

UNIVERSITI TEKNOLOGI MARA

**STUDY ON HYDRAULIC
CONDUCTIVITY BEHAVIOUR
WITH REGARDS TO SOIL
CHARACTERISTICS IN LANDFILL
PERFORMANCE**

**HARIS ASSIDDIQ BIN KHAIRUL
ANUAR**

MSc

July 2026

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HARIS ASSIDDIQ BIN KHAIRUL ANUAR

Thesis submitted in fulfilment
of the requirements for the degree of
**Master of Science
(Civil Engineering)**

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CONFIRMATION BY PANEL OF EXAMINERS

I certify that a Panel of Examiners has met on 26 June 2026 to conduct the final examination of Haris Assiddiq Bin Khairul Anuar on his Master of Science thesis entitled “Study on Hydraulic Conductivity Behaviour with regard to Soil Characteristics in Landfill Performance” in accordance with Universiti Teknologi MARA Act 1976 (Akta 173). The Panel of Examiners recommends that the student be awarded the relevant degree. The Panel of Examiners was as follows:

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ABSTRACT

Municipal solid waste generation continues to increase in Malaysia, placing greater demands on landfill containment systems to effectively prevent leachate migration and protect groundwater resources. The engineering performance of compacted landfill liners depends largely on the hydraulic conductivity achieved after compaction, which is governed by the combined influence of soil physical properties and compaction behaviour. However, the hydraulic performance of landfill-sourced residual soils in Malaysia remains insufficiently understood, particularly regarding the interaction between soil characteristics and hydraulic conductivity under realistic moisture and loading conditions. Therefore, this study investigates the relationship between hydraulic conductivity and residual soil characteristics obtained from the Tanjung Dua Belas (T12) and Air Hitam (AH) landfill sites to evaluate their suitability as compacted landfill liner materials through the development of a preliminary empirical hydraulic conductivity prediction model. Laboratory investigations were conducted in accordance with BS 1377:1990 to determine the physical properties, compaction characteristics and hydraulic conductivity of the investigated soils. Both soils were classified as Silty SAND, with the Tanjung Dua Belas soil exhibiting higher plasticity and moisture sensitivity, whereas the Air Hitam soil exhibited higher particle density. Standard Proctor compaction tests established the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), followed by specimen preparation at 3% below OMC, OMC and 3% above OMC to simulate field moisture tolerance. Tanjung Dua Belas achieved an MDD of 1.50 g/cm³ at an OMC of 18.56%, while Air Hitam attained an MDD of 1.88 g/cm³ at an OMC of 11.75%. Hydraulic conductivity was evaluated using a modified oedometer under incremental vertical loading from 25 kPa to 200 kPa. At 200 kPa, hydraulic conductivity ranged from 1.241×10^{-8} cm/s to 3.256×10^{-8} cm/s across the investigated moisture conditions. Specimens compacted wet of optimum consistently exhibited lower hydraulic conductivity than those compacted at optimum and dry of optimum, while the Air Hitam soil recorded lower hydraulic conductivity than the Tanjung Dua Belas soil due to its denser compacted structure and lower air void content. Statistical analyses using Microsoft Excel and Minitab, including descriptive statistics, Pearson correlation, regression analysis and paired t-test validation, confirmed that hydraulic conductivity is governed by the combined influence of moisture condition, dry density, particle density and air void. Regression analysis further produced a preliminary empirical prediction model based on the air void parameter, integrating dry density, moisture content and specific gravity into a single predictive relationship for the preliminary estimation of hydraulic conductivity. All measured hydraulic conductivity values satisfied the commonly adopted landfill liner requirement of 1×10^{-7} cm/s, confirming that both investigated residual soils are suitable for landfill liner applications, with the Air Hitam soil demonstrating comparatively superior hydraulic barrier performance. Overall, the findings provide valuable site-specific geotechnical data for Malaysian landfill residual soils, establish the engineering relationship between soil characteristics and hydraulic conductivity, and provide a practical preliminary predictive approach to support material selection, compaction control and landfill liner design.

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TABLE OF CONTENTS

	Page
CONFIRMATION BY PANEL OF EXAMINERS	ii
AUTHOR'S DECLARATION	iii
ABSTRACT	iv
ACKNOWLEDGEMENT	v
TABLE OF CONTENTS	vi
LIST OF TABLES	x
LIST OF FIGURES	xii
LIST OF SYMBOLS	xvi
LIST OF ABBREVIATIONS	xvii
CHAPTER 1 INTRODUCTION	1
1.1 Research Background	1
1.2 Problem Statement	2
1.3 Research Objectives	5
1.4 Scope and Limitation	5
1.5 Significance of Study	9
1.6 Thesis Layout	11
CHAPTER 2 LITERATURE REVIEW	14
2.1 Introduction	14
2.1.1 Landfill Systems	14
2.1.2 Landfill Liners Function as Hydraulic Barriers	17
2.1.3 Soil Materials for Landfill Liners	18
2.1.4 Residual Soils in Landfill Applications	19
2.2 Physical Properties	21
2.2.1 Selection of Soil	22
2.2.2 pH	23
2.2.3 Particle Density	24
2.2.4 Particle Size Distribution	25
2.2.5 Atterberg Limit	28
2.2.6 Shrinkage Limit	30

2.3	Compaction Behaviour of Soil Liners	32
2.3.1	Standard Proctor Compaction Test	34
2.3.2	Practical Considerations for Field Compaction of Soil Liners	36
2.3.3	Moisture Content Tolerance	37
2.4	Hydraulic Conductivity of Compacted Soils	39
2.4.1	Modified Oedometer Test for Hydraulic Conductivity Evaluation	40
2.4.2	Hydraulic Conductivity Requirements for Landfill Liners	42
2.4.3	Influence of Soil Type on Hydraulic Conductivity	44
2.4.4	Influence of Moisture Condition on Hydraulic Conductivity	47
2.5	Relationship of Hydraulic Conductivity with Soil Characteristics	48
2.5.1	Relationship of Particle Density with Hydraulic Conductivity	49
2.5.2	Relationship of Plasticity and Shrinkage Characteristics with Hydraulic Conductivity	51
2.5.3	Relationship of Dry Density with Hydraulic Conductivity	52
2.5.4	Relationship of Compaction Behaviour with Hydraulic Conductivity	53
2.5.5	Statistical Analysis of Hydraulic Conductivity with Soil Characteristics	57
2.6	Research Gap	59
CHAPTER 3 RESEARCH METHODOLOGY		62
3.1	Introduction	62
3.1.1	Soil Methodology Framework	62
3.1.2	Soil Collection and Sampling	64
3.2	Physical Properties	69
3.2.1	<i>pH</i> Test	70
3.2.2	Particle Density Test	71
3.2.3	Particle Size Distribution Test	72
3.2.4	Atterberg Limit Test	75
3.2.5	Shrinkage Limit Test	79
3.3	Compaction Test	80
3.3.1	Compaction Sample Preparation	80
3.3.2	Standard Proctor Compaction Test	81
3.3.3	Determination of OMC and MDD	83
3.3.4	Determination of Air Void in Compaction Curve	83
3.3.5	Moisture Conditioning Relative to OMC	84
3.4	Hydraulic Conductivity Test	85

3.4.1	Hydraulic Conductivity Sample Preparation	86
3.4.2	Modified Oedometer Test	87
3.4.3	Hydraulic Conductivity Analysis	94
3.5	Analysis of Relationship between Hydraulic Conductivity with Soil Characteristics	95
3.5.1	Relationship of Particle Density with Hydraulic Conductivity	96
3.5.2	Relationship of Plasticity and Shrinkage Characteristics with Hydraulic Conductivity	97
3.5.3	Relationship of Compaction with Hydraulic Conductivity	97
3.5.4	Minitab Normality Analysis of Hydraulic Conductivity with soil characteristics	98
3.5.5	Minitab Correlation Analysis of Hydraulic Conductivity with soil characteristics	98
3.5.6	Minitab Regression Analysis of Hydraulic Conductivity with soil characteristics	99
3.5.7	Minitab Paired t-Test Analysis of Hydraulic Conductivity	100
CHAPTER 4	RESULTS & DISCUSSION	102
4.1	Introduction	102
4.2	Physical Properties	102
4.2.1	<i>pH</i> Values	103
4.2.2	Particle Density	104
4.2.3	Particle Size Distribution	105
4.2.4	Atterberg Limit	108
4.2.5	Linear Shrinkage	109
4.3	Compaction Result	110
4.3.1	Sampling of Compaction	111
4.3.2	Moisture Variation around Optimum Moisture Content	114
4.3.3	Dry Density Result	118
4.3.4	Moisture Content Result	120
4.3.5	Air Void Percentage	121
4.4	Hydraulic Conductivity	122
4.4.1	Hydraulic Conductivity at Optimum Moisture Content	123
4.4.2	Hydraulic Conductivity under Wet-of-Optimum Conditions	125
4.4.3	Hydraulic Conductivity under Dry-of-Optimum Conditions	127

4.4.4	Comparison of Hydraulic Conductivity under Different Moisture Conditions	130
4.4.5	Summary of Hydraulic Conductivity and Soil Characteristics Result	133
4.5	Relationship of Hydraulic Conductivity with the Soil Characteristics	135
4.5.1	Relationship of Hydraulic Conductivity and Particle Density	136
4.5.2	Relationship of Hydraulic Conductivity with Plasticity and Shrinkage Characteristics	138
4.5.3	Relationship of Hydraulic Conductivity and Maximum Dry Density	139
4.5.4	Relationship of Hydraulic Conductivity and Moisture Content	141
4.5.5	Normally Distributed Analysis of Hydraulic Conductivity and Soil Characteristics	144
4.5.6	Pearson Correlation Analysis between Hydraulic Conductivity and Soil Characteristics	146
4.5.7	Regression Analysis of Hydraulic Conductivity and Soil Characteristics	149
4.5.8	Validation of the Empirical Regression Models Using Paired t-Test	151
4.5.9	Derivation of a Predictive Hydraulic Conductivity Model from the Regression Analysis	155
CHAPTER 5	CONCLUSION	158
5.1	Introduction	158
5.1.1	Physical Properties of the Residual Soils	158
5.1.2	Compaction Behaviour of the Residual Soils	159
5.1.3	Hydraulic Conductivity Performance of the Residual Soils	159
5.1.4	Relationship between Hydraulic Conductivity and Soil Characteristics	160
5.2	Recommendations	161
	REFERENCES	163
	APPENDICES	172
	AUTHOR'S PROFILE	188

LIST OF TABLES

Tables	Title	Page
Table 2.1	Percentage Distribution of Particle Sizes in Malaysian Residual Soils (Mohamed et al., 2024	27
Table 2.2	Atterberg Limits Values of Malaysian Residual Soils (Mohamed et al., 2024)	29
Table 2.3	Summary of Hydraulic Conductivity Values Reported From Previous Studies	44
Table 3.1	Soil Sampling Locations	69
Table 3.2	Sample Preparation for <i>pH</i> Test	70
Table 3.3	Sample Preparation for Particle Density Test	71
Table 3.4	Sample Preparation for Liquid Limit Test	76
Table 3.5	Sample Preparation for Shrinkage Limit Test	79
Table 3.6	Sample Preparation for Standard Proctor Compaction Test	80
Table 3.7	Sample Preparation for Hydraulic Conductivity Test	87
Table 4.1	Tanjung Dua Belas and Air Hitam <i>pH</i> Result	103
Table 4.2	Tanjung Dua Belas and Air Hitam Particle Density Result	104
Table 4.3	Tanjung Dua Belas and Air Hitam Particle Size Distribution Summary	107
Table 4.4	Tanjung Dua Belas and Air Hitam Atterberg Limit Result	108
Table 4.5	Tanjung Dua Belas and Air Hitam Linear Shrinkage Result	109
Table 4.6	Tanjung Dua Belas and Air Hitam Compaction Result	114

Table 4.7	Moisture Variation Conditions with Corresponding Dry Density and Air Void Percentage	117
Table 4.8	Hydraulic conductivity of Soil Sample at OMC	124
Table 4.9	Hydraulic conductivity of Soil Sample at +3 OMC	126
Table 4.10	Hydraulic conductivity of Soil Sample at -3 OMC	129
Table 4.11	Summary of Hydraulic Conductivity Result with different Moisture Content (%)	131
Table 4.12	Summary of Soil Characteristics and Hydraulic Conductivity for T12 and AH	133
Table 4.13	Input Variables for Minitab Statistical Analysis	144
Table 4.14	Summary of Descriptive Statistics	145
Table 4.15	Pairwise Pearson Correlations	147
Table 4.16	Empirical Modelling in Predicting k value	150
Table 4.17	P Value using t Paired Test	154

