UNIVERSITI TEKNOLOGI MARA

EMPIRICAL MODEL FOR SOIL LINER PERFORMANCE WITH KENAF FIBRE AND EMPTY FRUIT BUNCH ADMIXTURES

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Thesis submitted in fulfilment
of the requirements for the degree of
Doctor of Philosophy
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ABSTRACT

Residual soils are widely used in geotechnical and environmental engineering, particularly as compacted landfill liner materials, where adequate compaction characteristics, low hydraulic conductivity, and long-term sustainability are essential. An effective landfill liner should have a hydraulic conductivity not exceeding 1 x 10^{-9} m/s to minimise the migration of contaminants into the surrounding soil and groundwater. This study investigated the effects of kenaf fibre and empty fruit bunch (EFB) additives on the physical properties, compaction characteristics, and hydraulic performance of residual soil obtained from Salak Tinggi, with the aim of assessing its suitability as a sustainable landfill liner material and developing empirical models for estimating hydraulic conductivity. The residual soil was mixed with kenaf fibre and EFB at contents of 0%, 5%, 10%, 15%, and 20% by dry weight. The physical and index properties of the untreated and treated soils were evaluated using particle-size distribution, Atterberg limits, particle density, and shrinkage limit tests, while scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy were conducted to examine the microstructure and elemental composition of the soil–additive mixtures. The engineering properties were subsequently assessed through compaction and hydraulic conductivity tests, with hydraulic conductivity determined using a modified oedometer apparatus under applied pressures of 25, 50, 100, 200, and 400 kPa. The results showed that the addition of kenaf fibre and EFB altered the physical and compaction characteristics of the residual soil. The maximum dry density increased slightly when the additive content was increased from 5% to 10%, but decreased when the additive content exceeded 10%. The incorporation of kenaf fibre and EFB also reduced the hydraulic conductivity of the compacted soil, with measured values ranging from approximately 1 x 10^{-10} to 1 x 10^{-11} m/s, which satisfied the maximum allowable hydraulic conductivity requirement for compacted landfill liners. The findings demonstrate that residual soil treated with suitable proportions of kenaf fibre and EFB has the potential to be used as a sustainable landfill liner material. Empirical models were also successfully developed to estimate the hydraulic conductivity of the treated soil and may serve as supplementary guidance for engineers in the preliminary assessment and design of compacted landfill liners.

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Finally, it is my hope that the findings of this study will contribute meaningfully to the advancement of knowledge in the field of [field of study, e.g., Geotechnical Engineering / Civil Engineering] and serve as a useful reference for future research.

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LIST OF SYMBOLS

Symbols

a_b	Cross-sectional area of burette
A_s	Cross-sectional area of specimen
A_v	Air Void
C_g	Coefficient of Gradation
C_u	Coefficient of Uniformity
d_{10}	Maximum Size of the Smallest 10% of the Sample
d_{30}	Maximum Size of the Smallest 30% of the Sample
d_{60}	Maximum Size of the Smallest 60% of the Sample
Gs	Specific Gravity
H_0	Initial Hydraulic Head
k	Hydraulic Conductivity
L_0, L_t	Flow Path Length
t_t, t_0	Time Reading
ρ_d	Dry Density

LIST OF ABBREVIATIONS

Abbreviations

BS	British Standard
LKTM	Lembaga Kenaf dan Tembakau Negara
LL	Liquid Limit
MDD	Maximum Dry Density
MSW	Municipal Solid Waste
OMC	Optimum Moisture Content
PI	Plasticity Index
PL	Plastic Limit
PSD	Particle Size Distribution
SEM	Scanning Electron Microscopy
SL	Shrinkage Limit
ST	Salak Tinggi
UiTM	Universiti Teknologi MARA
XRD	X-ray Diffraction

CHAPTER 1
INTRODUCTION

1.1 Research Background

Municipal Solid Waste (MSW) refers to waste gathered by the municipality or discarded at municipal waste disposal facilities, encompassing residential, industrial, institutional, commercial, and building and demolition waste.(Stafford, 2019). The increasing production of solid wastage due to the rapid growth of populations and continuous development in industrial sector is one of the threats of our environment. Time to time, the decomposition of garbage and trash will be producing leachate and at the same time it will contaminating surrounding soil and groundwater. (Chuangcham et al., 2008). The most common heavy metals in landfill leachate are Chromium (Cr), Manganese (Mn), Cadmium (Cd), Iron (Fe), Nickel (Ni) and Zinc (Z)(Mojiri et al., 2021).

Therefore, engineered landfills were designed and constructed by using liners system to restrict the migration of leachate toxins to the underlying soil and groundwater to avoid the harmful effect by the leachate constituents. Modern landfill is highly engineered system that consists of a low permeable barrier which laid down under landfill sites. Mainly, it requires a compacted clay liner with a minimum requirement of thickness and maximum requirement of allowable hydraulic conductivity. It also overlaid by a high density of polyethylene geomembrane (Solomon & Poulose, 2008). Figure 1.1 shows the schematic diagram of modern sanitary landfill system.

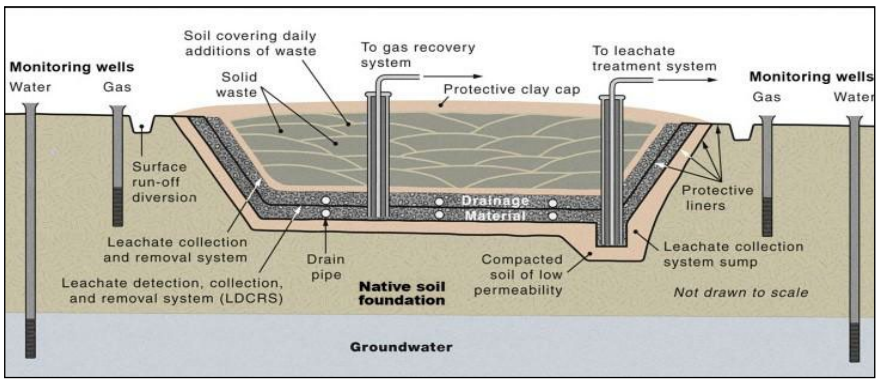


Figure 1.1 Modern Sanitary Landfill (Ahmad et al., 2019)

1.2 Problem Statement

Compacted Clay Liner (CCL) is widely used as the barrier layer in landfill that acts to reduce the flow of leachate infiltration underground that may cause the pollution to the environment. In producing the allowable design of compacted clay liner, Residual soil itself is difficult to achieve the requirement value of hydraulic conductivity, *k*. In achieving the requirement, soil liners and covers must consist of appropriately built-in cohesive soil layers, with a coefficient value of *k* less than 1×10^{-9} m/s, which are long-lasting ability to bond and interrupt chemical compounds from waste leachate (Koda & Osinski, 2017) (Stark, 2017)(Solomon & Poulose, 2008) (Saadeldin & Froc, 2017) (Zabielska-Adamska, 2020). Previous studies have revealed that multiple cracks are initiated in CCL after seasonal dry-wet cycles due the effect of climate. These cracks provide direct channels for rainwater infiltration and will threaten the safe operation of a landfill site causing the negative impact to the surroundings (Wan et al., 2016) (Li et al., 2016).

Therefore, to enhance the capability of the compacted clay liner system, materials such as synthetic fibre, additives including sodium bentonite, fly ash and nano materials had been emerged to improve the hydraulic conductivity of soil liner system. Impermeability of the waste disposal site is achieved by means of independent protective barriers in the form of geological barriers, artificial sealing layers, mineral soil liners and covers, and sidewall sealing (Zabielska-Adamska, 2020) . The increasing awareness and demand for sustainable materials have led to significant research and promotion of renewable and eco-friendly resources, particularly natural fibre reinforcement. Materials such as kenaf and oil palm have been extensively cultivated; however, their application in geotechnical design, particularly for soil improvement, remains limited. Recent research has demonstrated the potential of Kenaf Fibre and Empty Fruit Bunch in long-term slope stabilization for sustainable construction by enhancing their strength properties (Manaf et al., 2018). The research conducted by (Arifin et al., 2019a) demonstrated that the stability of soft soil, when compacted with EFB mixtures, significantly enhanced both shear strength and bearing capacity. Given the complexity of landfill applications and importance of an effective liner system for environmental contamination prevention, a thorough evaluation of Residual soil's physical characteristics together with additional Kenaf Fibre and EFB admixture must

take place to ascertain its suitability as a stronger liner material. The engineering properties of Residual soil, particularly when combined with admixtures, have not undergone deep investigation. Conducting a compaction test and permeability test on the behavior and suitability of soil for engineering applications is essential in understanding its behaviour and can serve as an indispensable way of discovering the impact of addition kenaf fiber on compaction characteristics.

Furthermore, compaction is normally carried out to reduce the volume of voids within the soil, increase its dry density, and improve its strength and hydraulic performance. However, the application of compactive effort alone may not be sufficient to improve the untreated residual soil to the level required for landfill liner applications. Even after compaction, interconnected pore spaces may remain within the soil structure, allowing water and leachate to flow through the compacted layer. The effectiveness of compaction is also influenced by the soil particle arrangement, moisture content, plasticity, and applied compactive energy. Therefore, suitable admixtures are required to modify the soil structure, improve particle bonding and densification, and reduce hydraulic conductivity more effectively than compaction alone (Khalid et al., 2020).

Although compaction generally reduces the hydraulic conductivity of soil by decreasing the pore spaces between soil particles, compacted untreated residual soil may still record a hydraulic conductivity equal to or greater than 1×10^{-9}m/s. Such a value does not satisfy the accepted requirement for compacted landfill liners and may allow leachate to migrate through the liner into the surrounding soil and groundwater. The high hydraulic conductivity may be associated with the soil particle distribution, insufficient fines, interconnected voids, and the formation of preferential flow paths within the compacted sample. Hence, the residual soil needs to be treated with suitable proportions of Kenaf Fibre and EFB to alter its internal structure, minimise the available flow paths, and improve its hydraulic performance. The optimum additive composition must therefore be identified to ensure that the treated soil fulfils the hydraulic conductivity requirement while maintaining appropriate compaction characteristics.

The determination of hydraulic conductivity through conventional laboratory testing is generally tedious, time-consuming, and highly dependent on sample preparation and testing conditions. The test may require a long duration before steady-state flow or a stable hydraulic conductivity value can be obtained, particularly for fine-grained soils with very low permeability. In addition, variations in compaction, moisture distribution, sample disturbance, saturation, applied pressure, and soil-additive

composition may influence the accuracy and consistency of the results. Laboratory-prepared samples of unsaturated residual soil may also not fully represent the actual field conditions experienced by a landfill liner. Therefore, a systematic testing programme involving different additive contents and applied pressures is required. The development of an empirical relationship is also necessary to provide an alternative means of estimating hydraulic conductivity and to support the preliminary assessment and design of treated residual soil for landfill liner applications.

Therefore, the potential of Kenaf Fibre and EFB is found to be a good material and has become a concern and great interest to close the limitation gap between the physical, engineering and mechanical behaviour since the hybrid compositions resulted to give an increased in strength characteristics and improve the soil stabilization. Thus, there is a need to scrutinize its behaviour in terms of its hydraulic conductivity and strength value by finding the best ratio of Kenaf Fibre:EFB in clay soil hence to optimise their use in the construction industry and finding the possibility for the new material to replace the use of geotextile in landfill system.

1.3 Research Objectives

The main objective of this study is to investigate the geotechnical behaviour of the Residual soil with different percentages of Kenaf Fibre and EFB. The specific objectives of this research are:

a) To determine the physical and engineering properties of Salak Tinggi residual soil (ST1 & ST2) to assess its baseline suitability as a landfill liner material.

b) To determine the influence of Kenaf Fibre and EFB additions at 0%, 5%, 10%, 15%, and 20% by dry weight on the physical and engineering properties of the soil.To investigate the physical and compaction behaviour for soil with different ratio of Kenaf Fibre:EFB

c) To determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of soil-fibre mixtures at varying Kenaf and EFB ratios using the Standard Proctor compaction test.

d) To measure the hydraulic conductivity (k) of compacted soil specimens at various Kenaf:EFB ratios at OMC using the modified oedometer falling head permeability test.

e) To develop a regression-based empirical model to predict hydraulic conductivity from measurable soil and fibre parameters, supporting sustainable soil liner design.

1.4 Significance of Study

The assessment of characteristics of soil in residual soil is essential, as it provides a foundational baseline for determining its appropriateness as a landfill liner material. Residual soils are common in tropical regions like Malaysia and are commonly employed due to their economic efficiency and local availability. Nonetheless, the engineering behavior may differ markedly based on mineral composition and weathering processes. An in depth understanding of the physical and index properties of residual soil is crucial for accurately evaluating the effects of fibre reinforcement, ensuring that any observed performance enhancements are due to the additives rather than the intrinsic variability of the soil.

The investigation of Kenaf Fibre and Empty Fruit Bunch (EFB) integration in compacted soil at different proportions is crucial for advancing sustainable material use in geotechnical engineering. Kenaf Fibre serves as a renewable natural resource characterized by advantageous tensile properties, whereas empty fruit bunch (EFB) represents a plentiful agricultural byproduct produced by the palm oil sector in Malaysia. The investigation of various kenaf–EFB ratios facilitates the identification of an optimal blend that maximizes engineering performance and minimizes environmental impact. This method facilitates waste reduction efforts and provides a beneficial application for bio-based materials in landfill liner systems.

Examining the physical and compaction characteristics of soil combined with different ratios of Kenaf Fibre and EFB is essential for ensuring the constructability and performance reliability of compacted liners. The inclusion of fibre can modify soil structure, influencing factors such as optimum moisture content, maximum dry density, and overall workability during field compaction. Comprehending these alterations enables engineers to formulate mix proportions that ensure sufficient compaction and uniformity, which are essential determinants affecting the long-term stability and efficacy of soil liner systems.

The analysis of hydraulic conductivity in soil–kenaf–EFB mixtures at optimal moisture content is crucial, as hydraulic performance serves as the principal criterion for the efficacy of landfill liners. Low hydraulic conductivity is crucial for preventing leachate migration and safeguarding adjacent soil and groundwater. Prior research has demonstrated that fiber reinforcement can diminish void spaces and enhance dimensional stability, resulting in reduced permeability. This study presents essential

data regarding the impact of different kenaf–EFB ratios on hydraulic conductivity, thereby aiding in the advancement of bio-based liners that comply with regulatory permeability standards.

Establishing a sustainable soil liner model incorporating various ratios of Kenaf Fibre and EFB is significant in advancing environmentally responsible landfill design. The proposed model aims to demonstrate the feasibility of replacing or supplementing conventional geosynthetic liners with locally sourced, biodegradable materials. By integrating performance, sustainability, and resource efficiency, this model contributes new knowledge to geotechnical engineering practice and provides a foundation for future research, field implementation, and policy development focused on sustainable waste containment systems.

1.5 Scope and Limitation

The research will extensively examine the physical properties of Salak Tinggi residual soil and the soil mix with Kenaf Fibre admixture. The scope includes a thorough analysis of Particle Size Distribution (PSD), particle density, Atterberg Limit including liquid limit, plastic limit and plasticity index, and shrinkage limit. These analyses are conducted at Building 1 Soil Laboratory, College of Engineering, UiTM Shah Alam. The geographical focus will be on two (2) specific locations in Salak Tinggi where the residual soil is prevalent to provide valuable insights into the potential application of these materials as an engineered landfill soil liner. However, the findings may be site specific, and generalizability to other regions may require additional studies. Compaction test has contributed to assess the engineering properties of Salak Tinggi residual soil when mixed with Kenaf Fibre admixture. The compaction test is performed using 2.5 kg standard proctor. The research aims to understand the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the mix soil by obtaining from compaction curve at different percentages of Kenaf Fibre and Empty Fruit Bunch (EFB). The findings will contribute valuable information to optimize the engineering properties of the soil mix, but the controlled nature of laboratory testing is a limitation as the onsite field conditions are uncertainties. The study will highlight the hydraulic conductivity properties of the residual soil mixed with different percentage of Kenaf Fibre and EFB as admixtures, with a specific focus on application of landfill liners. Falling Head Test which represent permeability test is conducted in the laboratory to obtain the parameter of hydraulic conductivity, k. The parameter is influent by the soil and Kenaf Fibre properties. All the laboratory tests conducted are repeated three (3) times to obtain the average readings and ensure higher accuracy. The objective in this study also involves an in-depth analysis of the relationship between hydraulic conductivity and varying percentages of Kenaf Fibre and EFB used as the admixture in the soil mix. The analysis is conducted using Minitab Software as lack of expertise of the researcher in using advance engineering analysis software. Time constraints may limit the ability to capture the long-term effects of certain factors on soil properties. Despite these limitations, the research is expected to contribute valuable knowledge to the field of geotechnical engineering and soil management, informing future studies and applications.

1.6 Thesis Outline

The thesis is mainly consisting of five (5) chapters to cover the significant aspect of the physical properties, engineering properties and all related investigations in this research.

Chapter One includes the general knowledge of landfill layer systems, problem statements and Kenaf Fibre and Empty Fruit Bunch (EFB) as an alternative additive in linear systems. Details on the research objective, the study hypothesis, the significant and limitation are all discussed in this chapter.

Chapter two discusses the comprehensive literature review associated with soil liner, Kenaf Fibre and Empty Fruit Bunch (EFB) as an alternative additive material that is used in the study. A review on the current and previous method used in strengthening the soil liner system also presented. A comprehensive literature was collected from the various source such as journals, conference proceeding, established report and standards. The discussion and explanation in this chapter are related to the application of additives in increasing the strength and hydraulic conductivity in soil liner, as well as the advantage of finding sustainable materials in construction of soil liner system.

Chapter three presents the methods and procedures that were employed to meet the objectives of this study. The procedures describe the experimental investigations involving the methods of preparing the samples to determine the physical properties, engineering properties and modelling. The parameters involved in the research thorough the experimental are describe.

Chapter four reports the experimental findings retrieved from physical and engineering properties testing of the soil with different percentages of kenaf. The results obtained are discussed and analysed accordingly before proceed to the modelling. Regression analysis was used to analyse the data from the lab to create the model.

Chapter five concludes the study by highlighting the significant study outcomes and the achievements of the research objectives outlined in this study. Several suggestions for further research in the future within this field of study are also given in this chapter.

CHAPTER 2
LITERATURE REVIEW

2.1 Residual Soil Characteristics

In Malaysia, the population surged to 32.6 million in 2019, resulting in substantial trash generation estimated at approximately 38,200 tons daily (1.12 kg per capita per day) (Ahmad et al., 2019). A solution to eliminate this garbage is to collect and transport it to the municipal waste disposal facility. Municipal Solid Waste (MSW) refers to waste gathered by the municipality or discarded at municipal waste disposal facilities, encompassing residential, industrial, institutional, commercial, and building and demolition waste (Stafford, 2019). A favoured approach to addressing this environmental issue is the disposal of garbage in sanitary landfills, owing to its minimal capital expenditure and straight forwardness. The increasing demand for unbreakable and sustainable infrastructure necessitates creative approaches to environmental control.

The readily traditional soil liners often grapple with limitation in hydraulic conductivity. This limitation can lead to inadequate drainage, ponding and soil pollution that compromised liner performance. Currently, the method used to strengthen the capability of soil liners are bentonite and geopolymer. However, in this context, the emergence of natural readily available material such as Kenaf Fibre and Empty Fruit Bunch (EFB) as potential soil stabilizer for liner construction presents a fascinating and potentially opportunity. Residual soil develops in situ as a result of the extended weathering processes acting on the parent rock, leading to soils that preserve numerous mineralogical characteristics of the initial material (Rahman & Omar, 2020).

The soils frequently display significant heterogeneity, characterized by differences in grain size, structure, and weathering intensity, which are influenced by the local climate and geological conditions (Huat et al., 2019). In tropical regions like Malaysia, residual soils are generally abundant in kaolinitic clay minerals and iron oxides, which affect their plasticity, strength, and permeability properties (Lim & Kassim, 2021). Given these unique characteristics, it is crucial to comprehend the

engineering properties of residual soils for their applications in geotechnical and environmental engineering (Tan & Goh, 2022).

2.1.1 Definition and Formation of Residual Soil

Residual soils are generated in situ by the extensive weathering of parent rock and are distinguished by a significant correlation between their engineering properties and the mineralogical composition of the underlying geology. In humid tropical regions like Malaysia, extensive chemical weathering generates highly diverse profiles, varying from saprolite at depth to lateritic crusts at the surface. These soils are typically characterized by the predominance of Kaolinite, Gibbsite, and Iron and Aluminum Oxides, including Goethite and Hematite, which confer characteristic reddish-brown hues and affect their plasticity, structure, and drainage properties (Yamusa et al., 2022)

Residual soils differ from transported soils in that their properties change gradually with depth and they still have structures from the source rock. When building a landfill liner, this inherited structure may affect how strong and permeable it is in different directions. It needs to be carefully regulated with the right compaction methods. Prior evaluations of Residual soils utilized as compacted soil liners have underscored their prospective benefits, including sufficient fines content and plasticity, alongside the difficulties posed by their unpredictability and susceptibility to compaction water content (Emmanuel, 2019; Taha & Kabir, 2005).

2.1.2 Engineering Properties of Residual Soil

The engineering qualities of residual soils that are most important for liner performance are particle size distribution, Atterberg limits, specific gravity, compaction characteristics, and mineralogical composition. Fines content (silt and clay fraction) in tropical residual soils considered as suitable liners is frequently recorded in the range of 30-80%, with plasticity index values classed as low to medium plastic clays or silty clays (Yamusa et al., 2022). These soils may have specific gravity values ranging from 2.55 to 2.80, indicating the presence of quartz, feldspar, and clay minerals with varied Iron Oxide contents (Yong et al., 2019).

Recent investigations into tropical residual soils for sustainable landfilling have demonstrated that hydraulic conductivity can fluctuate by several orders of magnitude, ranging from approximately 1×10^{-3} m/s in coarser, less weathered materials to as low as 1×10^{-11} m/s in well-compacted fine-grained residual soils (Yamusa et al., 2022). The wide range of behaviour is strongly influenced by clay fraction, pore structure, compaction effort and initial degree of saturation. Many residual soils can meet the usual standards for hydraulic conductivity for landfill liners when they are compacted properly (Chinade & Yunusa, 2024).

Figure 2.1 illustrates a illustrates the three-stage pedogenic transformation of parent rock into a mature residual soil profile, highlighting the gradational transition from unweathered bedrock to fully weathered material. Over thousands of years, the combined effects of physical disintegration and intense chemical weathering specifically the hydrolysis of feldspars and oxidation result in the development of a stratified regolith characterized by distinct A, B, and C horizons. For engineering applications, the B-horizon is identified as the optimal depth interval for liner construction due to its high fines content (>55%) and plasticity (PI > 15%), which allow for the achievement of low hydraulic conductivity targets (1 x 10^{-9} m/s) when properly compacted(Yong et al., 2019). Conversely, the saprolite (C-horizon) and deeper highly weathered zones are deemed marginal or unsuitable because relict rock structures and corestones create preferential flow paths that compromise the integrity of hydraulic barriers (Yamusa et al., 2022).

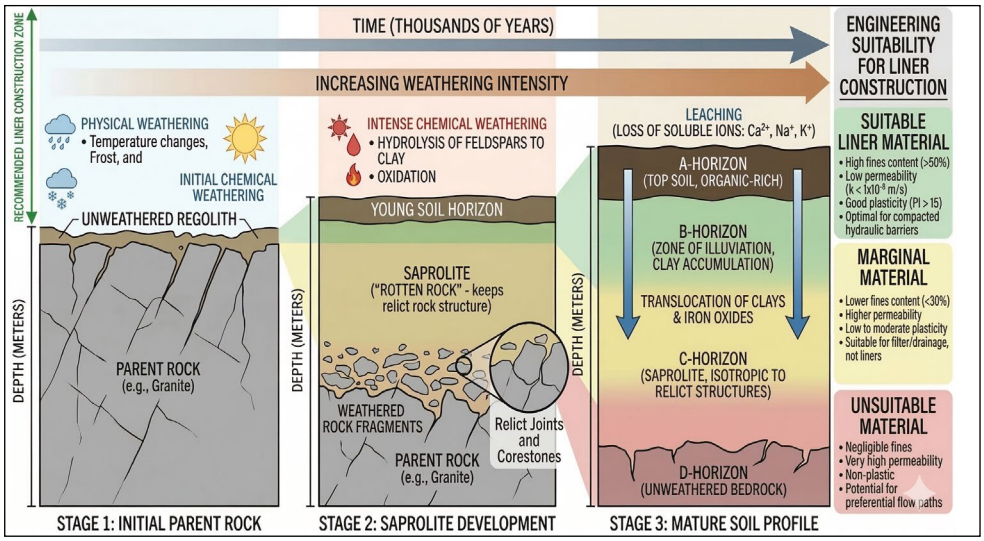


Figure 2.1 Formation of Residual soil

Figure 2.2 depicts a standard Residual soil profile, emphasizing the gradational transitions from decomposed rock to fully weathered material, as well as the area's most appropriate for liner construction. The picture highlights the depth intervals where the fines content and plasticity are suitable for hydraulic barrier applications. Table 2.1 presents the typical engineering properties of tropical Residual soils that are commonly considered for landfill liner applications, including parameters such as fines content, clay content, Atterberg limits, compaction characteristics, and hydraulic conductivity. The values indicate that tropical residual soils generally meet or exceed the recommended liner criteria, particularly in terms of fines content, plasticity, and low hydraulic conductivity, which are essential for providing effective containment and minimizing leachate migration in landfill systems.

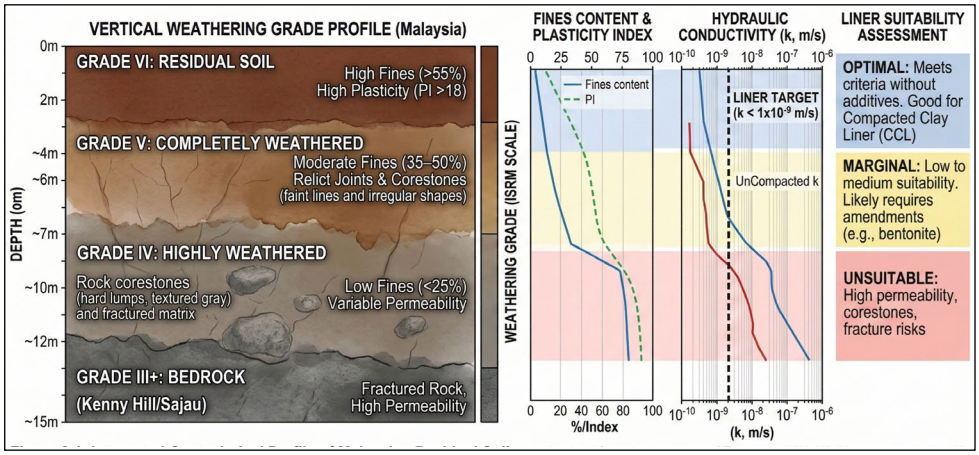


Figure 2.2 Typical Profile of Tropical Residual Soil in Malaysia (Yamusa et al., 2022; Yong et al., 2019)

Table 2.1
Typical engineering properties of tropical residual soils considered for landfill liner applications (Yamusa et al., 2022a; Yong et al., 2019)

Property	Typical Value/Range	Recommended Liner Criteria
Fines Content (< 0.075 mm)	55% – 95%	≥ 30%
Clay Content (< 0.002 mm)	25% – 50%	≥ 15%
Liquid Limit (LL, %)	40% – 85%	≥ 20%
Plasticity Index (PI, %)	15% – 45%	≥ 10% - 12%

Specific Gravity (G_s)	2.55 – 2.75	N/A
Optimum Moisture Content (OMC, %)	18% – 28%	N/A
Maximum Dry Density (MDD, Mg/m³)	1.45 – 1.85	N/A
Hydraulic Conductivity (k, m/s)	10^{-7} to 10^{-10} m/s	$\leq 1 \times 10^{-9}$ m/s

2.1.3 Suitability of Residual Soil as Landfill Liner

The appropriateness of residual soil as landfill liner material is essentially determined by its capacity to meet established criteria for hydraulic conductivity, strength, and volumetric stability. International guidelines and recent reviews indicate that soils employed as liners for hazardous and non-hazardous waste should demonstrate saturated hydraulic conductivity of approximately 1×10^{-9} m/s or lower, whereas less rigorous standards up to 1×10^{-7} m/s may be permissible for inert wastes (Chinade & Yunusa, 2024). Moreover, minimum fines content, minimum unconfined compressive strength, and restrictions on volumetric shrinkage strain are typically mandated to guarantee the enduring integrity of the barrier (Yong et al., 2019); (Taha & Kabir, 2005)

Research on compacted tropical residual soils has shown that these standards can frequently be achieved when the soil is compacted at or just above its optimal moisture content, provided there is sufficient compactive effort and stringent quality control (Yamusa et al., 2022a). Nevertheless, other studies have indicated that variations in gradation and fabric may result in erratic trends in hydraulic conductivity and shear strength, highlighting the necessity for project-specific characterization and, when necessary, modification using additives or stabilizers (Yong et al., 2019). Figure 2.3 illustrates the comparative performance envelopes for standard compacted clay liners (CCL) and processed tropical residual soils, defining the "acceptable zone" where the dual requirements for hydraulic conductivity $k \leq 1 \times 10^{-9}$ m/s and minimum shear strength are simultaneously satisfied. As evidenced by the shaded overlap, residual soils which naturally exhibit erratic geotechnical trends due to relict rock fabrics and the presence of pseudo-particles can achieve a performance level equivalent to standard liners when appropriately remoulded and compacted at a moisture content typically 2% to 4% wet of optimum (WOP) (Emmanuel & Akinyemi, 2020). This processing window

effectively collapses the internal soil microstructure, reducing the bimodal pore distribution and ensuring a more homogeneous, low-permeability barrier suitable for waste containment applications (Yamusa et al., 2022).

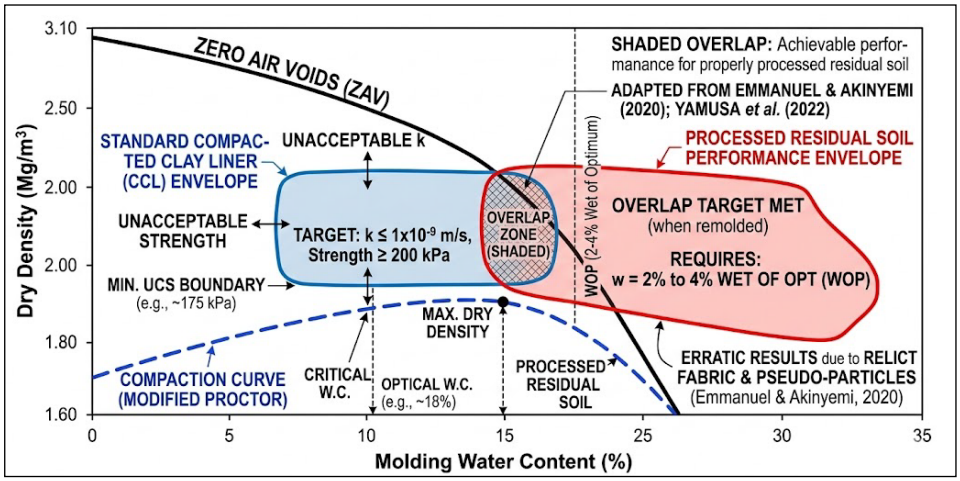


Figure 2.3 Comparative Performance Envelopes for Standard CCL and Processed Compacted Tropical Residual Soil

2.2 Bio-Fibres as Soil Improvement Materials

Bio-fibres have garnered significant interest as sustainable materials for soil enhancement, attributed to their natural abundance, affordability, and lower environmental footprint in comparison to traditional synthetic additives (Sharma & Kumar, 2020). The incorporation of fibres like kenaf, coconut coir, and EFB significantly enhances soil performance. These materials improve tensile resistance, mitigate shrink-swell behaviour, and reinforce the soil matrix through effective fibre-soil interlocking mechanisms (Ali et al., 2021). With the increasing global focus on sustainable engineering, the incorporation of bio-fibres presents a valuable option for improving soil stability, while also promoting waste utilization and practices aligned with the circular economy (Hameed & Aziz, 2022).

2.2.1 Kenaf Fibre in Geotechnical Engineering

Kenaf (Hibiscus cannabinus L.) is a rapidly growing annual plant which bast and core fibers have garnered significant interest as reinforcement in polymers, concrete, and soil. Recent evaluations of Kenaf Fibre composites have highlighted their considerable tensile strength and stiffness, low density, and advantageous

biodegradability, all of which enhance its appeal as a sustainable reinforcement material (Huang et al., 2025). A significant portion of the existing research has concentrated on polymer matrices, however an increasing number of studies investigate the integration of kenaf fibers in clayey soils and clay-based composites for geotechnical purposes (Emmanuel & Akinyemi, 2020; Yonli et al., 2025).

In minimal proportions, kenaf fibers serve as discrete reinforcing components that connect microcracks, augment ductility, and boost post-peak strength, thus diminishing the probability of desiccation cracking in compacted liners. Experimental investigations on marine clay–kenaf composites intended for landfill liners have indicated an optimal kenaf fiber content of approximately 4%, at which hydraulic conductivity is sustained within acceptable thresholds ($\approx 10^{-8}$ to 10^{-9} m/s), while maximum dry density and stiffness are either preserved or marginally enhanced (Emmanuel & Akinyemi, 2020). The findings indicate that kenaf fibre, when administered in precise quantities, can augment the mechanical properties of clay liners without detriment, and in certain instances, enhance their barrier efficacy. Figure 2.4 may be used to show a scanning electron micrograph of Kenaf Fibre surface morphology, highlighting its rough texture and fibrillated structure, which promote mechanical interlocking with soil particles.

