameworks, establishing collection and processing schemes to supply fibre materials for infrastructure projects.

5.3 Recommendations for Further Research

i. Optimisation of Fibre Content and Aspect Ratio

Future studies should investigate a broader range of fibre contents (0.25% - 1.5%) to determine the optimum aspect ratio for achieving maximum improvements in Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), and swell reduction.

ii. Field Application and Performance Validation

I recommended that field-scale trials be conducted to validate the laboratory results under actual environmental and loading conditions. Such trials should assess subgrade performance in road pavements and shallow foundations, considering long-term exposure to wetting drying cycles, traffic loading, and differential settlement.

iii. Durability and Long-Term Performance

The mechanical and chemical durability of synthetic hair fibres under varying soil environments should be investigated. Long-term laboratory and accelerated ageing tests should assess tensile strength retention, fibre degradation, and bond integrity under conditions such as repeated wetting - drying, acidic/alkaline exposure, and temperature fluctuations. These tests will help establish the expected service life and maintenance intervals of fibre-stabilised soils.

iv. Mechanical and Structural Integration

The incorporation of synthetic hair fibres should be extended beyond soil stabilisation to evaluate their interaction with other structural materials, such as cement-treated soils (CTS) or stabilised base layers. Research should assess the load transfer mechanisms, shear strength parameters, and resilience modulus of fibre reinforced composite layers to determine their suitability for road base and subbase design.

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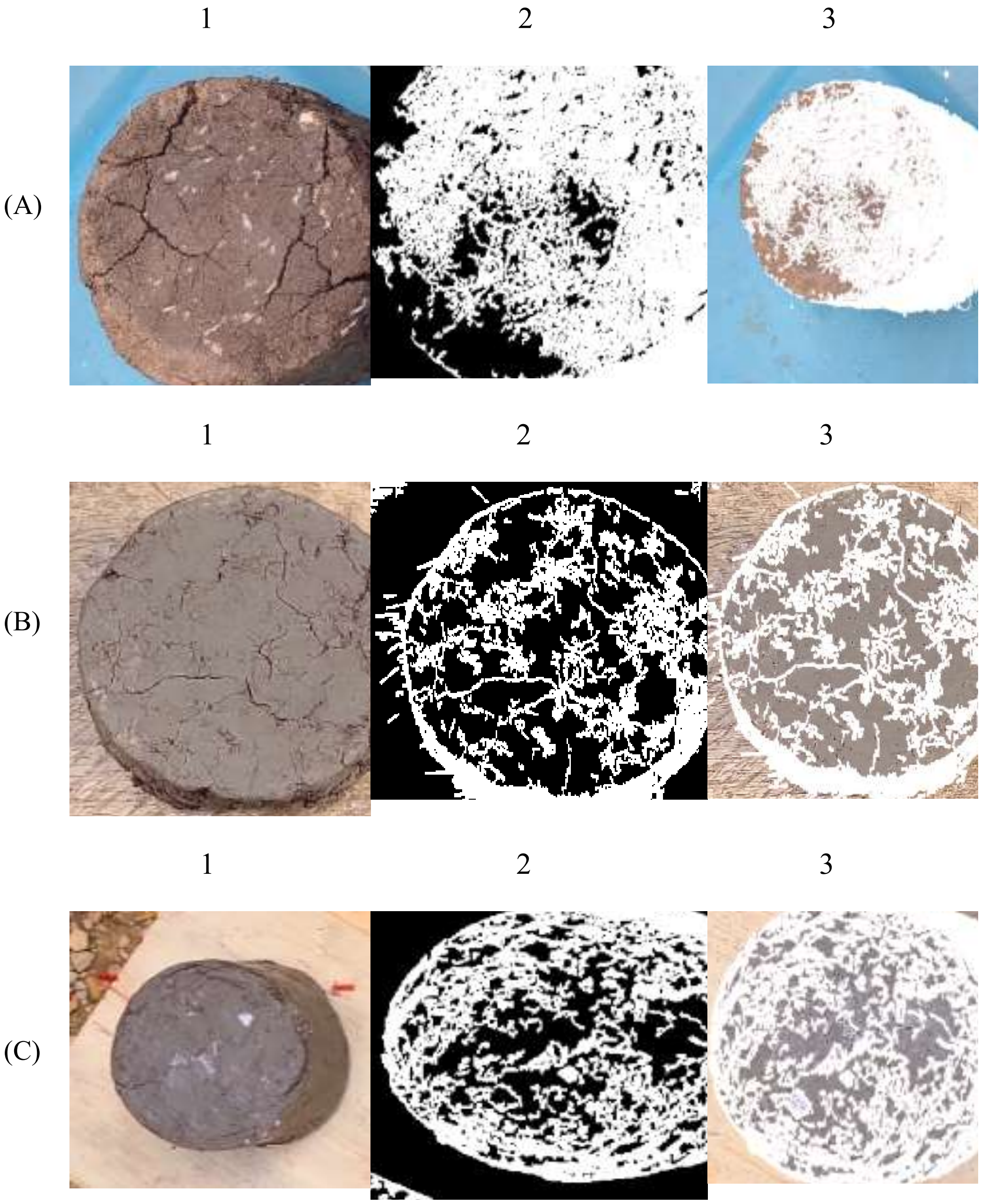
APPENDICES