LIST OF FIGURES

Figures	Title	Page
Figure 2.1	Typical Components of an Engineered Municipal Solid Waste Landfill Containment System (adapted from International Geosynthetics Society, 2022)	16
Figure 2.2	Relationship Between Moulding Water Content and Hydraulic Conductivity Under Different Compaction Conditions (Adeyemo and Bello, 2024).	54
Figure 3.1	Methodological Framework	64
Figure 3.2	Location of Tanjung Dua Belas Landfill on Google Maps	65
Figure 3.3	Location of Air Hitam Landfill on Google Maps	66
Figure 3.4	Extraction of residual soil samples at depths between 1.0-1.5 m.	67
Figure 3.5	30 kg of Soil Sample Stored in Each Sack	68
Figure 3.6	Oven Drying Process of Soil Sample	68
Figure 3.7	Temperature Setting of Oven	69
Figure 3.8	Preparation of the Soil–water Suspension for the <i>pH</i> test	70
Figure 3.9	50mL Small Pycnometer	71
Figure 3.10	Desiccator Used to Remove Entrapped Air Bubbles	72
Figure 3.11	Wet Sieving Process for Separation the Fine Soil Particles	73
Figure 3.12	Removal of Excess Water Using the Siphoning Method.	73
Figure 3.13	Mechanical Sieving Arrangement	74
Figure 3.14	Soil Suspensions for Hydrometer Analysis	75
Figure 3.15	Groove Closure using Casagrande Apparatus	76

Figure 3.16	Liquid Limit Sample after Oven Drying	77
Figure 3.17	Crumbling of Soil Threads During Plastic Limit Determination	78
Figure 3.18	Plastic Limit Sample After Oven Drying	78
Figure 3.19	Linear Shrinkage Measurement of the Residual Soil After Oven Drying	79
Figure 3.20	Automatic Proctor Compactor used for Standard Compaction Test	81
Figure 3.21	Standard Compaction Mould Used for Compaction Test	81
Figure 3.22	Weighing of Compacted Soil And Mould After Compacted	82
Figure 3.23	Compacted Soil Sample after Oven Drying for Moisture Content Determination	83
Figure 3.24	Expected Compaction Curve With Moisture Variation	85
Figure 3.25	Residual Soil Specimens Sealed in Plastic Bags for Moisture Conditioning	86
Figure 3.26	Initial Weighing of the Empty Cutting Ring	88
Figure 3.27	Compacted Residual Soil Specimen in the Standard Proctor Mould	89
Figure 3.28	Horizontal Extrusion of the Compacted Soil into the Cutting Ring	89
Figure 3.29	Compacted Residual Soil Specimen after Extrusion	90
Figure 3.30	Weighing of the Cutting Ring Containing the Soil Specimen	90
Figure 3.31	Assembly of the Modified Oedometer Cell	91
Figure 3.32	Installation of the Modified Oedometer Cell in the Consolidation Frame	92

Figure 3.33	Complete Modified Oedometer Hydraulic Conductivity Test Setup	93
Figure 3.34	Application of Incremental Vertical Loads During the Modified Oedometer Test	94
Figure 3.35	Oven Drying and Final Weighing of the Tested Soil Specimen	94
Figure 4.1	Particle Size Distribution Curves	106
Figure 4.2	Compaction Curve of Tanjung Dua Belas	112
Figure 4.3	Compaction Curve of Air Hitam	113
Figure 4.4	Comparison of Compaction Curves for Tanjung Dua Belas and Air Hitam	114
Figure 4.5	Compaction Curve of Tanjung Dua Belas under Moisture Variation around the Optimum Moisture Content	116
Figure 4.6	Compaction Curve of Air Hitam under Moisture Variation around the Optimum Moisture Content	117
Figure 4.7	Hydraulic Conductivity (cm/s) vs Applied Load (kPa) at OMC	123
Figure 4.8	Hydraulic Conductivity (cm/s) vs Applied Load (kPa) at +3% OMC	126
Figure 4.9	Hydraulic Conductivity (cm/s) vs Applied Load (kPa) at -3% OMC	128
Figure 4.10	Comparison of Hydraulic Conductivity (cm/s) versus Applied Load (kPa) under different Moisture Content (%)	130
Figure 4.11	Relationship of Hydraulic Conductivity (cm/s) with Particle Density (Mg/m^3)	137
Figure 4.12	Relationship of Plasticity and Shrinkage (%) vs Hydraulic Conductivity (cm/s)	138

Figure 4.13	Relationship of Hydraulic Conductivity (cm/s) with MDD (Mg/m ³)	140
Figure 4.14	Relationship of Hydraulic Conductivity (cm/s) with Moisture Content (%)	142
Figure 4.15	Relationship of Hydraulic Conductivity (cm/s) and Moisture Condition (%)	143
Figure 4.16	Validation of the Load-Based Regression Model Using Measured and Predicted k	153
Figure 4.17	Validation of the Air Void-Based Regression Model Using Measured and Predicted k	154

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
$D_{10, 30, 60}$	Effective Particle Size
G_s	Specific Gravity
H_o	Initial Hydraulic Head
k	Hydraulic Conductivity
L_o, L_t	Flow path length
r	Pearson Correlation
R^2	Coefficient of Determination
t_i, t_o	Time reading
w	Water Content
α	Significance Level
δH	Change in Hydraulic Head
ρ_d	Dry Density

LIST OF ABBREVIATIONS

Abbreviations

AH	Air Hitam
BS	British Standard
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
SDG	Sustainable Development Goals
SEM	Scanning Electron Microscopy
SL	Shrinkage Limit
T12	Tanjung Dua Belas
UCS	Unconfined Compressive Strength
XRD	X-ray Diffraction

CHAPTER 1

INTRODUCTION

1.1 Research Background

Malaysia's growing population and rapid urbanisation have accelerated urban development, resulting in a substantial increase in Municipal Solid Waste (MSW) generation. Effective waste management is necessary to reduce environmental and health-related issues, as Malaysians currently generate approximately 39,078 tonnes of solid waste daily, averaging 1.17 kg per person (Zainal, 2024). The Solid Waste and Public Cleansing Management Corporation (SWCorp) reported that from January to October 2023, approximately 2.67 million tonnes of waste were disposed of in states governed under Act 672, compared to 3.1 million tonnes in 2022 and three million tonnes in 2021 (Chonghui, 2024). These figures demonstrate the mounting pressure on landfill capacity and highlight ongoing challenges in Malaysia's waste management system.

Landfilling remains the primary disposal method for MSW in many countries, including Malaysia. This practice leads to continuous leachate generation as rainwater infiltrates through waste layers and interacts with decomposing materials. With global MSW production reaching approximately 2.2 billion tonnes annually (Chen et al., 2020), leachate contamination has become increasingly severe. Typical leachate contains harmful organic and inorganic substances, heavy metals, and ammonia nitrogen compounds that threaten groundwater, soil, and air quality (Mohamed et al., 2023). Malaysia currently operates 137 landfill sites, with only 21 classified as sanitary landfills designed to minimise leachate leakage, while the remaining non-sanitary landfills continue releasing methane gas and untreated leachate into the surrounding environment (Shuen, 2024). The Malaysian government allocates approximately USD 5.24 billion annually for solid waste management, with almost 60% of the expenditure dedicated to waste collection and disposal, further highlighting the urgency of improving landfill performance (Jeffreychiak, 2023).

Landfill leachate is considered one of the most hazardous by-products of municipal solid waste disposal due to its high concentration of organic pollutants, heavy metals, ammonia nitrogen and pathogenic microorganisms, which pose serious threats

to groundwater and soil quality when uncontrolled (Mohamed et al., 2023). As rainwater percolates through landfill waste, complex leachate is continuously generated and can migrate downward into the subsurface environment if effective containment systems are not in place. Compacted soil liners serve as the primary hydraulic barrier in landfill engineering and are designed to restrict leachate movement through low hydraulic conductivity and favourable attenuation capacity (Rowe et al., 2012). Failure or underperformance of these liner systems has been directly associated with groundwater contamination, long-term ecosystem degradation and elevated public health risks in surrounding communities (Chen et al., 2020). Therefore, understanding how soil properties and compaction conditions influence the effectiveness of soil liners is essential to ensure reliable leachate containment and sustainable landfill performance.

The performance of landfill containment systems is highly dependent on the engineering properties of the soils used as liner materials (Rowe et al., 2012). Soil physical properties, including particle size distribution, fines content, plasticity index and particle density, together with compaction behaviour and moulding water content, strongly influence the hydraulic conductivity of compacted landfill liners (Benson et al., 2010). Studies on tropical residual soils have confirmed that these soils can satisfy the hydraulic conductivity requirements for landfill liner applications when appropriate compaction control is adopted (Albrecht et al., 2006). However, the hydraulic performance of residual soils can vary considerably depending on their physical characteristics and their response to moisture variation during compaction. Therefore, a comprehensive evaluation of soil physical properties, compaction behaviour and hydraulic conductivity is essential for improving the design and long-term performance of compacted landfill liner systems. In addition, developing a preliminary empirical hydraulic conductivity prediction model based on measurable soil characteristics provides a practical approach for estimating hydraulic conductivity behaviour prior to the completion of time-consuming laboratory hydraulic conductivity tests, thereby supporting more efficient preliminary assessment of residual soils for landfill liner applications.

1.2 Problem Statement

The suitability of engineered barriers in liner systems is critical for maintaining long-term structural stability and environmental protection in waste containment

facilities. Although clayey soils are commonly preferred for landfill liner and cover systems due to their low hydraulic conductivity value, locally available residual soils may also offer potential as alternative materials when their hydraulic and compaction properties satisfy landfill performance requirements. The utilisation of these locally available residual soils, particularly those obtained from existing landfill sites, offers the potential to reduce material transportation, construction costs and dependence on imported liner materials, provided that their engineering performance satisfies landfill liner requirements. However, the engineering behaviour of these residual soils remains highly variable and is governed by intrinsic characteristics such as particle size distribution, plasticity, moisture content, and compaction conditions (Oluwapelumi et al., 2015). In Selangor, comprehensive geotechnical data describing the physical and engineering characteristics of residual soils within active landfill environments remain limited (Emmanuel et al., 2020). The absence of such site-specific geotechnical baselines increases the risk of inappropriate material selection, potentially leading to liner instability, excessive structural settlement, and subsequent leachate leakage into surrounding ecosystems.

One of the main construction challenges in compacted residual soil liner applications is achieving adequate field density under moisture conditions that often deviate from laboratory optimum moisture content values (Daniel et al., 1993). Variability in the in-situ moisture profile caused by tropical rainfall, evaporation, and groundwater fluctuations frequently leads to inconsistent dry density and non-uniform soil structure during field placement (Benson et al., 1999). Laboratory studies have shown that both maximum dry density and optimum moisture content are critical parameters controlling soil strength, pore structure, and hydraulic conductivity characteristics (Mitchell and Soga, 2005). However, these parameters are typically evaluated under strictly controlled laboratory setups, which fail to replicate realistic field placement scenarios. When residual soils are compacted outside the specified moisture limits, the resulting hydraulic performance can deviate significantly from design expectations, compromising the effectiveness of the containment barrier (Osinubi et al., 2015). This highlights the need to evaluate the compaction behaviour and hydraulic conductivity of residual soils under moisture conditions at, below and above the optimum moisture content, thereby providing a more realistic representation of field compaction conditions encountered during landfill liner construction.

Uncertainty in soil hydraulic conductivity remains a major concern in landfill engineering due to its direct impact on leachate migration and groundwater contamination risks. Compacted fine-grained materials are widely used as hydraulic barriers because of their ability to achieve a low hydraulic conductivity when properly selected and constructed (Nikbakht, 2023). However, hydraulic conductivity is governed by the combined interaction of soil physical properties, compaction behaviour and moisture condition rather than by any individual soil property alone. Variations in plasticity, fines content, dry density, air void and moulding water content have been shown to significantly influence the hydraulic performance of compacted residual soils. Regulatory standards internationally such as the United States Environmental Protection Agency (US EPA) guidelines strictly require a maximum hydraulic conductivity value of 1×10^{-7} cm/s to ensure adequate containment performance and prevent toxic seepage from penetrating underlying aquifers (EPA, 1993). In Malaysia, this identical benchmark is strictly enforced by the Ministry of Housing and Local Government (KPKT) and the Department of Environment (DOE) for engineered sanitary landfills. The absence of verified hydraulic conductivity data and engineering correlations for locally sourced residual soils therefore introduces considerable uncertainty regarding their suitability for landfill liner applications and their ability to consistently satisfy these national and international hydraulic performance requirements.

Despite existing studies on landfill liner materials, there remains a limited integrated understanding of how physical soil properties and compaction behaviour collectively control hydraulic conductivity in residual soils obtained from Malaysian landfill environments. Previous studies have commonly evaluated individual soil properties or compaction characteristics independently, with limited emphasis on their combined influence on hydraulic conductivity under varying moisture conditions and applied loading. Consequently, the interaction between soil physical properties, compaction behaviour and hydraulic conductivity remains insufficiently understood for Malaysian residual soils intended for landfill liner applications (Francisca et al., 2010). This limitation restricts the ability to establish practical engineering relationships between measurable soil characteristics and hydraulic conductivity behaviour, making it difficult to predict field performance during preliminary site evaluation (Onyelowe et al., 2021). The interaction between moisture tolerance, dry density and soil structure is particularly important because it governs the stability and long-term hydraulic

conductivity of landfill liner systems, yet this relationship remains insufficiently explored for soils in the Tanjung Dua Belas and Air Hitam landfill sites (Omar et al., 2024). Therefore, a comprehensive investigation is required to establish clear relationships between physical properties, compaction behaviour and hydraulic conductivity performance of locally sourced residual soils, thereby improving the understanding of their engineering behaviour for landfill liner applications. In addition, the development of a preliminary empirical hydraulic conductivity prediction model based on measurable soil characteristics would provide a practical engineering tool for estimating hydraulic conductivity behaviour prior to conducting the more time-consuming laboratory hydraulic conductivity tests.