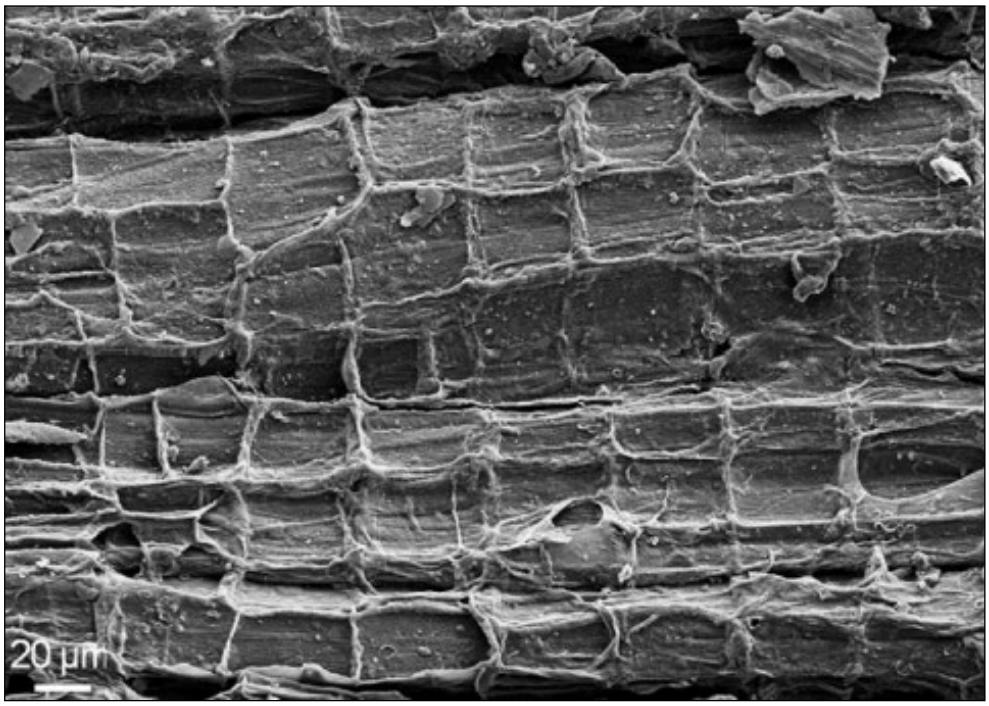


Figure 2.4 SEM Image of Kenaf Fibre (Hanipah et al., 2025)

2.2.1.1 Characterization and Properties of Kenaf

Kenaf is produced in more than 20 countries, with a total output of 216,200 tonnes of kenaf and related fibres in 2014 to 2015(Chu et al., 2021). It originated in Africa, but India and China produce more than 70% of the world's kenaf, making it the major source of bast fibre in these countries (Yi Sim & Lin Nyam, 2021).

According to (Ridzuan et al., 2018), natural fibres are characterized by their high content of cellulose, hemicelluloses, pectin, and lignin, and they are notable for their plentiful hydroxyl groups. One of the examples of these fibres is kenaf. The distinct characteristics of these fibres include their hydrophilic properties and strong polarization, distinguishing them from polymer materials that are inherently nonpolar and hydrophobic. Kenaf has been identified as a crucial source of fibre for numerous industrial applications and composite materials. To enhance the mechanical strength of composites, it is essential to impart hydrophobic properties to these fibres, typically achieved through surface treatments. Natural fibres can undergo physical and chemical modifications to enhance their performance in composite materials.

2.2.1.2 Composition of Kenaf Fibre

Kenaf Fibre has emerged as a significant plant cultivated in developing countries and is recognized as an industrial crop. It holds significant promise for substituting synthetic fibres like glass fibre. The application of kenaf fibre offers mechanical properties, such as tensile strength, that are comparable to synthetic fibre, while maintaining a lower density than conventional materials. This leads to the development of lightweight and environmentally friendly polymer composites. The performance of kenaf-reinforced polymer composites is influenced by various factors, including chemical treatment, fiber content, the specific part of the kenaf fiber utilized, the fiber form, and water absorption (Tezara et al., 2016) .

2.2.1.3 Effects of Kenaf Fibre in Increasing Soil

The influence of fiber content on the tensile strength of pultruded kenaf fiber composites was investigated by (Fauzi et al., 2016). The study revealed that the tensile strength of the pultruded kenaf fiber composites improved as the fiber percentage

increased by 50%. When fiber loading exceeds 50%, there is a slight reduction in tensile strength. In addition to the fiber content, the tensile properties of kenaf-reinforced polymer composites are significantly affected by the orientation of the fibers. (Yong et al., 2019)investigated the influence of fiber orientation on the mechanical characteristics of kenaf–polyester sandwich composites.

In addition to bentonite, kenaf fiber has garnered significant interest as a compelling topic of discussion within this research domain. (A. Rahman et al., 2023) have conducted a study on the use of kenaf core fiber combined with marine clay as a material for landfill liners. The key findings of the study indicate that the incorporation of kenaf core fiber into marine clay soil has led to an improvement in maximum dry density and a reduction in permeability. This demonstrates the potential of utilizing natural materials, such as kenaf core fibre, to enhance the performance of landfill liner materials.

Another study by (Shirvani et al., 2019) focused on the enhancement of the engineering behaviour of sand-clay mixtures through the incorporation of kenaf fiber reinforcement. The study clearly highlighted that the combination of kenaf fiber with the soil mixture enhances the ductility of the mixture and improves the shear strength parameters. This illustrates the possible use of kenaf fiber in improving the engineering properties of sandy-clay mixtures for a range of geotechnical applications.

2.2.1.4 Physical and Chemical Properties of Kenaf

The evaluation of the physical properties of marine clay soil indicated characteristics that render it appropriate for landfill applications. The findings from the Atterberg limit tests indicated a plastic limit of 28.8%, a liquid limit of 49.31%, and a plasticity index of 20.51%, all aligning with industry standards for liner suitability. The composition consists predominantly of silt at 65.01%, followed by sand at 17.89%, and clay at 17.03%. The total fine particle content, which includes both silt and clay, reaches 82%, satisfying the criteria for materials designated for landfill liners. The particle density test result of 2.61 mg/m^3 indicates its suitability as a liner material, as it falls within the acceptable range for landfill applications. The low hydraulic conductivity of

this marine clay enhances its effectiveness as a soil liner for landfills(A. Rahman et al., 2023).

2.2.2 Empty Fruit Bunch (EFB) Fibre

Oil Palm Empty Fruit Bunch (OPEFB or EFB) constitutes a significant solid waste produced by the palm oil industry. Significant volumes of EFB are generated each year in Malaysia and adjacent nations, making its sustainable utilization a prominent area of research. Recent state of the art reviews indicates that EFB fibres are lignocellulosic materials with relatively high cellulose content, low density and significant surface roughness. They have been extensively studied as reinforcements in polymer and cementitious composites, as well as in asphalt and lightweight concrete (Pickering et al., 2016; Rama Rao & Ramakrishna, 2022)

From a geotechnical standpoint, EFB have been examined as stabilizing agents in soft clays and other problematic soils. Durability studies indicate that EFB maintain a considerable percentage of their tensile strength after prolonged soil exposure. However, biodegradation and moisture sensitivity remain key challenges for natural fibre-based materials, and these limitations often need to be mitigated through chemical treatment and durability-oriented design strategies for long-term applications (Arunachalam et al., 2024; Ramful, 2024). Incorporating EFB fibres into clay soils at low to moderate levels might enhance shear strength and diminish brittleness and it may also elevate void ratio and affect compaction behaviour and moisture retention (Rama Rao & Ramakrishna, 2022). Figure 2.5 can be used to present the microstructural characteristics of EFB fibre under SEM, emphasising the lumen, cell wall structure and surface roughness that influence water absorption and bonding with soil particles.

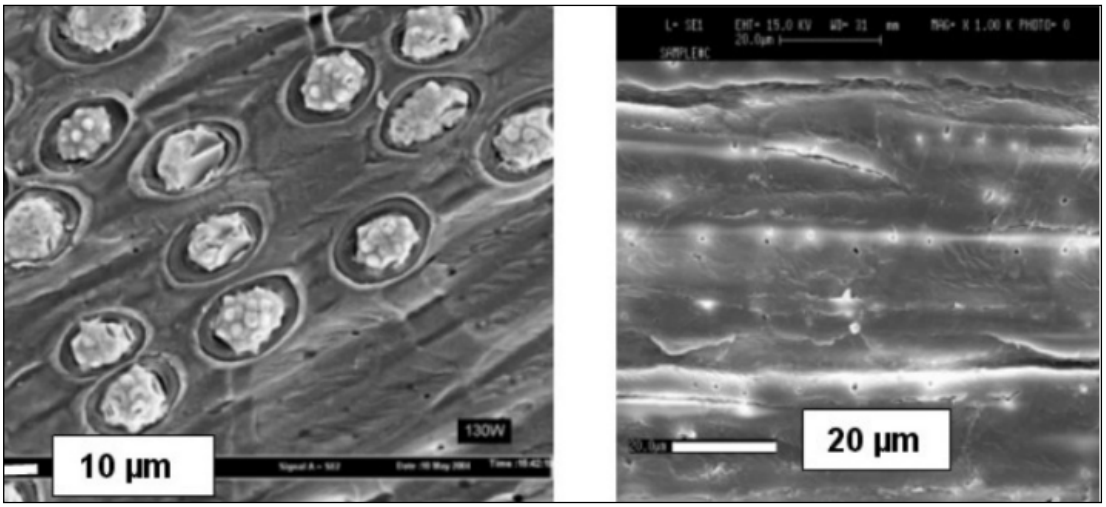


Figure 2.5 SEM Micrograph of EFB Fibre Relevant to Water (Law et al., 2007)

2.2.2.1 Characterization and Properties of Empty Fruit Bunch

In Malaysia, the excessive production of agricultural commodities, including oil palm fibre and its byproducts (EFB, Oil Palm Trunks, and Oil Palm Fronds), occurs in numbers reaching millions of tons annually (Ashik & Sharma, 2015). Malaysia, a tropical nation, experiences a consistently hot climate year-round, facilitating the production of oil palm. Commencing in 1960, the Malaysian oil palm sector has evolved into a significant contributor to Malaysia's Gross Domestic Product (GDP) and has generated substantial employment possibilities. The export volume of palm oil surged from 1.17 million tonnes in 1975 to 16.05 million tonnes in 2016, reaching over 200 global markets (Nambiappan et al., 2018). Malaysia, being one of the top producers of oil palm globally, has generated significant waste from the oil palm industry.

Empty fruit bunches enhance the physical properties of soil by augmenting its water retention capacity, hence allowing soft soil to be compacted (Arifin et al., 2019a). A substantial quantity of empty fruit bunches is available due to numerous oil palm plantations worldwide. Typically, 16 empty fruit bunches are classified as waste due to the few applications available for them. Carelessly disposing of an empty fruit bunch generates considerable greenhouse gas emissions (Chew et al., 2023).

2.2.2.2 Changes in Liquid Limit (LL), Plastic Limit (PL) and Plasticity Index(PI)

Adding Kenaf Fiber and EFB to soil usually modifies its Atterberg limits, although the amount of change depends on the fibre concentration, fibre length, and how they are mixed. Kenaf fibres have a rough surface and can hold water molecules through capillary action. When modest amounts of fibres are introduced, the Liquid Limit (LL) goes up slightly. This happens because more water is needed to make the interactions between the fibre surface and soil particles smoother, which makes the soil look more "plastic." (Nguyen & Indraratna, 2023) said that adding natural fibre usually raises LL by 2–10%, depending on the amount used. However, the rise is not big enough to change the soil into a high-plasticity clay that would not work for liner applications . *PL* however, may increase or decrease depending on the Kenaf Fibre:EFB ratio. Long kenaf fibres tend to increase *PL* by reducing soil workability and increasing resistance to deformation as the soil begins to lose moisture. Meanwhile, the more porous EFB fibres enhance water retention, which may also cause a slight increase in *PL*. Overall, the *PI* of the blended soil typically remains within a moderate range of approximately 15–25%, a range considered stable and suitable for liner applications because it minimises shrink–swell risks.

2.2.3 Synergistic Behaviour of Mixed Natural Fibres (Kenaf Fibre and EFB)

The hybridization of natural fibre has surfaced as an effective approach to enhance mechanical performance while mitigating variability and durability concerns. Recent evaluations of natural fibre-reinforced hybrid composites indicate that the amalgamation of fibres with varying stiffness, aspect ratio, and surface properties can yield synergistic enhancements in strength, toughness, and dimensional stability, contingent upon the meticulous optimization of proportions and processing conditions (Suriani et al., 2021) as shown in Figure 2.6.

This work aims to combine Kenaf Fibre and EFB (KEFB) in residual soil to leverage the superior stiffness and tensile strength of kenaf alongside the large surface area and moisture interaction properties of EFB. Research on hybrid kenaf–EFB composites demonstrates that optimal combinations of these fibres enhance load

transmission, impact resistance, and crack-bridging capability relative to single fibre systems (Hanan et al., 2020).

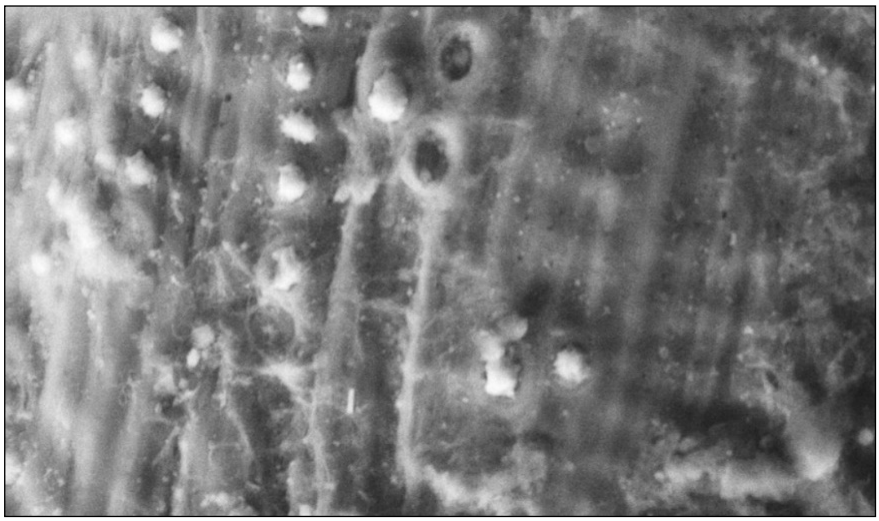


Figure 2.6 Microstructural Characteristics of EFB Fibre under SEM(Suriani et al., 2021)

2.2.4 Potential of Using Empty Fruit Bunch as Soil Stabilizer in Soil Liner

Recent developments have heightened industry understanding regarding sustainable materials. The utilization of renewable materials and environmentally sustainable resources, such as natural fibres, has demonstrated significant demand, concurrently fostering interest among researchers to further investigate natural materials like Kenaf Fiber and EFB. EFB is an easily accessible agricultural byproduct from oil palm cultivation. Agricultural waste represents a viable and sustainable substitute for conventional soil stabilizing techniques. Their qualities offer potential for addressing diverse engineering challenges.

EFB by-product from the palm oil industry comprises cellulose, hemicellulose, and lignin, which are anticipated to serve as fiber material when combined with cement for soil stabilization (Simarmata et al., 2023). The porous composition of EFB facilitates enhanced water drainage, hence augmenting the efficacy of soil liners and drainage systems (Rosenani et al., 2016). EFB serves as a natural fiber to enhance the stability of fragile soil, facilitating compaction to augment overall strength (Arifin et al., 2019). Moreover, EFB possesses a significant capacity for water absorption, thereby facilitating the soil stabilization process(Arifin et al., 2019).

2.2.5 Previous Research on EFB as Soil Additive

Soil compaction is the densification of soil by minimizing the voids or air spaces between soil particles. It transpires when soil particles are compacted to diminish the interstitial space among them. Research has determined that compacted laterite soil containing 8% EFBA is an appropriate material for constructing low-volume roads. This may result from cation exchange processes and the presence of EFBA populating the voids within the soil matrix (Oke et al., 2020). A recent study examined the physical and mechanical properties of oil palm empty fruit bunch (EFB) woven kenaf fabric-reinforced epoxy, revealing that an increase in kenaf fiber content in compacted soil resulted in enhanced tensile strength and improved flexural properties (Hanan et al., 2020).

2.2.6 Implications for Workability and Soil Classification

The addition of fibers affects the Atterberg limits, which in turn has significant implications for soil workability during compaction. Soils exhibiting excessively high liquid limit (LL) and plastic limit (PL) necessitate increased compaction energy, while soils characterized by very low plasticity index (PI) tend to become brittle and susceptible to cracking during drying.

2.3 Influence of Kenaf–EFB Admixture on Physical and Compaction Behaviour

The incorporation of Kenaf Fibre and EFB into soil markedly influences its physical properties and compaction characteristics. The interaction of these materials with soil particles occurs through various microstructural mechanisms, including mechanical interlocking, pore filling, and alterations in aggregate arrangement. The modifications affect the soil mixture's ability to achieve optimal density, control shrinkage behaviour, and maintain a stable matrix structure suitable for low-permeability liner applications. Understanding these interactions is crucial, as the hydraulic performance of a liner system is greatly affected by its initial compaction structure and the subsequent changes in soil porosity following compaction.

2.3.1 Effects on Compaction Behaviour in Residual Soil

The behaviour of compaction in Residual soils is significantly affected by their mineral composition, the arrangement of particles, and the processes of natural weathering. Residual soils, originating in place from the extended weathering of parent rock, generally exhibit a significant composition of fines, diverse clay mineralogy, and an irregular microstructure. The characteristics significantly influence the determination of the soil's Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). For instance, soils that contain greater amounts of clay and silt typically show elevated optimum moisture content and reduced maximum dry density, attributed to their enhanced ability to adsorb water and the formation of diffuse double layers surrounding the finer particles (Ghazali, 2015). As a result, residual soils commonly require greater moisture to achieve effective compaction compared to sedimentary soils with more uniform grain sizes.

The variation in moisture content is a crucial factor influencing the compaction behaviour of residual soil. Elevating water content at the outset enhances particle lubrication, enabling soil grains to reorganize into a more compact packing arrangement, which in turn raises the maximum dry density. Once the OMC is surpassed, the extra water fills void spaces and diminishes matric suction, resulting in a reduction of dry density (Rahardjo et al., 2019) . The relationship between moisture and density is especially significant in tropical areas like Malaysia, where residual soils are prevalent and variations in moisture content can greatly impact compaction

performance. Residual soils composed of active clay minerals such as kaolinite and halloysite exhibit elevated sensitivity to moisture due to their fine mineral structures and water retention characteristics, which influence plasticity characteristics and soil behaviour under varying moisture conditions (Huat et al., 2012; Indrawan et al., 2024).

The behaviour of compaction is also affected by the soil structure, level of weathering, and the existence of both macro- and micro-pores. Residual soils that have undergone significant weathering frequently exhibit aggregates and cemented structures, which pose challenges to densification during the compaction process. The disintegration of these aggregates necessitates increased compactive energy, and even so, the resulting densities might be inferior when compared to less weathered soils (Gofar & Kassim, 2020). The differences in microstructure result in non-linear compaction behaviours, causing the soil to respond differently when subjected to Standard Proctor compared to Modified Proctor energy levels. Observations indicate that greater compactive energy is more effective in collapsing weak aggregates, resulting in a denser structure, although this may lead to increased brittleness in certain instances (Shukla et al., 2022).

In engineering applications, the compaction characteristics of residual soils significantly influence the performance of infrastructure, including landfills, embankments, and road subgrades. Attaining suitable MDD and OMC is essential for guaranteeing low hydraulic conductivity, sufficient shear strength, and enduring stability. A number of studies highlight that inadequate management of moisture and compaction efforts can lead to significant settlement, heightened permeability, or deterioration of structural integrity when subjected to load (Abdullah et al., 2023). Consequently, grasping the distinct compaction characteristics of residual soils is crucial for the design of sustainable and dependable geotechnical structures, especially in tropical settings.

2.3.1.1 General Trends of Fibre Content on OMC and MDD

The inclusion of organic fibres such as kenaf and oil palm empty fruit bunch (EFB) generally results in a reduction in Maximum Dry Density (MDD) and a slight increase in Optimum Moisture Content (OMC). This behaviour is primarily attributed to the lower specific gravity of fibres relative to mineral soil particles, as well as the

formation of additional void spaces within the soil matrix that are difficult to compress fully. Furthermore, the water absorption capacity of natural fibres increases the moisture demand during compaction. Similar trends have been reported in fibre-reinforced soils, where increasing fibre content led to higher OMC values and reduced maximum dry density due to fibre-induced porosity and lightweight characteristics (Rajaee et al., 2021; Akinwumi et al., 2021).

However, at low fibre contents, a slight increase in MDD has been observed in certain fibre–soil systems. This improvement is attributed to enhanced soil particle interlocking and improved aggregate breakdown, which may promote more efficient packing at optimum fibre inclusion. Beyond this optimum level, further increases in fibre content typically result in a decline in MDD due to fibre crowding, disruption of soil matrix continuity, and increased uncontrolled porosity. This competing mechanism between improved packing at low fibre content and void generation at higher fibre content has been documented in recent fibre-reinforced soil studies (Mirzababaei et al., 2019; Rajaee et al., 2021).

However, at an optimal content, fibres can produce higher MDD values than soil without fibres because they help break down soil aggregates and fill voids more efficiently. This phenomenon was reported in clay–kenaf and residual soil–kenaf mixtures by Rahmana et al. (2023), where MDD increased at low fibre percentages (<10%) but decreased again at higher contents because excessive fibres generated uncontrolled porosity in the mix.

2.3.1.2 Compaction Behaviour of Kenaf-Reinforced Soils

The compaction behavior of residual soils is significantly affected by their mineralogical composition, particle arrangement, and natural weathering processes. Residual soils, formed in situ through the extended weathering of parent rock, generally exhibit a high content of fines, diverse clay mineralogy, and a heterogeneous microstructure. The characteristics significantly influence the soil's Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). Soils characterized by elevated clay and silt fractions typically demonstrate increased optimal moisture content (OMC) and decreased maximum dry density (MDD), attributable to enhanced water adsorption capacity and the formation of diffuse double layers surrounding fine particles (Ng et al.,

2020). Consequently, residual soils typically necessitate increased moisture levels to attain effective compaction in comparison to sedimentary soils characterized by more uniform grain sizes.

Moreover, moisture variation significantly influences the compaction behaviour of residual soil. An increase in water content initially enhances particle lubrication, enabling soil grains to reorganize into a denser packing arrangement, which subsequently raises the maximum dry density (MDD). Once the optimal moisture content is surpassed, the excess water fills voids, diminishing matric suction and resulting in a reduction of dry density (Rahardjo et al., 2019). The moisture-density relationship is critical in tropical regions like Malaysia, where residual soils are prevalent and variations in moisture content can significantly impact compaction performance. The sensitivity to moisture increases when residual soils include active clay minerals like kaolinite or halloysite, recognized for their distinctive water absorption and structural characteristics (Huat et al., 2012; Indrawan et al., 2024).

The compaction behaviour is influenced by soil fabric, weathering degree, and the presence of macro- and micro-pores. Residual soils that have undergone significant weathering frequently exhibit aggregates and cemented structures, which impede densification during the compaction process. Lateritic residual soils often contain weakly bonded soil aggregates formed through tropical weathering processes. During compaction, the application of high compactive effort may cause these aggregates to break down and alter the soil particle-size distribution. However, increasing the compactive effort does not necessarily result in a proportional increase in dry density because the compaction response is also controlled by the soil moisture condition and degree of saturation.

Consequently, relatively low levels of compaction may still be obtained despite the application of high compactive effort (Ampadu & Arthur, 2022). The variability in microstructure results in non-linear compaction responses, causing soil behavior to differ under Standard Proctor and Modified Proctor energy levels. Greater compactive effort can overcome part of the resistance provided by the aggregated structure of tropical residual soil, reducing the size and frequency of dominant macropores and producing a denser soil fabric. Nevertheless, even high compactive effort may not completely eliminate the bimodal pore structure inherited from the natural soil aggregation(Lopes et al., 2022).

Recently, the researchers have come with few ideas of mixing the natural fibers as a soil stabilizer to increase the properties of soil. As the result, the admixture samples became prominent in solving the geotechnical issues such as settlement problem and bearing capacity failures. Soil improvement interacts with the soil through friction and adhesion properties. (Manaf et al., 2018). (Rashid et al., 2017) conducted laboratory model tests to examine the effects of single-layer woven kenaf geotextile reinforcement on the bearing capacity of the reinforced sand. The study has found that the bearing capacity of the kenaf-reinforced sand was increased when compared to that of the untreated sand.

The present study revealed that marine clay possesses sufficiently favourable physical properties for application as a landfill liner, with tests conducted on mixtures of Kenaf Fibre and Marine Clay to evaluate their effectiveness as enhanced landfill liner material. The results indicate that marine clay possesses notably sufficient physical and engineering properties. The permeability test conducted on marine clay soil with the inclusion of kenaf core fibre revealed that the hydraulic conductivity of the sample's admixture at 4% yielded permeability values of 6.68×10^{-9} and 1.57×10^{-8} m/s, meeting the requirements for liner material (Rahman et al., 2023). Extended and robust kenaf fibers improve the microstructural formation of soil during compaction. When Kenaf Fibers are compressed with soil, they serve as links between soil aggregates and diminish the propensity of the aggregates to create macrovoid networks. The decrease in macrovoids leads to a denser soil structure, facilitating a more uniform compaction state.

2.3.1.3 Compaction Behaviour of EFB-Amended Soils

EFB fibres behave somewhat differently because they are lighter, more porous, and absorb significantly more water. At low percentages, EFB fibres help maintain moisture during compaction, creating a more stable condition for achieving OMC accurately. However, at higher contents, soil density decreases because EFB fibres form a more open, porous structure that increases the number of larger void pathways. In liner applications, this may adversely affect hydraulic conductivity if fibre dosage is not controlled properly.

2.3.1.4 Microstructural Interpretation of Kenaf–EFB–Soil Interaction

The microstructural interaction of kenaf fibre, empty fruit bunch (EFB), and residual soil is pivotal in augmenting soil behavior via enhanced bonding, interlocking, and pore modification. Lignocellulosic fibers create rough surfaces and irregular geometries that modify particle arrangement and diminish void continuity, thereby affecting compaction, shear strength, and hydraulic conductivity (Ibrahim et al., 2021). Comprehending these micro-level dynamics is crucial for assessing the efficacy of natural fibre–stabilised soil systems and for facilitating their implementation in sustainable geotechnical applications (Hosseini et al., 2023).

2.3.1.5 Expected Behaviour of Residual Soil with Different Kenaf:EFB Ratios

In residual soils, these impacts are anticipated to be more severe due to their inherent composition of sand, silt, and clay mixes. The intrinsic bigger pore spaces in residual soils can be markedly diminished with the incorporation of fibers. The ideal kenaf:EFB ratio is expected to range from 1:1 to 2:1 (e.g., 5% kenaf + 5% EFB or 7.5% kenaf + 5% EFB), as shown by Ahmad et al. (2024), as this ratio optimally combines the reinforcing power of kenaf with the pore-filling capacity of EFB.

2.3.1.6 Optimal Fibre Content from Previous Studies

Previous studies consistently show that combined Kenaf Fibre and EFB at a total dosage of 5% to 10% provide the best improvements in OMC, MDD, reduction of desiccation cracking, and development of a denser microstructure. When the dosage exceeds 15% to 20%, soil performance generally declines because excessive fibres create large interconnected voids and reduce soil density. Therefore, these findings underscore the need to determine the optimum Kenaf Fibre:EFB ratio specifically for Residual soil, which is a central focus of the present study in subsequent chapters.

2.4 Hydraulic Conductivity Behaviour of Fibre-Reinforced Soil

The hydraulic conductivity, (k), of fibre-amended soil is influenced by the properties of the parent soil as well as fibre type, content, length and morphology. Fibre

inclusion modifies the soil pore structure and may create additional flow paths within the fibres or along the soil–fibre interfaces. Consequently, natural lignocellulosic fibres may increase water permeability by introducing internal and interfacial flow channels, whereas synthetic fibres may either decrease or increase hydraulic conductivity depending on their dosage and arrangement within the soil matrix. Therefore, the hydraulic response of fibre-reinforced soil is not uniform, and an optimum fibre content may exist for achieving the desired hydraulic performance (Amini et al., 2021; Ni et al., 2019).

The incorporation of fibres may reduce soil hydraulic conductivity by modifying pore connectivity and restricting the development of continuous seepage pathways. When fibres are uniformly distributed, they can interact with soil particles to form a fibre-netting or bridging mechanism that obstructs interconnected pores, limits the migration of fine particles and improves resistance to seepage-induced internal erosion. This effect may be more pronounced in denser soil matrices, where the reduced pore space allows the fibres to interact more effectively with the surrounding particles (Yang et al., 2019) . Furthermore, improved bonding and sealing at the fibre–soil interface can restrict preferential flow channels. In bio-cemented fibre-reinforced sand, calcium carbonate seed pretreatment promoted mineral precipitation around natural fibres, enhanced fibre–matrix interfacial bonding and effectively sealed preferential flow paths, thereby reducing hydraulic conductivity (Guo et al., 2023).

These findings indicate that the hydraulic performance of fibre-reinforced soil depends not only on fibre content and distribution but also on soil density and the effectiveness of bonding at the fibre–soil interface. Figure 2.7 shows the example of fibres whose irregular and fibrous structure can influence soil pore structure and contribute to the modification of hydraulic conductivity when mixed with soil.



Figure 2.7 Irregular and Fibrous Structure

2.4.1 Hydraulic Conductivity Requirements for Liner Materials

The main factor that influences the barrier function of landfill liners is hydraulic conductivity (k). International guidelines typically require that compacted liners for both municipal and hazardous waste exhibit a saturated hydraulic conductivity of around 1×10^{-9} m/s or lower. However, more adaptable standards permit values reaching up to 1×10^{-7} m/s for inert wastes (Chinade & Yunusa, 2024). The aim of these limits is to regulate the flow of leachate into the subsurface during both the operational phase and the post-closure period of a landfill.

For compacted clay and residual soil liners, achieving low k values depends on having an adequate fines content, reaching high dry density through effective compaction, ensuring proper moisture management, and minimizing macro-defects such as cracks and poorly compacted joints. Studies on tropical residual soils and laterites reveal that hydraulic conductivity decreases with an increase in dry unit weight and initial degree of saturation. Additionally, it has been noted that target k values can be attained when specimens are compacted at or slightly above the optimum moisture content (Ahmad et al., 2019; Indrawan et al., 2024; Yamusa et al., 2022).

2.4.2 Effect of Kenaf and EFB on Hydraulic Conductivity

The influence of natural fibres on hydraulic conductivity is intricate and can either be advantageous or disadvantageous, contingent upon factors such as fibre type, dosage, geometry, and their interaction with the soil matrix. Fibres can alter the pore

structure by creating additional voids nearby, which may result in an increase in *k*, especially at higher concentrations. On the other hand, fibres can improve moisture retention, minimize desiccation cracking, and uphold a more stable microstructure, which can lead to a gradual reduction in *k* over time (Emmanuel & Akinyemi, 2020; Arifin et al., 2022).

Emmanuel and Akinyemi (2020) indicated that in marine clay–kenaf mixtures designed for potential liner applications, moderate fibre contents (approximately 4% by dry mass) maintained hydraulic conductivity within the 1×10^{-8} to 1×10^{-9} m/s range when specimens were compacted at optimum moisture content. With the increase in kenaf percentage, a clear trend of k rising was observed, indicating a disruption in the fine pore network. Similarly, clay–EFB mixtures show that low EFB dosages have little impact on k, whereas higher fiber contents can lead to the formation of interconnected macro-voids and an increase in permeability (Arifin et al., 2019b; Rama Rao & Ramakrishna, 2022)

2.4.3 Hydraulic Conductivity Properties of Soil Liner

This research identifies hydraulic conductivity, or permeability, of the soil liner as the primary metric indicating the acceptability and prospective application of the examined soil liner admixture. The measured hydraulic conductivity value must be compared to the regulation standard for landfill soil liner permeability. Tiongson & Adajar (2021) said that the hydraulic conductivity findings, ranging from 1.98×10^{-6} to 1.0×10^{-7} cm/s, comply with the standards set by municipal authorities in the Philippines. Emmanuel et al. (2020) said that the Malaysian regulatory limit for bottom soil permeability is $\leq 1\times10^{-8}$ cm/s. Value of k is crucial for limiting leachate migration in landfills. Leachate is a liquid produced in landfills that contains contaminants from decomposing trash. If the liner possesses high hydraulic conductivity, leachate can readily permeate, leading to the contamination of groundwater and soil (Tiongson & Adajar, 2021).

Effective compaction and appropriate moisture content are essential for attaining minimal hydraulic conductivity (Dąbska, 2019). Dąbska's study (2019) determined that a compaction degree between 0.95 and 1.05, along with a moisture content of approximately 31%, produced optimal results. The nature of the liquid

leachate considerably influences the hydraulic conductivity of the soil liner (Dąbska, 2019). The study by Dabska (2019) examined that the value of k using tap water, distilled water, and a solution containing Sodium Hydroxide (NaOH) and Hydrochloric Acid (HCl). The results indicate that tap water and distilled water marginally reduced potassium levels with time, whereas NaOH and HCl solutions elevated them (Dąbska, 2019). This underscored the necessity of evaluating waste composition and anticipated leachate properties in landfill liner design.

2.4.4 Limitation of Traditional Soil Liner

Landfills represent a significant challenge in the realm of waste management. A primary concern is to prevent the leachate from dispersing into the soil to safeguard the environment. Traditionally, clay liners have been utilized; however, the use of unsustainable materials poses a risk to the environment. This constraint underscores the necessity for creative approaches. EFB, a byproduct of the palm oil industry, presents a promising alternative to conventional methods owing to its distinctive attributes, including fibre characteristics, porosity, and lightweight nature.