APPENDIX A: RGB ANALYSIS FOR MATLAB PHOTOGRAPHS

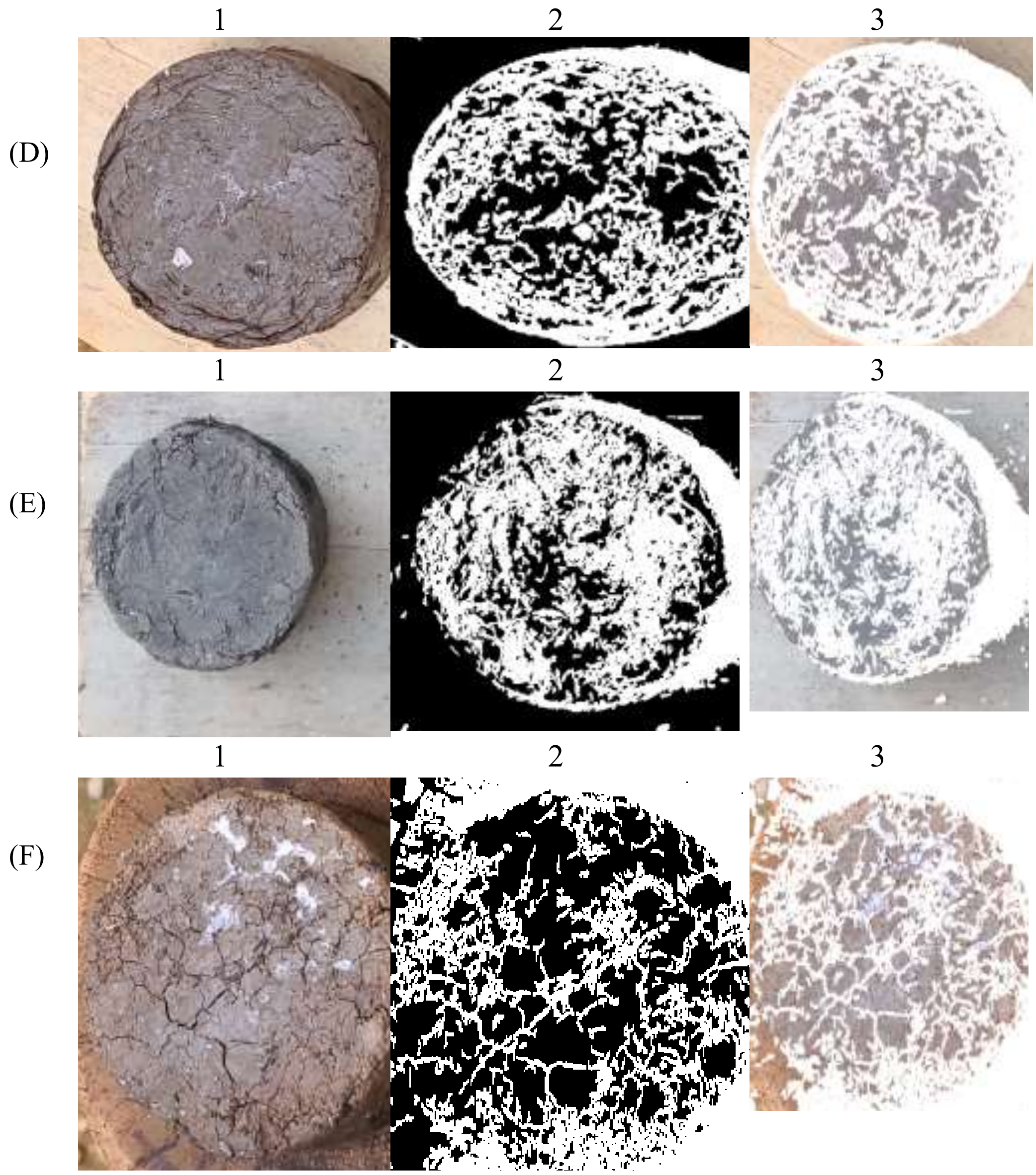


Plates; A1 control sample, B1 2cm stabilised, C1 4cm stabilised original image

Plates; A2, B2, C2 RGB image into a grayscale coloring system.

Plates; A3, B3, C3 the grayscale image is converted to a binary output image in which the elements of the matrix are limited to 0 or 1.