1.3 Research Objectives

The objectives of this research are to systematically investigate the engineering characteristics and hydraulic performance of residual soils for landfill liner applications as follows:

- i) To determine the physical properties of residual soils obtained from Tanjung Dua Belas and Air Hitam landfill sites.
- ii) To assess the compaction behaviour of the residual soils under dry of optimum, optimum and wet of optimum moisture conditions.
- iii) To evaluate the hydraulic conductivity of compacted residual soil specimens prepared under different moisture conditions.
- iv) To analyse the relationship between soil characteristics, comprising physical properties and compaction characteristics, and hydraulic conductivity for landfill liner performance.

1.4 Scope and Limitation

This research focuses on evaluating the physical properties of selected residual soils to determine their suitability for use as landfill liner materials. This study collects a total of 90 kilograms of soil samples from each of the two selected landfill sites in Selangor, namely the Tanjung Dua Belas Landfill and the Air Hitam Landfill, yielding a cumulative sample size of 180 kilograms across both locations. These landfill sites were selected because they represent residual soils developed under different landfill

environments within Selangor, allowing the physical and engineering characteristics of the soils to be comparatively evaluated. To ensure that the collected material represents natural, in-situ residual soils from the landfill environments rather than imported fill material, soil sampling is conducted at three separate points within each landfill area. The sampling points are purposefully located within a close horizontal distance of approximately five metres from one another, while this localized configuration may not capture the macro-spatial variability of the entire landfill geography, it serves as a deliberate engineering measure to ensure uniform local site conditions while providing structural verification of immediate soil consistency. At each sampling point, soil is excavated at a depth between 1.0 m and 1.5 m below the ground surface to minimise the influence of recently placed surface material or daily cover soils. Approximately 30 kilograms of soil are obtained from each point, resulting in 90 kilograms per landfill site. The three sampling locations serve as representative sampling points to verify the consistency of the measured geotechnical index properties within each landfill site. Laboratory investigations take place at Makmal Tanah 1 and Makmal Tanah 2, Universiti Teknologi MARA Shah Alam, utilizing particle size distribution, particle density, Atterberg limits and linear shrinkage tests. All laboratory testing procedures strictly follow BS 1377:1990 to ensure standardization, accuracy, and reliability of the experimental results. Consequently, these laboratory findings serve as a controlled performance baseline, and careful engineering interpretation is required when correlating these ideal laboratory index results to heterogeneous, full-scale field landfill liner applications.

This research further evaluates the compaction behaviour of residual soils to understand their engineering response under controlled moisture conditions. To contextualize these materials, the material is explicitly defined across specific operational stages, it originates as "soils from landfill environments" or "landfill soils," represents "in situ residual landfill soils" in its native undisturbed state, becomes "landfill-sourced residual soils" upon excavation, and undergoes final placement as "compacted residual soil liners." A desktop review of technical specifications for landfill construction, including those adopted at Crookwell Landfill in 2017, indicates that compacted clay fill is typically placed in layers not exceeding 150 millimetres in thickness and compacted at moisture contents ranging from optimum moisture content to three percent above optimum moisture content, while achieving a minimum field density of ninety-five percent of the Standard Proctor maximum dry density. The

technical specification from the Crookwell Landfill (2017) was purposefully selected as a benchmark because its stringent focus on controlling volumetric desiccation cracking and ensuring low hydraulic conductivity closely aligns with the engineering needs of tropical environments. This international protocol is highly applicable to Malaysian landfill liner practices, because Malaysia experiences extreme weather cycles of heavy rainfall and high evaporation, evaluating the performance bounds established by rigorous international standards provides a reliable blueprint for preventing containment breach. In this study, laboratory compaction testing is carried out in accordance with BS 1377 Part 4:1990 using the Standard Proctor method to establish the optimum moisture content and maximum dry density of each soil sample. Moisture conditioning is subsequently applied by preparing specimens at OMC, 3% below OMC (dry of optimum) and 3% above OMC (wet of optimum) to simulate the allowable moisture variation commonly encountered during field compaction. This approach enables the influence of realistic field moisture variation on compaction behaviour and subsequent hydraulic conductivity to be systematically evaluated under controlled laboratory conditions. The scope of this work is explicitly limited by the use of laboratory-controlled compaction energy and moisture adjustments, which do not address full-scale landfill liner performance evaluation or capture macro-structural field defects such as lift-boundary shearing, compaction equipment differences, and environmental desiccation cycles encountered during actual large-scale landfill construction.

This study evaluates the hydraulic conductivity behaviour of residual soils under stress-dependent conditions using a modified oedometer-based test in accordance with BS 1377 Part 5:1990. The adaptation of the standard oedometer consolidation test for determining hydraulic conductivity is firmly rooted in Terzaghi's classical one-dimensional consolidation theory (Terzaghi, 1943). While traditional indirect methods mathematically derive hydraulic conductivity from the linear segments of settlement curves during early consolidation phases (Sawicki & Stróżyk, 2009), they introduce theoretical limitations regarding active fluid flow mechanics. The apparatus is enhanced by integrating a built-in base water inlet connected to an external graduated burette, an upper outflow point to maintain a stable water level, and external O-ring seals between the porous stone and the centering plate to strictly eliminate lateral fluid bypass. Testing is conducted under incremental vertical loading stages ranging from 25, 50, 100 and 200 kPa to simulate landfill liner overburden pressures. The maximum applied stress of

200 kPa is adopted to represent the higher overburden pressures that may develop during progressive waste placement in landfill operation and is consistent with the maximum loading stage adopted in the modified oedometer test. Under this framework, each load stage operates in a dual-phase sequence. The flow valve remains closed during the primary consolidation phase to prevent consolidation-induced excess pore water pressure from interfering with the hydraulic gradient, once compression stabilizes under the designated stress state, the system is opened to directly monitor the transient fluid drop through the soil matrix under a controlled hydraulic head. This stress-controlled testing approach enables the combined influence of moisture condition and vertical stress on hydraulic conductivity to be evaluated under conditions that more closely represent field landfill loading than conventional laboratory hydraulic conductivity tests. However, a major limitation of this testing framework is the absence of field hydraulic conductivity testing, such as borehole or double ring infiltrometer tests to account for macro-pores, fissures, and spatial placement heterogeneity.

Experimental data obtained from the laboratory tests are systematically organised and analysed using Microsoft Excel to establish structured datasets, identify trends and perform preliminary evaluations. Microsoft Excel is used for data organisation, basic statistical calculations and graphical presentation of the experimental results. Further statistical analysis is performed using Minitab Statistical Software (Minitab LLC, 2023) to evaluate the relationships between soil characteristics and hydraulic conductivity and to develop preliminary empirical predictive models. In this study, soil characteristics represent the combined influence of soil physical properties and compaction behaviour. The statistical analysis includes normality assessment, correlation analysis, regression modelling and paired t-tests to evaluate data distribution, determine the strength of relationships and assess the predictive capability of the developed hydraulic conductivity model. The analysis focuses on identifying key soil parameters that significantly influence hydraulic conductivity behaviour, including particle size distribution, plasticity index, dry density and moisture content. Particular emphasis is placed on evaluating the influence of moisture condition, dry density, air void and applied vertical stress on hydraulic conductivity, as well as developing a preliminary empirical hydraulic conductivity prediction model based on measurable soil characteristics. Nevertheless, the developed empirical equations are intended only as preliminary predictive tools based on controlled laboratory conditions. Although they provide useful estimates of hydraulic conductivity using measurable soil characteristics,

the models do not replace conventional laboratory hydraulic conductivity testing and require further validation using residual soils from additional landfill sites before wider engineering application.

1.5 Significance of Study

The significance of this research lies in its potential to provide critical technical contributions to the geotechnical and environmental engineering fields, particularly towards improving the engineering performance and long-term reliability of landfill containment systems. By systematically assessing and establishing the relationships between the physical properties of residual soils, including particle size distribution, plasticity characteristics, dry density, pH, moisture content, and shrinkage behaviour, this study supports the development of more stable and durable landfill liner barriers. These physical parameters directly govern soil fabric, pore structure, and hydraulic response, which are essential for effective liner performance. An improved understanding of these engineering characteristics enhances the ability to control and restrict fluid flow, thereby reducing the risk of leachate migration and minimizing environmental contamination. In addition, the research provides scientific evidence that can inform the selection of locally available materials, reducing reliance on costly imported alternatives and improving the economic feasibility of landfill construction projects. The findings further contribute to Malaysia's national efforts to strengthen solid waste management infrastructure and promote sustainable engineering practices, aligning with global environmental protection goals and supporting Sustainable Development Goal 11: Sustainable Cities and Communities through the promotion of resilient and environmentally responsible waste containment systems (United Nations, 2015).

This research is also significant because it provides practical engineering insight into the performance of landfill liner barriers under moisture conditions that deviate from laboratory optimum values, which commonly occur in real field construction environments. By evaluating the behaviour of residual soils under controlled wetting and drying conditions, the research strengthens the understanding of how moisture tolerance ranges influence the achievement of maximum dry density, air void reduction, and the stability of compacted soil barriers (Daniel et al., 1993). This approach bridges the gap between ideal laboratory settings and realistic field compaction scenarios. The

findings help engineers better understand the allowable moisture tolerance that can be adopted during field compaction when achieving the exact optimum moisture content is impractical, thereby improving construction decision-making and quality control procedures (Benson et al., 1999). The results also support the development of more realistic construction specifications that account for moisture variability, leading to improved reliability of landfill liner performance under actual operational conditions. This contribution is particularly valuable for landfill systems in tropical climates such as Malaysia, where rainfall intensity, high evaporation rates, and fluctuating groundwater levels make moisture control especially challenging during liner construction.

In the context of waste management and geotechnical construction, this research offers practical engineering benefits by improving the understanding of the hydraulic conductivity performance of residual soils used in landfill liner and cover systems. By identifying locally available residual soils that can meet the commonly adopted landfill liner hydraulic conductivity criterion of 1×10^{-7} cm/s or lower, this study supports the design of safer and more efficient containment systems while reducing dependency on expensive imported barrier materials. This is especially relevant for developing regions where cost-effective and locally sourced solutions are prioritized. Previous studies have shown that optimization of clay content and compaction effort can significantly reduce hydraulic conductivity while minimizing material usage and construction costs, particularly in bentonite-enhanced and compacted soil barrier systems. The evaluation of the hydraulic conductivity behaviour of residual soils from the Tanjung Dua Belas and Air Hitam landfills provides valuable site-specific performance data, enabling engineers to make evidence-based decisions on material selection and design under realistic stress conditions (Rowe et al., 2012). The findings contribute to improved groundwater protection, reduced environmental risk, and enhanced engineering reliability, while supporting Sustainable Development Goal 12: Responsible Consumption and Production through more efficient use of natural resources and safer landfill infrastructure development.

Finally, this research provides a valuable scientific contribution by advancing the understanding of the interaction between soil physical properties, compaction behaviour, and hydraulic conductivity in landfill engineering applications. Through the systematic investigation of residual soils obtained from Malaysian landfill environments, the study addresses the limited availability of site-specific data on the

hydraulic conductivity behaviour of natural, in-situ residual soils under applied loading and moisture conditioning (Emmanuel et al., 2020). The research evaluates how variations in particle size distribution, plasticity, dry density, moisture condition, air void content, and hydraulic loading directly influence the magnitude of hydraulic conductivity and affect the long-term effectiveness of leachate containment systems (Yamusa et al., 2017). By establishing clear relationships between material properties and hydraulic conductivity responses, the findings provide scientific guidance on the conditions under which compacted residual soils can maintain hydraulic conductivity at minimal levels and comply with standard regulatory requirements for landfill barrier systems (Oluwapelumi et al., 2015). Furthermore, this research develops a preliminary empirical hydraulic conductivity prediction model based on measurable soil characteristics, providing engineers with a practical engineering tool for obtaining an initial estimate of hydraulic conductivity before conducting the more time-consuming laboratory hydraulic conductivity tests. Although the developed model is intended as a preliminary predictive tool and should not replace conventional hydraulic conductivity testing, it provides valuable guidance during preliminary engineering assessment and material selection. Ultimately, these outcomes establish a controlled laboratory baseline that supports the development of more robust predictive design approaches and technical guidelines, enabling engineers to select, compact, and condition residual soils more effectively before scaling up to full-scale, long-term field operations.

1.6 Thesis Layout

This thesis is organized into five chapters, each systematically addressing different aspects of the evaluation of landfill liner performance in relation to residual soil characteristics and hydraulic conductivity behaviour. The overall structure of the thesis follows a logical progression beginning with the research background and theoretical foundation, followed by the experimental methodology, analysis of laboratory results, and final interpretation of the findings. This arrangement ensures that the study develops in a coherent and structured manner, allowing each chapter to contribute progressively to the understanding of how residual soil characteristics influence hydraulic conductivity behaviour in landfill liner systems. The organisation of the chapters also aligns closely with the research objectives established for this study,

enabling a clear connection between the research problem, the adopted methodology, and the final conclusions drawn from the experimental investigation.