Most of the existing studies focusing on EFB in combination with other materials such as clay and synthetic fibers. This complicates the identification of its independent effectiveness. The absence of dedicated research on EFB as a singular admixture application leaves the ideal quantity for landfill liner and the optimal dosage for improving hydraulic conductivity unclear. The design and implementation of an effective liner system utilizing EFB are increasingly challenging. This investigation will assess various dosages of EFB in isolation from other materials. This will reveal the actual capabilities and limitations of it in enhancing drainage efficiency. Using EFB as a singular admixture aid in reducing agricultural waste while enhancing resource efficiency and achieving cost savings compared to conventional liners.

2.4.5 Correlation between Hydraulic Conductivity and Different Percentages of Admixture

A. Rahman et al. (2023) conducted a study on the use of kenaf core fibre and marine clay as materials for landfill liners. The study investigated the correlation

between hydraulic conductivity and varying percentages of kenaf core fibre in marine clay soil. The findings indicated that incorporating kenaf core fibre into the soil mix enhanced hydraulic conductivity, with the peak value recorded for the sample containing 12% fibre inclusion. All samples tested exhibited hydraulic conductivity values that fall within the acceptable range for materials used in landfill liners. The investigation revealed that the ideal proportion of kenaf core fibre in the soil admixture was 4%, leading to the lowest hydraulic conductivity value observed across all tested samples. The findings indicate that incorporating kenaf core fibre into marine clay soil enhances its hydraulic conductivity, positioning it as a viable option for landfill liner applications.

2.4.6 Previous Studies on Bio-Fibre Impact on Permeability

Research on natural fibre-reinforced soils extends beyond kenaf and empty fruit bunch fibres to include jute, coir, sisal, straw and various other lignocellulosic fibres(Nguyen & Indraratna, 2023). Recent experimental findings demonstrate that fibre inclusion can alter the soil pore-size distribution, pore connectivity and hydraulic behaviour. When fibres are adequately dispersed and occupy or obstruct interconnected pore spaces, hydraulic conductivity may decrease, with the magnitude of reduction depending on fibre type, content, length and curing condition(Moslemi et al., 2022). Conversely, fibre inclusion may increase the proportion and connectivity of macropores or create interfacial voids between the fibres and surrounding soil particles, resulting in higher hydraulic conductivity (Fard et al., 2022; Gomes et al., 2023). Therefore, the hydraulic response of natural fibre-reinforced soil is not uniform but depends on whether pore obstruction and microstructural refinement or fibre-induced macropore formation becomes the dominant mechanism.

Studies on fly ash–stabilised clay liners, although not centered on fibre content, underscore the important connection between microstructure and k. Although studies on fly ash-stabilised clay are not primarily concerned with fibre reinforcement, they demonstrate the close relationship between soil composition, compaction characteristics, microstructure and hydraulic conductivity. Hydraulic conductivity is strongly influenced by void ratio and clay content because these parameters control the volume and continuity of the pore network available for fluid flow (Bilardi et al., 2020).

For fly ash–clay landfill liner mixtures, fly ash content, fines content, liquid limit, maximum dry density and optimum moisture content have also been identified as important predictors of hydraulic conductivity (Devarangadi et al., 2025). Furthermore, microstructural investigations indicate that fly ash and lime treatment can induce particle flocculation, aggregation, cementation and the formation of pozzolanic products, thereby modifying pore geometry and flow-path continuity. Depending on whether aggregation creates larger interconnected pores or cementitious products progressively fill and obstruct the pores, hydraulic conductivity may either increase or decrease (Di Sante et al., 2025).

2.5 Modelling Soil Liner Sustainability with KEFB Mixtures

The incorporation of natural fibres and agricultural by-products into soil-liner systems offers a sustainable alternative to conventional compacted clay and synthetic barrier materials. Natural fibres such as kenaf and empty fruit bunch can support waste valorisation, reduce dependence on virgin construction materials and contribute to circular-economy practices in geoenvironmental engineering (Marchiori et al., 2025; Nguyen & Indraratna, 2023). Previous studies have shown that fibre inclusion can modify soil compaction, pore structure and hydraulic behaviour. However, the effect on hydraulic conductivity depends on fibre type, content, distribution and interaction with the soil matrix. Therefore, the performance of combined kenaf–EFB mixtures should be evaluated experimentally rather than assumed to consistently reduce hydraulic conductivity or improve long-term durability.

Predictive modelling can support the optimisation of KEFB soil-liner mixtures by relating hydraulic conductivity to fibre proportion, compaction energy, moisture content, dry density, fines content and applied stress. Modelling studies on waste-amended lateritic soils and fly ash–clay liners have demonstrated that empirical and machine-learning approaches can successfully identify the material and compaction parameters that most strongly influence hydraulic conductivity (Devarangadi et al., 2025; Onyelowe et al., 2022). Such modelling frameworks can reduce reliance on extensive laboratory testing and assist in selecting suitable kenaf-to-EFB proportions. Nevertheless, laboratory validation remains necessary before KEFB-modified residual soil can be recommended as a sustainable and economical landfill-liner material.

2.5.1 Soil Liners

A component of the landfill system is a landfill liner, which is also referred to as a composite liner. The properties include a low permeable barrier situated beneath engineered landfill sites (Shankar & Thankam, 2017). A well-designed liner in a landfill system regulates water flow and safeguards the environment. The mechanism controls the movement away from the waste zone and retains the waste materials as they are introduced into the designated landfill site. Water traverses the landfill and descends through the composite liner. The ultimate cover serves to prevent water from infiltrating the contaminant and to regulate the runoff from accessing the system. This

serves to protect plants and animals from the detrimental effects of waste-contaminated water leachate.

Numerous recent investigations have highlighted various shortcomings related to artificial lining systems, especially those involving synthetic membrane systems. As a result, it is essential to quantify and analyse the failure modes of landfill liners (Hanan & Jawaid, 2018). A probabilistic approach, typically utilized for the proposed admixture, can be effectively applied to assess the integrity of Compacted Soil Liners and to elucidate the reliability concerns associated with the liners currently in use (Pivato, 2011). This method can effectively incorporate the waste product into the Compacted Soil Liner, ensuring it possesses the same characteristics as a high-performance soil liner design. The schematic diagram of a modern sanitary landfill system is illustrated in Figure 2.8.

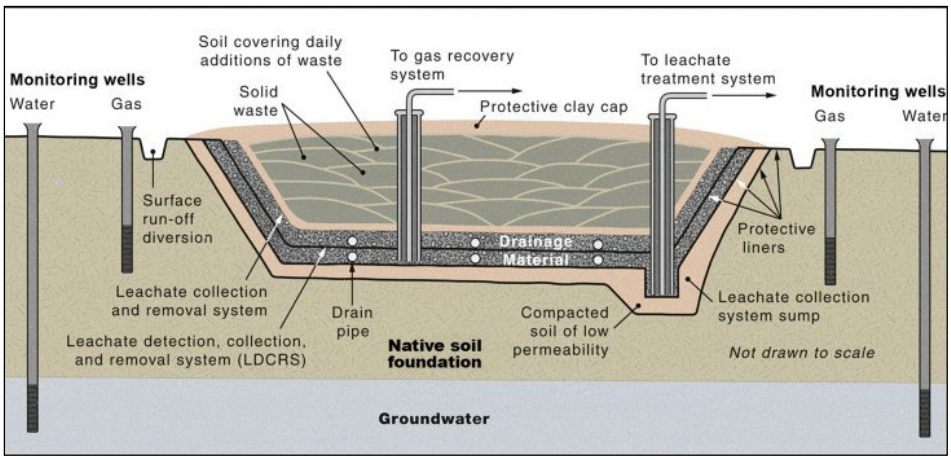


Figure 2.8 Modern Sanitary Landfill (Ahmad et al., 2019)

2.5.2 General Overview of Traditional Soil Liners

Soil stabilisation refers to the modification of soil properties to improve its suitability for construction and environmental-engineering applications. In landfill earthen liners, stabilisation may be used to reduce hydraulic conductivity, improve soil structure and enhance resistance to the adverse effects of leachate exposure. Mohammed et al., 2024) demonstrated that treating silty clay with lime and silica fume substantially reduced its hydraulic conductivity under landfill-leachate exposure, indicating that pozzolanic stabilisation can improve the performance of earthen liner

materials. Conventional chemical stabilisation commonly employs materials such as cement, lime and fly ash, which modify soil behaviour through hydration, cation exchange, flocculation and pozzolanic reactions (Barman & Dash, 2022).

Conventional compacted soil liners may also be constructed using suitable fine-grained soils without additional stabilising admixtures, provided that the required hydraulic, strength and shrinkage criteria are satisfied. Tiongson and Adajar (2021) investigated a highly plastic fine-grained soil classified as elastic silt under USCS and clay loam under the USDA system. Hydraulic-conductivity values ranging from 1.98×10^{-6} to 1.0×10^{-7}cm/s were obtained under different compactive efforts. The soil was considered suitable for use as a top liner or landfill cover. However, further assessment of strength, volumetric shrinkage and field hydraulic conductivity was recommended before its use as a bottom liner.

Nevertheless, other researchers are investigating the engineered landfill soil liner approach with addition of other admixture material, literature review has shown the similarity of the type of soil sample collected which basely contained clay-silt composition (A. Rahman et al., 2023; EsmaeilpourShirvani et al., 2019; Mazidah Mukri, 2025).

2.5.3 Development of Empirical Model and Correlation Analysis

Empirical modelling plays a significant role in geotechnical engineering, particularly when dealing with complex materials such as residual soils whose behaviour is governed by multiple interacting variables. In compacted soil liners, engineering properties such as hydraulic conductivity, maximum dry density (MDD) and optimum moisture content (OMC) are influenced by soil composition, particle-size distribution, plasticity, compactive effort, moulding moisture content, dry density and degree of saturation (Craig Benson et al., 1994; Hama Ali, 2023; Tan et al., 2023). Due to these interactions, empirical models based on statistical relationships are widely used to establish predictive correlations between measurable soil and compaction parameters. Recent studies have applied regression and intelligent modelling approaches to predict the hydraulic conductivity of modified lateritic soils and compacted landfill barriers using parameters such as additive content, compaction

energy, liquid limit, fines content, void ratio and degree of saturation (Onyelowe et al., 2022; Tan et al., 2023).

Correlation analysis is commonly performed as a preliminary step in empirical model development to identify the strength and direction of relationships between the selected variables. In modified soil-liner studies, parameters such as fibre or additive content, Atterberg limits, MDD, OMC and hydraulic conductivity are interrelated because changes in material composition can affect the soil pore structure, moisture–density relationship and resulting flow behaviour (Onyelowe et al., 2022; Gomes et al., 2023). Previous studies have demonstrated that multivariable approaches generally provide more reliable predictions than single-parameter correlations, particularly for hydraulic conductivity, which may vary by several orders of magnitude even when one soil parameter remains similar (Tan et al., 2023). Therefore, correlation analysis provides an important basis for selecting the most relevant independent variables before developing an empirical model for predicting the hydraulic conductivity of fibre-modified residual soil.

2.5.4 Regression Equations and Predictive Models in Geotechnical Engineering

Regression analysis has been widely applied in geotechnical engineering to establish predictive relationships between soil properties and engineering behaviour. In landfill liner design, regression models are particularly useful for estimating hydraulic conductivity and compaction characteristics based on readily measurable parameters (Craig Benson et al., 1994; D. E. Daniel, 1993). Wang and Huang (1984) developed empirical correlations as shown in Figure 2.9 relating soil classification properties to compaction characteristics and permeability. Their study demonstrated that parameters such as grain size distribution and plasticity can be used to estimate engineering properties through regression-type relationships, forming an early foundation for predictive modelling in geotechnical engineering.

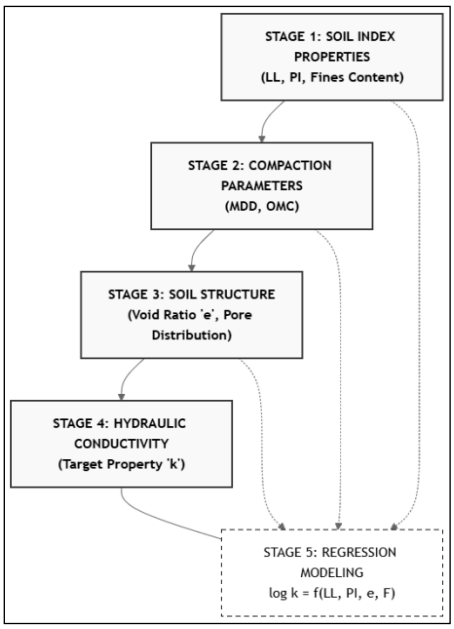


Figure 2.9 Conceptual Framework of Empirical Regression Modelling for Prediction of Soil Properties (Wang et al., 1984)

Khalid (2024) developed a multiple linear regression model to predict the hydraulic conductivity of sedimentary residual soil mixed with bentonite for landfill liner applications as shown in Figure 2.10 . The model incorporated key variables such as maximum dry density, optimum moisture content, effective stress, and bentonite content, demonstrating that hydraulic conductivity is governed by the interaction of compaction characteristics and soil composition. The developed model showed good predictive performance with a coefficient of determination exceeding 0.79, indicating strong agreement between predicted and measured values. The study further confirmed that increasing bentonite content and dry density significantly reduces *k*, enabling the mixture to meet the regulatory requirement of less than 1×10^{-9} m/s for liner materials of regression modelling for liner performance evaluation in Malaysian Residual soils.

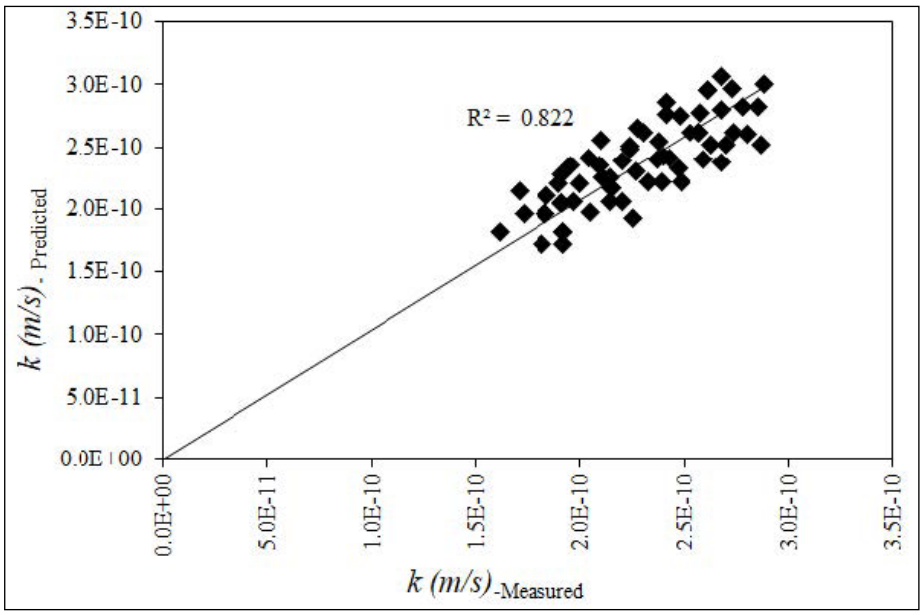


Figure 2.10 Regression Modelling ((N. Khalid et al., 2024)

2.5.5 Traditional Methods for Enhancing Soil Liner Performance

Various conventional techniques are available for soil stabilisation, including mechanical compaction and the incorporation of additives such as cement, lime and industrial by-products. In landfill engineering, compacted clay liners represent a conventional containment approach rather than a soil-stabilisation method. A properly compacted layer of suitable fine-grained soil with low hydraulic conductivity serves as a physical barrier that restricts the migration of leachate and contaminants into the surrounding soil and groundwater (Kumar & Kumari, 2023).

However, the suitability of compacted clay as a liner material depends on its mineralogical composition, particle-size distribution, plasticity, moisture condition and degree of compaction. Conventional compacted clay liners may have difficulty satisfying both low-permeability and crack-resistance requirements. Drying–wetting cycles, shrinkage and inadequate compaction can produce cracks and interconnected preferential flow paths, resulting in increased hydraulic conductivity and reduced barrier effectiveness (Tao et al., 2023).

Aside from that, there are synthetic liners. Synthetic liners are engineered membranes, similar to geosynthetics, that are utilized to create an impermeable barrier. Geomembranes are engineered polymeric sheets with very low permeability that restrict the migration of leachate and contaminants. They can be used independently or, more commonly, together with compacted clay liners or geosynthetic clay liners to form

composite barrier systems. Although geosynthetic liners offer low permeability, reduced thickness and greater construction flexibility, their application may involve higher material and installation costs, specialised quality-control requirements and uncertainties associated with long-term polymer ageing and site-specific exposure conditions. Therefore, the economic and environmental performance of geosynthetic liners should be evaluated throughout their service life rather than assumed to be either more or less sustainable than compacted clay liners (Marchiori, Albuquerque, et al., 2025).

Chemical stabilisation represents another established approach for improving soil properties. Conventional binders such as cement, lime and fly ash react physically and chemically with soil particles through hydration, cation exchange, flocculation and pozzolanic reactions, thereby improving soil strength, stiffness, cohesion and volume stability. Nevertheless, treatment effectiveness depends on the soil type, mineralogical composition, binder content, moisture condition and curing period. The presence of potentially deleterious constituents, particularly sulfates and organic matter, may interfere with stabilisation reactions and result in undesirable performance(Barman & Dash, 2022). Furthermore, conventional cement-based stabilisation may involve considerable energy consumption and greenhouse-gas emissions, creating a need for waste-derived or lower-impact alternatives such as palm oil fuel ash and other pozzolanic by-products (Alhokabi et al., 2022; Al-Subari et al., 2023).

2.6 Research Gap and Summary

Table 2.2 shows the findings and identified research gaps from previous studies, clearly indicating the need for further investigation on residual soil reinforced with kenaf fibre and EFB, particularly in developing predictive models and evaluating its suitability as a compacted landfill liner material.

Table 2.2
Research Gap

Research Title	**Objective**	**Methodology**	**Result**	**Research Gap**
Improvement of the engineering behaviour of sand-clay mixtures using kenaf fibre reinforcement (Shirvani *et al.,* 2019)	The objective of this study is to identify the mechanical attributes, compaction features, failure mode, and weakness of KFRS in order to assess its appropriateness for augmenting load-bearing capability and shear strength in construction.	The methodologies used in this research paper are case study, experiment and data analysis	The Kenaf Fibre Reinforced Soil (KFRS) lab tests showed significant findings. Increasing clay content notably boosted soil density, particularly at lower clay concentrations, with diminishing returns at higher levels due to reduced space between sand grains. The soil's moisture-density relationship remained relatively stable with kenaf fibres'	In contrast to this article, which uses sand-clay soil and large-scale direct shear tests to determine fibre shear strength, the proposed research concentrates on residual soil without using direct shear tests. The differences between the studies point to a number of unfulfilled research needs. First off, the proposed study's lack of direct shear testing restricts its

			addition, despite clay's moisture-absorbing capacity. Reinforced sand displayed notably improved shear strength, especially with higher fibre content. Kenaf fibres reduced volume change and increased ductility, while clay primarily affected stiffness. These results highlight kenaf fibre's potential in stabilizing soil at a lower cost than synthetic alternatives, making it a promising soil reinforcement option..	capacity to comprehend the features of residual soil-specific shear strength. Second, a direct comparison of residual soil and sand-clay soil, especially with regard to its physical characteristics .
Utilization of Kenaf Core Fiber – Marine Clay Mixture as a Landfill Liner Material (Rahman *et al.,* 2023)	The study aims to assess landfill leachate's impact on groundwater, evaluate leachate	The methodologies used in this research paper are case study, experiment and data	The physical properties of marine clay soil were investigated, and promising characteristics for its	There is a significant research gap between the proposed research, which involves

	treatment methods, analyse marine clay's suitability as a liner, and explore enhancing it by adding kenaf core fibre. It involves studying marine clay's properties, kenaf core fibre's influence on soil mechanics and leachate reduction potential.	analysis	potential use as a liner material, particularly in landfill applications, were discovered. The soil met the requirements specified in numerous studies and regulations for this kind of work by displaying appropriate liquid limits and plasticity index values. The analysis of the distribution of particle sizes revealed that silt dominated, meeting the requirements for fine content as a material for landfill liners. The addition of kenaf core fibre has been shown to improve soil compaction. A 4% fibre inclusion was found to increase	residual soil mixtures combined with Kenaf and EFB (with percentages ranging from 0%, 5%, 10%, 15%, 20%), and this article, which concentrated on marine clay mixtures with varying percentages of kenaf (0%, 4%, 8%, 12%). The notable variation in admixture composition and range creates a noteworthy research void, providing a chance to investigate the impact of elevated kenaf and EFB concentrations on the geotechnical characteristics of residual soil.

			maximum dry density. Furthermore, the soil mixture met landfill liner standards at the lowest permeability, with 4% fibre content. According to the study's findings, 4% of kenaf core fibre in the soil is the ideal amount to add to improve its permeability and compaction qualities, making it appropriate for use in landfill liners.	
Effect of natural fibres on the soil compaction Characteristics (Bawadi *et al.,* 2020)	The study aims to explore how incorporating natural fibres improves soil and emphasizing their impact on maximum dry density and optimum moisture	The methodologies used in this research paper are case study, experiment and data analysis	The results of the study suggest that natural fibres have the ability to strengthen soil by reacting chemically with soil constituents. The study	The proposed study involving residual soil with a single admixture of Kenaf and Empty Fruit Bunch (EFB) and the this article, which focuses on

	content. Specifically, it seeks the ideal proportion of kenaf fibres for enhancing clay soil strength to mitigate settling issues, aiming to offer insights into optimizing the use of kenaf fibres for enhancing soil strength and stability.	demonstrates how varying percentages of natural fibres affect the properties of soil compaction. It finds that although adding fibres usually raises the maximum dry density (MDD), an excessively high fibre content, especially above 1% can lower MDD because of the fibres' increased ability to absorb water. Furthermore, it is advised to incorporate natural fibres up to an ideal percentage of 0.5% in order to strengthen soil without sacrificing its dry density and strength.	clay soil and examines three different fibres (banana, coconut, and kenaf) while providing detailed chemical compositions, are different from each other in terms of materials, admixture complexity, and lack of chemical composition details. This significant discrepancy indicates a research gaps.

Development of Natural Fiber as a Filter Media in Removing Organic Pollutants from Greywater (Ridzuan *et al.,* 2018)	The aim is to evaluate kenaf dust and chitosan powder as greywater treatment agents, assessing their impact on COD, TSS, pH, and turbidity. The study seeks to optimize treatment conditions, determining ideal adsorbent concentrations and preparation methods for enhancing water quality.	The methodologies used in this research paper are case study, experiment and data analysis	The study used chitosan powder and kenaf dust to treat greywater, finding they effectively removed COD (above 50%), TSS (up to 100% removal), and showed notable turbidity reduction (up to 90%). SEM analysis revealed surface modifications enhancing their composite-forming ability. These natural materials showcase potential for environmental remediation due to their efficient greywater treatment and pollutant reduction	There are various areas where the proposed study and the article different in their level of research. The article uses SEM morphology for imaging and kenaf dust loaded with chitosan powder as adsorbents to study the removal of organic pollutants using greywater. However, compaction and hydraulic conductivity tests are absent. The proposed study, on the other hand, uses a residual soil mix with Kenaf-EFB admixture, incorporating fibres from

			capacities.	Kenaf and Empty Fruit Bunch, and investigates the hydraulic conductivity with relation to leachate without imaging the adsorbents.
Potentiality of pressmud-EFB & soil mixtures as an adsorption Material (Mohamad *et al.,* 2018)	The study aimed to enhance landfill soil covers using palm oil and sugar industry by-products (pressmud and Empty Fruit Bunches - EFB). The goal was to identify optimal combinations through characterizing soil, pressmud, and EFB, along with batch tests for common landfill metals, aiming to improve sustainable waste management practices.	The methodologies used in this research paper are case study, experiment and data analysis	The study revealed high organic matter content in pressmud and Empty Fruit Bunches (EFB), significantly higher than soil. Both pressmud and EFB exhibited higher Cation Exchange Capacity (CEC) compared to soil. Soil-pressmud-EFB mixtures showed increased adsorption of heavy metals, especially with a ratio of 50% soil, 40% pressmud, and 10% EFB. These findings suggest the	The article uses batch equilibrium tests to investigate the absorption of heavy metals from press mud-EBF mixed soil. The proposed study, on the other hand, concentrates on Kenaf-EFB soil mixtures but does not include these equilibrium tests. Instead, it emphasizes compaction and hydraulic conductivity tests to determine the ideal admixture percentage. This gap occurs

			potential of these mixtures for effective heavy metal adsorption, highlighting their suitability for environmental remediation.	between the investigation of ideal admixture proportions and the in-depth analysis of heavy metal absorption.
Preparation of activated carbon from oil palm empty fruit bunch by physical activation for treatment of landfill leachate (Ismail *et al.,* 2018)	The study aims to assess the feasibility of utilizing oil palm empty fruit bunches (EFB) for producing activated carbon and to optimize its efficacy in treating landfill leachate by varying activation conditions. Specifically, it targets identifying optimal activation parameters to maximize the removal of COD, ammoniacal nitrogen, and colour, key	The methodologies used in this research paper are case study, experiment and data analysis	The study investigated oil palm empty fruit bunch-based activated carbon (EFBAC) for treating landfill leachate. EFBAC displayed enhanced pore volume and surface area compared to EFB due to micropore development caused by volatile release at higher temperatures. Increasing activation temperature and time reduced yield	While the proposed study examines the EFB-Kenaf admixture mix residual soil liners, with a focus on identifying the optimal percentage for optimizing hydraulic conductivity in landfill applications, the article examines EFB-based activated carbon for COD removal in leachate. This discrepancy draws attention to a difference between the

	components in landfill leachate treatment.		but improved surface area. EFBAC's efficacy varied with different pollutants; higher temperatures increased COD removal, while longer times enhanced COD and colour removal. Optimal activation was at 800°C, beyond which pollutant removal did not notably increase. EFBAC demonstrated potential for effective and economically viable landfill leachate treatment due to its improved adsorption capacities.	study's emphasis on finding the best EFB-Kenaf admixture for maximizing leachate hydraulic conductivity in landfill areas and the article's focus on COD removal using activated carbon.
Utilization of Empty Fruit Bunch Fibre as Potential Adsorbent for	The study aims to use empty fruit bunches (EFBs) as an affordable adsorbent for	The methodologies used in this research paper are case study,	The research demonstrated that Empty Fruit Bunches (EFB) possess cellulose,	The main focus of the article is using citric acid-modified Empty Fruit

Ammonia Nitrogen Removal in Natural Rubber Wastewater (Nasir *et al.,* 2018)	removing nitrogen and ammonia from natural rubber wastewater. It seeks to optimize parameters like adsorbent dosage, pH, speed, and time to enhance ammonia nitrogen removal. Additionally, it evaluates EFB's effectiveness in treating ammonia nitrogen using Langmuir and Freundlich models.	experiment and data analysis	hemicellulose, lignin, and ash, enhancing their adsorption capabilities for oil, heavy metals, and pollutants. Wastewater analysis revealed high levels of ammonia nitrogen, surpassing standard regulations and posing an environmental risk. The study identified key factors influencing ammonia nitrogen removal, achieving a notable 79.5% removal under optimal conditions: 69.8% EFB dosage, pH 7, 150 rpm shaking speed, and 120 minutes contact time. Langmuir isotherm modelling indicated monolayer	Bunches as an adsorbent for industrial wastewater. On the other hand, the proposed study aims to address leachate adsorption in landfill areas by using residual soil and a Kenaf-EFB admixture. This differentiation highlights a divergence between the former's emphasis on treating industrial wastewater using a modified EFB and the research focus on managing leachate in landfill environments by using the Kenaf-EFB mix within residual soil.

			adsorption behaviour. EFB proved cost-effective for eliminating ammonia nitrogen from natural rubber wastewater, suggesting further research for its effectiveness against other contaminants like colour, suspended solids, and COD.	
Effect of oil palm empty fruit bunch ash (OPEFBA) on the compaction and some Index Properties of Sand-Bentonite Mixtures (Nwaiwu *et al.,* 2022)	Emphasizing landfill liners, the article investigates improving sand-bentonite combinations for waste containment. It investigates the effects on their characteristics of additives such as oil palm empty fruit bunch ash (OPEFBA) and sodium bentonite. It attempts to increase the compaction	The methodologies used in this research paper are case study, experiment and data analysis	The use of sand-bentonite mixtures as waste containment barriers is the main topic of this article on waste management. These mixes, which are frequently used as landfill liners, satisfy regulatory requirements due to their high shear strength and low hydraulic conductivity.	The article investigates sand-bentonite mixtures with different percentages of bentonite using ash from empty fruit bunches. By contrast, a residual soil blend containing different proportions of Kenaf and Empty Fruit Bunch admixture is used in the proposed

	strength, decrease leaks, and minimize hydraulic conductivity in waste containment systems using laboratory testing and statistical analysis.		The purpose of the study is to determine how Oil Palm Empty Fruit Bunch Ash (OPEFBA), which increases mixture strength and lowers leakage risk, affects these mixes. Standards were followed in the laboratory testing, which showed that bentonite had a considerable impact on the mixture but that OPEFBA had an unclear effect.	study. This discrepancy reveals a gap between the study's focus on residual soil mixed with Kenaf-EFB blends and the article's examination of sand-bentonite mixtures.
Characterizatio n the geotechnical properties of a Malaysian	The purpose of the study is to assess the suitability of Malaysian	The methodologie s used in this research paper are case	The primary goal of this study was to evaluate the geotechnical	The article's main focus is on examining the physical characteristics

granitic residual soil grade V (Saffari P. *et al.,* 2019)	grade V granitic residual soil for construction. It evaluates the particle distribution, specific gravity, shear strength, and Atterberg limits in both saturated and unsaturated states. Through an examination of soil behaviour at different weathering grades, the study offers crucial information for construction choices involving residual soils.	study, experiment and data analysis	characteristics of grade V Malaysian granitic residual soil, which is significant for building. The study confirmed the soil's status as well-graded, very gravelly SAND with consistent properties by highlighting unique attributes influenced by particle distribution and weathering grade. The behaviour of the soil under various matric suctions, which showed a residual suction of 70 kPa and significant sensitivity of shear strength to fine particle content, were among the key findings. The study emphasized how critical it is to take	of residual soil for construction in various locations. On the other hand, the proposed study concentrates on just two sites and intends to examine the physical characteristics of residual soil especially for landfill applications. This discrepancy draws attention to a difference between the proposed study's targeted analysis for landfill use and the wider investigation of residual soil for construction.

		weathering grades into account when assessing the engineering behaviour of granitic residual soil in order to make well-informed construction decisions.

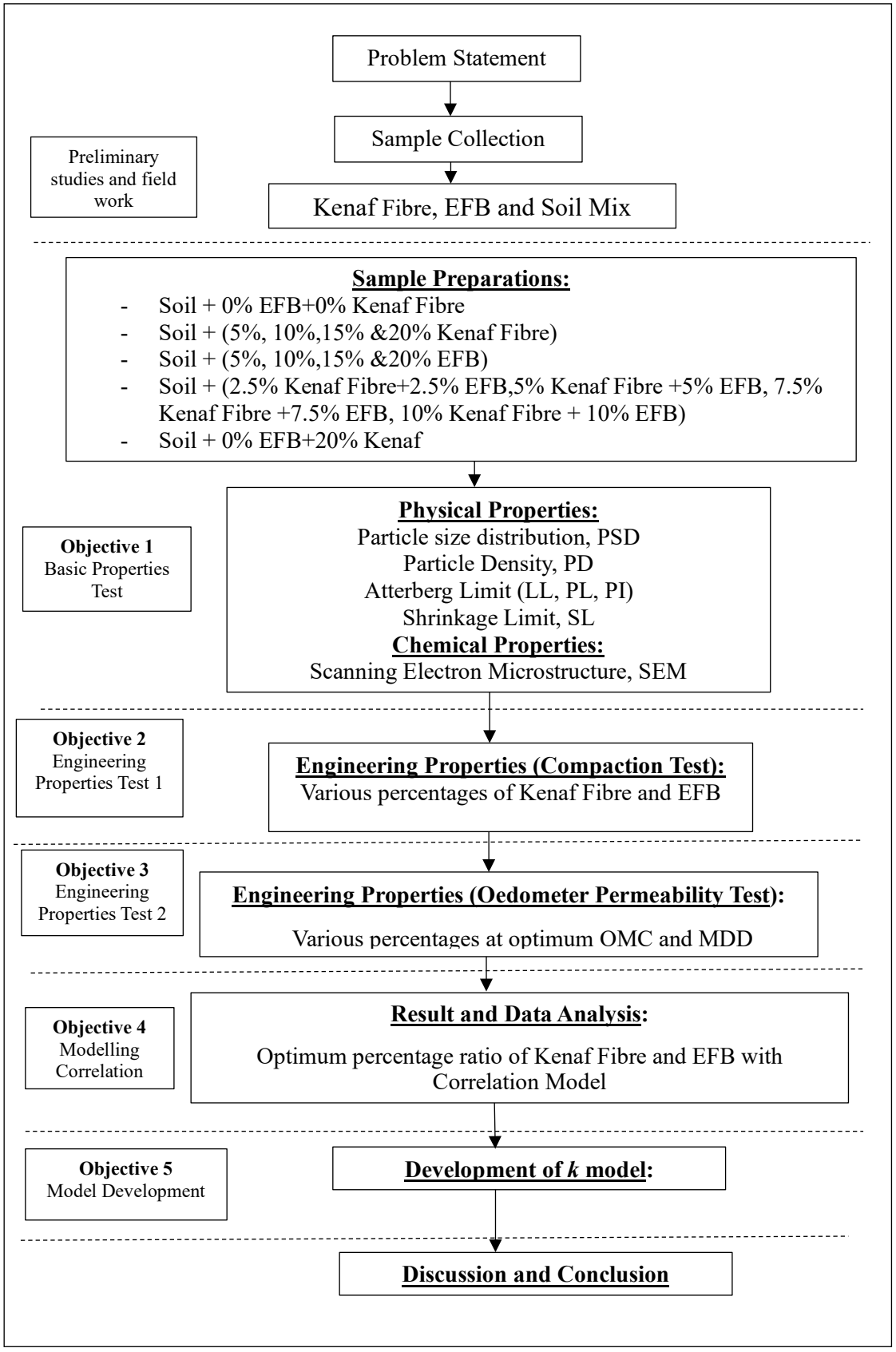
CHAPTER 3
RESEARCH METHODOLOGY

3.1 Introduction of Research Methodology

This section presented a comprehensive and detailed description of the research methodology. This chapter describes the samples and materials evaluated, the experiments conducted, and the procedures of the empirical formula derived via software analysis. Based on soil's physical features, this research intends to create models and Nomographs for estimating soil properties using an empirical formula. British Standard (BS) practise guideline standards were used to determine the acceptable range for the test parameter.