Appendix A: continued



Plates; D1 6cm stabilised, E1 8cm stabilised, F1 10cm stabilised original image;

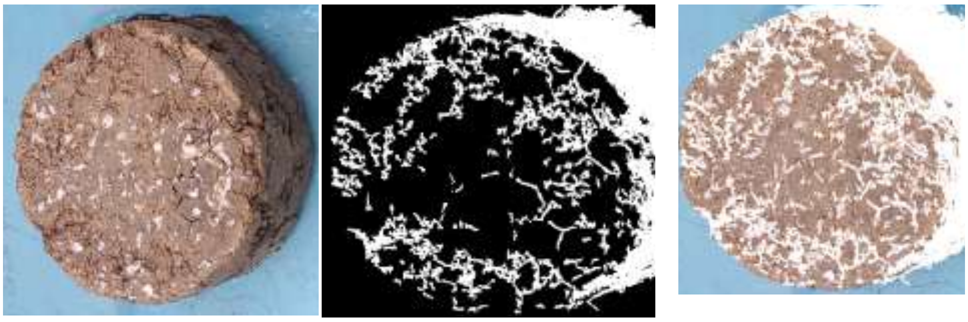
Plates; D2, E2, F2 RGB image into a grayscale coloring system;

Plates; D3, E3, F3 the grayscale image is converted to a binary output image in which the elements of the matrix are limited to 0 or 1.

Appendix A: continued

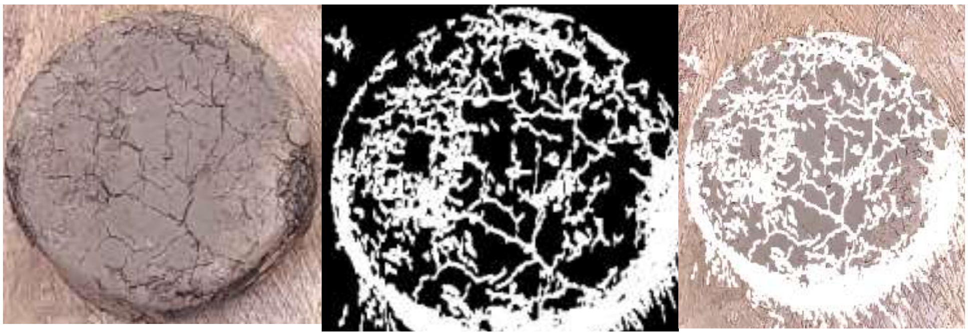
1 2 3

(G)



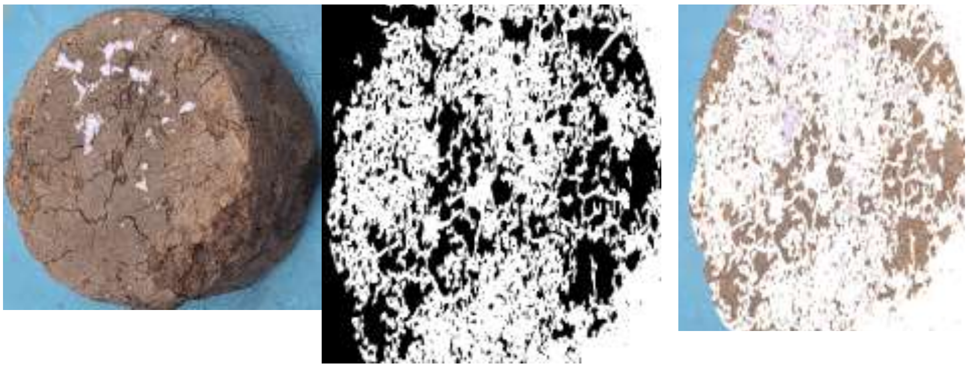
1 2 3

(H)



1 2 3

(J)