Chapter 1, Introduction, presents the background of the study, the problem statements, research objectives, scope and limitations, and the significance of the research. This chapter establishes the context of increasing solid waste generation and the growing need for effective landfill containment systems to minimise environmental impacts. Particular emphasis is placed on the importance of compacted residual soil liner systems in restricting fluid flow and protecting surrounding groundwater resources. The chapter also outlines the motivation for investigating residual soils obtained from landfill environments in Selangor and explains the relevance of evaluating residual soil characteristics and hydraulic conductivity behaviour for landfill engineering applications in Malaysia.

Chapter 2, Literature Review, provides a comprehensive review of previous research related to residual soil characteristics, compaction behaviour under varying moisture conditions, and hydraulic conductivity performance of residual soils used in landfill applications. The chapter examines theoretical concepts and experimental findings from previous studies on soil physical properties, moisture-controlled compaction, and hydraulic conductivity behaviour in fine-grained residual soils commonly used as hydraulic barriers. Particular attention is given to the influence of particle size distribution, plasticity index, dry density, and moisture content on hydraulic conductivity performance. This chapter also identifies knowledge gaps in existing studies, particularly regarding residual soils sourced from Malaysian landfill environments, and justifies the need for the present investigation by linking prior research findings to the objectives established in this study.

Chapter 3, Research Methodology, describes the experimental programme and procedures adopted in this study. This chapter explains the soil sampling strategy used at the selected landfill sites and outlines the laboratory testing standards followed throughout the investigation. Detailed descriptions are provided for the procedures used to determine residual soil characteristics, including particle size distribution, particle density, Atterberg limits, linear shrinkage, and compaction characteristics. The chapter also explains the compaction testing procedures used to determine optimum moisture content and maximum dry density, as well as the preparation of specimens under wet-of-optimum and dry-of-optimum conditions. In addition, the methodology for evaluating hydraulic conductivity using a modified oedometer apparatus under

controlled loading conditions is presented to ensure reliable and repeatable experimental measurements. The chapter further describes the statistical procedures performed using Microsoft Excel and Minitab Statistical Software, including descriptive statistics, normality assessment, Pearson correlation analysis, regression modelling, and paired t-test validation to evaluate the relationships between soil characteristics and hydraulic conductivity.

Chapter 4, Results and Discussion, presents the experimental findings and provides a detailed analysis of residual soil characteristics, compaction behaviour, and hydraulic conductivity results obtained from the laboratory testing programme. The results are systematically interpreted to examine how variations in residual soil characteristics influence hydraulic conductivity behaviour under different moisture conditions and loading levels. Graphical analyses using Microsoft Excel are first presented to illustrate the direct relationships between soil characteristics and hydraulic conductivity. This is followed by statistical analyses using Minitab, including descriptive statistics, normality assessment, Pearson correlation analysis, regression modelling, and paired t-test validation to quantify the relationships between the investigated variables and evaluate the predictive capability of the developed empirical hydraulic conductivity model. The findings are compared with relevant engineering standards and previously published research to assess the suitability of the investigated residual soils for use as landfill liner materials.

Chapter 5, Conclusion and Recommendations, summarizes the key outcomes of the research and highlights their implications for landfill engineering practice. The chapter synthesizes the main findings related to residual soil characteristics, compaction behaviour, hydraulic conductivity performance, and the statistical relationships established between soil characteristics and hydraulic conductivity. Based on the results obtained in this study, several recommendations are proposed to support improved soil selection, moisture control, and compaction practices in landfill liner construction. Recommendations are also provided for further validation of the preliminary empirical hydraulic conductivity prediction model using residual soils from additional landfill sites to enhance its reliability and wider engineering application. The chapter also outlines potential directions for future research, such as expanding into full-scale field testing, mineralogical tracking, and long-term leachate chemical interaction analysis to further enhance the understanding of hydraulic conductivity behaviour in residual soils used for landfill containment systems in Malaysia.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews the literature related to the application of residual soils as compacted landfill liner materials and the soil characteristics that influence their hydraulic performance. The review begins with an overview of landfill systems, followed by the function of landfill liners in preventing leachate migration and protecting the surrounding soil and groundwater environment. Various liner materials used in landfill engineering are then discussed, with emphasis on compacted soil liners because of their widespread use as hydraulic barriers in municipal solid waste disposal facilities. The discussion subsequently focuses on residual soils as a potential alternative liner material owing to their widespread occurrence in tropical regions, favourable engineering characteristics and economic advantages. The influence of soil characteristics, including particle size distribution, particle density, Atterberg limits and shrinkage behaviour, is then reviewed to establish their relationship with soil behaviour. This is followed by a discussion of compaction behaviour, particularly the effects of moisture content, dry density and air voids on the development of soil structure and hydraulic performance. The review then examines hydraulic conductivity as the principal parameter used to evaluate the effectiveness of compacted landfill liners, with particular attention given to the influence of compaction conditions and applied loading on hydraulic conductivity. Finally, the chapter identifies the existing research gap by highlighting the limited understanding of the combined influence of soil characteristics and compaction behaviour on the hydraulic conductivity of Malaysian residual soils, thereby establishing the justification for the present study.

2.1.1 Landfill Systems

Landfilling remains one of the most widely adopted methods for the disposal of municipal solid waste (MSW) because it provides a practical and economically viable solution for managing large volumes of waste. However, modern landfill systems differ significantly from conventional open dumping practices by incorporating engineered containment measures that minimise adverse environmental impacts throughout the

operational and post-closure periods. Rowe et al. (2012) comprehensively reviewed the development of engineered barrier systems for waste disposal facilities, focusing on the integration of landfill liners, leachate collection systems, drainage layers and final cover systems. Their review concluded that the overall performance of a landfill depends on the combined effectiveness of these engineered components in limiting contaminant migration and maintaining long-term environmental protection. These findings establish the fundamental concept of modern landfill engineering and provide the basis for evaluating the hydraulic performance of landfill liner materials investigated in the present study.

The primary objective of an engineered landfill is to isolate waste from the surrounding environment while preventing contaminants from reaching the underlying soil and groundwater. Christensen et al. (2001) investigated the biogeochemical processes occurring within municipal solid waste landfills and examined the characteristics of landfill leachate generated during waste degradation. Their study demonstrated that landfill leachate contains high concentrations of dissolved organic matter, ammonia, heavy metals and inorganic constituents that can migrate into surrounding geological formations if effective containment systems are not provided. More recently, Wdowczyk et al. (2021) reviewed the characteristics of landfill leachate and its environmental impacts on surrounding soil and groundwater systems. They reported that leachate composition varies according to landfill age, waste composition and climatic conditions but consistently poses a significant risk of groundwater contamination when hydraulic barriers fail. These findings emphasise the importance of incorporating reliable containment systems capable of restricting leachate migration throughout the landfill service life, thereby supporting the need to evaluate suitable landfill liner materials.

Modern sanitary landfills consist of several engineered components that function collectively to ensure effective waste containment and environmental protection. Ozbay et al. (2021) reviewed the design and operational principles of engineered landfill systems and highlighted that modern landfills typically incorporate waste cells, daily and final cover systems, leachate collection and removal systems, gas collection systems and liner systems that function together to minimise environmental pollution. Their review further concluded that an integrated landfill design significantly reduces the potential for leachate infiltration, groundwater contamination and greenhouse gas emissions compared with conventional disposal methods. Similarly,

Touze-Foltz et al. (2021) critically reviewed the long-term performance of landfill barrier systems and reported that the efficiency of landfill containment depends on the interaction between drainage systems, mineral liners and geosynthetic barriers rather than on individual components operating independently. These studies demonstrate that successful landfill performance relies on the integrity of the complete containment system, with the landfill liner serving as the principal hydraulic barrier responsible for restricting contaminant transport.

Figure 2.1 illustrates the general configuration of an engineered landfill containment system, showing the interaction between waste placement, daily cover, leachate collection systems, drainage layers, landfill liners and the surrounding geological environment. The schematic highlights the sequence of engineered barriers adopted to minimise contaminant migration and protect groundwater resources throughout landfill operation and post-closure management. The overall containment concept presented in Figure 2.1 provides the engineering framework for the subsequent discussion on the function of landfill liners and the selection of suitable liner materials for hydraulic barrier applications.

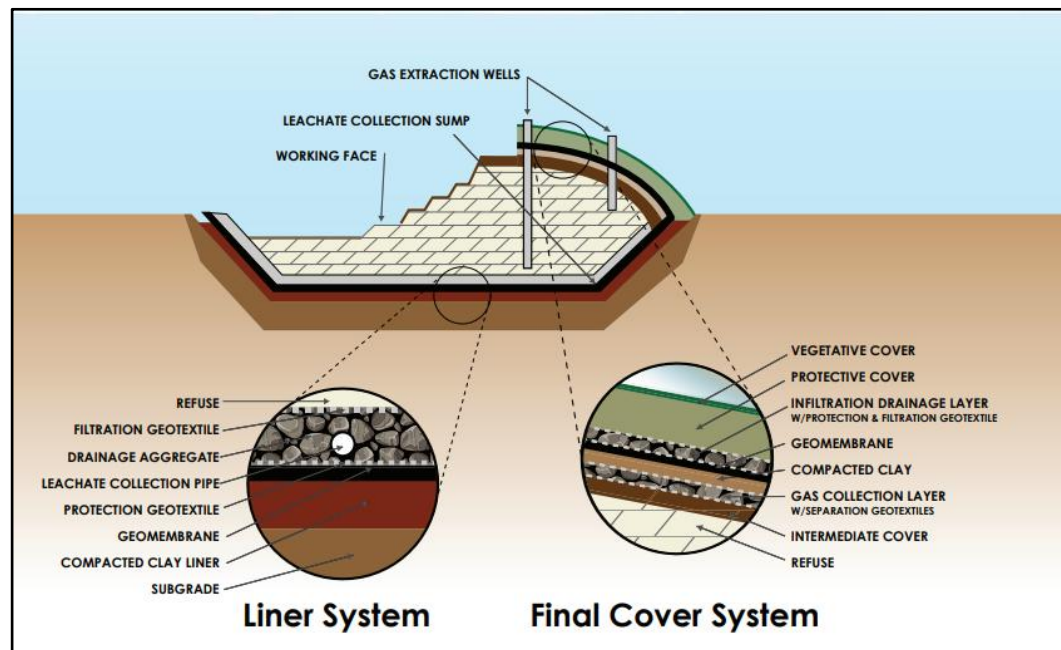


Figure 2.1 Typical Components of an Engineered Municipal Solid Waste Landfill Containment System (adapted from International Geosynthetics Society, 2022)

2.1.2 Landfill Liners Function as Hydraulic Barriers

Rowe et al. (2012) investigated the performance of engineered barrier systems used in modern waste disposal facilities by reviewing the hydraulic behaviour of compacted clay liners, geomembranes and composite liner systems. Their study concluded that the overall effectiveness of a landfill liner depends on maintaining low hydraulic conductivity throughout its service life, while also considering construction quality, moisture control and long-term stress conditions. Similarly, Benson et al. (2010) evaluated the hydraulic conductivity of compacted clay liners and demonstrated that moisture condition during compaction, soil composition and achieved dry density collectively govern liner hydraulic conductivity. Their findings showed that soils compacted under appropriate moisture conditions consistently achieve hydraulic conductivity values that satisfy regulatory requirements for landfill containment. These studies establish that hydraulic conductivity is the primary engineering parameter used to assess landfill liner performance and provide the technical basis for evaluating residual soils in the present study.

The hydraulic performance of landfill liners is also influenced by changes that occur after construction. Touze-Foltz et al. (2021) reviewed the long-term behaviour of mineral and composite barrier systems subjected to mechanical loading, environmental exposure and chemical interaction. Their review found that changes in stress history, moisture variation and construction quality can gradually alter hydraulic performance by modifying soil fabric and pore continuity. Likewise, Shackelford et al. (2016) investigated the hydraulic behaviour of soil-bentonite barrier systems and reported that proper compaction and moisture conditioning significantly reduce pore connectivity, resulting in lower hydraulic conductivity even under sustained loading. These findings indicate that achieving low hydraulic conductivity value depends not only on the intrinsic properties of the liner material but also on the manner in which the material is compacted during construction.

Besides engineering performance, landfill liners play an important role in environmental protection by reducing the risk of contaminant transport into surrounding soil and groundwater systems. Wdowczyk et al. (2021) reviewed the characteristics of landfill leachate and its impact on subsurface environments, concluding that inadequate hydraulic barriers remain one of the major causes of groundwater contamination around municipal solid waste landfills. In addition, Özçoban (2022) investigated the influence

of landfill leachate on compacted liner materials and observed that prolonged chemical interaction may alter soil structure and hydraulic behaviour depending on the characteristics of the liner material. These studies highlight the importance of selecting soils that are capable of maintaining stable hydraulic performance under landfill conditions. Consequently, understanding the engineering characteristics of different soil materials becomes essential when evaluating their suitability for landfill liner applications, which is discussed in the following section.