The first step in this study's methodology is collecting samples from two different locations and data from four different site investigations by conducting in-situ and laboratory tests and assessing the findings. The soil was tested for various physical parameters, including grain size analysis, moisture content, particle density, shrinkage limit, Atterberg Limit and Morphography. The purpose of these analyses was to ascertain whether the soil was suitable for developing the strength and hydraulic conductivity ‘s model for the Residual soil. The majority of the study's preliminary laboratory testing was done in the Geotechnical Laboratory in the Civil Engineering Department at UiTM, where the basic properties test was carried out in line with BS 1377: Part 2: 1990.

After that, the hydraulic conductivity result are compared with the parameters from the laboratory tests. Minitab 21 was used to analyse the laboratory data and confirm the link between k-value and other soil parameters. This chapter also details the empirical formula created with Minitab 21 that evaluates the statistical analysis via correlation and regression. The research process was organised according to the flow chart below, based on the guidelines provided in this chapter.



Flow Chart of the Research

3.2 Soil Sampling

In this study, type of soil that is used in this research is residual soil sample from two different areas with same formation in Salak Tinggi, Selangor. Then, the ratio between the soil is calculated accordingly based on the percentage that has been decided based on the past literature. Figure 3.1shows the geological map of Peninsular Malaysia which categorizing each area based on their parents' rock either Sedimentary, Igneous or Metamorphic Rock. The site location was located at Salak Tinggi where the rock units classify as Carboniferous Permian mainly consist of Schist, Phylite and Slate. Lithology mainly including sandstone with subordinates' Shale, Mudstone, Siltstone and Conglomerate. Disturbed soil samples of yellowish Residual soil Grade IV used in this study were derived from sedimentary

Residual soil and was collected at two different locations in Salak Tinggi, Selangor, Malaysia. This soil samples were named as Salak Tinggi Residual soil 1 (ST1) and Salak Tinggi Residual soil 2 (ST2). In order to minimize the organic matter content, the soil was taken at 1.5 m to 2.5 m below from ground surface. From Figure 3.2, based on the geological map obtained from Minerals and Geoscience Department Malaysia(Hussin et al., 2017), the Salak Tinggi area classified as sedimentary soil derived from phyllite, schist and slate: limestone and sandstone prominent. The yellowish-brown colours of Salak Tinggi soil were due to the changes on the mineral composition from the erosion of the top layer of parent rock. Seepage of the soluble minerals in the eroded materials deep underneath surface layer making the insoluble Fe and Al ions remains on the top. These metallic oxides create a new soil and gave the brownish colour. The physical properties were investigated guided from BS 1377: Part 2: 1990.

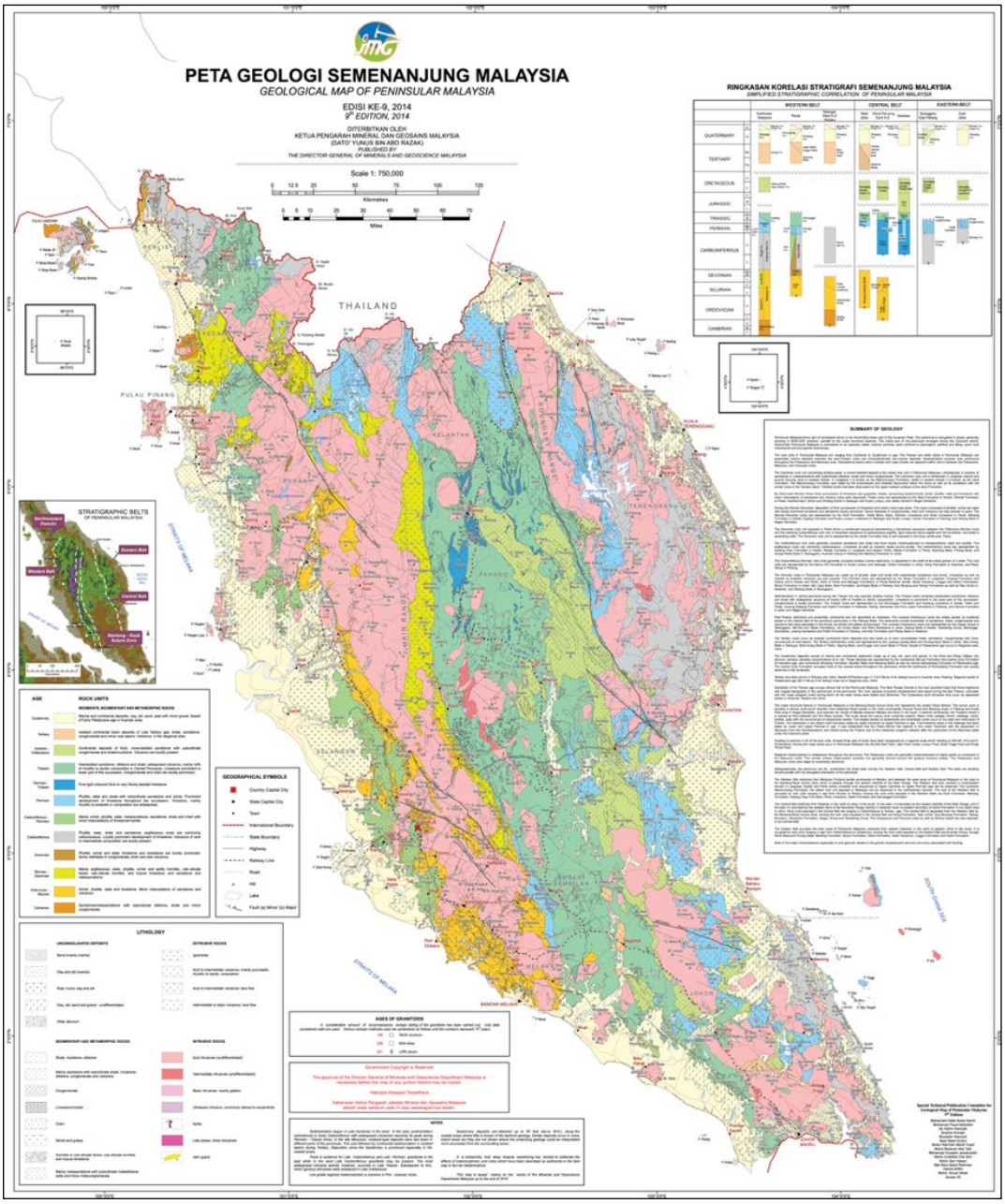


Figure 3.1 : Geological Map of Peninsular Malaysia

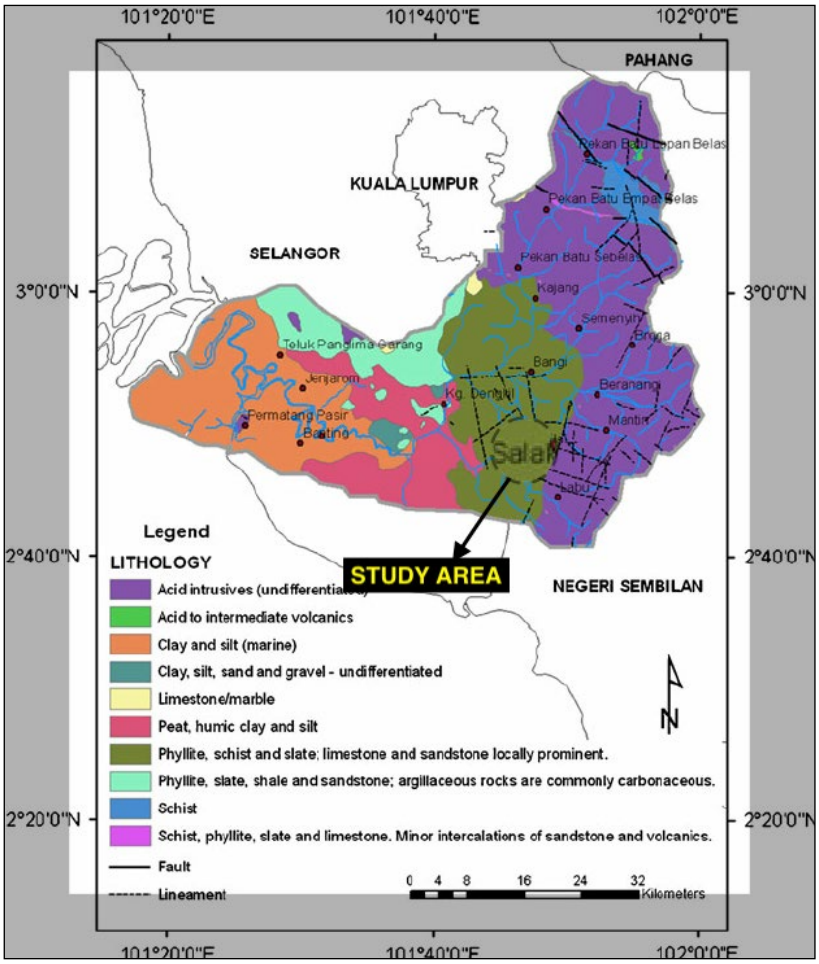


Figure 3.2 Geological map of Selangor(Hussin et al., 2017)

3.2.1 Location and Method of Collecting Samples

The soil sample was taken at depth of 1.5 m to 2.0 m below the ground surface to collect the original soil without humus layer and any roots. Hand Auger and excavator machine were used to collect the soil to a required depth. Figure 3.3 shows the site location Salak Tinggi 1 (ST1) and Figure 3.4 shows the site locations at Salak Tinggi 2 (ST2). About 200kg of disturbed soil sample was taken from both sites and brought to the UiTM Shah Alam laboratory. Figure 3.5 shows the soil samples taken from the sites before conducting laboratory testing.



Figure 3.3 Site Location at Salak Tinggi 1 (ST1)



Figure 3.4 Site Location Salak Tinggi (SB)



Figure 3.5 Soil Sample from the Site

3.2.2 Kenaf Fibre

One of the additives used in this study is Kenaf core fibre of 40 mesh that taken from Lembaga Kenaf dan Tembakau, Malaysia as shown in Figure 3.6. The colour of

kenaf is described as yellow creamy to light brown with moisture content of less than 12%. Around 20 kg of kenaf mesh was brought back to the laboratory from Lembaga Kenaf dan Tembakau Negara, Kota Bharu. The picture of kenaf fibre used in this study is shown in Figure 3.7.



Figure 3.6 Lembaga Kenaf dan Tembakau Negara



Figure 3.7 Kenaf Core Fibre at 40 Mesh Size

3.2.3 Source of Empty Fruit Bunch

The second primary source material, Empty Fruit Bunch (EFB)originated from Palm Oil Mill Sepang, Selangor. It is washed thoroughly before grinded to the exact size as Kenaf Fibre which was 40 mesh.

3.2.4 Kenaf-EFB Mixing Preparation

The preparation of the sample including mixing the soil with different percentage of Kenaf Fibre and EFB with percentages of 0%, 5%, 10%, 15% and 20% (Hassian et al,2014; Adnan et al,2015; Mukri et al (2018); Nik, 2019, Zainuddin,2022). Table 3.1 and Table 3.2 shows the percentage ratio soil samples, Kenaf Fibre and EFB for each sample. The total number of different compositions of 30 samples were tested including 380 samples for physical properties, 26 samples for compaction value, and 18 samples for hydraulic conductivity with a grand total of 424 samples. All tests were repeated at least three (3) times to ensure precise results.

Table 3.1
Percentages of Soil and Additives at Salak Tinggi 1(ST1)

Sample	EFB (%)	Kenaf Fibre (%)
ST1	0	0
ST1-5K	0	5
ST1-10K	0	10
ST1-15K	0	15
ST1-20K	0	20
ST1-5EFB	5	0
ST1-10EFB	10	0
ST1-15EFB	15	0
ST1-20EFB	20	0
ST1-2.5KEFB	2.5	2.5
ST1-5KEFB	5	5
ST1-7.5KEFB	7.5	7.5
ST1-10KEFB	10	10

Table 3.2
Percentages of Soil and Additives at Salak Tinggi 2 (ST2)

Sample	EFB (%)	Kenaf Fibre (%)
ST2	0	0
ST2-5K	0	5
ST2-10K	0	10
ST2-15K	0	15
ST2-20K	0	20
ST2-5EFB	5	0
ST2-10EFB	10	0
ST2-15EFB	15	0
ST2-20EFB	20	0
ST2-2.5KEFB	2.5	2.5
ST2-5KEFB	5	5
ST2-7.5KEFB	7.5	7.5
ST2-10KEFB	10	10

3.3 Soil Testing- Physical Properties Test

All the physical properties testing were conducted according to British Standard (BS 1377: Part 2: 1990) as guidance. The experimental test includes the physical properties and engineering properties of soil. For physical properties includes Particle Size Distribution Test (PSD), Atterberg Limit, Particle Density Test, Shrinkage Limit Test, and Scanning Electron Microscopy Test.

3.3.1 Particle Size Distribution Test

The Particle Size Distribution Test of soil was conducted by using method of wet and dry sieving by according to BS1377:Part 2:1990:9.2. If a soil contains silts or clay or both, even in small quantities, it is necessary to carry out a wet sieving procedure in order to measure the proportion of fine material present. Washing is the only practicable means of ensuring complete separation of fines for a reliable assessment of their percentage. The material is first pretreated for a sedimentation test and continue by washing itu sing 63μm sieve. The material passing the 63μm sieve is collected for a sedimentation analysis. Figure 3.8 and Figure 3.9 shows the apparatus and machines used in conducting PSD Test for the soil.



Figure 3.8 Sieve Shaker and Pan Used to Sieve the Soil Samples



Figure 3.9 Sieving Pan with Soil Retained After Sieving

3.3.2 Hydrometer Test

Hydrometer test is a procedure of density hydrometer of special design is used to measure the density of a soil pretreated in a water suspension at various intervals of time. From this measurement the distribution of particle sizes in the silt range (2 to 60 μm) can be assessed. The suspension of pretreated soil passing the 63μm sieve is transfer from the receiver into a 1000 ml sedimentation cylinder without losing any soil.

Based on the BS 1377, the wet sieving procedure in a hydrometer test begins by placing the prepared soil sample into a sieving pan fitted with a 63 μm sieve as shown in Figure 3.10. The soil is then gently washed using water as shown in Figure 3.10 Figure 3.11 while being carefully agitated to ensure the soil particles are fully dispersed. During this process, the fine particles (silt and clay smaller than 63 μm) pass through the sieve along with the wash water, while the coarser particles such as sand are retained on the sieve surface. Care must be taken to avoid excessive force during washing so that the soil structure is not altered and fine particles are not lost. The material retained on the 63 μm sieve is collected as shown in Figure 3.11 and Figure 3.12, oven-dried, and weighed to determine the proportion of coarse fraction, while the soil suspension that passes through the sieve is collected and used for the subsequent hydrometer analysis, which determines the particle size distribution of the finer soil particles.



Figure 3.10 Soil Sample in Wet Sieving



Figure 3.11 Wet Sieving Process



Figure 3.12 Passing Soil Poured Into a Tray Before Oven-Dried in 24-hours

3.3.3 Atterberg Limit

Atterberg limits are the basic test to measure the critical water content from solid to liquid of fine-grained soil. It can be in four (4) states such as solid, semi-solid, plastic and liquid. This method was suggested by(Clayton & Jukes, 1978) as a possible less elaborate routine method of assessing the liquid limit of soil than the four-point cone penetrometer test. Based on the water content, in may appear in four states which are solid, semi solid, plastic and liquid. Every state represents the consistency and behaviour of the soil. This test was performed to identify the plastic and liquid limit of fine grained soil. The liquid and plastic limit for the sample were determined using the procedures describe in BS 1377:Part 2:1990. " Standard Test Methods for Liquid Limit, Plastic Limit and Plasticity Index of Soils".

3.3.3.1 Plastic Limit

The behaviour change between the plastic and semi solid state of slits and clay is corresponding by the water content. The plastic limit test is simpler in operation and no requires equipment other than the means of determining the water content of soil. The plastic limit is determined by rolling out a thread of the fine portion of a soil on a flat, non-porous surface. The plastic limit (PL) is the water content, in percent, at which a soil can no longer be deformed by rolling into 3.2 mm (1/8 in.) diameter threads without crumbling. A soil is considered non-plastic if a thread cannot be rolled out down to 3mm at any moisture. According to (BS1377:Part 2:1990:4.2.3), when the soil consists of clay and silt with little or no material retained on a 425μm sieve, it can be prepared for testing from its natural state. Figure 3.13 shows the process of plastic limit in the laboratory.

The plastic limit (PL) test was also performed according to BS 1377-2 using the same prepared soil mixtures. After determining the appropriate moisture condition from the LL test, a portion of the soil paste was taken and allowed to partially dry until it reached a plastic consistency suitable for rolling. Approximately 20 g of soil was taken and rolled manually on a clean glass plate to form a thread. The soil thread was continuously rolled until it reached a uniform diameter of approximately 3 mm. If the thread could be rolled without breaking, the soil was remoulded and rolled again until crumbling occurred at the specified diameter. The water content at which the soil thread

just begins to crumble at 3 mm diameter was taken as the plastic limit. This procedure was repeated for each mixture containing kenaf, EFB, and KEFB fibres to evaluate the influence of different fibre types and percentages on the plastic behaviour and consistency characteristics of the soil.



Figure 3.13 Plastic Limit

3.3.3.2 Liquid Limit (LL)

Firstly, the soil is oven-dried for 24 hours and sieved with 4.75 µm as required for the test. Kenaf Fibre and empty fruit bunch with different percentages of 0%, 5%, 10%, 15% and 20% is added to the soil accordingly. Figure 3.14 shows the set-up of the apparatus on Atterberg Limit test. The *LL* is evaluated by determining the water content of the soil at the point that allows a cone, weighing 80 g to penetrate the specimen by 20 mm. The test is repeated for various water contents, and the relationship between penetration and water content is established. *LL* is determined at the water content at 20 mm penetration.

The liquid limit (LL) test was conducted in accordance with BS 1377-2 using the cone penetrometer method. Prior to testing, the soil samples were first air-dried and passed through a 425 µm sieve to remove coarse particles and obtain a uniform fine fraction. The prepared soil was then mixed with different fibre contents to evaluate the effect of reinforcement on the consistency limits. Three groups of mixtures were prepared: soil reinforced with kenaf fibre at 5%, 10%, 15%, and 20%, soil mixed with oil palm empty fruit bunch (EFB) fibre at 5%, 10%, 15%, and 20%, and soil reinforced

with kenaf–EFB hybrid fibre (KEFB) at 2.5%, 5%, 7.5%, and 10% by dry weight of soil. Each mixture was thoroughly blended in dry condition to ensure uniform fibre distribution before distilled water was gradually added. The mixture was then placed in an airtight container and allowed to equilibrate so that moisture could be uniformly distributed throughout the sample. For the LL test, the prepared paste was placed into the cone penetrometer cup and levelled, and the penetration of the standard cone was measured at different moisture contents until the water content corresponding to 20 mm penetration was obtained, which represents the liquid limit.



Figure 3.14 Liquid Limit Using Cone Penetrometer

3.3.3.3 Plasticity Index (PI)

The plasticity index (PI) is a measure of the plasticity of a soil. The plasticity index is the size of the range of water contents where the soil exhibits plastic properties. PI is difference between Liquid Limit (*LL*) and Plastic Limit (*PL*). Soils with a high *PI* tend to be clay, those with a lower *PI* tend to be silt, and those with a *PI* of 0 (non-plastic) tend to have little or no silt or clay. Equation 3.1 of plasticity index is shown below.

$$PI = w_L - w_P \quad (3.1)$$

where:

w_L = *Liquid Limit (%)*

w_P = *Plastic Limit (%)*

P.I = Plasticity Index

3.3.4 Particle Density Test

The small pykonometer method will be used to find out the specific gravity (Gs) for soil samples. After the soil sample and distilled water put into the pykonometer, dessicator will use to take out the air between the soil particle in soil sample (BS 1377:Part 2:1990). The concept of particle density is well known and refers to mass per unit volume of the solid particle or grains.

The test of soil was conducted in accordance with BS 1377-2 using the density bottle method. Prior to testing, the soil samples were air-dried, lightly pulverized, and passed through a 2 mm sieve to remove coarse particles and obtain a representative fine fraction. The prepared soil was then mixed with the respective fibre contents to examine the influence of reinforcement materials on soil properties. Three sets of mixtures were prepared which were soil reinforced with Kenaf Fibre at 5%, 10%, 15%, and 20%, soil mixed with EFB at 5%, 10%, 15%, and 20%, and soil mixed with Kenaf Fibre and EFB (KEFB) at 2.5%, 5%, 7.5%, and 10% by dry weight of soil. Approximately 5 to 10 g of the prepared soil sample was placed into a clean and dry density bottle as shown in Figure 3.16, after which de-aired, distilled water was added to cover the soil. The bottle was gently agitated and, if necessary, subjected to mild vacuum as shown in Figure 3.17 to remove entrapped air bubbles to ensure accurate measurement.

After removing the trapped air, the density bottle was filled completely with distilled water, cleaned externally, and weighed to obtain the combined mass of the bottle, soil, and water. The bottle was also weighed when filled only with distilled water to determine the reference mass. These measurements were then used to calculate the specific gravity of the soil solids based on the mass relationships between the soil, water, and density bottle. The test was repeated for each mixture containing Kenaf Fibre, EFB, and KEFB fibre, allowing comparison of the specific gravity values and

assessment of how different fibre types and contents influence the density characteristic. Equation 3.2 shows the equation used to calculate the particle density of the sample.

$$\rho_s = Gs\ \rho_w \tag{3.2}$$

where;

ρ_w = the density of the water (Mg/m^3)

Gs = specific gravity of soil (Mg/m^3)

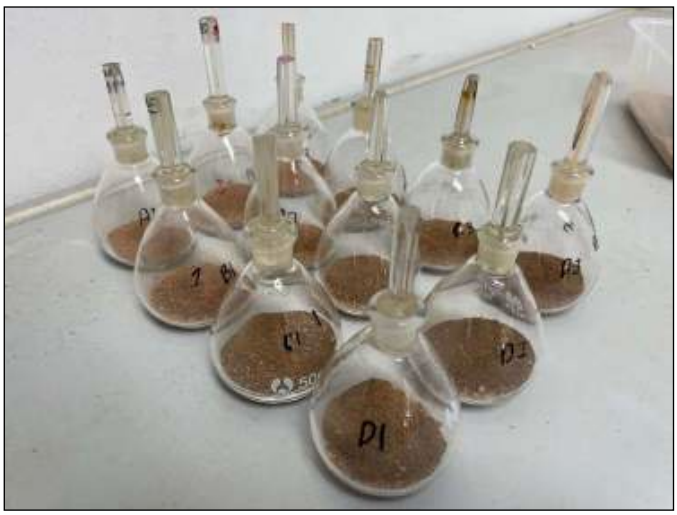


Figure 3.15 Particle Density's Bottles with Samples



Figure 3.16 Dessicator Machine to prevent air bubbles

3.3.5 Scanning Electron Microscopy Test (SEM) and Energy Dispersive X-ray Spectroscopy (EDX)

Scanning Electron Microscopy (SEM) is a technique that employs an electron beam to examine a sample, yielding a highly magnified image for detailed analysis. In SEM testing, high electron microscopy generates high-resolution images and accurately quantifies microscopic features and objects. This study employs SEM to analyse the morphology of soil structure incorporating additives as raw materials. The SEM machine can magnify images of the specimen's surface and cross-section of the membrane by factors ranging from 1000x to 10000x, allowing for a detailed visualization of how much larger the image structures or features appear compared to the actual sample. (Ali et al., 2023). A SEM test was performed in the laboratory of the Faculty of Mechanical Engineering at UiTM Shah Alam.

The objective of conducting the test was to identify the mineralogical trends to explore the development of soil incorporating both kenaf and EFB fibre. Initially, the samples were prepared, which included soil without any additives as well as soil samples containing varying percentages of Kenaf Fibre and EFB. In order to achieve optimal results, it is essential that SEM samples are both dry and electrically conductive. The coating process was crucial, and in this preparation, carbon coating was applied to all samples to prevent charge buildup and enhance image quality. Figure 3.18 illustrates the coating machine utilized for the preparation of the specimen. The images are subsequently analysed through advanced image processing software. The details obtained from the test included mineral abundance, mineral grain size, liberation, and association. Figure 3.19 illustrates the SEM Machine used in this study.



Figure 3.17 Coating Machine



Figure 3.18 Scanning Electron Machine

3.4 Compaction Test

The second purpose of this study is to determine the compaction characteristics of compacted residual soil incorporating varying percentages of Kenaf Fibre and EFB. The engineering properties test was performed in accordance with BS 1377: Part 4: 1990. The tests conducted were the Compaction Test and the Permeability Test. The

compaction method employed involved a 2.5 kg rammer. This test procedure detailed in the BS1377: Part4:1990: Clause 5.4 (Standard Compaction Test). Prior to the test, the samples were subjected to oven drying at temperatures ranging from 60°C to 70°C for 1.5 hours to preserve the mineral content and structural integrity of the soil mixture.

3.4.1 Compaction Sample Preparation

Five (5) different percentages of Kenaf Fibre and EFB (0%,5%,10%,15% and 20%) prepared accordingly until reached a homogenous state. The samples were dynamically compressed using a 2.5 kg steel hammer with a 50 mm diameter rammer, dropped freely from a height of 300 mm, delivering 27 blows for each of the three layers. Before compaction testing, the soil samples were oven-dried at 110 degrees Celsius for 24 hours to ensure that the compaction process began at a baseline condition of 0 percent moisture content. This drying procedure is commonly recommended in compaction studies to eliminate natural moisture variability and improve consistency of test results (Rahman et al., 2020). After drying, the soil was gently disaggregated, sieved through a 2 mm sieve and stored in airtight containers to prevent moisture uptake until testing commenced, thereby maintaining uniform initial conditions for all compaction trials.

As summarised in Table 3.3, a total soil mass of 2500 g was prepared for each compaction test, and distilled water was added incrementally to progressively increase the moisture content. The incremental addition of water allowed the development of a complete moisture and density relationship curve, enabling the determination of both the Optimum Moisture Content (OMC) and the corresponding Maximum Dry Density (MDD) for each soil sample. This controlled approach ensured repeatable compaction conditions and reliable identification of compaction characteristics relevant to subsequent permeability testing.

Table 3.3
Sample Preparation for Compaction Test

Sample	Weight of Soil (g)	Water Increment (ml)
ST1	2500	200
ST2	2500	200

3.4.2 Standard Proctor Compaction Test

The Standard Proctor Compaction Test was performed according to BS 1377 Part 4:1990 using an automatic Proctor compactor, as illustrated in Figure 3.20. The purpose of this test is to determine how dry density varies with different moisture contents under a standard compactive effort, thereby establishing the compaction characteristics of the soil under controlled laboratory conditions.



Figure 3.19 Compaction Machine with the Mould

A soil mass of 2.5 kilograms passing the 2 mm sieve was used for each trial to maintain uniformity, ensuring consistency in sample preparation and compaction energy application. The compaction mould shown in Figure 3.21 was filled in three equal layers, with each layer compacted using the standard rammer, in accordance with the requirements of BS 1377 Part 4:1990. Five trials were conducted with progressively increasing moisture contents to generate a complete compaction curve, allowing accurate identification of the Optimum Moisture Content (OMC) and the corresponding Maximum Dry Density (MDD). After compaction, the collar was carefully removed, and excess soil was trimmed flush with the top of the mould to ensure a consistent mould volume for density calculations. The mould containing the compacted soil was then weighed, as presented in Figure 3.22. The Standard Proctor compaction test is widely used to determine the maximum dry density and optimum moisture content of fine-grained soils for civil engineering applications (Khalid & Rehman, 2018).



Figure 3.20 : Sample of Residual Soil Mixed with Kenaf Fibre During Compaction Test



Figure 3.21 Weighing the Mould and Soil

A portion of each compacted soil sample was taken for moisture determination and oven-dried at 105 degrees Celsius for 24 hours, as shown in Figure 3.23, to accurately determine the water content corresponding to each compaction trial.



Figure 3.22 Samples After Oven-Dried

3.4.3 Determination of MDD and OMC

For each moisture level, the bulk density and dry density were calculated and tabulated, based on the measured mass and known volume of the compaction mould. The dry density values were then plotted against moisture content to produce a compaction curve, which illustrates the relationship between soil density and moulding water content under a constant compactive effort. The peak of this curve represents the Maximum Dry Density (MDD), and the corresponding moisture content is identified as 48 the Optimum Moisture Content (OMC). This graphical method is standard practice for interpreting compaction characteristics and is recommended in geotechnical guidelines for accurately determining soil compaction behaviour (Chen et al., 2021), particularly for applications requiring controlled density and permeability such as landfill liner construction. Equation 3.3 and 3.4 are used to calculate bulk density and dry density of the sample.

$$\rho_{bulk} = \frac{m_2 - m_1}{v} Mg/m^2 \qquad (3.3)$$

$$\rho_{dry} = (\frac{100}{100+w})\rho\, Mg/m^2 \qquad (3.4)$$

3.5 Permeability Test using Modified Oedometer Machine

The modified oedometer test was conducted to determine the hydraulic conductivity, (k), of the untreated and fibre-modified residual soil under different applied pressures. Conventional falling-head permeability tests can require a long testing period, particularly for compacted fine-grained soils with very low hydraulic conductivity, because only a small volume of water passes through the specimen over time. Testing multiple soil–fibre mixtures using the falling-head method would therefore require considerably longer laboratory testing periods.

In comparison, the modified oedometer method enables the hydraulic conductivity and consolidation behaviour of the soil specimen to be evaluated within the same testing process. Hydraulic conductivity can be determined at different applied vertical pressures while changes in specimen thickness, void ratio, and compressibility are recorded. This allows several stress-dependent hydraulic conductivity values to be obtained progressively from a single specimen without conducting a separate permeability test for every loading condition.

The method was particularly suitable for this study because landfill liner materials are subjected to increasing vertical stresses caused by the progressive placement of waste and cover materials. The modified oedometer test therefore not only accelerates data collection but also provides information on how hydraulic conductivity changes as the soil liner consolidates under different loading conditions. This relationship cannot be fully represented by a conventional falling-head test conducted under a single initial stress or compaction condition.

Furthermore, the large number of soil mixtures and fibre percentages investigated in this research required a testing method that could generate sufficient data within a practical laboratory period. The modified oedometer method facilitated the development of a comprehensive dataset for statistical and regression analyses by providing hydraulic conductivity values at several pressure stages. Consequently, the method was adopted as a time-efficient and technically relevant alternative to repeated falling-head permeability testing.

The preparation of sample for permeability test in Oedometer mould is shown in Figure 3.25. Some Oedometer cells are provided with a means of carrying out a direct permeability measurement while the specimen is under load. The essential features of such a cell are a bottom inlet, which can connect to a standpipe such as burette, sealing

rings to prevent water finding its way around the specimen and around the specimen and containing ring and an upper overflow outlet. A cell of this type, arranged for a falling head permeability test, is shown diagrammatically in Figure 3.24.

When equilibrium has been reached under the pressure at which the permeability is to be measured, connect the bottom inlet to a burette or to a suitably calibrated glass tube, by means of a length of rubber tubing fitted with pinch clip. Connect a length of rubber tubing to the upper outlet leading to a beaker. Fill to near top of the burette with de-aired water without trapping any air, and fill the cell up to the overflow level. Open the pinch clip, and start the clock when the level in the burette reaches a given mark. Record the time taken for the level in the standpipe tube to fall to a second mark. Repeat two or three times. From each set of readings calculate the permeability of the soil specimen as for the falling head permeability procedures.

At any stage during the consolidation test when 100% primary consolidation has been achieved, the permeability may be measured by opening valve P. The fall of water level in the standpipe is observed and time as for the falling head test, using three marks levels h_1,h_2 and h_3 . The length of sample during the test is the consolidated height of the sample at the end of the load increment (H_0-ΔH).



Figure 3.23 Modified Oedometer Permeameter

The procedure of preparing the Oedometer cells is different from the conventional method. Before the execution of the test, it must begin with the adjustment of the graduated burette. The position of the graduated burette is carefully adjusted so that the zero reading precisely so that the zero reading precisely coincides with the level of drainage hole in the cell. Next, the burette is fiilled with distilled water and the connecting valve is opened to allow the water to flow down to the lower porous stone inside the oedometer cell. The sample must in fully saturated condition by ensuring that there is no presence of air bubbles that might impact the test. Finally, the water level in the burette is restored to the desired value before closing the valve. Excess water in the lower of the porous stone is carefully removed.

The next phase of the test was the oedometer compression. It involved the load increments by applying several loads. The loads that applied to the sample were 25kPa, 50kPa, 100kPa,2000 kPa and 400 kPa. The valve connecting the oedometer cell and

burette is closed and the actual permeability measurement can only measured after 24 hours or after the settlement of the specimen under the vertical loading has stabilized.