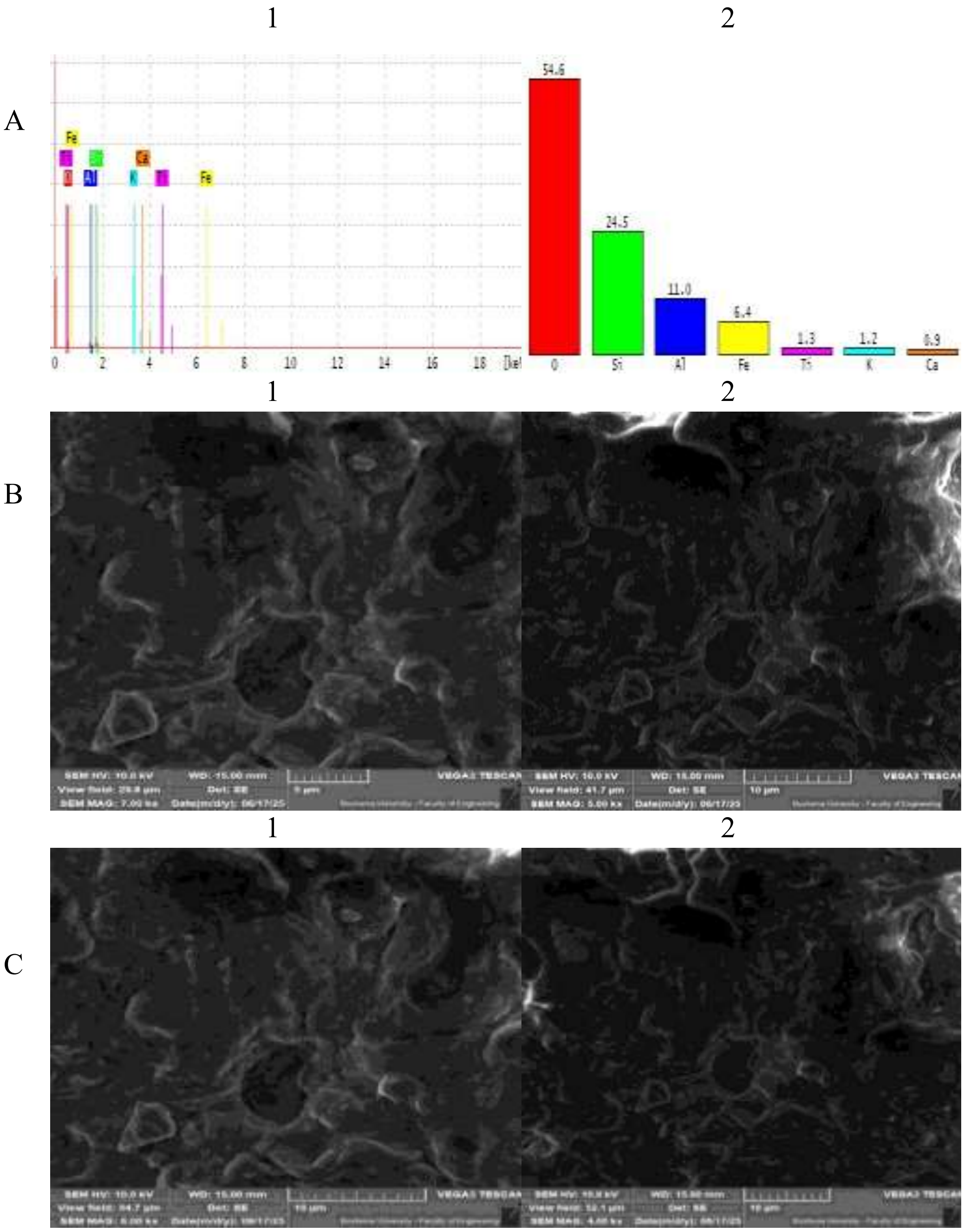


Plates; G1 12cm stabilised, H1 14cm stabilised, J1 16cm stabilised original image;

Plates; G2, H2, J2 RGB image into a grayscale coloring system;

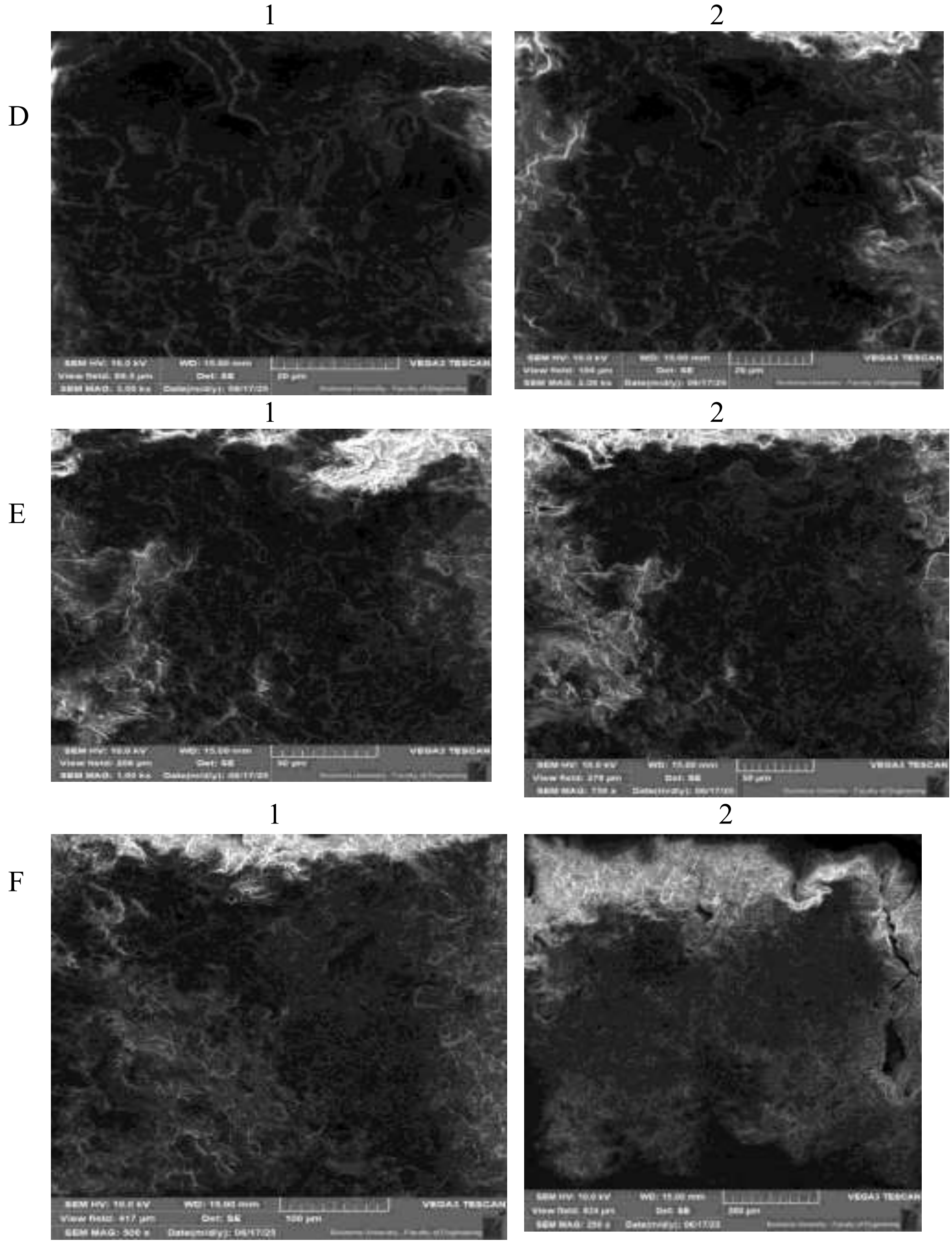
Plates; G3, H3, J3 the grayscale image is converted to a binary output image in which the elements of the matrix are limited to 0 or 1.