2.1.3 Soil Materials for Landfill Liners

Compacted clay has traditionally been regarded as the preferred natural material for landfill liners because of its low hydraulic conductivity and favourable sealing characteristics. Daniel and Trautwein (1993) investigated the influence of moulding water content and dry density on the hydraulic conductivity of compacted clay liners through laboratory hydraulic conductivity testing. Their study demonstrated that properly compacted clay soils are capable of achieving hydraulic conductivity values below the commonly accepted regulatory requirement of 1×10^{-7} cm/s, provided that appropriate moisture control and compaction procedures are maintained. Similarly, Benson et al. (1999) evaluated the field performance of compacted clay liners installed at several landfill facilities and reported that well-constructed clay liners consistently maintained satisfactory hydraulic performance under operational conditions. These findings established compacted clay as the benchmark material for landfill liner construction and provide an important performance reference for evaluating alternative residual soils investigated in the present study.

Despite their excellent hydraulic performance, high-quality natural clays are not always readily available near landfill construction sites, leading many researchers to investigate alternative liner materials using locally available soils. Latifi (2016) reviewed the engineering behaviour of tropical residual soils for geotechnical applications and reported that many residual soils possess favourable plasticity, strength and compaction characteristics that make them suitable for hydraulic barrier systems when properly compacted. Likewise, Kassim et al. (2018) evaluated tropical residual soils as landfill barrier materials and concluded that several locally available residual soils satisfied the engineering requirements for landfill liners after achieving adequate dry density and moisture control during compaction. These studies demonstrate that

locally available residual soils can provide a practical and economical alternative to conventional compacted clay liners, particularly in tropical countries where residual soils are widely distributed.

Recent studies have also focused on improving landfill liner performance by modifying natural soils or incorporating additional fine materials. Abichou et al. (2000) investigated the hydraulic performance of foundry green sands as alternative hydraulic barriers and reported that the addition of fine-grained constituents significantly reduced hydraulic conductivity by decreasing pore continuity. More recently, Lat et al. (2023) evaluated kenaf fibre–marine clay mixtures as sustainable landfill liner materials and found that the incorporation of natural fibres improved the engineering behaviour of marine clay while maintaining acceptable hydraulic conductivity for landfill applications. These studies indicate that material modification can further enhance liner performance. However, they also demonstrate that naturally occurring soils with favourable physical characteristics remain attractive because they eliminate the need for extensive material processing or stabilisation.

2.1.4 Residual Soils in Landfill Applications

Residual soils are naturally weathered soils that remain in situ above their parent rock without undergoing significant transportation by water, wind or glacial processes. Their engineering behaviour is primarily governed by the degree of weathering, mineral composition and climatic conditions during formation. In tropical regions such as Malaysia, prolonged chemical weathering produces thick residual soil deposits that are generally characterised by relatively high fines content, variable particle size distribution and heterogeneous mineral composition. These characteristics distinguish tropical residual soils from transported soils and contribute to their unique geotechnical behaviour. Rahardjo et al. (2013) investigated the engineering characteristics of tropical residual soils by reviewing their geological formation, mineralogical composition and engineering properties. Their study reported that tropical residual soils exhibit considerable variability in grading, plasticity and compressibility due to differences in parent rock and weathering intensity. The authors concluded that understanding the origin and formation of residual soils is essential for predicting their engineering performance. These findings provide an important basis for the present study, which

evaluates residual soils collected from two landfill sites developed on different geological formations.

The increasing demand for sustainable and economical engineering materials has encouraged researchers to investigate the potential use of residual soils in environmental geotechnical applications. Latifi (2016) reviewed the engineering behaviour of tropical residual soils used in geotechnical infrastructure and reported that many residual soils exhibit favourable compaction characteristics, acceptable strength and adequate volumetric stability when properly compacted. Similarly, Mohamed et al. (2024) evaluated the engineering properties of Malaysian residual soils collected from the Universiti Teknologi Malaysia campus by examining particle size distribution, Atterberg limits and compaction characteristics. Their study demonstrated that the engineering behaviour of residual soils is strongly influenced by weathering grade and mineral composition, resulting in significant variations in density and moisture response. These studies indicate that residual soils possess engineering characteristics that vary considerably between locations, highlighting the importance of site-specific characterisation before they are adopted for engineering applications.

Residual soils have also received increasing attention for landfill engineering because they are widely available in tropical countries and can substantially reduce construction costs associated with importing high-quality clay materials. Kassim et al. (2018) investigated tropical residual soils as potential landfill barrier materials by evaluating their physical properties, compaction behaviour and hydraulic performance. Their study concluded that several residual soils satisfied the engineering requirements for landfill liner applications when appropriate moisture control and compaction procedures were adopted. Likewise, Yamusa et al. (2022) examined the geotechnical properties of tropical residual soils for sustainable landfill development and reported that locally available residual soils can provide practical alternatives to conventional liner materials due to their favourable engineering characteristics and widespread availability. These findings support the concept of utilising locally available residual soils as environmentally sustainable construction materials while reducing transportation costs and dependence on imported clay resources.

2.2 Physical Properties

The evaluation of physical properties is a fundamental step in determining the suitability of residual soils for landfill liner applications because these properties govern the engineering behaviour of the soil during compaction and subsequently influence its hydraulic performance. Physical characteristics such as particle size distribution, particle density, Atterberg limits and shrinkage behaviour collectively control soil fabric, pore structure and moisture retention, which directly affect the ability of the soil to achieve low hydraulic conductivity after compaction. Nikbakht et al. (2023) investigated the engineering performance of compacted fine-grained soils as hydraulic barriers by examining the influence of fundamental soil properties on hydraulic conductivity and barrier performance. Their study reported that soils possessing favourable physical characteristics and adequate fines content consistently exhibited lower hydraulic conductivity and greater long-term stability, demonstrating that physical characterisation is an essential stage in landfill liner evaluation. These findings support the present study, where the physical properties of residual soils are comprehensively determined prior to assessing their compaction behaviour and hydraulic conductivity.

Previous studies have consistently demonstrated that individual physical properties should not be considered independently because their combined influence governs the engineering performance of compacted soils. Rahardjo et al. (2013) reviewed the engineering behaviour of tropical residual soils and reported that variations in weathering intensity, mineral composition and grading significantly influence particle arrangement, plasticity and moisture sensitivity. Similarly, Mohamed et al. (2024) investigated the physical characteristics of Malaysian residual soils by evaluating particle size distribution, Atterberg limits and compaction-related properties, concluding that differences in soil composition produce distinct engineering responses even among soils of similar classification. These observations indicate that comprehensive physical characterisation is necessary to understand the behaviour of residual soils under engineering loading conditions. Therefore, the following sections review the principal physical properties evaluated in the present study, including soil pH, particle density, particle size distribution, soil classification, Atterberg limits and linear shrinkage, which collectively establish the basis for interpreting compaction behaviour and hydraulic conductivity.

2.2.1 Selection of Soil

The selection of appropriate residual soils is an important consideration in evaluating their suitability for landfill liner applications because their engineering behaviour is strongly influenced by geological origin, weathering processes and long-term environmental exposure. Tropical residual soils exhibit considerable spatial variability in particle size distribution, mineral composition and plasticity due to differences in parent rock and weathering intensity. Rahardjo et al. (2013) reviewed the engineering behaviour of tropical residual soils by examining the influence of geological formation and weathering on their geotechnical properties. Their study reported that residual soils derived from different parent materials exhibit distinct engineering characteristics, even when located within the same climatic region. These findings demonstrate that site-specific characterisation is essential before residual soils can be considered for engineering applications such as landfill liners.

Previous investigations have also shown that landfill environments may further modify the engineering behaviour of residual soils through prolonged exposure to waste decomposition products and landfill leachate. Samsudin et al. (2005) investigated groundwater contamination associated with the Air Hitam Landfill in Selangor by monitoring the migration of landfill leachate and evaluating its influence on the surrounding subsurface environment. Their study identified elevated concentrations of leachate-related contaminants in groundwater surrounding the landfill, indicating that prolonged interaction between leachate and the underlying geological materials may alter subsurface conditions over time. Although the study primarily focused on groundwater quality rather than soil engineering behaviour, its findings demonstrate that residual soils beneath landfill sites experience continuous exposure to landfill leachate, highlighting the importance of evaluating their physical and hydraulic characteristics before considering them as landfill liner materials.

Regional studies have further emphasised that residual soils collected from different locations often exhibit considerable variability in engineering performance because of differences in weathering intensity, mineral composition and environmental history. Mohamed et al. (2024) investigated the engineering properties of Malaysian residual soils by evaluating their particle size distribution, Atterberg limits and compaction characteristics. Their study concluded that residual soils with similar classifications may still exhibit different engineering behaviour due to variations in

geological formation and weathering conditions. Likewise, Latifi (2016) reviewed the engineering behaviour of tropical residual soils and reported that locally available residual soils possess significant potential for geotechnical applications, although comprehensive laboratory characterisation remains necessary because of their heterogeneous nature. These findings support the selection of residual soils from more than one landfill site, allowing engineering behaviour to be evaluated across different geological and environmental conditions.

Based on the findings reported in previous studies, the present research focuses on residual soils collected from the Tanjung Dua Belas Landfill and Air Hitam Landfill in Selangor. These landfill sites represent different operational histories and environmental conditions, providing an opportunity to compare the physical properties, compaction behaviour and hydraulic conductivity of residual soils subjected to different landfill environments. The selection of these two sites therefore provides a broader understanding of the engineering performance of Malaysian residual soils and supports the evaluation of their suitability as landfill liner materials.

2.2.2 pH

The *pH* test is a crucial indicator of a soil's chemical environment because it identifies whether the soil is acidic or alkaline and how these conditions may influence its engineering behaviour. Soil *pH* affects mineral stability, cation exchange capacity, and the interaction between soil particles and pore fluids, which in turn can influence the soil's structure, plasticity, and hydraulic conductivity behaviour (Lei et al., 2021). Rasheed and Atemimi (2025) investigated clayey soils exposed to sulfuric acid contamination and found that decreasing *pH* caused substantial deterioration in clay mineral structure. Their results showed that increasing acidity reduced the liquid limit and plasticity index by more than 60%, indicating a major decline in the soil's engineering performance. Monitoring *pH* is particularly important in landfill applications, where soils may interact with chemically variable leachate generated during waste decomposition. Such interactions can modify interparticle bonding and pore structure, indirectly affecting hydraulic conductivity performance. This consideration was highlighted by Yamusa et al. (2022), who noted that *pH* shifts can alter soil behaviour within containment systems. The influence of *pH* on hydraulic conductivity is also significant, as Gupta (2024) found that alkaline conditions may

initially promote particle aggregation and micropore formation, increasing hydraulic conductivity, whereas excessively high pH can lead to particle dispersion and eventual clogging of pore spaces, reducing overall hydraulic conductivity value.

2.2.3 Particle Density

Particle density, commonly expressed through specific gravity, represents the density of soil solids excluding pore spaces and is an essential parameter for understanding the mineral composition and physical characteristics of soils, as explained by Beemer et al. (2020). Their study examined the influence of mineral composition on soil physical properties and reported that particle density provides valuable information regarding the proportion of heavy and light minerals within the soil matrix, which subsequently influences compaction behaviour and pore structure development. Particle density is primarily governed by soil mineralogy and organic content, and it indirectly influences hydraulic conductivity by affecting soil fabric, packing efficiency and the achievable void ratio when soils are compacted under controlled moisture conditions. Soils with higher particle density typically contain heavier minerals such as quartz, feldspar and iron oxides, whereas lower particle density is commonly associated with clay minerals or organic matter, resulting in reduced mass of solids per unit volume (Hossne et al., 2017).

Although no specific minimum or maximum particle density is prescribed in landfill liner design standards, previous studies have consistently reported that natural soils successfully used as compacted landfill liners generally exhibit particle density values ranging between 2.60 and 2.80. Albrecht et al. (2006) investigated the hydraulic conductivity of compacted natural clays with different mineralogical compositions and reported particle density values of approximately 2.65–2.75, demonstrating satisfactory hydraulic performance after compaction. Similarly, Rahardjo et al. (2013) reviewed the engineering behaviour of tropical residual soils and observed particle density values within a comparable range for soils derived from granitic and sedimentary parent rocks. These studies indicate that particle density within this range is commonly associated with mineral compositions capable of achieving dense particle packing and favourable hydraulic barrier performance. Therefore, although particle density is not a direct acceptance criterion for landfill liners, it serves as an important indicator of mineral

composition and compaction potential when evaluating the suitability of residual soils for landfill liner applications.

Variations in particle density may also indicate the presence of weathered minerals, organic matter or contaminant interactions that influence soil engineering behaviour. Yamusa et al. (2022) investigated the geotechnical characteristics of tropical residual soils for sustainable landfill applications and reported that particle density contributes to differences in compaction efficiency and hydraulic conductivity through its influence on soil packing characteristics. Their findings demonstrated that soils with comparatively higher particle density generally achieved denser soil fabrics after compaction, contributing to lower hydraulic conductivity. These observations support the present study, where particle density is evaluated together with other physical properties to assess the engineering suitability of residual soils collected from the Tanjung Dua Belas and Air Hitam landfill sites.