The second stage provide the direct permeability test. It begins with applying preliminary hydraulic load. A sufficient amount of distilled water is added to achieve a hydraulic load of 50 cm. The water temperature is maintained with ambient temperature and recorded. Then, the initial water level is measured and recorded. Next, the valve is opened and the stopwatch is used to record the time. The measurement isncontinued until reach a hydraulic load of 10-15 cm. For each recorded hydraulicnload value, the coefficinet of permeability, *k* is calculated using the following expression:

$$k = (H_0) - (\delta H) \times \frac{a_b}{A_s} \times \frac{log_e \frac{L_0}{L_t}}{t_t - t_0} \times 10^{-2} \qquad (3.5)$$

where;

$H_0 =$ the initial hydraulic load (cm)

$\delta H =$ the change in hydraulic load (cm)

$a_b =$ the cross sectional aea of burette

$A_s =$ the cross $-$ sectional area of the specimen

$L_0 =$ the initial lenght of flow path

$L_t ==$ the current length of flow path t_t

$t_t =$ the subsequent time corresponding to the reading, L_t(sec)

$t_0 =$ the initial time corresponding to the reading, L_0(sec)



Figure 3.24 Arranged Sample in Oedometer Mould

3.6 New Model of Sustainable Soil Liner

From the correlation of optimum percentage of Kenaf Fibre and Empty Fruit Bunch, a correlation of laboratory data will be analysed in statistical analysis due to hydraulic conductivity value. Then, a model will be develop using statistical analysis by using Minitab 24 Software. Total of 20 data were collected to form an empirical modelling. The empirical model was run on 90% of the data while 10% from the laboratories was used to validate the predicted k-model (Zainuddin et al., 2022). Some factors that affect soil hydraulic conductivity including density, water content and void.

Green (1991) evaluated several rules of thumb for estimating the minimum sample size required for multiple regression analysis. The study suggested $N \geq 50 + 8m$ for testing the overall multiple correlation and $N \geq 104 + m$ for testing individual predictors, where $m$represents the number of independent variables. However, these formulas should be treated as general guidelines because the required sample size also depends on the expected effect size, statistical power and complexity of the regression model. Multiple regression analysis was selected in this study because it enables the combined relationships between several independent variables and hydraulic conductivity to be quantified and used to develop an empirical prediction model. Similar regression modelling approaches have been applied to physical properties, compaction characteristics and hydraulic conductivity in soil-liner research (Khalid et al., 2024). The model-development procedure, including screening, transformation and validation of laboratory data, was conducted following the statistical modelling principles described by (Diah J. et al., 2013).

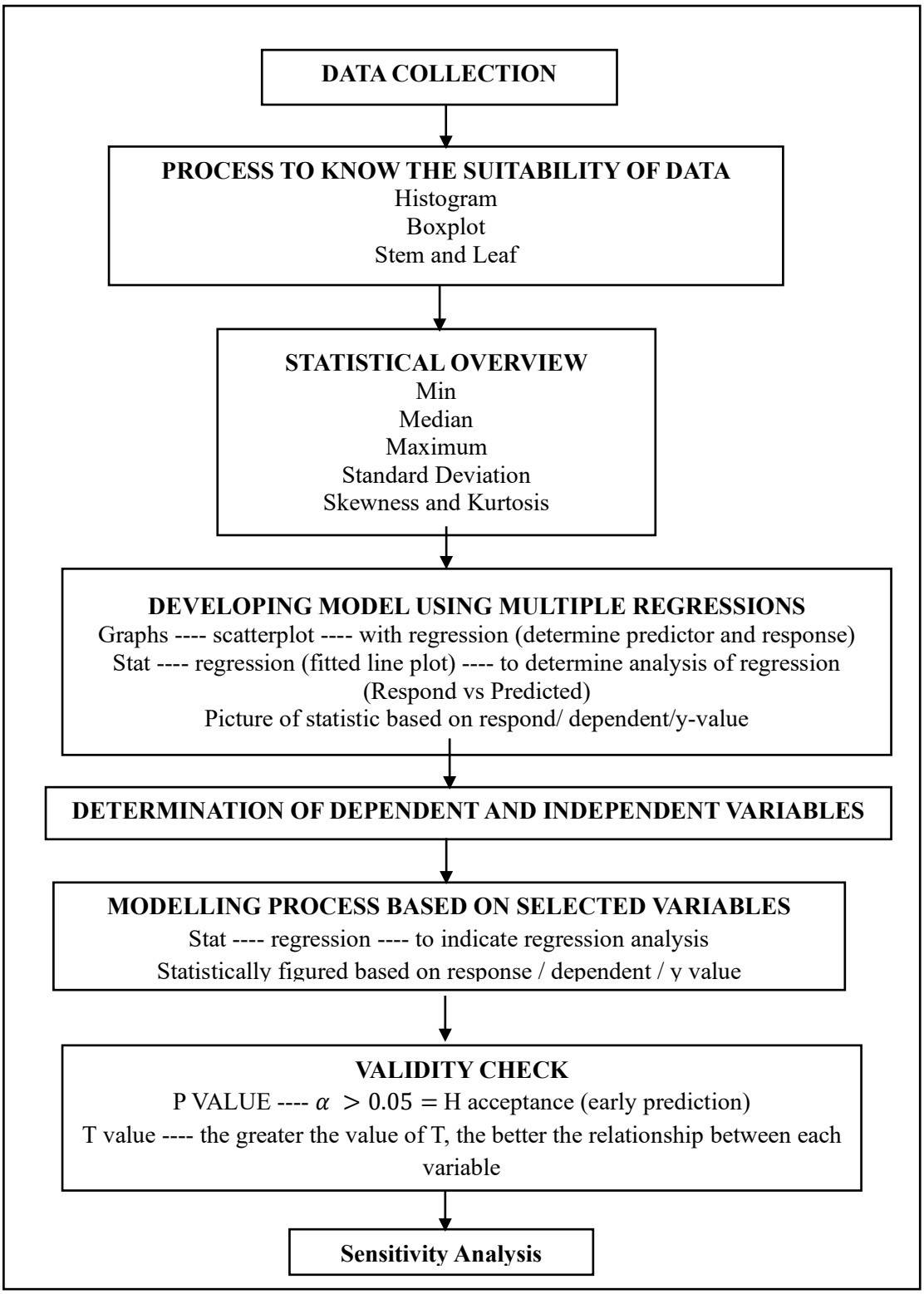


Figure 3.25 Flowchart of an Empirical Model (Diah J. et al., 2013)

3.6.1 Descriptive Statistic for All Data

Descriptive statistics provide crucial contextual information, such as the number of observations, average, standard deviation, minimum, median, maximum, skewness, kurtosis, and others. Data that had a statistically significant value were selected following sample testing. With a confidence level of 95%, the data that generated a graph in a bell shape and followed the empirical law were deemed normal (Aziz, 2018).

3.6.2 Normality Test for Model

A normality test is conducted after the descriptive analysis stage is done. A normality test was conducted to determine whether the dataset follows a normal distribution prior to performing further statistical analyses such as regression and correlation. The normality of the variables was evaluated using the Anderson–Darling test in Minitab statistical software, which is commonly used to assess the goodness-of-fit of data to a normal distribution. In this test, the null hypothesis assumes that the data are normally distributed, while the alternative hypothesis indicates that the data do not follow a normal distribution. A significance level of 0.05 was adopted, where a p-value greater than 0.05 indicates that the data do not significantly deviate from normality.

The normality assessment was performed using the probability plot function in Minitab, where the distribution of the data points is compared against a theoretical normal distribution line. In addition to the Anderson–Darling statistic and p-value, the graphical interpretation of the probability plot was also examined. Data points that closely follow the reference line indicate that the dataset approximates a normal distribution. If significant deviation from normality was observed, appropriate data transformation, such as logarithmic transformation, was applied to improve the distribution before conducting further statistical analyses.

3.6.3 Regression Analysis

Regression analysis is a statistical technique used to model the relationship between a response variable and one or more predictor variables and to predict the response based on known predictor values. In simple regression, one predictor variable is used, whereas multiple regression incorporates two or more predictor variables. The

relationship may be represented using a linear or nonlinear mathematical equation, depending on the characteristics of the data. In soil-liner research, Mukri et al. (2018) used measurable physical and engineering soil parameters to develop empirical equations for predicting hydraulic conductivity. A similar statistical framework involving variable selection, multiple regression, model calibration and validation was presented by Diah J. et al. (2013).

Correlation is one of the statistical tools used to explain the level of linear correlation between two variables (N. Khalid et al., 2024). The correlation analysis is necessary to describe in detail the degree of correlation between each variable if the y variable reclines to x. R stands for "correlation coefficient" in the field of statistics. The standard error value is expressed in the same measurement system as the coefficient. It is crucial to determine the validity of statistical analyses based on the ratio of standard error to coefficient. A good test result can be predicted from a minimal standard error value while applying a constant and coefficient.

3.6.4 Comparison between k-model with Pair T-test

Paired-T test is carried out to differentiate between the predicted data and measured data from the laboratory. During the analysis, the hydraulic conductivity value from the base data is compared before and after statistical analysis. A paired t-test was conducted to evaluate the agreement between the predicted hydraulic conductivity obtained from the regression model and the measured hydraulic conductivity values. The paired t-test is appropriate when two related datasets are compared, as it determines whether the mean difference between paired observations is statistically significant. In this study, the observed hydraulic conductivity values and the corresponding predicted values from the developed k-model were treated as paired samples.

The Paired T-test was performed using Minitab statistical software at a significance level of 0.05. The null hypothesis (H_0) assumes that there is no significant difference between the measured and predicted hydraulic conductivity values, while the alternative hypothesis (H_1) assumes that a significant difference exists. If the p-value is greater than 0.05, the null hypothesis cannot be rejected, indicating that the regression model predictions are statistically consistent with the experimental measurements. Conversely, a p-value less than 0.05 indicates that the predicted values differ

significantly from the measured values, suggesting that the model may require further refinement.

3.6.5 Validation Data Set

The validation of the regression model marks the conclusion of the modelling procedure. The final selected model is currently undergoing a comprehensive validation procedure. Two prevalent approaches for validating a regression model include the collection of new data and the assessment of the model's predictive accuracy. The process also entails utilizing holdout samples or previously unused data in the model calibration, followed by a comparison of the outcomes with those forecasted by theoretical frameworks and earlier empirical and simulation findings. Khalid (2021) indicated that the results of validation analyses require a P value greater than 0.05 to demonstrate that the validation process has been successful. (Kutner, 2005) assert that collecting pertinent data is the most efficient approach for constructing predictive models. This newly gathered information is utilized to enhance the understanding of existing data and to yield more precise predictions.

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 Composition of Residual soil, Kenaf Fibre and Empty Fruit Bunch

This chapter presents and discusses the experimental findings on the effects of kenaf fibre and empty fruit bunch (EFB) on the physical and engineering characteristics of residual soil intended for use as a compacted landfill liner. The performance of the untreated soil and soil–additive mixtures containing different percentages of kenaf fibre and EFB was evaluated through physical-property, compaction and hydraulic-conductivity tests. The results are analysed to determine the influence of additive type, additive content and applied pressure on the suitability of the treated soil as a low-permeability liner material. Statistical analyses were subsequently conducted using Minitab 24 to establish and validate empirical relationships for predicting the hydraulic conductivity of the soil mixtures. Based on the developed empirical models, nomographs were produced to facilitate the practical estimation of hydraulic conductivity for landfill-liner design. The locations of the residual-soil sampling sites, which were selected within areas characterised by predominantly clayey soil deposits, are presented in Figure 4.1.

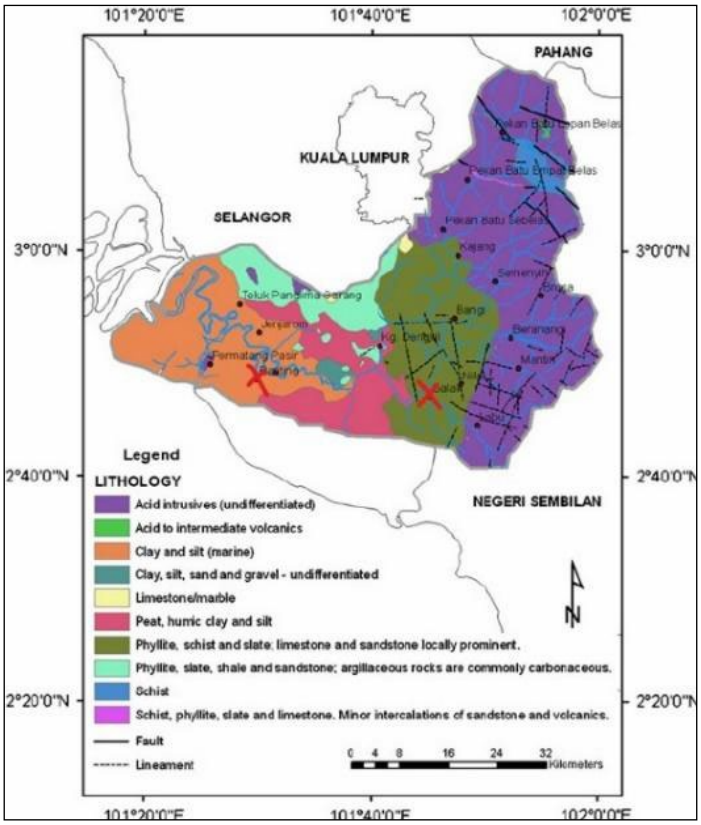


Figure 4.1 Location of the soil sample in Salak Tinggi

Soil sample is prepared according to the percentage of additives and mix thoroughly as shown in before conducting the tests. The samples used in this study shown in Table 4.1. The best percentages of EFB and Kenaf Fibre added to the soil was investigated based on the previous soil stabilization literature review.

Table 4.1

Soil Samples Based on Percentages of Additives

No	Sample	Sample	Sample Description
1	ST1	ST2	Soil (0% Kenaf and EFB)
2	ST1-5.0 K	ST2-5.0 K	Soil + 5.0% Kenaf
3	ST1-10.0 K	ST2-10.0 K	Soil + 10.0% Kenaf
4	ST1-15.0 K	ST2-15.0 K	Soil +15.0% Kenaf
5	ST1-20.0 K	ST2-20.0 K	Soil + 20.0 Kenaf
6	ST1-5.0EFB	ST2-5.0EFB	Soil + 5.0% EFB
7	ST1-10.0EFB	ST2-10.0EFB	Soil + 10.0% EFB
8	ST1-15.0EFB	ST2-15.0EFB	Soil +15.0% EFB
9	ST1-20.0EFB	ST2-20.0EFB	Soil + 20.0 EFB
10	ST1-2.5KEFB	ST2-2.5KEFB	Soil + 2.5% Kenaf + 2.5% EFB
11	ST1-5.0KEFB	ST2-5.0KEFB	Soil + 5.0% Kenaf + 5.0% EFB
12	ST1-7.5KEFB	ST2-7.5KEFB	Soil + 7.5% Kenaf + 7.5% EFB
13	ST1-10.0KEFB	ST2-10.0KEFB	Soil + 10.0% Kenaf + 10.0% EFB

4.1.1 Particle Distribution and Classification

Particle size distribution (PSD) delineates the ratio of soil particles, by dry mass, allocated across specified coarse and fine particle-size categories within the soil matrix. A series of characterization tests including particle size distribution analysis (through wet sieving and hydrometer methods), particle density measurement, pH determination, and Atterberg Limit tests were performed, and the resulting data were systematically analysed before advancing to subsequent experimental phases.

The particle size distribution curve for Salak Tinggi 1 (ST1), shown in Figure 4.2 , indicates that the soil is mainly composed of silt and sand particles, with smaller proportions of clay and gravel fractions. Based on the PSD analysis, ST1 contains approximately 35.6% sand, 36.8% silt, 16.0% gravel, and 11.6% clay. The effective particle-size values obtained from the PSD curve include approximately D_{60} = 1.08 mm, D_{50} = 0.084 mm, and D_{30} = 0.008 mm.

The particle size distribution curve for Salak Tinggi 2 (ST2), shown in Figure 4.3, indicates that the soil is predominantly composed of sand and silt particles with smaller proportions of clay and gravel fractions. Based on the PSD analysis, ST2 contains approximately 53.53% sand, 22.72% silt, 13.75% clay, and 10.00% gravel. Compared with ST1, the ST2 sample exhibits a higher sand content and lower silt fraction, suggesting a relatively coarser particle composition. The effective particle size values obtained from the PSD curve include D_{60} = 0.371 mm, D_{50} = 0.214 mm, and D_{30} = 0.051 mm.

The gradation characteristics of ST2 were further evaluated using the coefficient of uniformity (C_u) and coefficient of gradation (C_g). The calculated C_u value of approximately 185.5 indicates that the soil contains a wide range of particle sizes, reflecting a heterogeneous soil structure. Meanwhile, the coefficient of gradation (C_g) was determined to be approximately 3.50, which is slightly above the typical range of 1 to 3 for well-graded soils. This suggests that the soil gradation is somewhat irregular, with certain particle size ranges dominating the distribution.

Overall, both ST1 and ST2 soils are classified as sandy SILT, although ST2 exhibits a relatively coarser gradation due to its higher sand fraction. These differences in particle size distribution are expected to influence the soil's engineering behaviour, particularly in terms of compaction characteristics and hydraulic conductivity. Soils with higher sand content generally exhibit larger pore spaces and potentially higher

permeability, whereas soils with higher silt content tend to retain more water and display lower hydraulic conductivity. Therefore, the PSD results provide important insight into the subsequent analysis of compaction behaviour and permeability characteristics discussed in later sections.

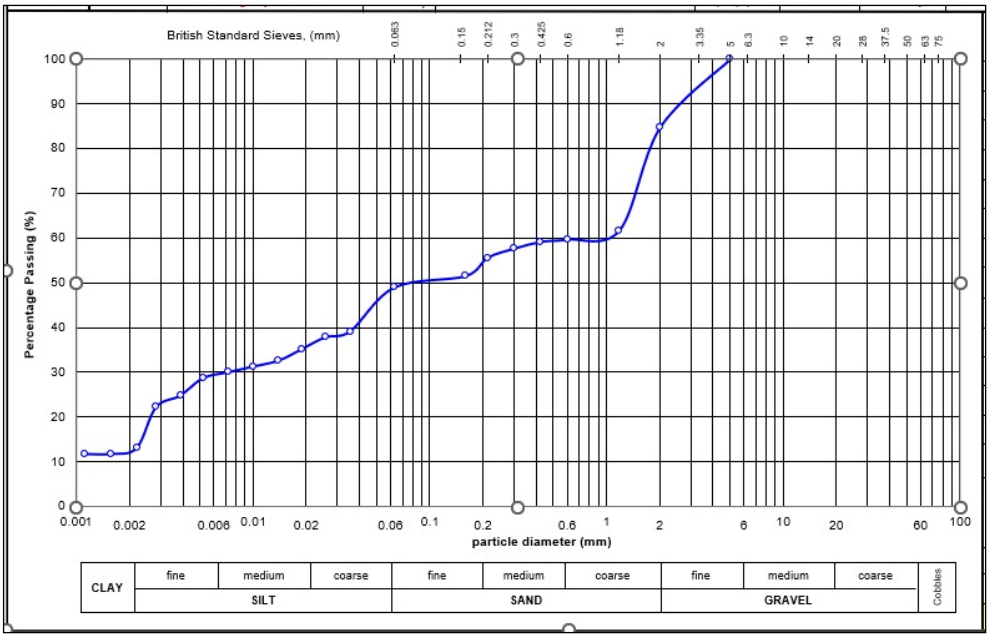


Figure 4.2Particle Size Distribution of Salak Tinggi 1(ST1)

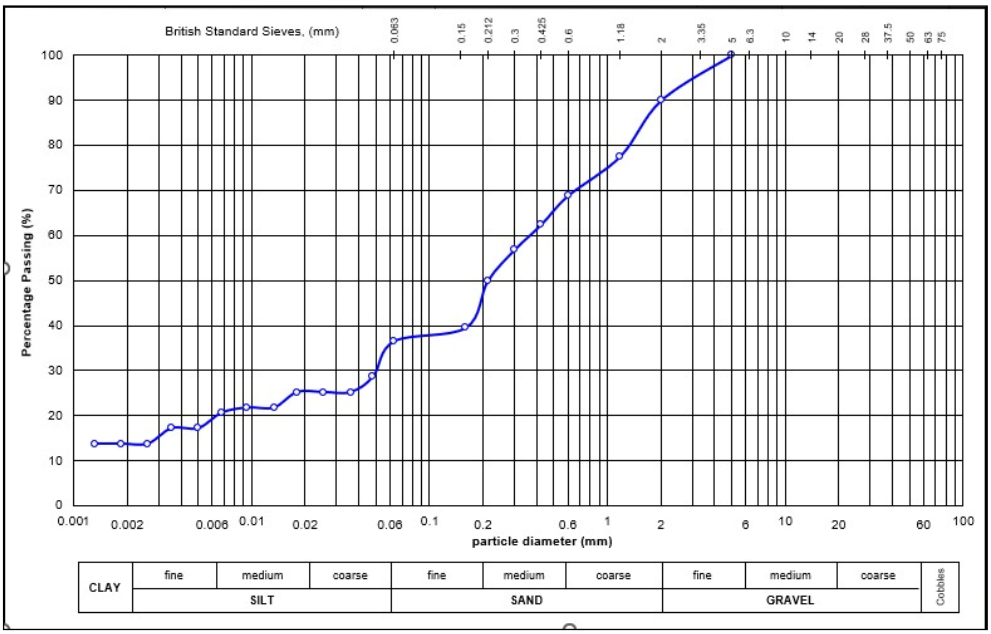


Figure 4.3 Particle Size Distribution of Salak Tinggi 2 (ST2)

Table 4.2
Physical Properties of Soil at Site ST1 and Site ST2

Properties	ST1	ST2
Depth (m)	1.5 - 2.0	1.5 - 2.0
Natural Moisture Content (%)	26.36	26.36
pH	5.5	5.5
Specific Gravity, (Gs)	2.388	2.378
Gravel (%)	15.31	10.00
Sand (%)	35.71	53.53
Silt (%)	37.23	22.72
Clay (%)	11.75	13.75
C_u	343.5	185.5
C_g	0.036	3.500
D_{60}	0.687	0.371
D_{50}	0.102	0.214
D_{30}	0.007	0.051
D_{10}	0.002	0.002
Soil Classification	Sandy SILT	Sandy SILT

4.1.2 Particle Density Test

Particle density determines in ratio on the relationship of heavier or lighter the soil mineral is than water. The pycnometer density bottle method is used to determine the particle density of the sample in this particle density test. The pycnometer density bottle method was chosen instead of the gas jar method since the soil were categorized as fine soil. Both samples from Salak Tinggi 1 and Salak Tinggi 2 were tested. Table 4.3 shows the particle density test value for all samples. With the additional of kenaf, value of specific gravity is reduced gradually.

Table 4.3 and Figure 4.4 presents the specific gravity values of Salak Tinggi soil mixed with different percentages of Kenaf Fibre (K), Empty Fruit Bunch (EFB), and mix of Kenaf Fibre and EFB (KEFB) additives. The untreated soil (ST1) recorded specific gravity values ranging between 2.378 and 2.388, with an average value of approximately 2.383. This value is slightly lower than the typical specific gravity range for mineral soils, which generally varies between 2.60 and 2.70, depending on the

mineralogical composition and organic content of the soil (Das & Sobhan, 2006). The relatively lower value observed in this study attributed to the presence of organic materials and the weathered characteristics of residual soils.

Table 4.3
Summary of Specific Gravity with Different Percentage of Additives

Sample	Specific Gravity	
	ST1	ST2
SS	2.388	2.378
SS-5.0K	2.362	2.482
SS-10.0K	2.347	2.417
SS-15.0K	2.356	2.366
SS-20.0K	2.245	2.287
SS-5.0EFB	2.523	2.623
SS-10.0EFB	2.433	2.553
SS-15.0EFB	2.356	2.490
SS-20.0EFB	2.320	2.380
SS-2.5KEFB	2.480	2.550
SS-5.0KEFB	2.545	2.570
SS-7.5KEFB	2.455	2.500
SS-10.0KEFB	2.366	2.440

For the soil treated with Kenaf Fibre (K), the specific gravity exhibited a decreasing trend as the fibre content increased. The value decreased from approximately 2.422 at 5% Kenaf Fibre to 2.266 at 20% kenaf fibre. This reduction is primarily associated with the relatively low density of natural fibres compared with soil minerals. Kenaf fibres are primarily composed of cellulose-based organic materials with a porous cellular microstructure, which results in relatively low density compared with mineral soil particles. When incorporated into soil mixtures, these lightweight fibres partially replace heavier soil particles and may introduce additional void spaces within the soil matrix, leading to a reduction in the overall density of the soil–fibre composite

(Mirzababaei et al., 2018). Additionally, the inclusion of higher fibre content can introduce additional void spaces within the soil matrix, thereby reducing the effective density of the mixture.

In contrast, the addition of EFB resulted in an initial increase in specific gravity at lower additive percentages. The maximum value was observed at 5% EFB, with an average specific gravity of approximately 2.573, which is significantly higher than the untreated soil. This increase may be attributed to the fibrous structure and possible mineral residues contained in the EFB material, which may contribute to improved packing between soil particles at moderate additive levels. However, when the EFB content exceeded this level, the specific gravity gradually decreased, reaching approximately 2.350 at 20% EFB. This behaviour suggests that excessive fibre inclusion leads to an increase in void ratio within the soil–fibre matrix, thereby reducing the overall density of the mixture. Similar observations have been reported in fibre-reinforced soils where excessive fibre content increases the void ratio and alters the soil structure, resulting in lower bulk density.

The hybrid Kenaf Fibre–EFB (KEFB) mixtures exhibited specific gravity values ranging between 2.403 and 2.558, with the maximum value occurring at 5% KEFB. The hybridization of fibres appears to provide a synergistic effect, where the combined structural characteristics of kenaf and EFB fibres improve soil particle interlocking and packing efficiency. At moderate additive percentages, the hybrid fibre system may enhance fibre–soil interaction, forming a reinforcing network within the soil matrix that improves structural stability. Previous studies have indicated that hybrid fibre reinforcement can improve the mechanical behaviour of soils by increasing interfacial bonding and distributing stresses more uniformly within the soil structure (Tang, Shi, Gao, Chen, & Cai, 2007). Nevertheless, similar to the single-fibre systems, the specific gravity decreased when the additive content exceeded the optimum level, which can be attributed to the dominance of lightweight organic fibres and the associated increase in void spaces.

Overall, the results indicate that the incorporation of natural fibres significantly alters the physical characteristics of the soil by affecting its density and internal structure. Moderate fibre contents tend to improve soil particle arrangement and packing efficiency, whereas excessive fibre addition reduces the overall specific gravity due to the lower density and higher void ratio associated with organic fibres. These

findings highlight the importance of identifying an optimum fibre content in soil stabilization applications to balance improvements in soil structure with potential reductions in density. These findings are crucial for evaluating soil appropriateness for geotechnical applications, including compaction, subgrade preparation, and stabilization efforts.

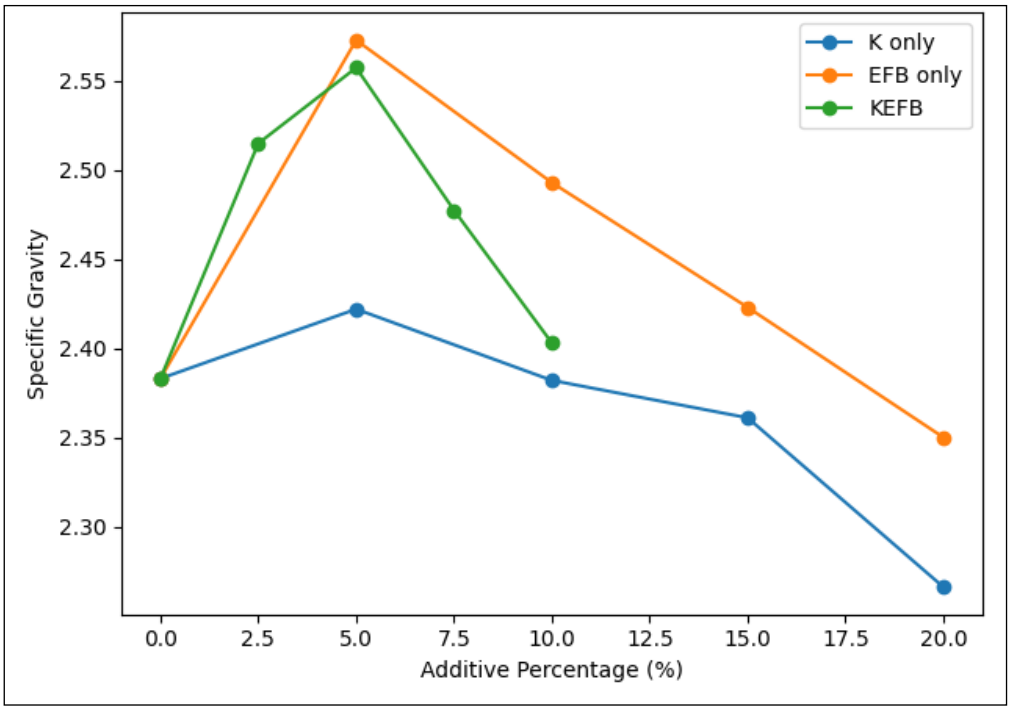


Figure 4.4: Variation of Specific Gravity with Different Percentages of Kenaf Fibre (K), Empty Fruit Bunch (EFB), and Hybrid Kenaf–EFB Additives

4.1.3 Atterberg Limit Test

The Atterberg limit test was conducted to evaluate the consistency characteristics of the residual soils obtained from Site 1 (ST1) and Site 2 (ST2). For the natural soil without additives (0%), ST1 recorded a liquid limit (LL) of 76.92%, a plastic limit (PL) of 49.34%, and a plasticity index (PI) of 27.59%, while ST2 showed slightly higher plasticity values with LL of 77.31%, PL of 47.50%, and PI of 29.81%. The results indicate that both soils possess relatively high plasticity characteristics, which is typical for tropical residual soils containing significant proportions of silt and clay minerals. The slightly higher PI value observed for ST2 suggests that the soil at this site may exhibit greater plastic deformation potential compared to ST1. High plasticity soils are generally associated with greater moisture sensitivity and volume change behaviour,

which may influence their engineering performance in geotechnical applications (Das & Sobhan, 2014; Holtz, Kovacs & Sheahan, 2011).

The addition of Kenaf Fibre influenced the Atterberg limits of both soils as shown in Figure 4.5 For ST1, the liquid limit and plasticity index generally decreased with increasing kenaf content, with PI reducing from 27.59% in the natural soil to 20.03% at 20% kenaf content. This indicates that the incorporation of kenaf fibre reduces the plasticity of the soil, likely due to the replacement of fine clay particles with fibrous materials and the formation of a soil–fibre network that restricts particle movement. In contrast, the results for ST2 show relatively smaller changes in plasticity, where PI values remained within the range of 27.01% to 30.37% for kenaf contents between 5% and 20%. The difference in response between the two sites may be attributed to variations in the initial soil structure and particle distribution. Previous studies have reported that natural fibres such as kenaf can reduce soil plasticity by limiting the interaction between clay particles and water while improving soil structure through fibre reinforcement (Tang et al., 2007; Mirzababaei et al., 2018).

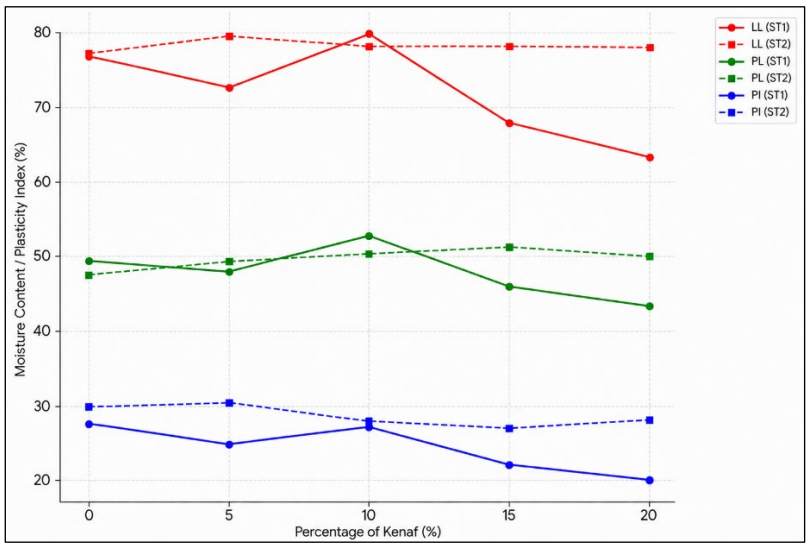


Figure 4.5 Effect of Kenaf Fibre on Atterberg Limit

The incorporation of EFB also affected the consistency limits of the soils as shown in Figure 4.6. For ST1, the addition of EFB significantly reduced the liquid limit and plasticity index at lower fibre contents, with PI decreasing to 10.73% at 5% EFB, indicating a substantial reduction in soil plasticity. This reduction may be attributed to the fibrous and porous structure of EFB, which replaces fine particles and reduces the

effective surface area available for water adsorption. For ST2, however, the effect of EFB was less pronounced, with PI values remaining relatively stable between 28.59% and 29.77% for EFB contents ranging from 5% to 20%. The difference in behaviour between ST1 and ST2 may be related to differences in their initial soil structure and clay content. Similar observations have been reported in previous studies where the addition of agricultural fibres alters the consistency characteristics of fine-grained soils by modifying the soil matrix and reducing plasticity (Horpibulsuk et al., 2011; Estabragh et al., 2014).