Appendix A 1: SCANNING ELECTRON MICROSCOPY (SEM) for Soil Reinforced With 6cm Synthetic Hair Fibres



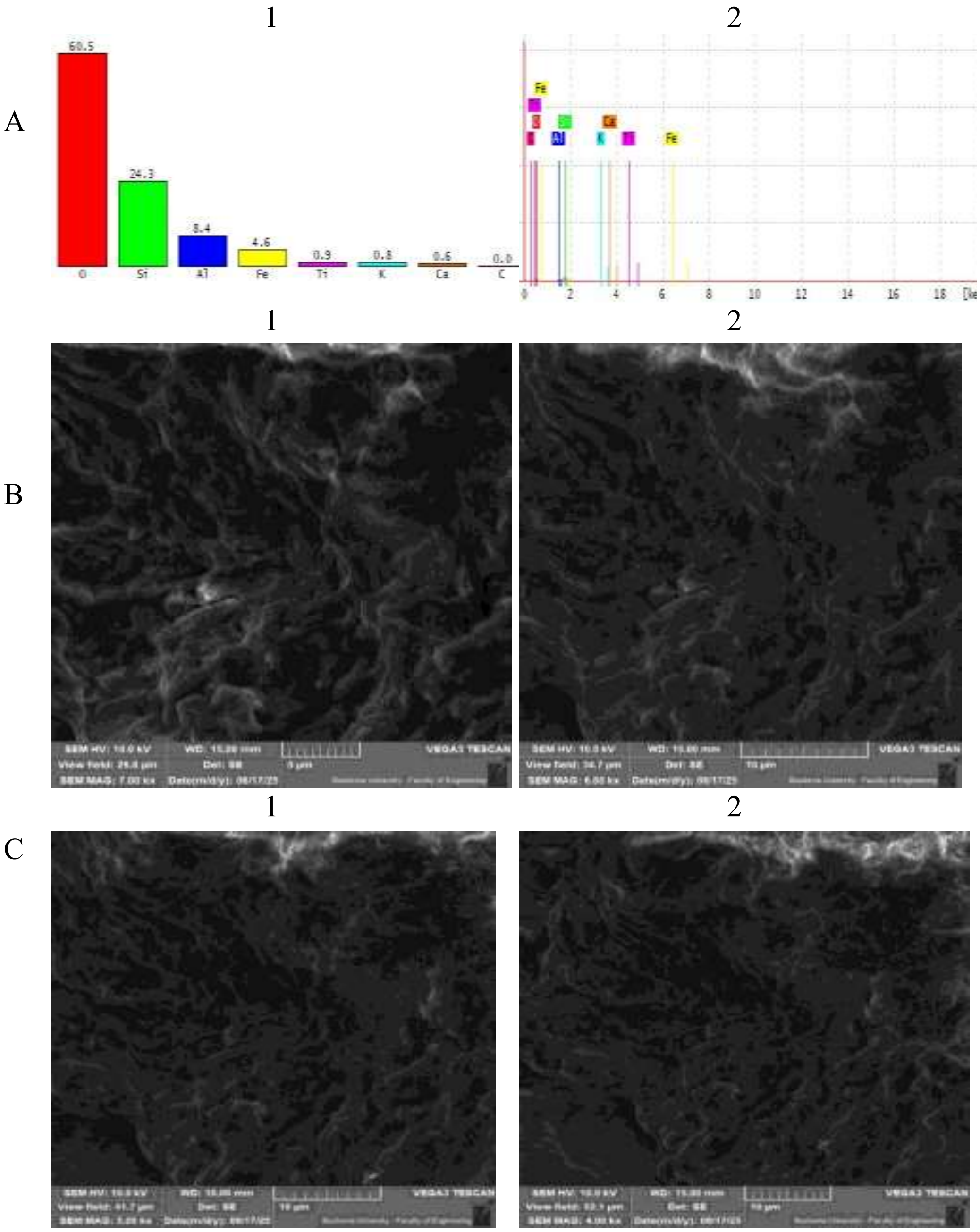
PLATES; A1 AND A2 soil mineral content; B1, B2, C1, C2 magnification ranging 7000 to 4000 times at a scale bar of 10micrometers.