2.2.4 Particle Size Distribution

Particle Size Distribution (PSD) is one of the most important physical properties used to evaluate the suitability of residual soils for landfill liner applications because it governs soil fabric, pore structure and the distribution of flow paths within compacted soils. The proportion of coarse and fine particles directly influences compaction behaviour, hydraulic conductivity and long-term engineering performance. Wuddivira et al. (2023) investigated the influence of particle size distribution on the engineering behaviour of soils by reviewing the effects of grading on density, strength and hydraulic response. Their study reported that soils containing higher proportions of fine particles generally exhibit lower hydraulic conductivity because fine particles occupy intergranular voids, reducing pore connectivity and restricting water flow. These findings demonstrate that PSD is a fundamental parameter for assessing the hydraulic performance of soils intended for landfill liner applications and support its evaluation in the present study. The influence of soil gradation on compaction behaviour has also been widely reported in the literature. Alzara et al. (2024) investigated the effect of soil gradation on compaction characteristics by analysing soils with different coarse-to-fine particle proportions. Their study found that particle gradation significantly affects particle packing efficiency, with well-graded soils producing higher dry density and lower void ratio than poorly graded soils under the same compactive effort. The authors

concluded that an appropriate balance between coarse and fine particles enhances soil densification while maintaining favourable engineering performance. These findings indicate that particle size distribution influences not only soil classification but also the ability of soils to achieve the dense structure required for landfill liner construction.

Previous studies have consistently emphasised the importance of fines content when selecting soils for landfill liner applications because the proportion of clay and silt particles governs pore continuity and hydraulic conductivity after compaction. Daniel and Benson (1990) investigated the influence of soil gradation and moulding conditions on the hydraulic conductivity of compacted clay liners and reported that soils containing more than approximately 20–30% fines passing the 0.075 mm sieve, together with an adequate clay fraction, consistently achieved hydraulic conductivity values below the commonly accepted design criterion of 1×10^{-7} cm/s. Although Malaysia does not prescribe a specific particle size distribution requirement for compacted soil liners, these internationally recognised recommendations are widely adopted in landfill engineering and provide an appropriate benchmark for evaluating the suitability of natural soils for hydraulic barrier applications. Benson et al. (1999) evaluated the long-term field performance of compacted clay liners and reported that soils containing sufficient clay and silt fractions developed lower hydraulic conductivity because the fine particles reduced pore continuity and improved sealing characteristics after compaction. Similarly, Shackelford et al. (2016) reviewed the hydraulic behaviour of compacted soil barriers and concluded that fine-grained soils with adequate plasticity and fines content consistently achieved superior hydraulic performance compared with coarse-grained soils. More recently, Nikbakht et al. (2023) investigated compacted fine-grained soils used as hydraulic barriers and found that soils with higher fines content exhibited lower hydraulic conductivity and greater resistance to contaminant migration due to their denser pore structure. These studies collectively demonstrate that the proportion of fine particles is one of the principal criteria considered when selecting soils for landfill liner construction and provide an important basis for evaluating the residual soils investigated in the present study.

Particle size distribution has also been investigated extensively in Malaysian residual soils. Mohamed et al. (2024) characterised residual soils collected from several locations in Peninsular Malaysia by determining the proportions of gravel, sand, silt and clay. Their study demonstrated considerable variation in particle composition among the investigated sites, despite the soils generally originating from tropical residual

deposits. The reported clay content ranged from approximately 1.85% to 49%, while silt content varied between 13% and 48.7%, indicating that weathering intensity and parent rock significantly influence particle distribution. The particle size distributions reported by Mohamed et al. (2024) are summarised in Table 2.1.

Table 2.1
Percentage Distribution of Particle Sizes in Malaysian Residual Soils (Mohamed et al., 2024)

Researcher	Location	Clay(%)	Silt(%)	Sand(%)	Gravel(%)
Mohamed	UTM Dusun, JB	20.4	44.7	30.1	4.8
Zolkepli	Pahang Matriculation	22.8	45.1	27.9	4.2
Ishak	UTM, JB	25.3	48.7	20.9	5.1
Salih	UTM, JB	15.8	25.8	11.9	35.3
Duraisamy	Gambang, Pahang	1.85	16.2	76	3.7
Tan and Yew	Kg. Awah, Pahang	48	34	27	19
Taha	Cheras, Kuala Lumpur	49	13	38	0

The data presented in Table 2.1 demonstrate that Malaysian residual soils exhibit considerable variability in particle size distribution, particularly in the proportions of clay and silt. Nevertheless, most of the reported soils contain fines contents that exceed the minimum range commonly recommended for compacted landfill liner materials, indicating favourable grading characteristics for hydraulic barrier applications after proper compaction. The variability reported by Mohamed et al. (2024) also highlights the necessity for site-specific characterisation, as soils with similar classifications may still exhibit different engineering behaviour due to differences in grading and weathering history. These observations support the present study, which evaluates the particle size distribution of residual soils collected from the Tanjung Dua Belas and Air Hitam landfill sites to determine whether their grading characteristics satisfy the engineering characteristics commonly recommended for landfill liner materials.

2.2.5 Atterberg Limit

The Atterberg limits are widely used to evaluate the consistency and plasticity characteristics of fine-grained soils and are considered important indicators of their engineering behaviour in landfill liner applications. Previous landfill liner studies have consistently reported that soils possessing moderate plasticity generally exhibit superior hydraulic barrier performance because sufficient plasticity promotes particle bonding, reduces pore continuity and enhances sealing after compaction. Daniel (1993) reported that soils used as compacted landfill liners commonly exhibit Plasticity Index values ranging from approximately 10% to 30%, while the Liquid Limit generally exceeds 20–30%, with many successful compacted liner soils exhibiting Liquid Limit values between 30% and 60%. These plasticity characteristics provide adequate workability during construction while maintaining favourable hydraulic barrier performance after compaction. Similarly, Rowe et al. (2012) emphasised that soils with moderate plasticity are more capable of achieving low hydraulic conductivity and maintaining long-term barrier performance than soils with either very low or excessively high plasticity. Although no specific Malaysian standard prescribes numerical Atterberg limit requirements for compacted soil liners, these internationally recognised engineering recommendations are widely adopted in landfill engineering and provide an appropriate benchmark for evaluating the suitability of residual soils investigated in the present study. Yamusa et al. (2022) investigated the geotechnical properties of tropical residual soils for sustainable landfill applications by evaluating their particle size distribution, Atterberg limits, compaction characteristics and engineering suitability. Their study reported that residual soils with moderate to high Plasticity Index values generally developed denser soil fabrics after compaction, resulting in lower hydraulic conductivity and improved resistance to leachate migration. The authors concluded that plasticity characteristics are among the principal engineering properties that should be considered when evaluating residual soils as landfill liner materials, as the investigated soils generally satisfied the Plasticity Index range commonly recommended for compacted landfill liners. These findings support the present study, where Atterberg limits are determined to assess the suitability of residual soils from the Tanjung Dua Belas and Air Hitam landfill sites.

The significance of plasticity has also been demonstrated through studies involving other fine-grained soils commonly used as hydraulic barriers. Zarime et al.

(2023) investigated the compaction and hydraulic conductivity behaviour of high-plasticity marine clay for landfill liner applications by examining its index properties, compaction response and hydraulic performance. Their study reported Plasticity Index values ranging from 20.15% to 34.22%, while the corresponding Liquid Limit values exceeded the minimum range commonly recommended for landfill liner materials. These values fall within or slightly exceed the engineering recommendations proposed by Daniel (1993), indicating favourable plasticity characteristics for hydraulic barrier applications for compacted landfill liner materials, classifying the material as highly plastic clay under the Unified Soil Classification System (USCS). The authors found that the high plasticity of marine clay promoted improved particle bonding and reduced pore continuity after compaction, contributing to lower hydraulic conductivity suitable for landfill liner applications. Although the present study focuses on tropical residual soils rather than marine clay, these findings demonstrate the beneficial influence of moderate to high plasticity on hydraulic barrier performance and provide a useful benchmark for evaluating the Plasticity Index of the investigated residual soils.

The engineering importance of the Plasticity Index has also been highlighted in Malaysian studies. Ibrahim et al. (2012) investigated the relationship between Plasticity Index and Compression Index of soils collected from Perlis by performing laboratory Atterberg limits and consolidation tests. Their study demonstrated that soils with higher Plasticity Index values generally exhibited greater compressibility and stronger water-retention characteristics, indicating that plasticity provides valuable information regarding the engineering behaviour of fine-grained soils. The authors concluded that the Plasticity Index is an effective indicator for evaluating soil behaviour and should be considered together with other physical properties during geotechnical assessment. These findings reinforce the importance of determining Atterberg limits in the present study, where plasticity characteristics are evaluated alongside particle size distribution, particle density and compaction behaviour to assess the engineering suitability of residual soils for landfill liner applications.

Table 2.2
Atterberg Limits Values of Malaysian Residual Soils (Mohamed et al., 2024)

Researcher	Location	Plasticity Index (%)	Liquid Limit (%)	Plastic Limit (%)
Mohamed	UTM Dusun, JB	27	64	37

Zolkepli	Pahang Matriculation	39	70	31
Ishak	UTM, JB	32	71	39
Salih	UTM, JB	25.6	68.4	42.8
Duraisamy	Gambang, Pahang	21.5	47	24.5
Tan and Yew	Kg. Awah, Pahang	15	79	63.5
Taha	Cheras, Kuala Lumpur	33.6	67.8	34.2

The data presented in Table 2.2 indicate that Malaysian residual soils generally exhibit Plasticity Index values ranging from approximately 15% to 39%, reflecting moderate to high plasticity depending on the degree of weathering and parent material. Most of the reported soils satisfy or slightly exceed the Plasticity Index range of approximately 10–30% commonly recommended for compacted landfill liner materials, while all reported Liquid Limit values are considerably higher than the minimum recommended value of approximately 20–30%. These observations indicate that the investigated Malaysian residual soils generally possess sufficient plasticity and workability to achieve favourable compaction characteristics and hydraulic barrier performance after proper moisture control. These observations suggest that the investigated residual soils possess sufficient plasticity to promote favourable compaction characteristics and reduced hydraulic conductivity after compaction. Nevertheless, the variability observed among the reported locations demonstrates that plasticity alone cannot be used to determine liner suitability, as hydraulic performance also depends on particle size distribution, compaction behaviour and moisture condition. These findings provide an important engineering benchmark for evaluating the Atterberg limits of the residual soils collected from the Tanjung Dua Belas and Air Hitam landfill sites in the present study.

2.2.6 Shrinkage Limit

The Shrinkage Limit (SL) is an important index property used to describe the volumetric stability of fine-grained soils during drying. It represents the moisture content at which further loss of water no longer results in a reduction in soil volume, making it an important parameter for evaluating the susceptibility of soils to shrinkage and desiccation cracking (Das et al., 2018). Although shrinkage limit is not specified as a direct design criterion for landfill liners, previous studies have consistently recognised

it as an important indicator of the long-term durability of compacted hydraulic barriers because excessive shrinkage may lead to cracking and deterioration of barrier integrity.

The significance of shrinkage behaviour has been demonstrated in previous landfill liner studies. Oluwapelumi et al. (2015) investigated the engineering behaviour of compacted natural soils proposed for landfill liner applications by evaluating their index properties, compaction characteristics and hydraulic performance. Their study reported that soils exhibiting favourable shrinkage behaviour maintained a more continuous soil fabric after drying, thereby reducing the formation of preferential flow paths that could increase hydraulic conductivity. Similarly, Hobbs et al. (2019) reviewed the shrink–swell behaviour of clay soils under repeated environmental drying and wetting cycles and concluded that desiccation cracking is one of the primary factors contributing to the long-term deterioration of compacted clay liners. Their findings demonstrated that repeated wetting–drying cycles enlarge crack networks and increase pore connectivity, resulting in higher hydraulic conductivity and reduced barrier efficiency over time. These observations indicate that shrinkage behaviour should be evaluated together with compaction and hydraulic conductivity when assessing the long-term performance of landfill liner materials.

Previous studies have also demonstrated that shrinkage behaviour is influenced by both soil composition and compaction conditions. Onyelowe et al. (2021) investigated the shrinkage behaviour of compacted clay modified with rice husk ash and lime by performing laboratory shrinkage and strength tests under different stabilisation conditions. Their study reported a shrinkage limit of approximately 12.2% for the treated soil and concluded that shrinkage behaviour is governed by mineral composition, moisture condition and soil structure rather than by shrinkage limit alone. The authors further showed that improved compaction and appropriate material composition reduced volumetric shrinkage and enhanced resistance to desiccation cracking. Although the present study focuses on untreated tropical residual soils, these findings demonstrate that shrinkage characteristics play an important role in maintaining the integrity of compacted soil liners and should therefore be considered alongside particle size distribution, plasticity, compaction behaviour and hydraulic conductivity when evaluating the suitability of residual soils for landfill liner applications.