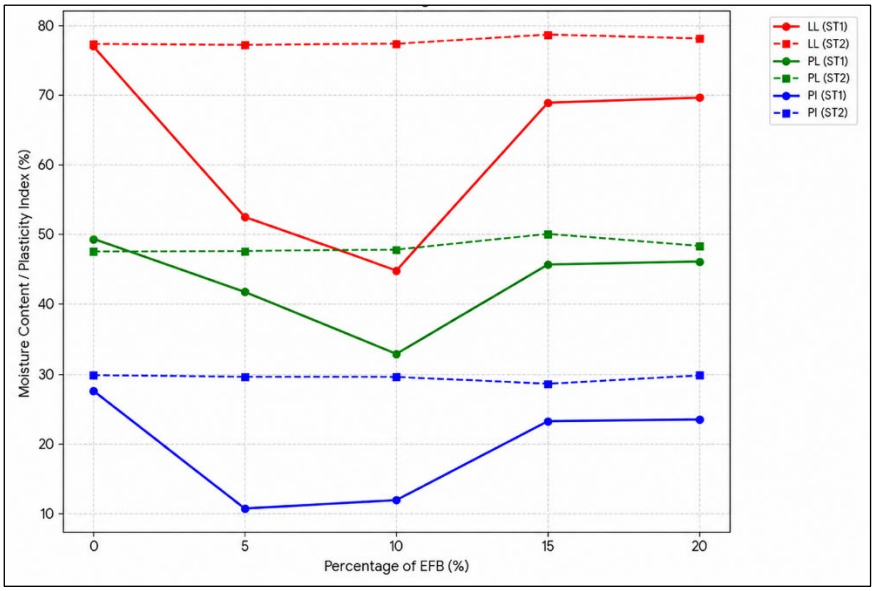


Figure 4.6 Effect of EFB on Atterberg Limit

The combined addition of Kenaf Fibre and EFB (KEFB) produced noticeable changes in the Atterberg limits of both soils as shown in Figure 4.7. For ST1, the liquid limit increased at lower fibre contents, reaching 85.44% at 5% KEFB, while the plasticity index showed a decreasing trend at higher fibre contents, reaching 19.97% at 10% KEFB. This behaviour may be attributed to the higher water absorption capacity of the combined organic fibres, which contain cellulose-based materials capable of retaining moisture within their porous structure. For ST2, the KEFB mixtures produced moderate variations in consistency limits, with *PI* values ranging between 22.79% and 30.77%. The results suggest that the interaction between kenaf and EFB fibres influences the soil's consistency behaviour by altering the soil and water interaction and fibre distribution within the soil matrix. Previous research has shown that natural fibre mixtures can significantly modify soil plasticity and improve the stability of fine-

grained soils by creating a reinforcing network within the soil structure (Mirzababaei et al., 2018; Anggraini et al., 2015).

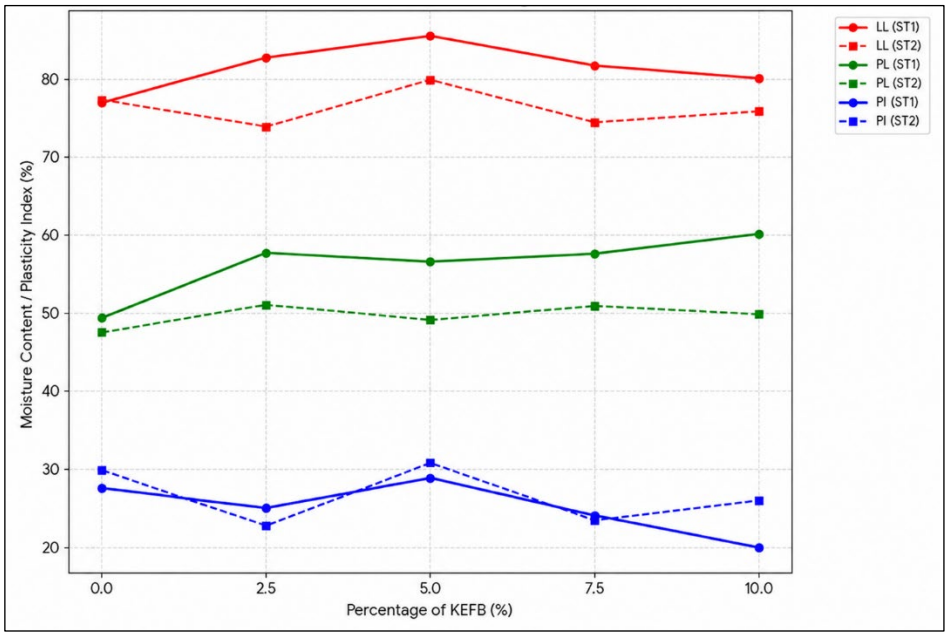


Figure 4.7 Effect of Kenaf Fibre and EFB on Atterberg Limit

The results from the plasticity chart, classified under BS 5930 as shown in Figure 4.8 reveal that the raw soils at both ST1 and ST2 are predominantly Silts of Very High Plasticity (MV). For ST1, the addition of Kenaf Fibre and EFB additives effectively shifted the soil classification toward the High (H) and Intermediate (I) plasticity zones, with the 10% EFB sample notably reaching the MI (Silt of Intermediate Plasticity) region. This shift is geotechnically significant while high plasticity is necessary for low permeability, excessive plasticity often leads to desiccation cracking. According to (D. E. Daniel, 1993), an ideal soil liner should maintain a *PI* between 10% and 30% to balance hydraulic performance with volumetric stability. The stabilization process at ST1 successfully brought several samples into this condition suggesting that these organic additives can mitigate the extreme plasticity of native soils to create a more stable engineering material.

In terms of liner suitability, the stabilized samples from ST1 meet the fundamental regulatory requirements of having a $LL > 20\%$ and $PI > 10\%$. As noted by (Rowe et al., 2004), fine-grained soils in the CI to CH/CV range can achieve the required hydraulic conductivity of 1×10^{-7} cm/s when compacted properly. However, the high *PI* values remaining in ST2 (consistently > 25%) indicate a higher risk of shrinkage induced leakage if the liner undergoes wetting-drying cycles.

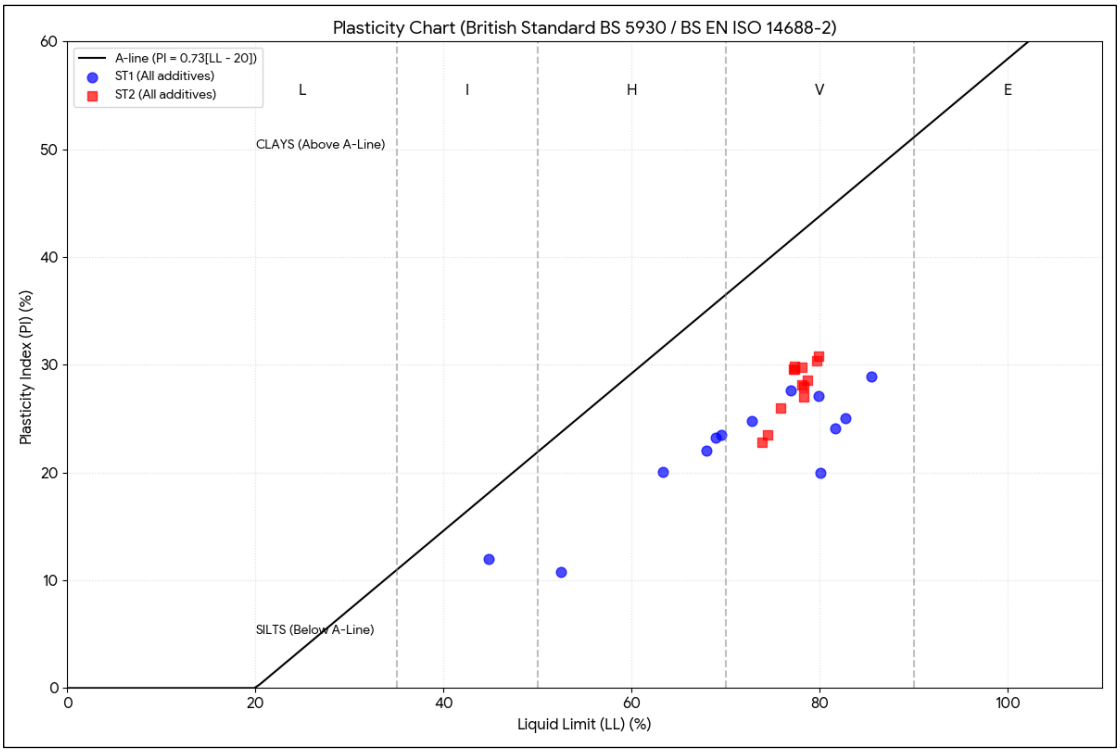


Figure 4.8 Plasticity Chart Based on BS5930

4.1.4 Microstructure by Scanning Electron Microscope (SEM) and EDX

A Scanning Electron Microscope (SEM) technique was utilized to investigate how the structure of Kenaf Fibre and EFB affects its strength properties. The morphology analysis of the different percentages of Kenaf Fibre and Empty Fruit Bunch (EFB) mix was done by using SEM. The formation developed between additives and the soil were analysed. Figure shows the characteristics of SEM structure of the original soil. It shows some angular and sharp-edge grain with some spherical (fine particles) attached to the surface of larger grains. However, with the additional additives tends to form attachments with the soil of larger particles and reduce the voids between the particles. It resulting the soil produces less pores.

The SEM micrograph of the untreated Salak Tinggi residual soil from Figure 4.9 reveals a characteristically flocculated and heterogeneous fabric, where clay platelets are clustered into larger aggregate peds separated by visible inter-aggregate macro-pores and micro-fissures. This morphology indicates a high specific surface area and significant topography, which contributes to the soil's natural water-retention capacity as observed in baseline consistency tests. Correspondingly, the EDX elemental profile confirms a mineralogy dominated by Oxygen (O), Silicon (Si), and Aluminum

(Al) peaks the distinctive signature of kaolinite minerals along with secondary Iron (Fe) and Potassium (K) traces that represent natural weathering oxides and primary mineral residuals.

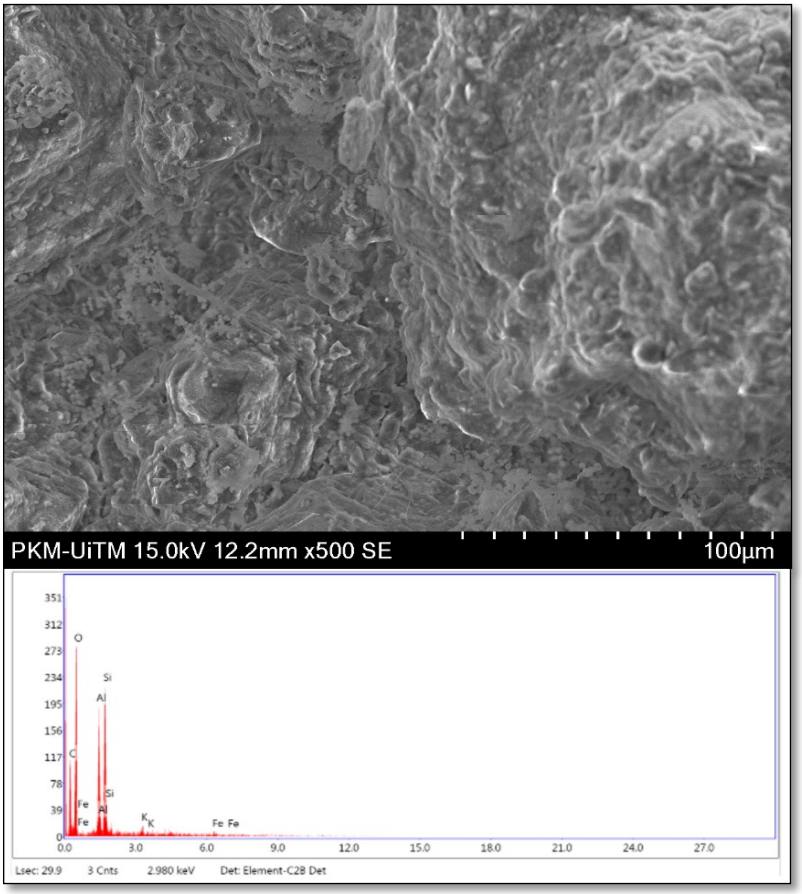


Figure 4.9 SEM-EDX Analysis of Salak Tinggi Residual Soil

The Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) analysis of the Kenaf-reinforced Salak Tinggi residual soil from Figure 4.10 demonstrates that the inclusion of fibers effectively transforms the soil into a stabilized bio-composite by bridging inter-aggregate macro-pores and micro-fissures. This physical reinforcement is characterized by the mechanical interlocking of the Kenaf fibers within the flocculated clay matrix, which is chemically verified by the appearance of a distinct Carbon (C) peak in the EDX spectrum that signifies the successful integration of organic cellulose into the mineral-dominant Silicon (Si) and Aluminum (Al) framework. According to(Nam et al., 2012), such fiber-soil interaction mechanisms

are critical in increasing the structural integrity and ductility of residual soils through the creation of a cohesive, interlaced reinforcement network.

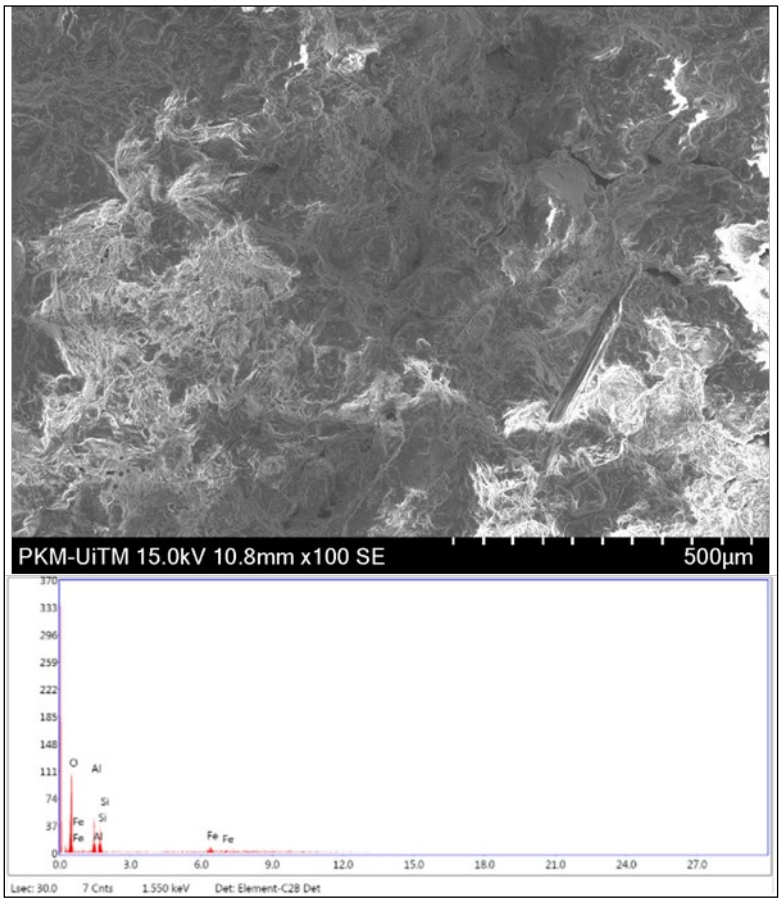


Figure 4.10 SEM-EDX Analysis of Soil Treated with Kenaf

The Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) analysis of the Salak Tinggi residual soil reinforced with Empty Fruit Bunch (EFB) in Figure 4.11fibers illustrate a robust mechanical interlocking between the rough, irregular fibre surfaces and the angular clay peds. This physical reinforcement is chemically validated by the emergence of a significant Carbon (C) peak in the EDX spectrum, signifying the presence of organic cellulose, along with trace biological markers such as Potassium (K). According to, the inherently high surface roughness of EFB fibres provides superior interfacial shear resistance compared to smoother natural fibres, effectively anchoring the reinforcement within the soil matrix to improve overall geotechnical stability.

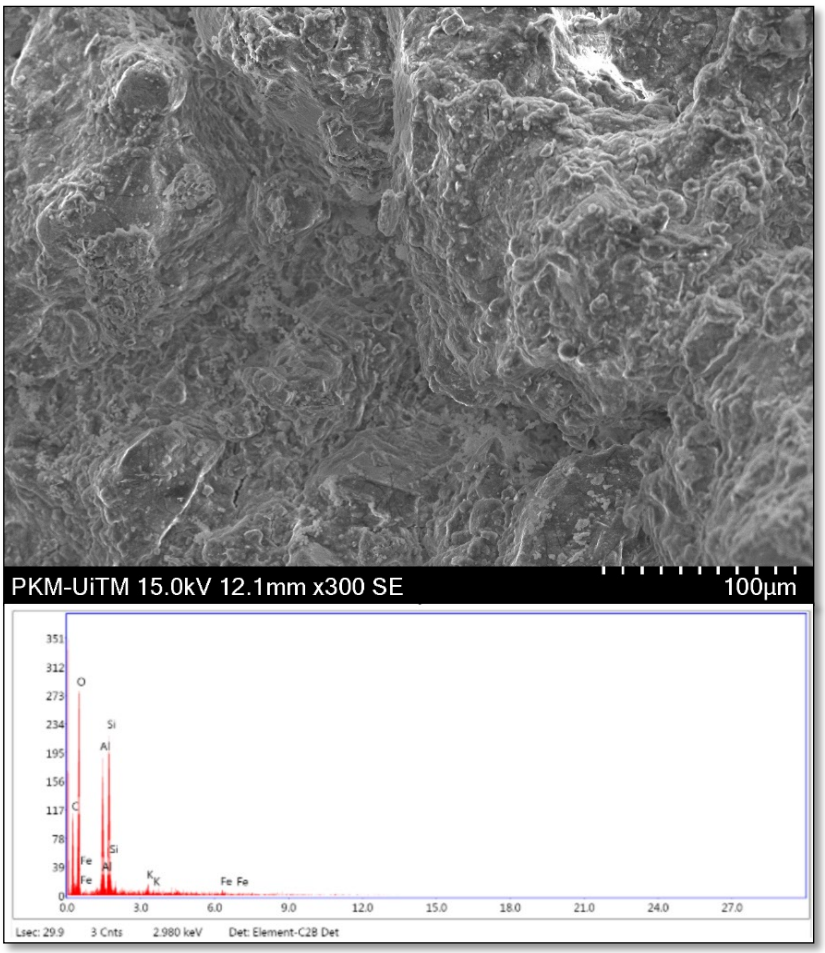


Figure 4.11 SEM-EDX Analysis of Soil Treated with EFB

4.2 Compaction Characteristics Result

Compaction test is the process by which the solid soil particles are packed more closely together by mechanical means, thus increasing the dry density. It is achieved through the reduction of the air void in the soil, with little or no reduction in the water content. The study indicates that soil compacted at optimum moisture content exhibits higher peak shear strength when sheared at residual moisture content. This suggests that at maximum dry density and optimum moisture content, the soil achieves its highest strength. The findings emphasize the importance of considering moisture content during compaction for accurate predictions of soil shear strength in geotechnical design, confirming that optimal conditions significantly enhance the soil's structural integrity. The OMC of soil in the moisture content at which the soil reached MDD state which is usually correlated with the maximum soil strength.(W. Ahmad & Uchimura, 2023). Following the mix proportion in the methodology, the standard compaction tests were conducted immediately after mixing the soil with Kenaf Fibre and EFB. Appendix

shows the compaction curve with different percentage of admixtures.

4.2.1 Compaction Behaviour of Soil Stabilized with Kenaf Fibre

The compaction behaviour of both ST1 and ST2 soils was influenced by the inclusion of Kenaf Fibre, as reflected in the variations MDD and OMC. For ST1, the untreated soil exhibited an MDD of 1.354 Mg/m³ at an OMC of 27.54%, representing the natural compaction condition of the residual soil. With the addition of kenaf fibre, the MDD generally decreased at lower fibre contents, particularly at 5% and 10% kenaf, which can be attributed to the low specific gravity and lightweight nature of natural fibres compared to mineral soil particles. The presence of fibres introduces additional voids and disrupts the close packing of soil grains during compaction, thereby reducing the achievable dry density. A similar trend has been reported in fibre-reinforced soils where increasing fibre content reduces the bulk density due to the replacement of heavier soil particles with lighter fibres and the formation of a more open soil–fibre matrix (Prabakar & Sridhar, 2002; Tang et al., 2007).However, a slight increase in density at higher fibre content indicates that the fibres may contribute to improved interlocking within the soil matrix, enhancing the structural stability of the compacted material.

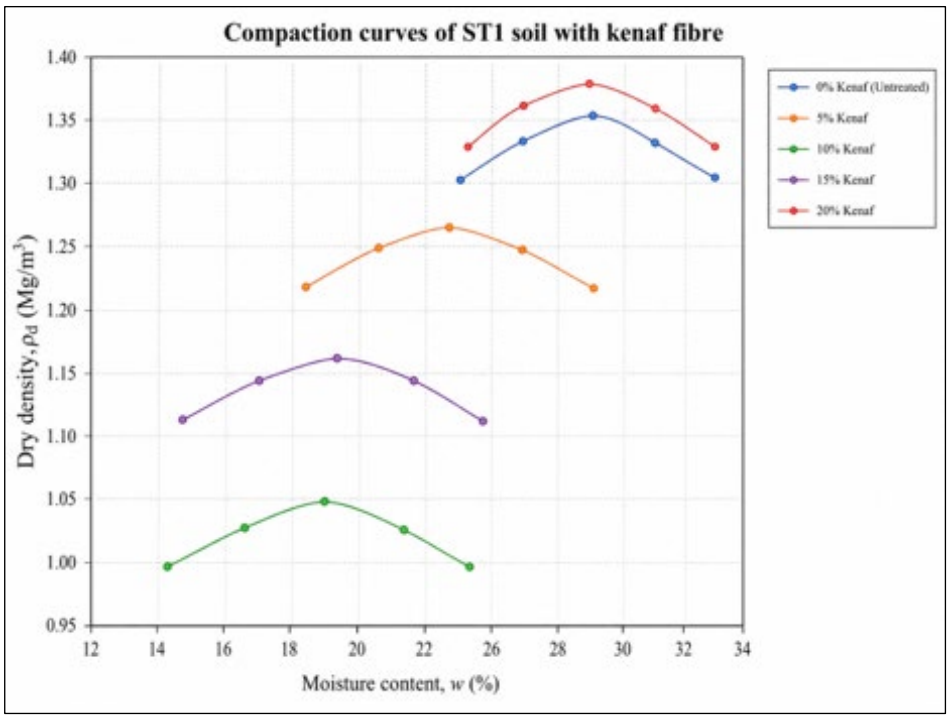


Figure 4.12 Compaction Curve Soil Mixed with Kenaf at ST1

For ST2 soil, a slightly different compaction response was observed as shown in Figure 4.14, where the MDD increased from 1.28 Mg/m³ for the untreated soil to approximately 1.39 Mg/m³ at 15% kenaf, before slightly decreasing at 20% fibre content. This suggests that moderate fibre addition can improve the compaction behaviour by enhancing particle interaction and reinforcing the soil structure during compaction. The corresponding OMC values also showed minor variations, indicating that the presence of natural fibres affects the moisture demand required to achieve maximum density. Fibres can absorb a portion of the water and modify the soil fabric, thereby influencing lubrication between soil particles during compaction (Maher & Ho, 1994; Tang et al., 2007). Overall, the results demonstrate that the inclusion of kenaf fibre alters the compaction characteristics of residual soils by modifying the soil structure, pore distribution, and water demand, highlighting the importance of identifying an optimum fibre content to achieve improved engineering performance.

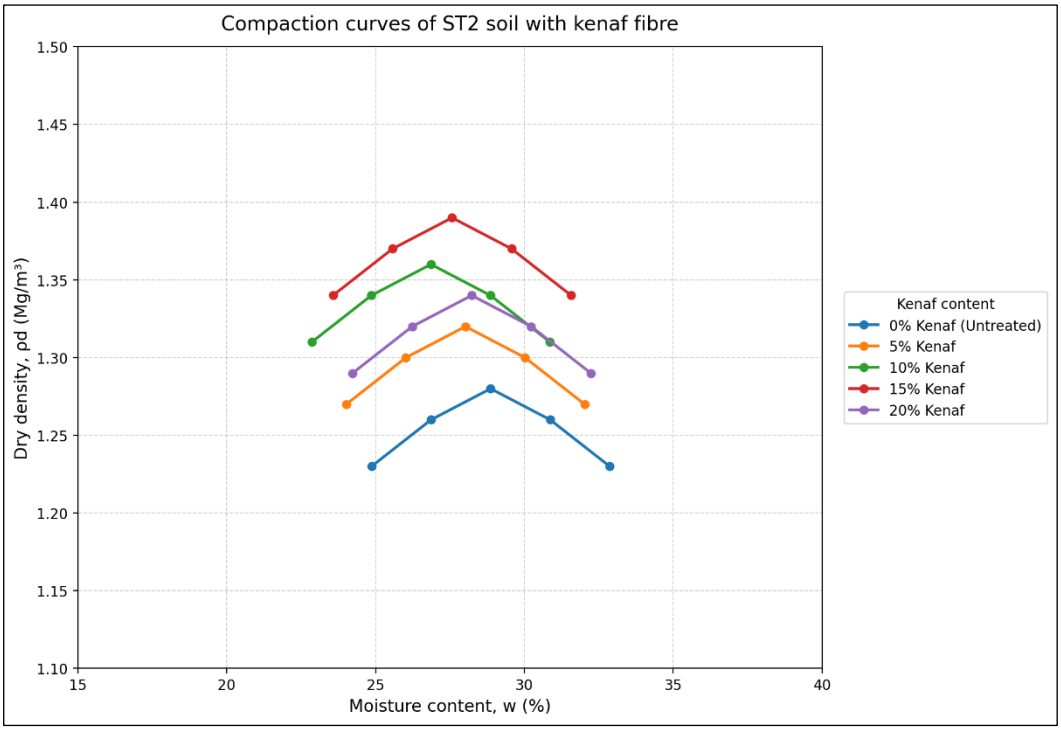


Figure 4.13 Compaction Curve Soil Mixed with Kenaf at ST2

4.2.2 Compaction Behaviour of Soil Stabilized with EFB

The compaction behaviour of ST1 soil mixed with EFB shows a noticeable improvement in maximum dry density (MDD) compared with the untreated soil as shown in Figure 4.15. The natural soil exhibited an MDD of 1.354 Mg/m³ at an OMC of 27.54%, while the addition of EFB increased the MDD, reaching a peak value of 1.557 Mg/m³ at 10% EFB. This increase suggests that the presence of EFB fibres improved the soil structure by enhancing particle interlocking and reducing large void spaces within the soil matrix during compaction. However, beyond the optimum fibre content, the MDD slightly decreased at 15% and 20% EFB, which may be attributed to excessive fibre inclusion that disrupts soil particle contact and creates additional voids. Similar trends have been reported in fibre-reinforced soil studies, where moderate fibre content improves compaction efficiency but excessive fibre content reduces density due to the lightweight nature of fibres and increased void ratio (Tang et al., 2007; Prabakar & Sridhar, 2002).

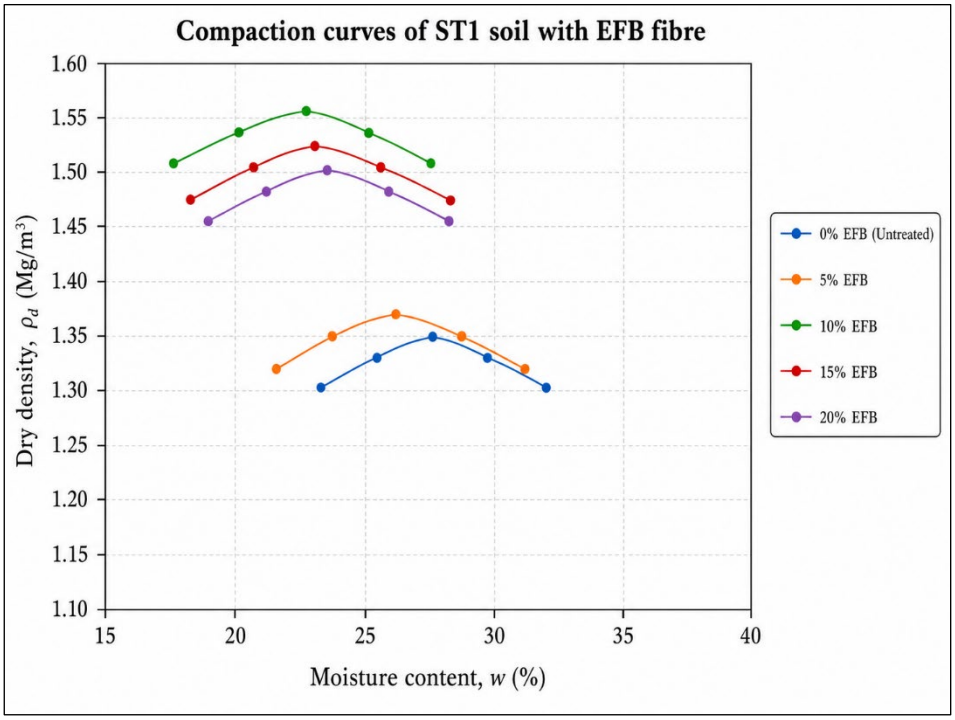


Figure 4.14 Compaction Curve Soil Mixed with EFB at ST1

For ST2 soil, a comparable trend was observed as in Figure 4.16, although the changes in density were less pronounced. The untreated soil had an MDD of 1.28 Mg/m³ at an OMC of 28.865%, and the addition of EFB generally increased the MDD to approximately 1.36 to 1.37 Mg/m³ at fibre contents between 5% and 15%, indicating

that moderate fibre inclusion improved soil compaction behaviour. The OMC values showed slight variations, suggesting that the fibres influenced the moisture required for optimal compaction by absorbing part of the water and altering the soil fabric. At 20% EFB, the MDD decreased slightly, indicating that excessive fibre content may reduce compaction efficiency due to increased void spaces within the soil–fibre mixture. These results demonstrate that EFB fibres can enhance the compaction characteristics of soil when used at an appropriate proportion, while excessive fibre content may negatively affect density due to the formation of a more porous soil structure (Prabakar & Sridhar, 2002; Tang et al., 2007).

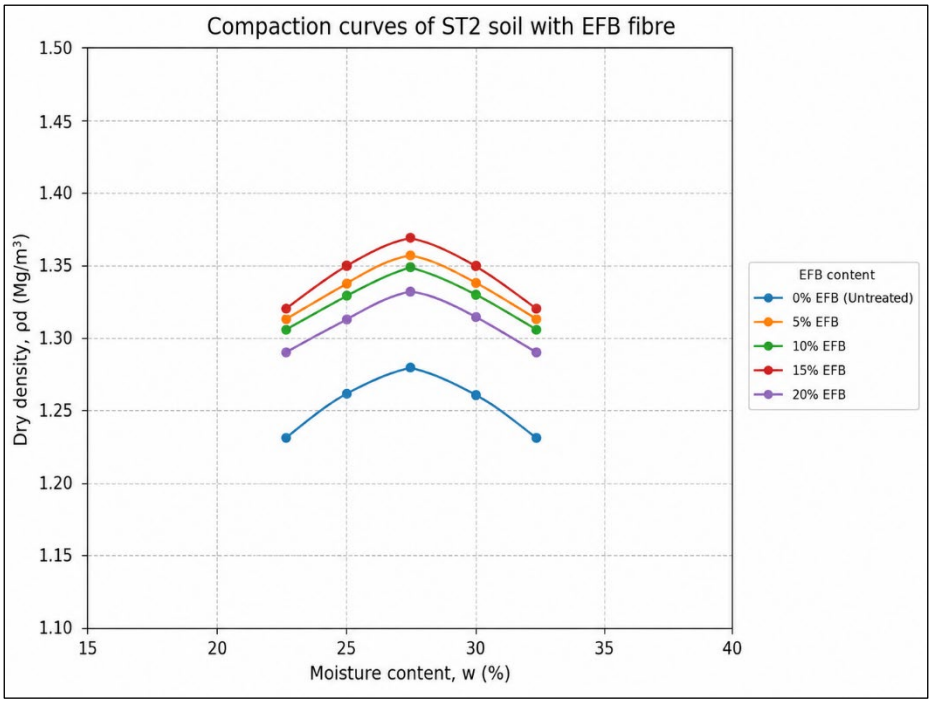


Figure 4.15 Compaction Curve Soil Mixed with EFB at ST2

4.2.3 Compaction Behaviour of Soil Stabilized with Kenaf and EFB

Figure 4.16 shows that the untreated ST1 soil recorded a maximum dry density (MDD) of approximately 1.35 Mg/m³ at an optimum moisture content (OMC) of about 28%. The addition of 5% KEFB increased the MDD to approximately 1.52 Mg/m³, while 10% KEFB produced the highest MDD of approximately 1.56 Mg/m³ at an OMC of about 23%. This indicates that moderate KEFB inclusion improved the compactability of ST1 soil, possibly by enhancing particle arrangement and reducing void spaces within the compacted mixture.

However, increasing the KEFB content to 15% and 20% reduced the MDD to approximately 1.12 Mg/m³ and 1.03 Mg/m³, respectively, while increasing the OMC to about 30% and 35%. This behaviour may be attributed to the lightweight and water-absorbing characteristics of natural fibres, which can create additional voids, retain more moisture and restrict the close packing of soil particles at higher fibre contents. Similar compaction trends have been reported for natural-fibre-reinforced soils (Lawer et al., 2021; Bekkouche et al., 2022). Overall, 10% KEFB was identified as the optimum content for improving the compaction characteristics of ST1 soil.