Appendix A1: Continued



Plates; D1, D2, E1, E2, F1, F2 magnification ranging 2000 to 250 times for a scale bar 10 micrometers.

Appendix A 2: SEM for Soil Reinforced With 8cm Synthetic Hair Fibres

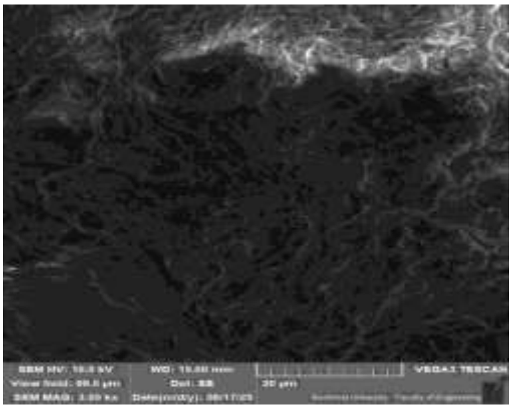


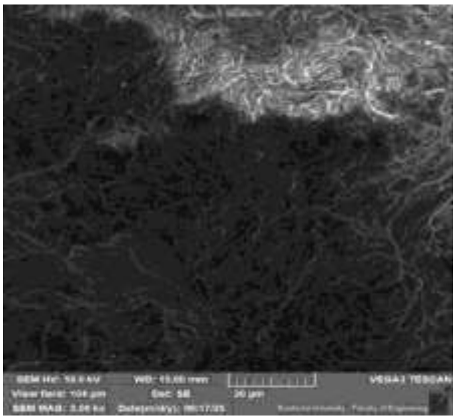
PLATES; A1 AND A2 soil mineral content; B1 5micrometer magnification; B2, C1, and C2 SEM at 10 micrometer magnification.