2.3 Compaction Behaviour of Soil Liners

Compaction is one of the most important processes in landfill liner construction because it directly influences the engineering performance and long-term integrity of compacted soil barriers. Unlike conventional earthworks, where compaction is primarily intended to improve bearing capacity and shear strength, the principal objective of compaction in landfill liner systems is to reduce hydraulic conductivity by producing a dense soil structure with minimal interconnected voids. As soil particles are compacted under mechanical effort, air voids decrease, particle contacts increase and the continuity of pore channels is reduced, thereby restricting the movement of water and leachate through the compacted liner. Kodikara et al. (2018) reviewed the historical development and recent advances in soil compaction by examining the effects of compactive effort, moisture condition and soil structure on engineering performance. Their review concluded that appropriate compaction improves particle packing efficiency, reduces void ratio and enhances the overall hydraulic performance of compacted soils. These findings demonstrate that compaction is a fundamental factor governing the effectiveness of landfill liners and provide the engineering basis for evaluating the compaction behaviour of the residual soils investigated in the present study.

The hydraulic performance of compacted soil liners depends not only on the degree of compaction achieved but also on maintaining appropriate moisture conditions during construction. Previous studies have shown that soils compacted under controlled moisture conditions develop denser soil fabrics with lower pore connectivity, resulting in reduced hydraulic conductivity. Matthews et al. (2010) investigated the influence of soil compaction on porosity, water retention and saturated hydraulic conductivity by combining laboratory measurements with numerical simulations. Their study demonstrated that increasing dry density reduced pore volume and improved pore continuity, while compaction performed near the optimum moisture condition promoted more efficient particle rearrangement and minimised the formation of macropores. Similarly, Shaker (2017) evaluated the hydraulic performance of compacted clay liners by investigating the influence of moulding water content and dry density on hydraulic conductivity behaviour. The study reported that soils compacted close to the optimum moisture condition consistently exhibited lower hydraulic conductivity because improved particle contact reduced interconnected flow paths within the compacted soil

matrix. These findings demonstrate that proper moisture control during compaction is equally as important as achieving adequate density and support the evaluation of compaction characteristics undertaken in the present study.

Engineering specifications adopted for landfill liner construction generally express compaction requirements as a percentage of the laboratory Maximum Dry Density rather than prescribing a fixed dry density value because the achievable dry density varies according to soil mineralogy, grading and weathering characteristics. The Crookwell Landfill Detailed Design Technical Specification developed by Roberts (2017) recommends that compacted soil liners achieve at least 95% of the Standard Proctor Maximum Dry Density, while the moulding water content should be maintained between the optimum moisture content and approximately 3% wet of optimum to achieve the design hydraulic conductivity requirement of 1×10^{-7} cm/s. Although this specification was developed for an engineered landfill in Australia, the compaction criteria are consistent with internationally recognised landfill liner practices reported by Benson et al. (1999) and Rowe et al. (2012). Malaysia currently does not prescribe a separate national compaction specification specifically for natural residual soil liners; therefore, internationally accepted engineering guidelines are widely adopted as technical references when evaluating landfill liner materials. Benson et al. (1999) evaluated the field performance of compacted clay liners constructed at several landfill sites and demonstrated that achieving the specified percentage compaction was more important than achieving a particular dry density value because hydraulic conductivity was governed primarily by the quality of compaction and moisture control. Their findings indicate that landfill liner performance should be assessed based on the relative degree of compaction rather than an absolute Maximum Dry Density value, making laboratory compaction testing essential for evaluating the suitability of natural soils.

Compaction quality also governs several long-term engineering properties that influence the serviceability and durability of landfill liners. In addition to reducing hydraulic conductivity, well-compacted soils exhibit improved resistance to settlement, deformation, desiccation cracking and long-term structural instability under sustained landfill loading. Poorly compacted soils retain larger air voids and more continuous pore channels, increasing the likelihood of differential settlement and crack formation during repeated wetting and drying cycles, which may subsequently increase hydraulic conductivity. Consequently, landfill liner performance depends not only on hydraulic behaviour but also on maintaining adequate mechanical stability throughout the

operational life of the landfill. The close relationship between compaction quality and hydraulic barrier performance provides the engineering justification for evaluating the compaction characteristics of residual soils before assessing their hydraulic conductivity. Therefore, laboratory determination of the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) using the Standard Proctor Compaction Test forms an essential component of landfill liner assessment and is discussed in the following section.

2.3.1 Standard Proctor Compaction Test

The Standard Proctor Compaction Test is one of the most widely adopted laboratory methods for evaluating the compaction characteristics of soils and is commonly used to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) required for engineering design and construction. The test is standardised under BS 1377-4 (1990) and involves compacting soil at various moisture contents using a specified compactive effort to establish the moisture–density relationship. The resulting compaction curve provides the MDD, which represents the highest dry density achievable under the applied compactive effort, and the OMC, which represents the moisture content at which maximum soil densification occurs. These parameters are fundamental for field compaction control because they establish the target conditions required to achieve the desired engineering performance of compacted soils.

The Standard Proctor test has been widely adopted in landfill engineering because it closely represents the compactive effort commonly applied during the construction of compacted soil liners. Apolonio et al. (2019) investigated the compaction characteristics of fine-grained soils using different Proctor compaction methods to evaluate the influence of compactive effort on soil density and engineering behaviour. Their study demonstrated that the Standard Proctor test provides reliable and reproducible estimates of MDD and OMC for fine-grained soils and is particularly suitable for evaluating soils intended for environmental containment systems. Similarly, Chen et al. (2021) examined the interpretation of moisture–density relationships of engineered soils by analysing compaction curves obtained from laboratory testing. The authors reported that the moisture–density curve provides valuable information on particle rearrangement, pore structure development and soil compressibility, making the

Standard Proctor test an effective tool for predicting field compaction behaviour. These findings support the use of the Standard Proctor test in the present study, where the compaction behaviour of residual soils is evaluated to determine their suitability as landfill liner materials.

Several studies have demonstrated that the Standard Proctor test is particularly appropriate for evaluating tropical residual and fine-grained soils because these materials exhibit significant moisture sensitivity during compaction. Rahman et al. (2020) investigated the influence of moisture control on the compaction behaviour of tropical residual soils by examining soils compacted under different moulding moisture conditions. Their study found that small variations in moisture content produced noticeable changes in dry density, highlighting the importance of accurately determining the OMC before field compaction. Likewise, Sharma et al. (2022) evaluated the effects of moisture variation on the compaction characteristics and engineering behaviour of fine-grained soils and reported that compaction performed near the OMC consistently produced higher dry densities and more uniform soil fabrics than compaction under excessively dry or wet conditions. These findings demonstrate that accurate determination of the moisture–density relationship is essential for achieving effective hydraulic barrier performance and provide direct support for the methodology adopted in the present study.

Although both the Standard Proctor and Modified Proctor tests are available for laboratory compaction assessment, the Standard Proctor method is generally preferred for evaluating natural soils intended for landfill liner construction. The Modified Proctor test applies a substantially higher compactive effort and is primarily used for heavily loaded infrastructure such as highways, airports and pavements. In contrast, compacted soil liners are typically constructed in thin lifts using conventional earthmoving equipment that produces compactive efforts more comparable to the Standard Proctor method. Rowe et al. (2012) emphasised that laboratory compaction procedures used for landfill liner evaluation should represent realistic field construction practices to ensure that laboratory hydraulic conductivity values accurately reflect field performance. Similarly, Benson et al. (1999) reported that successful compacted clay liners were commonly designed and quality-controlled using Standard Proctor compaction parameters because they more closely represented field compaction conditions adopted during landfill construction. Consequently, the Standard Proctor test provides an appropriate basis for determining the MDD and OMC of the residual soils

investigated in this study and for establishing the moisture conditions subsequently used in the hydraulic conductivity assessment.

2.3.2 Practical Considerations for Field Compaction of Soil Liners

Although the present study evaluates compaction behaviour under controlled laboratory conditions, understanding field compaction practices is important because the hydraulic performance achieved in the laboratory must ultimately be reproduced during landfill liner construction. In practice, achieving the laboratory-determined Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) is considerably more challenging due to variations in environmental conditions, material handling and construction procedures. Consequently, field compaction is discussed in this study to provide practical engineering context for interpreting the laboratory results rather than because field compaction testing was conducted.

During landfill liner construction, several factors influence the quality of field compaction, including rainfall, evaporation, ambient temperature, lift thickness, compaction equipment, soil variability and construction sequencing. These factors continuously affect the moisture content of the placed soil and may result in deviations from the target moisture condition established during laboratory compaction testing. Houston (2020) discussed the influence of field moisture variability on engineered earthworks and reported that fluctuations in environmental conditions frequently alter the moisture content of compacted soils before adequate densification can be achieved. Similarly, the Transportation Research Board (2016) emphasised that proper field compaction requires continuous control of lift thickness, compactive effort and moisture condition to minimise variability in achieved dry density throughout the constructed liner.

To ensure that field compaction satisfies design requirements, quality assurance and quality control procedures are commonly implemented throughout landfill liner construction. These procedures include regular verification of in-situ density and moisture content using methods such as nuclear density gauges or sand-cone testing, together with continuous documentation of construction records. Roberts (2017) specified that field compaction should achieve at least 95% of the Standard Proctor Maximum Dry Density while maintaining the moulding moisture content within the specified tolerance range to satisfy the target hydraulic conductivity requirement.

Similarly, Machado (2010) investigated the geotechnical behaviour of tropical soils used in landfill applications and reported that non-uniform field compaction could produce localised variations in density and pore structure, increasing the possibility of preferential flow paths through compacted liners. (Roberts, 2017).

2.3.3 Moisture Content Tolerance

Although the Optimum Moisture Content (OMC) determined from laboratory compaction testing represents the condition at which the maximum dry density is achieved, maintaining the exact OMC during field construction is seldom practical because soil moisture continuously changes due to rainfall, evaporation, material handling and construction delays. Consequently, landfill liner construction commonly adopts an allowable moisture tolerance around the OMC to accommodate field variability while maintaining satisfactory hydraulic performance. The Crookwell Landfill Detailed Design Technical Specification developed by Roberts (2017) specifies that compacted soil liners should be constructed within the range of approximately 0% to +3% of the OMC while achieving at least 95% of the Standard Proctor Maximum Dry Density. Similarly, Rowe et al. (2012) emphasised that moisture control during field compaction should be maintained within a narrow range around the OMC because reproducing laboratory moisture conditions precisely in the field is rarely achievable under practical construction environments. More recently, Tan et al. (2023) investigated the hydraulic performance of compacted clay liners by preparing laboratory specimens at 1% wet of the optimum moisture content, following the recommendations proposed by Benson et al. (1994) for landfill liner construction. Their study confirmed that compaction slightly wet of optimum produced a more uniform soil fabric and enhanced hydraulic barrier performance. Although no specific Malaysian guideline prescribes a fixed moisture tolerance for compacted soil liners, these internationally accepted engineering recommendations are widely adopted as practical guidance and provide the basis for the moisture conditions evaluated in the present study.

The influence of moisture content on hydraulic conductivity has been extensively investigated in landfill liner research. Daniel and Benson (1990) examined the relationship between moulding moisture content, dry density and hydraulic conductivity of compacted clay liners by performing laboratory hydraulic conductivity

testing under different compaction conditions. Their study demonstrated that soils compacted at or slightly wet of the OMC consistently exhibited lower hydraulic conductivity because the additional moisture promoted better particle lubrication, facilitated particle rearrangement and produced a denser soil fabric with fewer interconnected macropores. Similar observations were reported by Benson et al. (2014), who investigated the hydraulic conductivity of compacted clay liners under different compaction moisture conditions and found that wet-of-optimum compaction consistently generated lower hydraulic conductivity value than dry-of-optimum compaction, even when similar dry densities were achieved. Likewise, Osinubi et al. (2012) evaluated the acceptable compaction zone for lateritic soil–bentonite mixtures proposed as landfill liners and reported that the lowest hydraulic conductivity was consistently achieved when soils were compacted approximately 2% to 4% wet of the OMC, confirming that slight wet-side compaction provides more effective hydraulic barrier performance. More recently, Thangamani (2024) investigated the influence of moisture state on the hydraulic conductivity behaviour of compacted soils and confirmed that increasing moisture content from dry-of-optimum towards wet-of-optimum progressively reduced hydraulic conductivity because improved particle orientation and pore closure limited the continuity of flow channels. These studies collectively demonstrate that compaction slightly wet of the OMC provides more favourable hydraulic barrier performance than compaction on the dry side of optimum.

Conversely, soils compacted dry of the OMC generally retain larger and more continuous air-filled voids because insufficient moisture limits particle lubrication and restricts particle rearrangement during compaction. Bowders and Othman (1993) investigated the influence of compaction moisture on the hydraulic conductivity of compacted clay liners and reported that soils compacted under dry conditions developed larger interconnected macropores, resulting in higher hydraulic conductivity than soils compacted near or above the OMC. Similar conclusions were reported by Mbarki et al. (2023), who evaluated the effect of compaction moisture content on the hydraulic conductivity of compacted clay liners and found that dry-side compaction produced more heterogeneous soil fabrics with greater pore connectivity, leading to increased hydraulic conductivity under hydraulic loading. These findings indicate that moisture condition during compaction is one of the principal factors controlling the long-term hydraulic performance of compacted landfill liners and should therefore be carefully controlled during construction.