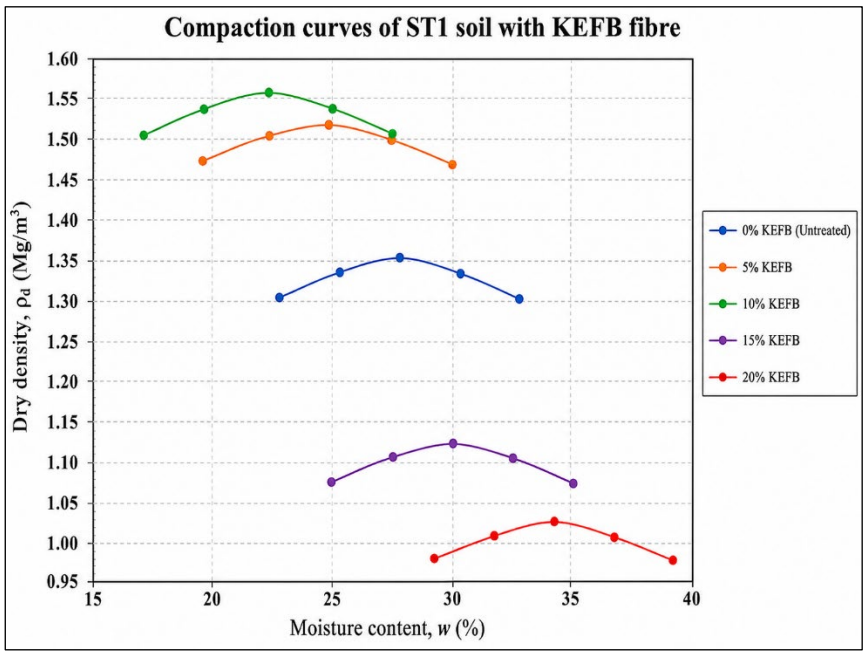


Figure 4.16 Compaction Curves of ST1 with KEFB

Figure 4.17 shows that the untreated ST2 soil recorded a maximum dry density (MDD) of approximately 1.28 Mg/m³ at an optimum moisture content (OMC) of about 29%. The addition of 5% KEFB increased the MDD to approximately 1.37 Mg/m³, while reducing the OMC to approximately 27%. The 10% KEFB mixture recorded an MDD of approximately 1.32 Mg/m³ at an OMC of about 27%. These results indicate that a small amount of KEFB improved the compactability of ST2 soil, possibly by assisting particle rearrangement and filling some of the void spaces within the soil matrix.

At higher KEFB contents, the MDD was approximately 1.35 Mg/m³ for 15% KEFB and 1.34 Mg/m³ for 20% KEFB, with both mixtures recording an OMC of approximately 28%. Although these values remained higher than that of the untreated soil, they were lower than the MDD obtained at 5% KEFB. This reduction may be

attributed to the lightweight and water-absorbing characteristics of natural fibres, which can restrict close soil-particle packing and create additional void spaces at higher fibre contents. Similar compaction behaviour has been reported for natural-fibre-treated soils (Lawer et al., 2021; Bekkouche et al., 2022). Overall, 5% KEFB was identified as the optimum content for improving the compaction characteristics of ST2 soil.

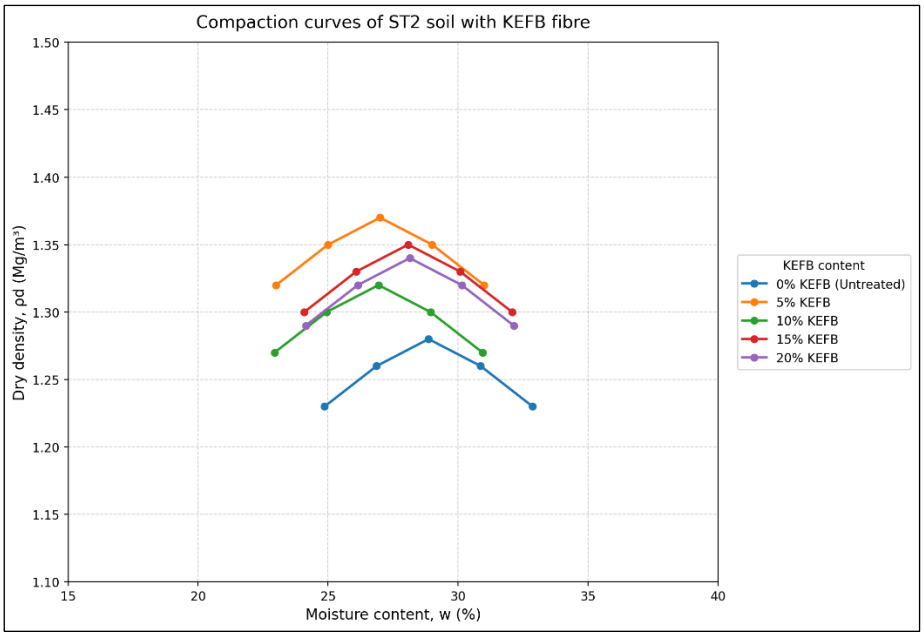


Figure 4.17 Compaction Curves of ST2 with KEFB

Table 4.4 presents the summary of the maximum dry density (MDD) and optimum moisture content (OMC) obtained from the compaction tests for ST1 and ST2 soils stabilized with Kenaf, EFB and combined Kenaf–EFB fibres at different fibre contents (0–20%). The results show that the addition of different fibre types influences the compaction behaviour of the soils, producing variations in both MDD and OMC depending on the fibre content and soil type.

Table 4.4
Optimum Compaction Characteristics of ST1 and ST2 Soils

Soil	Fibre Type	Fibre Content (%)	MDD (Mg/m³)	OMC (%)
	Kenaf	0	1.354	27.54
	Kenaf	5	1.268	22.29
	Kenaf	10	1.046	18.02
	Kenaf	15	1.164	18.8
	Kenaf	20	1.38	27.95
	EFB	0	1.354	27.54
	EFB	5	1.37	25.18
ST1	EFB	10	1.557	22.08
	EFB	15	1.526	23.2
	EFB	20	1.506	23.8
	Kenaf+EFB	0	1.354	27.54
	Kenaf+EFB	5	1.526	25.18
	Kenaf+EFB	10	1.557	22.08
	Kenaf+EFB	15	1.125	27.82
	Kenaf+EFB	20	1.028	32.51
	Kenaf	0	1.28	28.865
	Kenaf	5	1.32	28.02
	Kenaf	10	1.36	26.86
	Kenaf	15	1.39	27.57
	Kenaf	20	1.34	28.23
	EFB	0	1.28	28.865
	EFB	5	1.37	27.23
ST2	EFB	10	1.36	27.13
	EFB	15	1.37	26.75
	EFB	20	1.34	28.27
	Kenaf+EFB	0	1.28	28.865
	Kenaf+EFB	5	1.37	27
	Kenaf+EFB	10	1.32	26.94
	Kenaf+EFB	15	1.35	28.08
	Kenaf+EFB	20	1.34	28.14

4.2.4 Summary on the Compaction Results

The Compaction Test results indicate that the addition of fibres significantly influenced the MDD and OMC of both ST1 and ST2 soils. For ST1 soil, the inclusion of EFB and Kenaf–EFB fibres generally increased the MDD, with the highest value observed at 10% EFB and 10% KEFB, indicating improved compaction efficiency due to better soil fibre interaction. In contrast, the addition of Kenaf Fibre alone showed a reduction in MDD at lower fibre contents, which may be attributed to the lightweight nature of the fibres and the increase in void spaces within the soil matrix(Bawadi et al., 2020).

For ST2 soil, the compaction behaviour showed a slight improvement in MDD with increasing fibre content, particularly at 15% Kenaf and range 5 to 15% EFB, suggesting that moderate fibre addition enhanced the soil structure and particle interlocking during compaction. However, at higher fibre contents, the MDD tended to decrease slightly while the OMC generally increased, indicating that excessive fibre content may reduce compaction efficiency due to increased void ratio and higher moisture demand. Overall, the results demonstrate that the type and percentage of fibre reinforcement play an important role in determining the compaction characteristics of the soil, and an optimum fibre content is required to achieve the best compaction performance(Prabakar & Sridhar, 2002).

4.3 Hydraulic Conductivity of Soil Using Modified Oedometer Apparatus

The assessment of hydraulic conductivity through a modified oedometer apparatus facilitates the concurrent measurement of soil compressibility and one-dimensional flow behavior under regulated vertical stress. This method is especially beneficial for compacted or low-permeability soils, including residual and fibre-reinforced soils, as it more accurately simulates field drainage conditions by maintaining a constant load while allowing vertical flow through the specimen (Lee & Sivakugan, 2020). In the experiment, water flows through the soil column under a constant hydraulic gradient, and hydraulic conductivity is calculated based on the rate of volume change, pore water dissipation, and steady seepage behaviour (Zhou et al., 2021).

4.3.1 Hydraulic Conductivity Results

The Hydraulic Conductivity Test was conducted to evaluate the permeability behaviour of the untreated and fibre-reinforced soil samples under different applied pressures. The results obtained for Site 1 (ST1) and Site 2 (ST2) are presented in Table 4.5 and Table 4.6, respectively. The *k* values were measured at applied pressures of 25, 50, 100, 200, and 400 kPa for soils reinforced with different fibre types and contents, including Kenaf Fibre (K), Empty Fruit Bunch fibre (EFB), and mixed Kenaf Fibre–EFB (KEFB). These tables provide a comparison of the permeability characteristics of the soil with varying fibre compositions, which allows the influence of fibre type, fibre content, and applied pressure on hydraulic conductivity to be analysed.

Table 4.5
k-value of Residual Soil with Kenaf and EFB at ST1

Sample	*k*, 25kPa (m/s)	*k*, 50kPa (m/s)	*k*, 100kPa (m/s)	*k*, 200kPa (m/s)	*k*, 400kPa (m/s)
0%	3.19×10^{-11}	3.61×10^{-11}	3.92×10^{-11}	1.62×10^{-11}	1.94×10^{-11}
5%K	1.39×10^{-11}	1.30×10^{-11}	1.38×10^{-11}	1.49×10^{-11}	1.70×10^{-11}
10%K	2.06×10^{-11}	2.88×10^{-10}	2.70×10^{-10}	3.00×10^{-10}	3.34×10^{-10}
15%K	9.57×10^{-11}	1.12×10^{-10}	1.27×10^{-10}	1.27×10^{-10}	1.33×10^{-10}
20%K	6.10×10^{-10}	7.26×10^{-10}	1.17×10^{-09}	1.63×10^{-09}	2.46×10^{-09}
5%EFB	1.60×10^{-10}	1.91×10^{-10}	1.49×10^{-10}	1.32×10^{-10}	1.09×10^{-10}
10%EFB	5.63×10^{-11}	5.55×10^{-11}	5.16×10^{-11}	4.17×10^{-11}	3.21×10^{-11}
15%EFB	1.61×10^{-11}	1.30×10^{-11}	1.17×10^{-11}	9.82×10^{-12}	8.35×10^{-12}
20%EFB	5.93×10^{-10}	5.87×10^{-10}	7.67×10^{-10}	8.75×10^{-10}	9.74×10^{-10}
5%KEFB	3.92×10^{-10}	4.36×10^{-10}	5.57×10^{-10}	6.65×10^{-10}	8.07×10^{-10}
10%KEFB	2.05×10^{-10}	2.74×10^{-10}	2.09×10^{-10}	1.93×10^{-10}	1.74×10^{-10}
15%KEFB	2.08×10^{-11}	1.89×10^{-11}	1.66×10^{-11}	1.46×10^{-11}	1.35×10^{-11}
20%KEFB	1.23×10^{-10}	1.36×10^{-10}	1.24×10^{-10}	1.05×10^{-10}	8.80×10^{-11}

Table 4.6
k-value of Residual Soil with Kenaf and EFB at ST2

Sample	*k*, 25kPa (m/s)	*k*, 50kPa (m/s)	*k*, 100kPa (m/s)	*k*, 200kPa (m/s)	*k*, 400kPa (m/s)
0%	2.87×10^{-11}	3.25×10^{-11}	3.53×10^{-11}	1.46×10^{-11}	1.74×10^{-11}
5%K	1.25×10^{-11}	1.17×10^{-11}	1.24×10^{-11}	1.34×10^{-11}	1.53×10^{-11}
10%K	8.61×10^{-11}	1.01×10^{-10}	1.14×10^{-10}	1.15×10^{-10}	1.20×10^{-10}
15%K	5.49×10-^{10}	6.54×10^{-10}	1.05×10^{-09}	1.47×10^{-09}	2.22×10^{-09}
20%K	3.92×10^{-11}	3.92×10^{-11}	3.92×10^{-11}	3.92×10^{-11}	3.92×10^{-11}
5%EFB	1.91×10^{-10}	1.91×10^{-10}	1.91×10^{-10}	1.91×10^{-10}	1.91×10^{-10}
10%EFB	1.61×10^{-11}	1.61×10^{-11}	1.61×10^{-11}	1.61×10^{-11}	1.61×10^{-11}
15%EFB	5.63×10^{-11}	5.63×10^{-11}	5.63×10^{-11}	5.63×10^{-11}	5.63×10^{-11}
20%EFB	9.74×10^{-10}	9.74×10^{-10}	9.74×10^{-10}	9.74×10^{-10}	9.74×10^{-10}
5%KEFB	8.07×10^{-10}	8.07×10^{-10}	8.07×10^{-10}	8.07×10^{-10}	8.07×10^{-10}
10%KEFB	2.74×10^{-10}	2.74×10^{-10}	2.74×10^{-10}	2.74×10^{-10}	2.74×10^{-10}
15%KEFB	2.08×10^{-11}	2.08×10^{-11}	2.08×10^{-11}	2.08×10^{-11}	2.08×10^{-11}
20%KEFB	1.36×10^{-10}	1.36×10^{-10}	1.36×10^{-10}	1.36×10^{-10}	1.36×10^{-10}

A preliminary observation from the tabulated results indicates that *k* values vary depending on the type and percentage of fibre added to the soil. In general, the kenaf-reinforced mixtures tend to exhibit higher hydraulic conductivity compared to the untreated soil, particularly at higher fibre contents. Conversely, the soils reinforced with EFB and mixed KEFB demonstrate relatively lower *k* values, suggesting improved pore structure and reduced flow paths within the soil matrix. In addition, the hydraulic conductivity values show some variation with increasing applied pressure, indicating that confining stress also influences the permeability behaviour of the fibre-reinforced soils.

4.3.2 Effect of Kenaf Fibre on Hydraulic Conductivity

The hydraulic conductivity behaviour of kenaf-reinforced soil shows a similar trend for both Site 1 (ST1) and Site 2 (ST2) as shown in Figure 4.18 and Figure 4.19,

where the permeability generally increases with increasing kenaf fibre content. For ST1, the hydraulic conductivity increased significantly from approximately 1×10^{-11} m/s for untreated soil to about 1×10^{-9} m/s at 20% Kenaf Fibre, particularly under higher applied pressures. A comparable pattern was observed for ST2, where higher Kenaf Fibre contents also produced greater *k* values, with the 15% Kenaf Fibre mixture exhibiting the highest permeability. This behaviour suggests that increasing Kenaf Fibre content introduces additional voids and preferential flow paths within the soil matrix, which may reduce soil compactness and increase pore connectivity. Consequently, although Kenaf Fibres can enhance certain mechanical properties of soil, excessive fibre inclusion may increase permeability, particularly under elevated stress conditions.

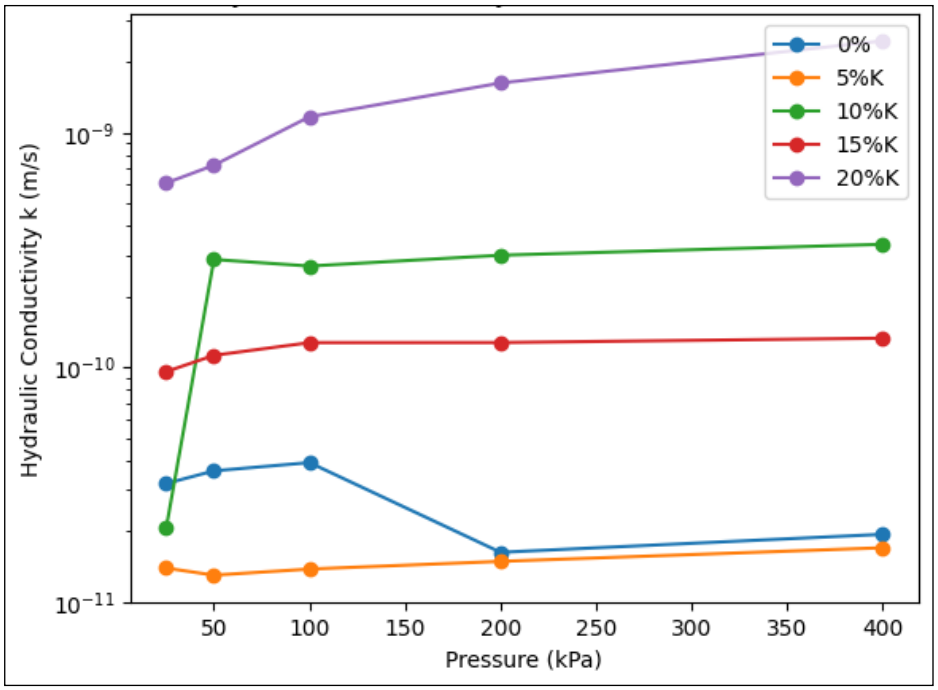


Figure 4.16 Hydraulic Conductivity of Soil Mixed Kenaf Fibre for ST1

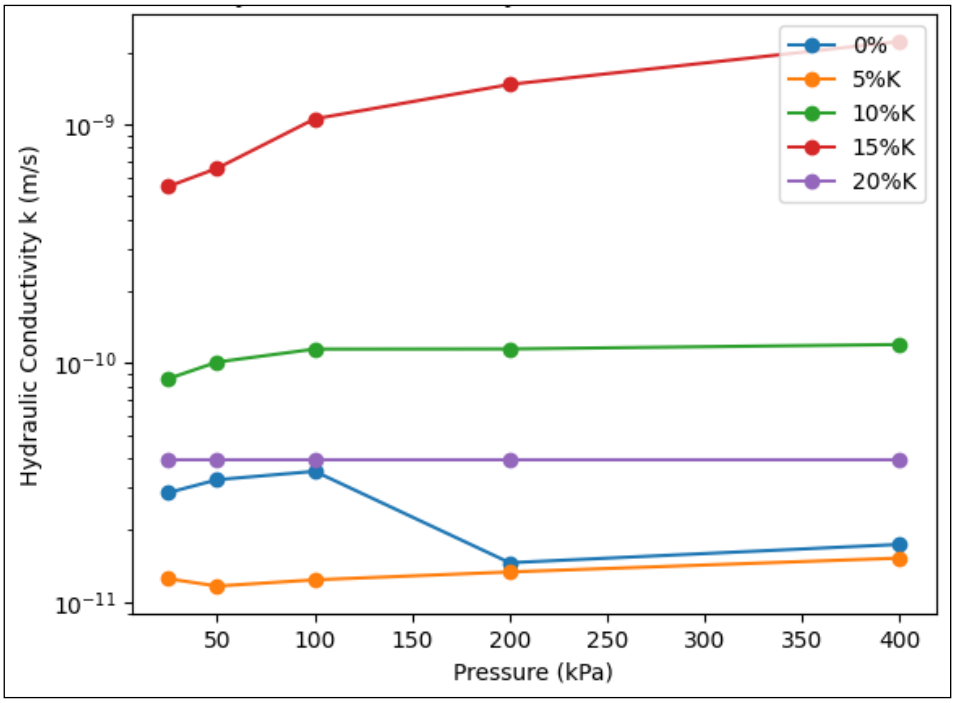


Figure 4.17 Hydraulic Conductivity of Soil Mixed with Kenaf Fibre for ST2

4.3.3 Effect of EFB on Hydraulic Conductivity

In contrast to the Kenaf Fibre mixtures, soils reinforced with EFB exhibited significantly lower k values for both ST1 and ST2. For ST1 as shown in Figure 4.18 and Figure 4.19 , the k ranged approximately between 1×10^{-10} and 1×10^{-11} m/s depending on the fibre content, with the 15% EFB mixture producing the lowest k values. A similar behaviour was observed for ST2, where the k remained relatively constant across the applied pressures and the values were generally within the same order of magnitude. The relatively stable permeability with increasing pressure indicates that EFB contribute to improved soil structure by filling void spaces and reducing pore connectivity. This suggests that EFB reinforcement enhances the barrier performance of the soil, making it potentially suitable for applications requiring low permeability such as landfill liners or containment barriers.

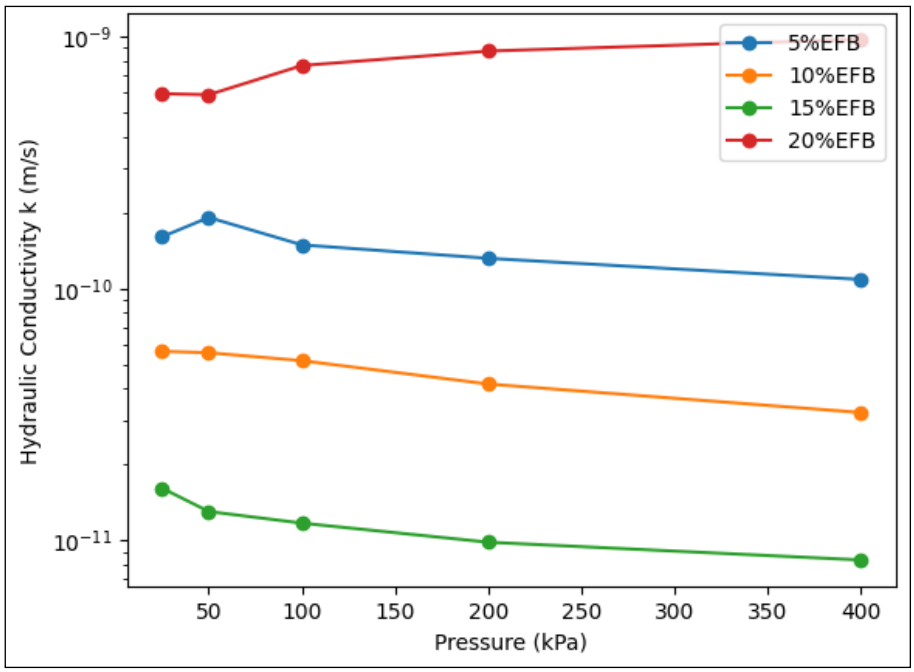


Figure 4.18 Hydraulic Conductivity of Soil Mixed EFB for ST1

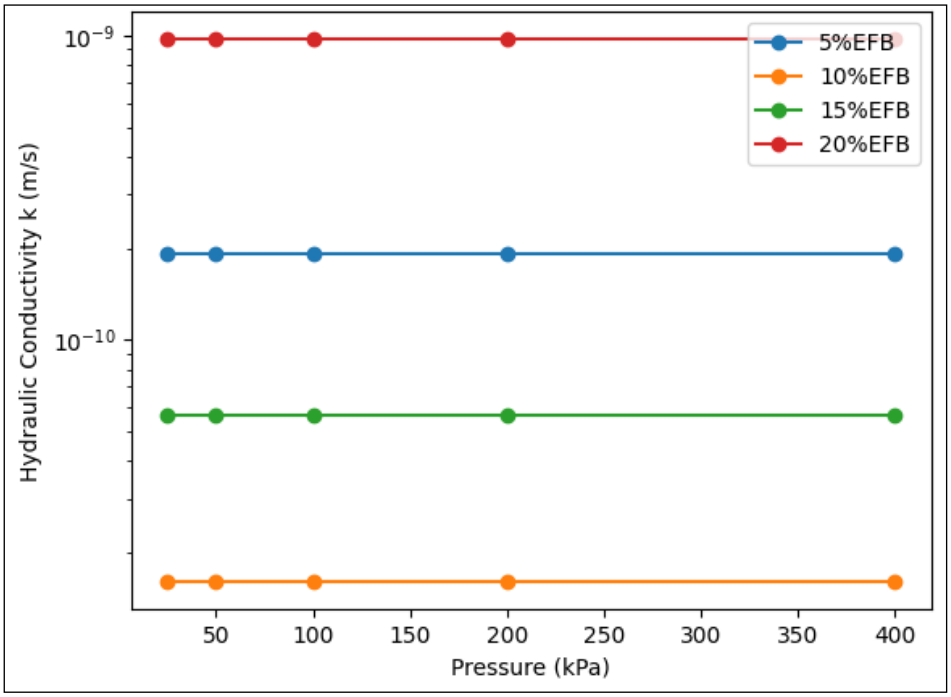


Figure 4.19 Hydraulic Conductivity of Soil Mixed EFB for ST2

The modified oedometer method differs from constant head or falling head permeameter tests by facilitating the measurement of hydraulic conductivity at varying stress levels. This approach allows for the analysis of the effects of applied load on pore structure, compression index, and flow paths. Elevated vertical stress generally leads

to a decrease in pore volume and micro-cracks, which in turn results in diminished hydraulic conductivity. This phenomenon is particularly evident in fine-grained tropical residual soils, where loading induces microstructural collapse and particle rearrangement (Rahardjo et al., 2019). The method is particularly appropriate for evaluating compacted soil liners, engineered barriers, and natural fibre–soil mixtures, including kenaf–EFB–reinforced soils, where stress-dependent permeability is essential for landfill and embankment applications (Hosseini et al., 2023). The hydraulic conductivity test was performed using modified Oedometer Apparatus. The permeability itself involved water flows through a fully saturated soil samples that connected to the standpipe that's provides the water heads and allows measuring of the water passing through the samples at few times intervals. Compacted untreated and treated soil at optimum moisture content and maximum dry density were tested during the test to determine the hydraulic conductivity of the soil (Ekta Chaudhary, 2024). Recent research also proves that the requirement for hydraulic conductivity for a soil liner in landfill construction is to maintain a value below $1x10^{-9}$ m/s. This ensures effective prevention of contaminated seepage into the aquifer, crucial for environmental protection.

4.3.4 Effect of Mixed Kenaf Fibre and EFB on Hydraulic Conductivity

For the mixed Kenaf Fibre and EFB (KEFB), the *k* behaviour for both ST1 and ST2 demonstrates improved permeability control compared with kenaf only mixtures. In ST1, the KEFB mixtures produced relatively low hydraulic conductivity values ranging approximately between 1×10^{-10} and 1×10^{-11}m/s, with the 15% KEFB mixture showing the lowest permeability among the hybrid combinations. A similar trend was observed in ST2, where the *k* remained relatively stable across the applied pressures, indicating that the combined fibres effectively reduced pore connectivity within the soil matrix. The interaction between Kenaf Fibre and EFB likely improves soil particle interlocking and enhances the filling of void spaces, thereby limiting fluid flow through the soil structure. As a result, the KEFB mixtures demonstrate a balanced behaviour where permeability is reduced while maintaining fibre reinforcement benefits.

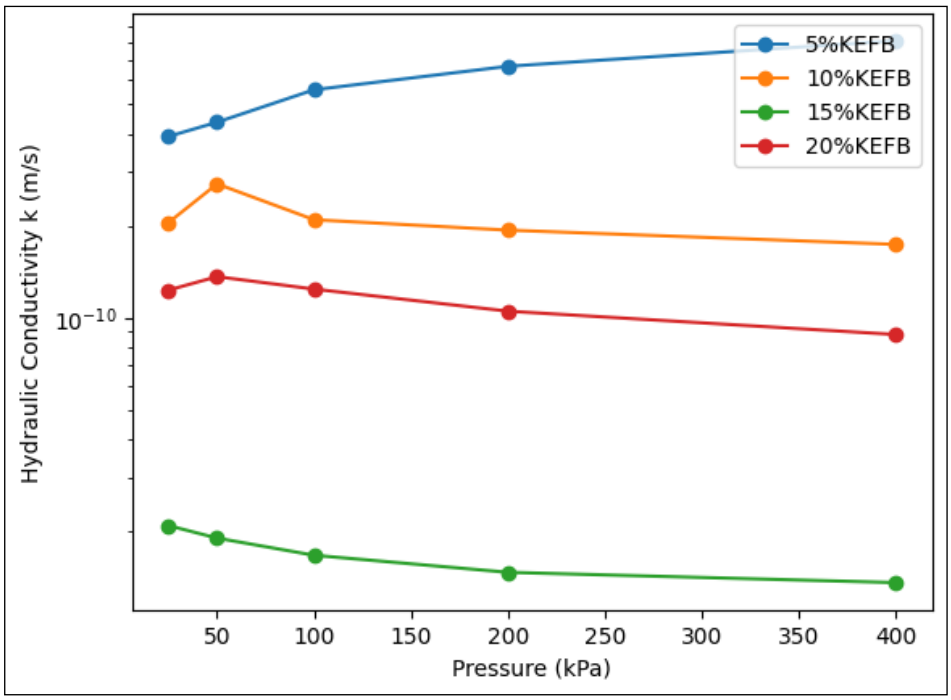


Figure 4.20 Hydraulic Conductivity of Soil Mixed KEFB for ST1

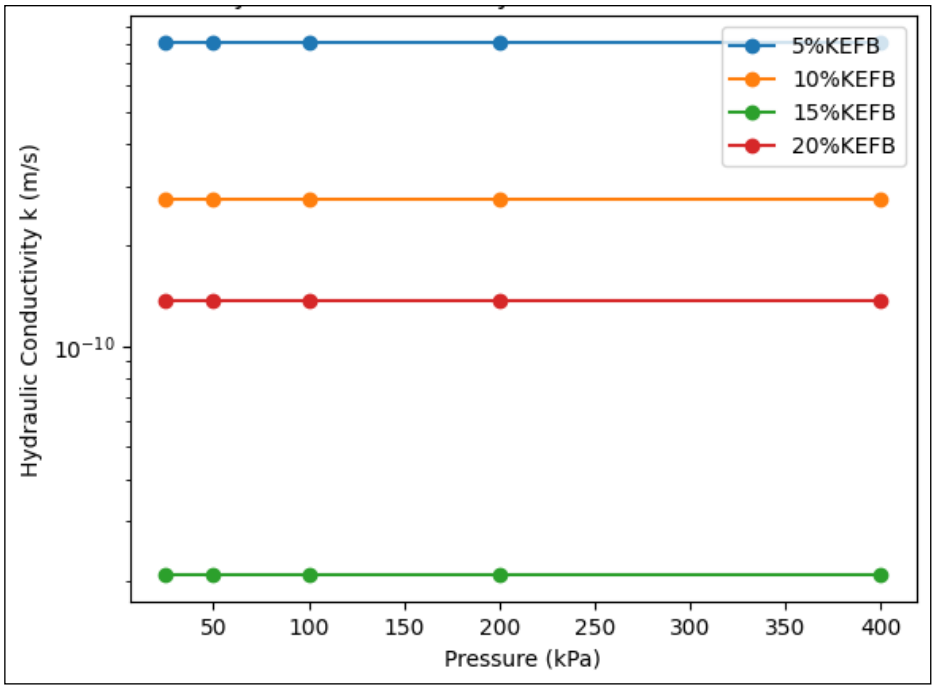


Figure 4.21 Hydraulic Conductivity of Soil Mixed KEFB for ST2

4.4 Minitab Data for k-model

Statistical analysis plays a crucial role in interpreting experimental data and establishing reliable relationships between engineering parameters in geotechnical studies. A

Pearson correlation matrix was generated to examine the linear relationships among the measured soil parameters and hydraulic conductivity. In this study, Minitab 24 was employed to analyse the experimental data obtained from laboratory testing of residual soil mixed with natural fibres. The software was used to perform exploratory data analysis, including matrix plots and Pearson correlation analysis, to evaluate the relationships among soil parameters such as fibre content, compaction characteristics, and Atterberg limits.

The Pearson correlation coefficient (R) measures the degree of linear association between two continuous variables and ranges from −1 to +1, where values close to +1 indicate a strong positive relationship, values close to −1 indicate a strong negative relationship, and values near zero suggest little or no linear correlation. In geotechnical datasets, correlation analysis is particularly useful for identifying potential dependencies among soil properties and detecting possible multicollinearity among predictor variables before performing regression modelling (Montgomery et al., 2012).

A matrix plot was generated using Minitab to examine the relationships among all variables, including sample content, pressure, Atterberg limits (LL, PL, PI), specific gravity (SG), compaction parameters (MDD and OMC), and hydraulic conductivity (k). The matrix plot provides scatter plots for each pair of variables together with the Pearson correlation coefficients and their 95% confidence intervals. This preliminary analysis helps to identify potential relationships and detect possible multicollinearity among the variables before performing regression analysis. The Pearson correlation heatmap shown in Figure 4.18 illustrates the pairwise relationships among the studied variables, providing a visual overview of the strength and direction of correlations within the dataset. In the heatmap, warmer colours represent strong positive correlations, whereas cooler colours indicate strong negative correlations. The figure clearly highlights a strong positive relationship between sample content and log hydraulic conductivity, suggesting that increasing fibre content significantly influences the permeability behaviour of the soil mixture. Conversely, several soil properties exhibit strong negative correlations with permeability, particularly shrinkage limit (SL), specific gravity (SG), and maximum dry density (MDD). These relationships indicate that soils with higher density and shrinkage characteristics tend to reduce pore connectivity and restrict seepage pathways, leading to lower hydraulic conductivity.Overall, the Pearson correlation matrix serves as an effective diagnostic tool for identifying relationships among variables, ensuring that the dataset is suitable

for multivariate statistical modelling and helping to avoid potential issues related to multicollinearity in regression analysis (Hair et al., 2019).