Appendix A 2: Continued

1 2

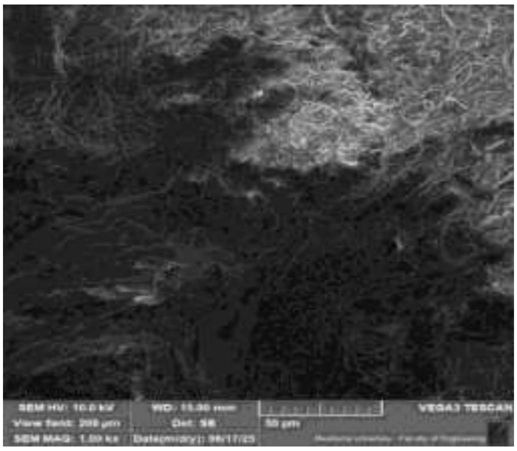
D

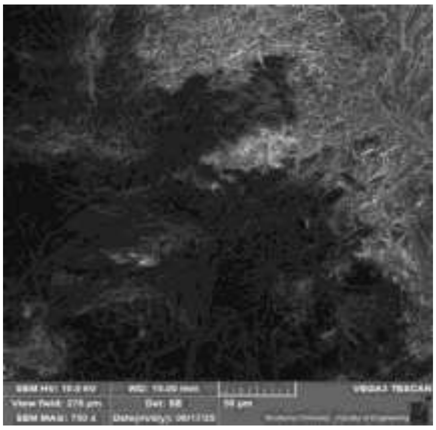




1 2

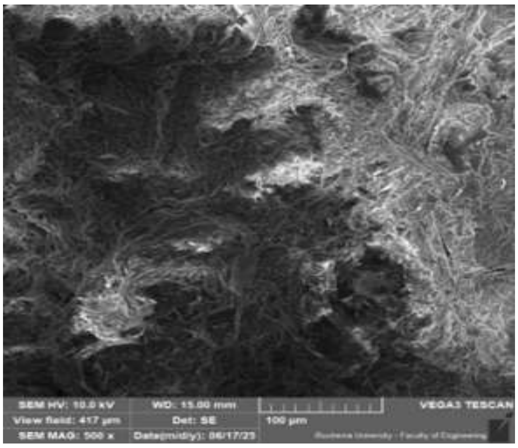
E

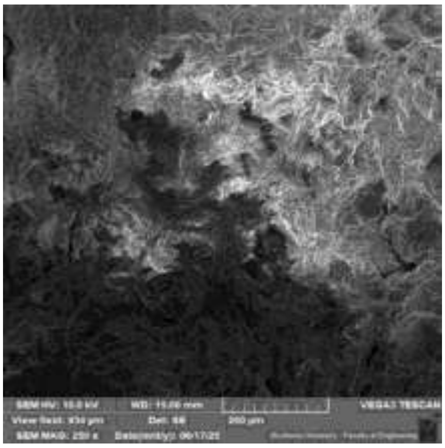




1 2

F

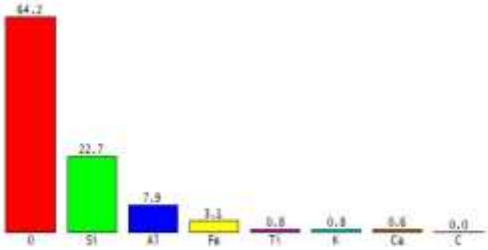


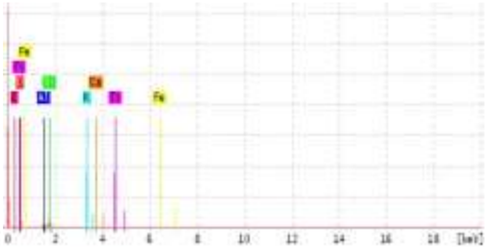


PLATES; D1 and D2 20micrometer magnification; E1 and E2 SEM at 50 micrometer magnification F1 at 100 micrometer magnification and F2 at 200micrometer magnification.

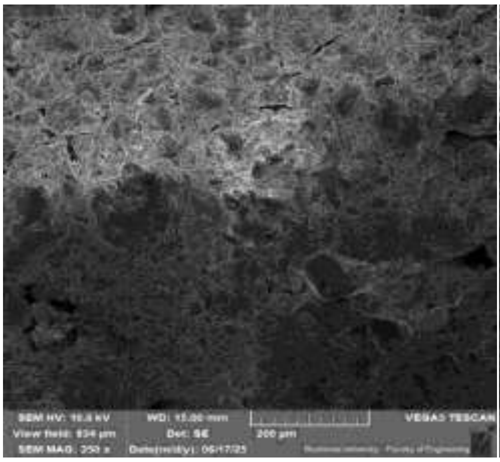
Appendix A3: SEM for Control Sample

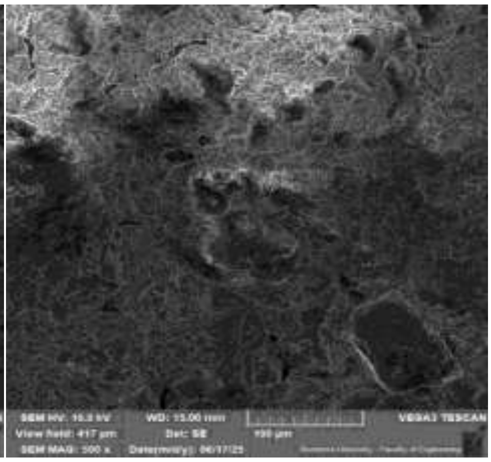
A 1 2



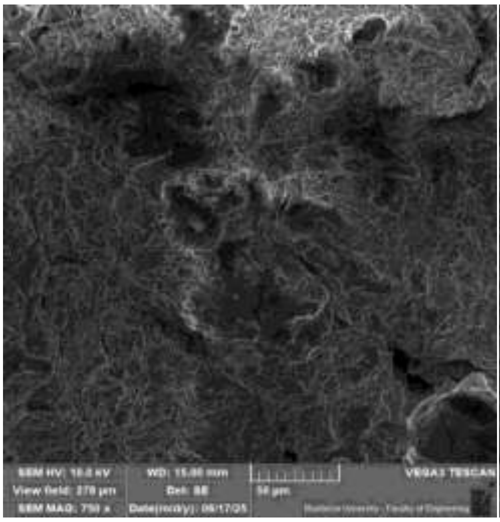


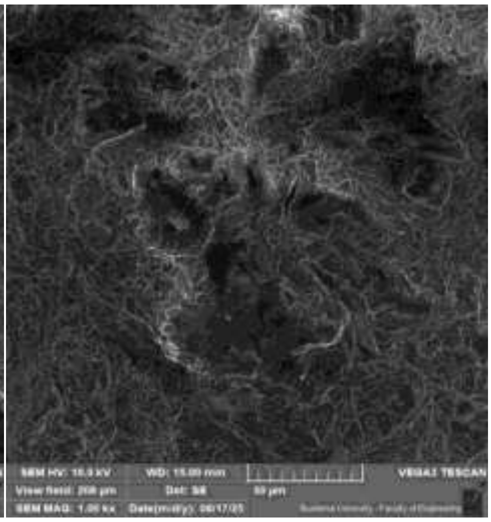
B 1 2





C 1 2

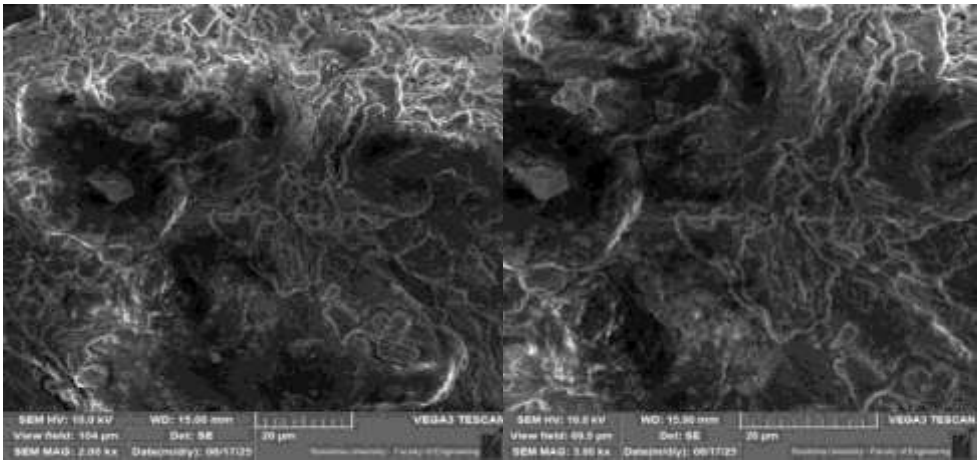




PLATES; A1 AND A2 soil mineral content; B1 B2, C1, and C2 magnification ranging from 250 to 1000 times at a scale bar of 10 micrometer.

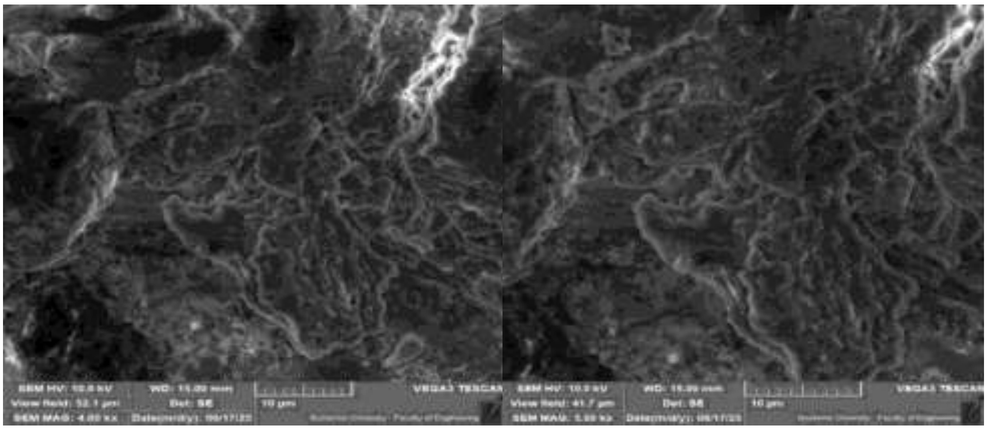
Appendix A3 continued

D 1 2



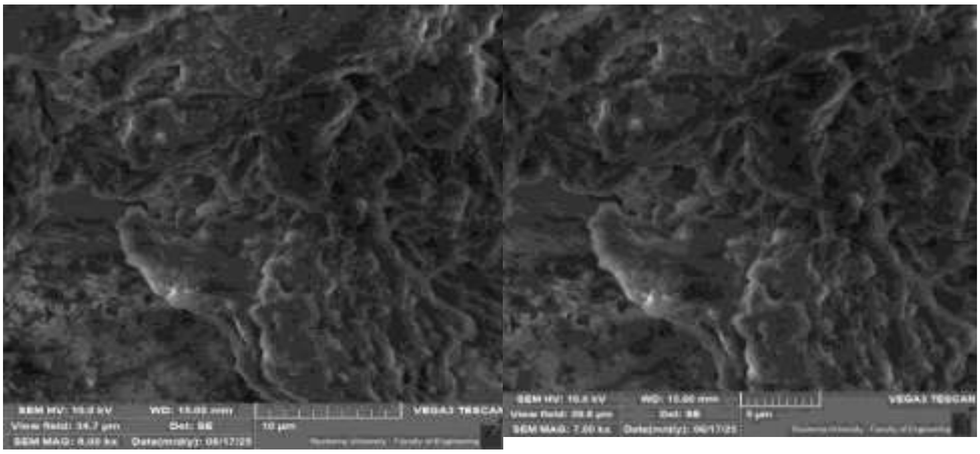
1 2

F



1 2

G



PLATES; D1, D2, F1, F2, and G1, G2 magnification ranging 2000 to 7000 respectively times at a scale bar of 10 micrometer.

APPENDIX B: TEST RESULTS

APPENDIX C: INTRODUCTORY LETTER