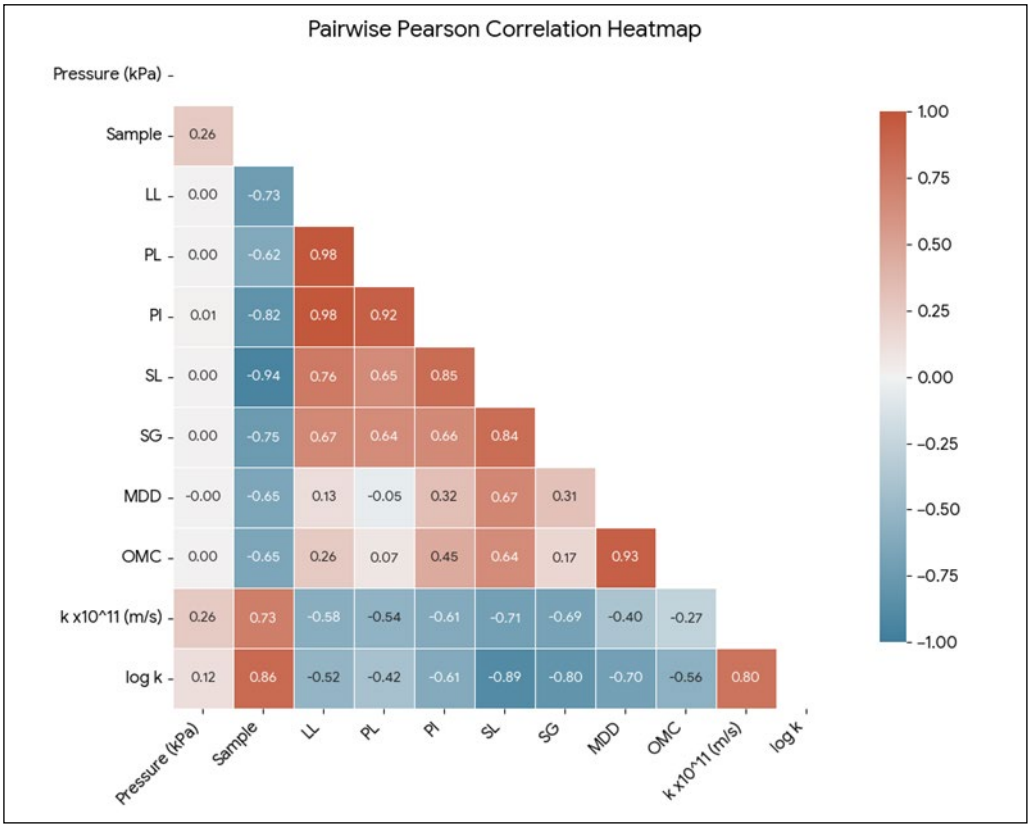


Figure 4.18: Matrix Plot of Pearson Correlation (Kenaf Fibre)

The numerical values corresponding to these relationships are summarized in Table 4.7, which presents the significant Pearson correlation coefficients between selected soil parameters and log hydraulic conductivity. Among the variables, sample content shows the strongest positive correlation ($r = 0.863$), while shrinkage limit demonstrates the strongest negative correlation ($r = -0.885$). In addition, specific gravity ($r = -0.799$) and maximum dry density ($r = -0.699$) also exhibit strong negative relationships with permeability. These results confirm that both fibre content and compaction-related parameters play important roles in controlling the hydraulic conductivity of the studied soil mixtures.

Table 4.7
Summary of Significant Pearson Correlations with log Hydraulic Conductivity

Variable	Correlation with log k (r)	P-value	Strength of Relationship
Sample	0.863	<0.001	Very strong positive
SL (Shrinkage Limit)	-0.885	<0.001	Very strong negative
SG (Specific Gravity)	-0.799	<0.001	Strong negative
MDD	-0.699	<0.001	Strong negative
PI	-0.612	0.001	Moderate to strong negative
OMC	-0.555	0.004	Moderate negative

4.5 Model Development

This chapter discusses the development of multiple regression model for hydraulic conductivity (k) for residual soil mixed with Kenaf and Empty Fruit Bunch (EFB) as compacted soil liner. All parameters obtained from the laboratories result and the established data were analysed with the statistical validation condition by using statistical software. The Minitab 21 software performs the standard statistical analyses for the results obtained throughout this study. Before statistical analyses were performed, all the data had been reorganised to accommodate the software. This section involved a regression analysis test to establish the coefficient of determination between two variables.

The development of empirical formulas for hydraulic conductivity models involving parameters for soil properties such as percentage of Kenaf, percentage of EFB, pressure, plastic limit (PL), liquid limit (LL), plasticity index (PI), Shrinkage Limit (SL), maximum dry density (MDD), and optimum moisture content (OMC).The engineering and physical characteristics of soil were used in the model creation process. This section discusses and analyses the development of the hydraulic conductivity (k) model through multi-linear regression analysis with Minitab 21 software to create predictive modelling between a dependent variable (y) and an independent variable (x).

4.5.1 Descriptive Statistical Data Set of (*k*) Model

All data and normal distribution graphs for these log *k*-model parameters are included in Appendix for the histogram chart results and box plot results for all the *k*-value for Kenaf Fibre and EFB variables, respectively. It can be seen that the histogram chart is normal because it shows bell shaped at 95% 0f confidence level. (William Mendenhall et al., 2006) stated that a graph can be considered normal when the graph indicates a bell shape and follow the empirical law that reaches 95% of confidence level.

The skewness and kurtosis values were examined to evaluate the distribution characteristics of the studied variables prior to conducting further statistical analyses. Skewness measures the degree of asymmetry in the data distribution, whereas kurtosis describes the peakiness or flatness of the distribution relative to a normal distribution. In general, skewness values between −1 and +1 indicate approximately symmetrical distributions, while kurtosis values close to zero suggest distributions similar to the normal distribution (Hair et al., 2019).

Based on the results presented in Table 4.8, most of the studied variables exhibit skewness values within the acceptable range of −1 to +1, indicating that the distributions are reasonably symmetrical. For instance, the skewness values for Kenaf (0.33), LL (−0.19), PI (−0.30), MDD (0.24), and log k (0.36) fall well within this range, suggesting that the data do not exhibit severe asymmetry. The kurtosis values for these variables are all negative, ranging from −1.55 to −0.45, indicating relatively flatter distributions compared to the normal distribution. Such distributions are commonly observed in geotechnical datasets due to natural variability in soil properties.

Among the variables, OMC exhibits the highest skewness value (0.98), indicating a slight positive skewness where a small number of higher values extend the right tail of the distribution. However, the value still remains within the acceptable range for approximate normality. Similarly, the log-transformed hydraulic conductivity log(k) shows a relatively small skewness value (0.36), indicating that the logarithmic transformation successfully reduced the asymmetry commonly associated with permeability data. Previous studies have reported that permeability data are typically positively skewed due to the strong influence of soil structure and pore distribution on flow behaviour, and logarithmic transformation is commonly applied to achieve a more symmetrical distribution suitable for statistical modelling (Craig Benson et al., 1994; Montgomery, 2012).

Overall, the skewness and kurtosis results suggest that the distributions of the analysed variables are reasonably close to normal, supporting the suitability of the dataset for subsequent statistical analyses such as correlation and regression modelling.

Table 4.8
Summaries Descriptive Statistics Data for k-model (Kenaf)

Variable	Mean	Standard Deviation	Minimum	Maximum	Skewness	Kurtosis
Kenaf	0.076	0.0679	0	0.2	0.33	-1.16
LL	0.7215	0.0607	0.6335	0.7988	-0.19	-1.37
PI	0.243	0.0295	0.2003	0.2759	-0.3	-1.55
MDD	1.1904	0.1111	1.046	1.354	0.24	-1.29
OMC	0.2133	0.0349	0.1802	0.2754	0.98	-0.45
log k	0.993	0.724	0.113	2.391	0.36	-1.09

4.5.2 Normality Test for k-Modelling

Normality Test was performed to assess if the residuals from the k-model regression analysis adhere to a normal distribution, a critical assumption for linear modeling and inferential statistics Prior to conducting regression analysis, the normality of the dataset was evaluated to ensure that the assumptions of parametric statistical methods were satisfied. In general, a dataset is considered approximately normally distributed when the graphical representation exhibits a symmetric bell-shaped pattern and follows the empirical rule, where approximately 68%, 95%, and 99.7% of the observations fall within one, two, and three standard deviations from the mean,

respectively (William Mendenhall et al., 2006) . In addition to graphical assessment, statistical normality tests are commonly employed to further evaluate the distribution characteristics of the data.

Figure 4.22 presents the normal probability plot of log-transformed hydraulic conductivity (log *k*) obtained from Minitab. The probability plot is used to visually assess the normality of a dataset by examining whether the data points align closely with the reference line. As shown in the figure, the plotted points generally follow the straight reference line with only minor deviations, indicating that the transformed permeability data are approximately normally distributed. This graphical observation suggests that the logarithmic transformation effectively reduced the skewness typically associated with hydraulic conductivity datasets.

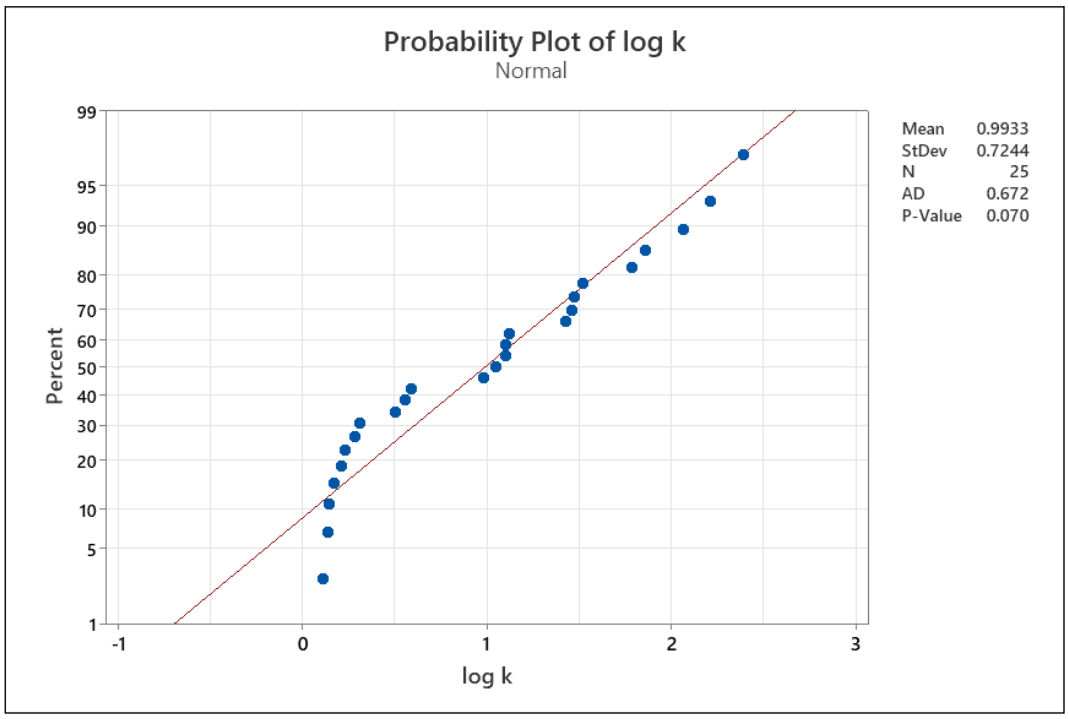


Figure 4.22 Normal Probability Plot of Log-Hydraulic Conductivity (log *k*).

To further confirm the normality of the data, the Anderson–Darling (A–D) normality test was performed. The Anderson–Darling test is widely used because it gives greater weight to deviations in the tails of the distribution compared to other goodness-of-fit tests, making it particularly sensitive in detecting departures from normality (Diah J. et al., 2013). The results show a p-value of 0.070, which is greater than the commonly adopted significance level of 0.05. As for EFB, p-value was 0.112.

Therefore, the null hypothesis that the dataset follows a normal distribution cannot be rejected. This indicates that the log-transformed hydraulic conductivity data satisfy the assumption of normality and are suitable for subsequent statistical analyses such as correlation and regression modelling.

4.5.3 Regression Analysis for Modelling Hydraulic Conductivity, *k*-model

The regression coefficients presented in Table 4.9 indicate that all predictor variables are statistically significant at the 95% confidence level ($p < 0.05$). In regression analysis, a variable is considered statistically significant when its p-value is lower than the chosen significance level, indicating that the variable contributes meaningfully to explaining the variability of the dependent variable (Montgomery, 2012). In this study, sample content shows the strongest positive influence on log hydraulic conductivity, suggesting that the addition of fibres significantly affects the permeability behaviour of the soil mixture.

The compaction-related parameters also demonstrate significant negative relationships with hydraulic conductivity. The negative coefficient for MDD^2 indicates that increasing soil density reduces hydraulic conductivity, which is consistent with geotechnical principles where higher compaction decreases void ratio and limits seepage pathways within the soil structure. Previous studies have reported similar findings, where increased compaction leads to reduced permeability due to the tighter packing of soil particles and reduced pore connectivity (Craig Benson et al., & Shackelford, 2005)

The negative regression coefficient obtained for MDD^2 ($\beta = -0.846$) indicates that an increase in maximum dry density is associated with a reduction in the predicted log hydraulic conductivity, while the other variables in the model are held constant. Physically, a higher MDD represents a more compact soil structure with reduced pore spaces and lower pore connectivity. Consequently, the available pathways for water flow become narrower and more tortuous, resulting in a lower hydraulic conductivity. The relationship is statistically significant at the 5% significance level, as indicated by the p-value of 0.015. Therefore, MDD^2 is considered a significant predictor of hydraulic conductivity in the kenaf fibre-treated soil. However, the negative coefficient should be

interpreted as a partial effect within the regression model because MDD is also incorporated into the MDD/OMC ratio.

In addition, the Variance Inflation Factor (VIF) values for all predictor variables are below 2, indicating that multicollinearity among the variables is minimal. According to(Hair et al., 2019) , VIF values lower than 5 generally indicate that collinearity is not a serious concern in regression analysis. Therefore, the regression model developed in this study can be considered statistically stable and reliable for predicting the hydraulic conductivity behaviour of the studied soil mixtures.

Table 4.9
Regression Coefficients, p-values, and Variance Inflation Factors (VIF) for the Developed log *k* Model (Kenaf Fibre)

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	4.17	1.02	4.07	0.001	
Kenaf	7.79	1.22	6.38	0.000	1.82
MDD2	-0.846	0.318	-2.66	0.015	1.92
MDD/OMC	-0.447	0.137	-3.26	0.004	1.13

The regression analysis demonstrates that EFB fibre content in Table 4.10 , OMC and *LL* significantly influence the hydraulic conductivity of the soil, as all variables show p-values less than 0.05. The positive coefficients of EFB and OMC indicate that fibre inclusion and higher moisture content enhance permeability, likely due to increased pore connectivity and reduced soil stiffness. In contrast, LL exhibits a negative relationship with hydraulic conductivity, suggesting that soils with higher plasticity restrict water movement due to finer particle size and stronger interparticle bonding. Although the VIF values indicate moderate multicollinearity, particularly between OMC and *LL*, all values remain below the acceptable threshold of 10, confirming that the model is statistically reliable and suitable for predicting hydraulic conductivity behaviour.

Table 4.10
Regression Coefficients, p-values, and Variance Inflation Factors (VIF) for the Developed log *k* Model (EFB)

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-15.71	1.54	-10.19	0.000	
EFB	19.32	1.60	12.06	0.000	1.31
OMC	81.60	7.48	10.91	0.000	6.18
LL	-8.420	0.829	-10.15	0.000	4.03

The regression model summary is presented in Table 4.10. The model produces a coefficient of determination (R^2) of 84.89%, indicating that approximately 84.89% of the variability in the log-transformed hydraulic conductivity (log k) can be explained by the selected predictor variables, namely sample content, MDD^2, and the ratio of MDD to OMC. This high R^2 value suggests that the regression model provides a strong explanatory capability for the permeability behaviour of the studied soil mixtures.

The adjusted R^2 value of 82.73% further confirms the reliability of the model by accounting for the number of predictor variables included in the regression equation. The small difference between R^2 and adjusted R^2 indicates that the included variables contribute meaningfully to the model without introducing unnecessary complexity. In addition, the predicted R^2 value of 77.10% suggests that the model maintains good predictive capability when applied to new observations. The standard error of the regression (S = 0.301) represents the average deviation of the observed values from the fitted regression line, indicating that the predicted log hydraulic conductivity values are reasonably close to the observed data.

According to Montgomery et al. (2012), a regression model with high R^2 and relatively small differences between R^2, adjusted R^2, and predicted R^2 generally indicates a stable and reliable predictive model. Therefore, the model developed in this study can be considered statistically robust for predicting the hydraulic conductivity behaviour of the fibre-reinforced soil mixtures.

Table 4.11
Summary Statistics of the Developed Regression Model

Equation	S	R-sq	R-sq(adj)	R-sq(pred)
4.1	0.301069	84.89%	82.73%	77.10%
4.2	0.245699	87.51%	85.72%	82.50%

The first relationship between hydraulic conductivity and the selected soil parameters can be expressed by the following regression equation 4.1:

$$log_{10}\, k = 4.17 + 7.79\, Kenaf - 0.846 MDD^2 - 0.447\left(\frac{MDD}{OMC}\right) \qquad (4.1)$$

The second relationship between hydraulic conductivity and the selected soil parameters can be expressed by the following regression equation 4.2:

$$log_{10}\, k = -15.71 + 19.32\, EFB + 81.6\, OMC - 8.42\, LL \qquad (4.2)$$

It can be seen that *log k* represents the logarithm of hydraulic conductivity, *Sample* denotes the fibre content incorporated into the soil mixture, *MDD* represents the maximum dry density, and *OMC* refers to the optimum moisture content.

The regression equation indicates that sample content has a positive influence on hydraulic conductivity, as reflected by the positive coefficient of the Sample variable. This suggests that increasing fibre content tends to increase the permeability of the soil mixture due to the modification of the soil structure and pore connectivity. In contrast, the negative coefficients associated with MDD² and MDD/OMC indicate that increasing soil density and compaction conditions reduce hydraulic conductivity. This behaviour is consistent with geotechnical principles, where higher compaction reduces void ratio and limits water flow pathways within the soil structure (Mitchell & Soga, 2005).

Overall, the developed regression model indicates that Kenaf Fibre content plays a dominant role in influencing the hydraulic conductivity behaviour of the residual soil mixtures. The positive coefficient associated with the Sample variable suggests that the addition of kenaf fibres modifies the internal soil structure, potentially altering pore connectivity and flow paths within the soil matrix. Such structural changes may influence the permeability characteristics of the soil–fibre mixture, reflecting the interaction between natural fibres and soil particles.

In addition, the regression analysis for EFB demonstrates strong predictive capability, with an R^2 value of 87.51%, indicating that a large proportion of the variability in hydraulic conductivity (log k) is explained by the selected variables. The adjusted R^2 value of 85.72% shows only a slight reduction, suggesting that the included

predictors are relevant and the model is not overfitted. Furthermore, the predicted R^2 of 82.50% indicates good predictive performance for new data. The standard error of regression (S = 0.2457) is relatively small, reflecting a low level of deviation between observed and predicted values.

4.5.4 The Validation for the Hydraulic Conductivity, k-model

Descriptive statistics were conducted to compare the observed hydraulic conductivity values with the predicted values obtained from the regression model. As presented in Table 4.11, both the measured log k and the regression-predicted log k regression values show identical statistical characteristics, with a mean value of 0.824, a standard deviation of 0.585, and a standard error of 0.169 based on 12 observations.

Table 4.12
Descriptive Statistics of Observed and Regression-Predicted Log Hydraulic Conductivity Values for Kenaf Fibre

Sample	Mean	StDev	SE Mean
log *k*	0.824	0.585	0.169
log_*k*_regression	0.824	0.585	0.169

The identical descriptive statistics indicate that the regression model successfully reproduces the distribution characteristics of the observed permeability data. This suggests that the model predictions closely match the measured values and do not introduce additional bias or variability into the dataset. Such consistency between observed and predicted values is desirable in regression modelling, as it demonstrates that the model adequately represents the underlying relationship between the predictor variables and hydraulic conductivity (Montgomery, 2012).

The similarity in the descriptive statistics between the experimental and predicted datasets provides preliminary evidence that the developed regression model is capable of representing the permeability behaviour of the studied soil mixtures. This result further supports the reliability of the regression model before conducting additional validation tests such as the paired t-test.

4.5.5 Comparing of k-model using T-paired Test

To further evaluate the accuracy of the developed regression model, a paired comparison was conducted between the observed log hydraulic conductivity (log k) values and the regression-predicted values (log k regression). The estimation results for the paired difference are presented in Table 4.13. The mean difference between the observed and predicted values is −0.000003, which is extremely close to zero. This indicates that, on average, the regression model does not introduce systematic bias when predicting hydraulic conductivity.

The comparison between the predicted and measured values of hydraulic conductivity using the Kenaf and EFB regression models indicates that both models provide highly accurate estimations. The mean difference for the Kenaf model is approximately zero (-0.000003), while the EFB model shows a slightly higher but still negligible mean difference of 0.02. In addition, the T-values for both models are close to zero and the P-values are greater than 0.05, indicating that there is no significant difference between the predicted and experimental values. This suggests that both regression equations are statistically reliable and capable of accurately predicting hydraulic conductivity behaviour. Overall, the developed models demonstrate good agreement with the measured data and can be confidently used for further analysis.

Table 4.13
Estimation of Paired Differences

Equation	Mean	T-Value	P-Value
$log_{10}\, k = 4.17 + 7.79\, Kenaf - 0.846 MDD^2 - 0.447\left(\frac{MDD}{OMC}\right)$	-0.000003	-0.03	0.975
$log_{10}\, k = -15.71 + 19.32\, EFB + 81.6\, OMC - 8.42\, LL$	0.000200	0.02	0.105

4.6 Summary of Research Result

This study presents quantitative evidence regarding the effects of the combined Kenaf–EFB admixture on the compaction, plasticity, and permeability of residual soil, an area that has not been extensively documented in prior research. The regression analysis indicates that the KEFB mixture significantly decreases hydraulic conductivity at optimal percentages by improving particle interlocking and minimizing pore

pathways. The analysis identifies a critical threshold at which fibre content becomes counterproductive, leading to increased void spaces and, consequently, higher permeability. This research provides insights into the behavior of agricultural fibers in combination and their optimal utilization for the production of sustainable, low-permeability soil liners.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Introduction

Chapter 5 presents a summary of the findings from the study, focusing on each of the objectives that were established prior to the research. This is done to establish whether or not the goals and objectives outlined in the thesis have been accomplished. In consideration of the information obtained, a list of suggestions has been constructed. Furthermore, the chapter emphasised the challenges that were encountered throughout this investigation.

a) Salak Tinggi residual soil is classified as sandy SILT with very high plasticity with specific gravity range of 2.6.

b) The additional of 5 to 15% of Kenaf Fibre and EFB tends to shows suitability in physical properties and engineering properties of the Residual soil. The additional addition of the admixtures to the residual soil satisfies the requirement for plasticity index and liquid limit in soil liner accordingly.

c) Optimum compaction performance was achieved at 10% EFB / 10% KEFB in ST1, where the soil recorded the highest MDD of 1.557 Mg/m³ at a relatively low OMC of 22.08%The additional of 5% and 10 % of kenaf and EFB respectively will also tend to reduce the hydraulic conductivity of the Residual soil thus satisfy the requirement of soil liner in landfill. However, after further additional of the additive will cause the value of MDD decreased while value of OMC increased significantly.

d) Site 1 15%EFB was identified as the optimum treatment because it produced the lowest hydraulic conductivity of 8.35×10^{-12} m/s, indicating the best performance in reducing soil permeability and satisfying the compacted soil liner requirement. far exceeds regulatory requirement of 1×10^{-9} m/s.

e) Two predictive equations were successfully developed, with R^2 values greater than 0.80, indicating strong predictive performance. Both equations were validated using paired t-tests with p-values greater than 0.05, confirming no significant difference between the measured and predicted log k values. The use of log-transformed hydraulic conductivity improves linearity, stabilizes variance, and enhances model reliability. These findings highlight the importance of optimizing both compaction and fibre dosage to achieve desirable permeability performance for soil liner applications.

5.2 Contribution to Knowledge

This study contributes to the existing knowledge on the prediction and engineering of hydraulic conductivity in fibre-reinforced residual soil used as landfill liner material. It provides an integrated approach that combines soil index properties, compaction characteristics, fibre content, hydraulic conductivity testing, and regression-based modelling. Through this approach, the study improves the understanding of how the physical and engineering properties of fibre-modified residual soil interact and influence its hydraulic performance.

A key contribution of this research is the identification and ranking of the soil parameters that have the greatest influence on hydraulic conductivity. The statistical analysis indicates that maximum dry density (MDD) and optimum moisture content (OMC) are among the most influential parameters because they directly affect soil particle arrangement, degree of compaction, pore size, and pore connectivity. The liquid limit (*LL*) and plasticity index (*PI*) also contribute significantly by influencing the soil's water-retention behaviour, plasticity, and microstructural characteristics. Fibre content exhibits a nonlinear effect on hydraulic conductivity. At an appropriate fibre content, the fibres may improve particle interlocking and reduce the continuity of water-flow paths. However, excessive fibre addition may create additional voids, reduce compactability, and increase pore connectivity. This ranking of influential parameters provides engineers with a clearer basis for identifying and controlling the key properties required to achieve the desired hydraulic conductivity in liner construction.

The study also contributes to sustainable geotechnical engineering by demonstrating the potential use of locally available residual soil modified with agricultural by-products, particularly kenaf fibre and empty fruit bunch fibre, as an alternative landfill liner material. The findings show that, when the soil–fibre mixture is properly designed and compacted, it can achieve hydraulic conductivity values that satisfy the recommended requirements for landfill liner applications. This offers a more sustainable alternative to conventional clay liners, which may be expensive, limited in availability, and require transportation over long distances.

Furthermore, the regression models developed in this study provide a practical method for estimating hydraulic conductivity from measurable soil and compaction parameters. The models can support preliminary material assessment and mixture design while reducing dependence on repeated, time-consuming, and costly laboratory

permeability tests. Overall, the study establishes a systematic framework for selecting fibre content, controlling compaction conditions, and predicting hydraulic conductivity. It also supports the beneficial reuse of Malaysian agricultural biomass waste and contributes to the development of more economical and environmentally sustainable landfill liner systems.

5.3 Recommendation

Future studies should incorporate microstructural characterisation techniques, such as Scanning Electron Microscopy (SEM), X-ray diffraction (XRD), and micro-computed tomography (micro-CT), to examine changes in pore structure, fibre–soil bonding, particle aggregation, and fibre distribution within the soil matrix. These techniques would provide direct visual evidence to support the mechanisms inferred from the regression analysis, particularly the influence of kenaf–empty fruit bunch (KEFB) fibres on pore size, pore continuity, and water-flow pathways. The resulting microstructural observations could therefore strengthen the interpretation and validation of the developed hydraulic conductivity prediction models.

Field-scale pilot studies should also be conducted to evaluate the compaction behaviour, moisture retention, hydraulic conductivity, and long-term stability of fibre-reinforced residual soil under actual landfill liner conditions. Moving from laboratory-scale testing to field application would provide valuable information regarding constructability, achievable field density, uniformity of fibre distribution, quality-control requirements, and performance under variable environmental and loading conditions.

The findings from these pilot studies could also be used to calibrate and validate the regression models for full-scale engineering applications.

For modified oedometer testing, future research is recommended to include applied vertical pressures below 25 kPa when determining the hydraulic conductivity, (k), of fibre-modified residual soil. The use of lower pressure increments would allow the hydraulic behaviour of the soil to be evaluated under relatively low-stress conditions before substantial compression or particle rearrangement occurs. This is important because higher applied pressures may reduce the void ratio, alter the pore structure, and

produce lower hydraulic conductivity values that may not fully represent the material's initial or near-surface field condition. Testing at pressures below 25 kPa, together with the existing higher loading stages, would therefore provide a more complete understanding of the relationship between applied stress, soil compression, fibre interaction, and hydraulic conductivity.

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APPENDICES

APPENDIX 1

APPENDIX

Mass of dry soil used		980 g			
Seive Size (mm)	Mass Seive (g)	Mass Soil Retained (g)	Mass Soil (g)	% Retained	% Percent Passing
5	0	0	0	0	100
3.35	565.6	865.6	300	30.61	69.39
2	472.42	522.42	50	5.10	64.29
1.18	431.29	456.29	25	2.55	61.73
0.6	332.98	352.98	20	2.04	59.69
0.425	376.18	381.18	5	0.51	59.18
0.3	393.25	408.25	15	1.53	57.65
0.212	351.85	371.85	20	2.04	55.61
0.15	377.53	417.53	40	4.08	51.53
0.063	357.57	382.57	25	2.55	48.98
Pan	242.52	722.52	480	48.98	0

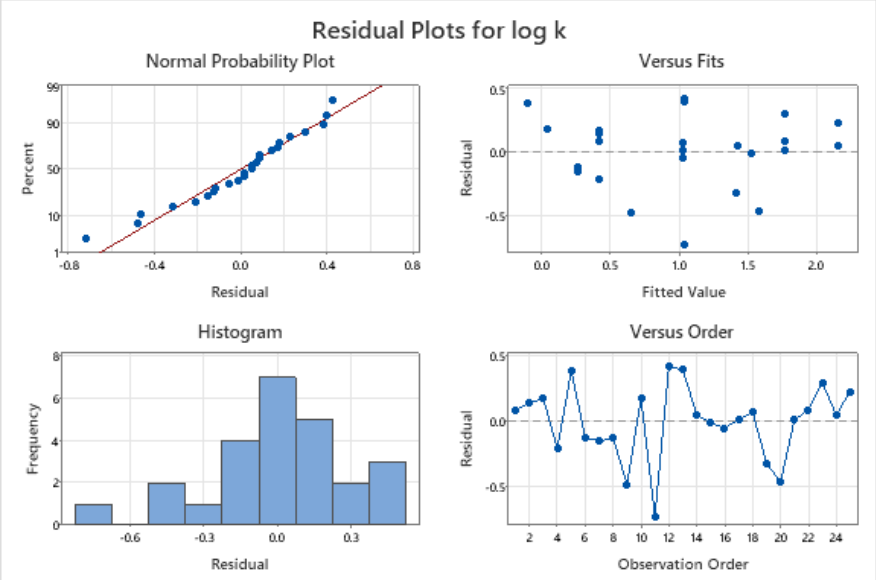
Table 4.1: Result of sieving analysis test for sample Salak Tinggi 1

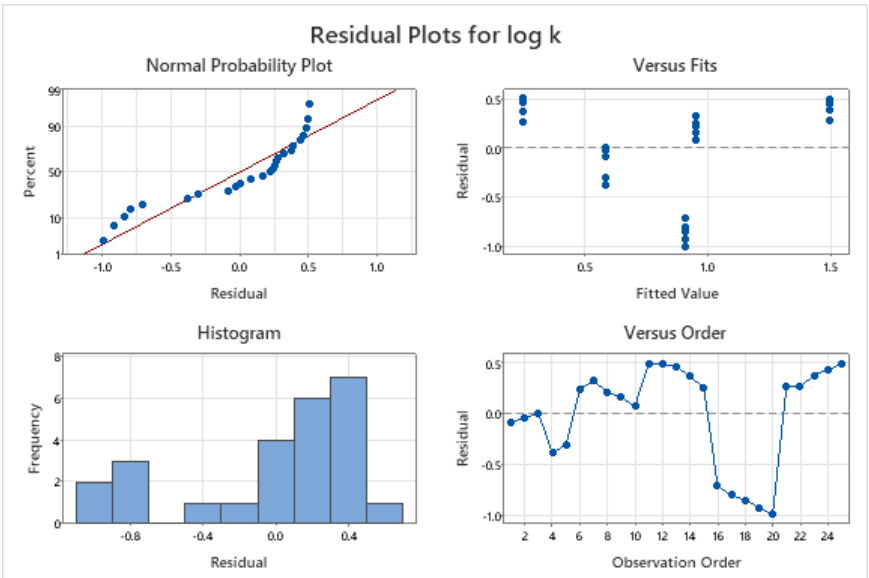
Mass of dry soil used		762.69 g			
Seive Size (mm)	Mass Seive (g)	Mass Soil Retained (g)	Mass Soil (g)	% Retained	% Percent Passing
5	0	0	0	0	100
3.35	565.6	752.67	187.07	19.09	80.91
2	472.42	551.36	78.94	8.06	72.86
1.18	431.29	529.34	98.05	10.01	62.85
0.6	332.98	452.38	119.4	12.18	50.67
0.425	376.18	426.34	50.16	5.12	45.55
0.3	393.25	438.16	44.91	4.58	40.97
0.212	351.85	406.34	54.49	5.56	35.41
0.15	377.53	459.39	81.86	8.35	27.05
0.063	357.57	381.43	23.86	2.43	24.62
Pan	242.52	293.47	50.95	5.20	19.42

Table 4.3: Result of sieving analysis test for sample Salak Tinggi 2

APPENDIX 2

Residual Plot for log k





APPENDIX 3



Soil Sample



Preparation of Sample using MK Digester Machine

AUTHOR'S PROFILE



Farah Hafifee Ahmad obtained Bachelor of Civil Engineering (Hons.) in 2009 from University Teknologi MARA Shah Alam and MSc in Civil Engineering (2013) from Universiti Teknologi MARA. This PhD research focuses on the development of a novel design approach for soil liner systems incorporating natural additives, namely Kenaf Fibre and Empty Fruit Bunch (EFB). The study aims to enhance the hydraulic performance of compacted soil liners, particularly in achieving the required low hydraulic conductivity for landfill barrier applications. In addition to permeability performance, the research evaluates the effects of these natural fibres on key geotechnical properties, including strength, compaction characteristics, and hydraulic conductivity. By utilizing agricultural by-products as reinforcing additives, the study contributes to the advancement of sustainable and environmentally friendly solutions in geotechnical and waste containment engineering.

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Farah Hafifee Ahmad, Mazidah Mukri, Ng Kok Shien, Faizah Kamarudin, Nor Ashikin Yahaya. Innovative Soil Liner Design : Utilising Kenaf Fibre and Empty Fruit Bunch for Enhanced Performance. Proceedings of the 3rd International Symposium of Reaction Engineering, Catalysis & Sustainable Energy: RECaSE 2025; 02July; Kuantan, Malaysia. (to be publish) 2014.

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