2.4 Hydraulic Conductivity of Compacted Soils

Hydraulic conductivity is one of the most important engineering parameters used to evaluate the performance of compacted soil liners because it governs the movement of water and leachate through the soil mass. In landfill engineering, the primary function of a compacted soil liner is to minimise the migration of contaminants into the surrounding soil and groundwater, making hydraulic conductivity the principal indicator of barrier effectiveness. Hydraulic conductivity describes the ease with which a fluid flows through interconnected pore spaces under a hydraulic gradient and is controlled by both the physical characteristics of the soil and the properties of the permeating fluid. Das et al. (2018) explained that hydraulic conductivity is influenced by factors including particle size distribution, pore geometry, void ratio, degree of saturation and fluid viscosity, all of which collectively determine the continuity of flow paths within the soil structure. These characteristics are particularly important for landfill liner applications because even small changes in soil fabric may produce significant variations in hydraulic performance. Consequently, hydraulic conductivity has become the principal design parameter adopted worldwide for evaluating the suitability of natural soils as hydraulic barrier materials.

The hydraulic conductivity of compacted soils is governed by the combined interaction of soil characteristics, compaction conditions and applied stress rather than by any single engineering property. Mesri and Olson (2014) investigated the mechanisms controlling water flow through clay soils and concluded that hydraulic conductivity is strongly influenced by pore size distribution, clay mineral arrangement and the continuity of interconnected voids. Similarly, Ghanbarian et al. (2016) developed a universal scaling relationship for soil hydraulic conductivity by analysing a wide range of soil types and reported that changes in pore structure and soil fabric exert greater influence on hydraulic conductivity than individual index properties alone. These findings demonstrate that hydraulic conductivity should be interpreted as a response to the combined effects of soil physical properties and compaction behaviour rather than as an isolated material property. This concept forms the basis of the present study, which evaluates how residual soil characteristics influence hydraulic conductivity under controlled laboratory conditions.

2.4.1 Modified Oedometer Test for Hydraulic Conductivity Evaluation

Hydraulic conductivity of compacted soils can be determined using several laboratory methods, including the constant head test, falling head test, triaxial hydraulic conductivity test and oedometer-based hydraulic conductivity test. The selection of an appropriate testing method depends on the hydraulic conductivity range of the soil, specimen condition and the engineering application under investigation. Constant head and falling head tests are generally suitable for coarse-grained soils with relatively high hydraulic conductivity, whereas triaxial hydraulic conductivity testing enables hydraulic conductivity to be evaluated under controlled stress conditions. However, for compacted fine-grained soils used as landfill liners, hydraulic conductivity is highly dependent on changes in void ratio and soil structure caused by increasing vertical stress. Consequently, laboratory methods capable of evaluating hydraulic conductivity under loading conditions representative of landfill environments are considered more appropriate than conventional hydraulic conductivity tests. Shackelford et al. (2016) reviewed the hydraulic conductivity testing of low- hydraulic conductivity barrier materials and emphasised that hydraulic conductivity should be evaluated under representative stress and saturation conditions because changes in effective stress significantly influence hydraulic conductivity. These findings support the need for stress-dependent laboratory testing when assessing compacted soils intended for landfill liner applications.

The modified oedometer hydraulic conductivity test has therefore become an increasingly adopted method for evaluating the hydraulic conductivity of compacted fine-grained soils under one-dimensional compression. The test is adapted from the conventional consolidation test specified in BS 1377 Part 5 (1990), but unlike the traditional consolidation procedure, the applied vertical load is maintained throughout hydraulic conductivity measurement without unloading the specimen. This modification enables hydraulic conductivity to be determined continuously at different loading stages while simulating the progressive increase in overburden stress experienced by landfill liners during waste placement. The modified apparatus incorporates an external burette connected to the base porous stone through a hydraulic inlet, together with an outlet port for maintaining hydraulic head and sealing components that minimise leakage during testing. This configuration enables controlled falling-head hydraulic conductivity measurements to be conducted while the specimen

remains under constant vertical loading, thereby improving the representation of field conditions encountered in landfill liner systems. These modifications and testing procedures are described in the GeoStru technical guide for hydraulic conductivity testing using an oedometer cell.

Compared with conventional hydraulic conductivity tests, the modified oedometer method offers several practical advantages for evaluating low- hydraulic conductivity soils. Traditional falling head hydraulic conductivity tests generally determine only a single hydraulic conductivity value under one stress condition, requiring separate specimens or repeated testing if the influence of different loading levels is to be investigated. Because compacted clay and residual soils exhibit very low hydraulic conductivity, these conventional tests are often time-consuming due to the slow movement of water through the soil specimen. In contrast, the modified oedometer allows hydraulic conductivity to be measured sequentially under progressively increasing vertical loads using the same specimen, thereby reducing specimen preparation while providing additional information on stress-dependent hydraulic behaviour. Sawicki and Stróżyk (2009) proposed a modified oedometer approach for estimating hydraulic conductivity directly from one-dimensional consolidation behaviour and demonstrated that the technique produced hydraulic conductivity values comparable to those obtained from conventional laboratory hydraulic conductivity tests while significantly improving testing efficiency.

The suitability of the modified oedometer for landfill liner investigations has been demonstrated by several recent studies. Hamdi et al. (2013) investigated the stress-dependent hydraulic conductivity of compacted clayey soils and reported that hydraulic conductivity decreased progressively with increasing vertical stress because compression reduced the void ratio and restricted pore connectivity within the soil structure. Similarly, Oluwapelumi et al. (2022) evaluated hydraulic conductivity using a modified oedometer hydraulic conductivity method and concluded that the technique provides an effective means of assessing stress-dependent hydraulic behaviour under loading conditions representative of landfill environments. These findings support the methodology adopted in the present study, where hydraulic conductivity is determined using a modified oedometer under progressively increasing vertical loads to simulate the stress conditions experienced by compacted residual soil liners beneath municipal solid waste.

2.4.2 Hydraulic Conductivity Requirements for Landfill Liners

Hydraulic conductivity is the principal engineering parameter used to evaluate the performance of compacted soil liners because it determines the ability of the liner to minimise the migration of leachate into the surrounding soil and groundwater. For landfill containment systems, the compacted soil liner must maintain sufficiently low hydraulic conductivity throughout its service life to prevent contaminant transport and protect the surrounding environment. Consequently, internationally recognised landfill design guidelines specify a maximum allowable hydraulic conductivity for compacted soil liners. The United States Environmental Protection Agency (USEPA) recommends that compacted clay liners used in municipal solid waste landfills should achieve a maximum hydraulic conductivity of 1×10^{-7} cm/s (USEPA, 1993). This criterion has subsequently been adopted and referenced in numerous international landfill engineering publications, including Rowe et al. (2012) and Shackelford et al. (2016), and is widely accepted as the benchmark for evaluating the hydraulic performance of compacted soil liners. Although Malaysia does not currently prescribe a separate numerical hydraulic conductivity limit specifically for natural compacted soil liners, landfill design practices implemented by the Department of Environment (DOE) and the National Solid Waste Management Department (JPSPN/KPKT) generally follow internationally accepted engineering recommendations based on the USEPA criterion. Therefore, the hydraulic conductivity requirement of 1×10^{-7} cm/s is adopted throughout the present study as the engineering benchmark for assessing the suitability of residual soils as landfill liner materials.

Numerous studies have demonstrated that properly compacted fine-grained soils are capable of satisfying this hydraulic conductivity requirement when appropriate material selection and compaction control are achieved. Shackelford et al. (2016) reviewed the hydraulic performance of soil-bentonite barrier systems by evaluating laboratory and field hydraulic conductivity data from various engineered liner materials. Their review concluded that compacted fine-grained soils with adequate fines content and plasticity consistently achieved hydraulic conductivity values below 1×10^{-7} cm/s because bentonite swelling and improved particle bonding reduced pore continuity and restricted seepage. Similarly, Cortellazzo and Rizzo (2020) critically reviewed the design and construction of compacted soil liners and reported that well-compacted clay liners generally exhibit hydraulic conductivity values ranging between

1×10^{-9} and 1×10^{-7} cm/s, depending on mineralogy, moisture condition and dry density. Their study emphasised that hydraulic conductivity is governed not only by soil type but also by the quality of compaction and moisture control during liner construction.

The application of tropical residual soils as landfill liner materials has also been widely investigated because these soils are naturally abundant throughout tropical regions and represent a cost-effective alternative to imported clay materials. Unlike conventional compacted clay liners, residual soils are formed through prolonged in-situ weathering of parent rock and therefore exhibit greater variability in particle size distribution, mineral composition and degree of weathering. As a result, their hydraulic behaviour cannot be generalised and requires site-specific evaluation. Adeyemo and Bello (2024) investigated the hydraulic barrier performance of compacted residual soils by evaluating their compaction characteristics and hydraulic conductivity under controlled laboratory conditions. Their study reported hydraulic conductivity values ranging from approximately 5.14×10^{-8} to 8.73×10^{-8} cm/s, demonstrating that properly compacted residual soils were capable of satisfying the recommended landfill liner criterion. Similarly, Kassim et al. (2018) investigated the engineering behaviour of tropical residual soils for landfill barrier applications and concluded that residual soils possessing adequate fines content, moderate plasticity and appropriate moisture-controlled compaction exhibited hydraulic conductivity comparable to conventional compacted clay liners. More recently, Lat et al. (2023) evaluated kenaf fibre–marine clay mixtures as landfill liner materials and highlighted that the hydraulic performance of tropical fine-grained soils depends primarily on soil fabric development during compaction rather than soil classification alone. These findings demonstrate that residual soils can provide hydraulic barrier performance comparable to conventional clay liners when suitable physical characteristics and compaction conditions are achieved.

The hydraulic conductivity performance of other fine-grained soils has also been extensively reported in the literature. Rahman et al. (2013) investigated the hydraulic conductivity of Malaysian marine clay using falling-head hydraulic conductivity testing and reported hydraulic conductivity values of approximately 1.77×10^{-7} cm/s, indicating that hydraulic performance is highly dependent on compaction quality and moisture condition. Likewise, Lu et al. (2017) evaluated compacted silty clay under controlled laboratory conditions and reported hydraulic conductivity values of

approximately 1.10×10^{-7} cm/s, demonstrating that well-compacted silty clay can approach the hydraulic conductivity criterion recommended for landfill liners. More recently, Zarime et al. (2023) investigated the compaction and hydraulic conductivity behaviour of high-plasticity marine clay and demonstrated that increasing fines content and improved particle bonding reduced hydraulic conductivity to values between 3.10×10^{-8} and 7.80×10^{-8} cm/s. These studies collectively indicate that hydraulic conductivity is controlled by the combined effects of soil mineralogy, particle size distribution, compaction quality and moisture condition rather than by soil classification alone.

A summary of hydraulic conductivity values reported for soils commonly investigated as landfill liner materials is presented in Table 2.3. The reported values indicate that many compacted fine-grained soils, including tropical residual soils, are capable of satisfying the internationally accepted hydraulic conductivity criterion when appropriate material selection and compaction control are achieved. Nevertheless, the variability observed among different soil types highlights the importance of conducting site-specific hydraulic conductivity assessments before locally available residual soils are adopted as natural landfill liner materials.

Table 2.3
Summary of Hydraulic Conductivity Values Reported From Previous Studies

Researcher	Soil Type	Hydraulic Conductivity (cm/s)	($\leq 1 \times 10^{-7}$ cm/s)
Cortellazzo & Rizzo (2020)	Compacted clay liner	$1 \times 10^{-9} - 1 \times 10^{-7}$	Yes
Adeyemo & Bello (2024)	Residual soil	$5.14 \times 10^{-8} - 8.73 \times 10^{-8}$	Yes
Rahman et al. (2013)	Marine clay	1.77×10^{-7}	Borderline
Lu et al. (2017)	Silty clay	1.10×10^{-7}	Borderline
Zarime et al. (2023)	Marine clay	$3.10 \times 10^{-8} - 7.80 \times 10^{-8}$	Borderline

2.4.3 Influence of Soil Type on Hydraulic Conductivity

Hydraulic conductivity is strongly influenced by soil type because differences in mineral composition, particle size distribution, soil fabric and pore structure govern

the movement of water through compacted soils. Consequently, selecting an appropriate soil material is one of the most important considerations in landfill liner design. Various natural and engineered materials have been investigated for landfill liner applications, including compacted natural clays, tropical residual soils, marine clays, bentonite-amended soils and geosynthetic clay liners. Each material exhibits distinct hydraulic characteristics depending on its physical properties, mineralogy and response to compaction, resulting in varying levels of hydraulic barrier performance.

Among these materials, tropical residual soils have received increasing attention because they are widely available in many tropical countries, including Malaysia, and therefore represent a potentially economical alternative to imported clay materials. Unlike conventional sedimentary clays, residual soils are formed through prolonged in-situ weathering of parent rock, resulting in soils with highly variable particle size distribution, mineral composition and engineering behaviour. Consequently, hydraulic conductivity of residual soils is influenced not only by clay content but also by the degree of weathering, soil fabric and compaction condition. Machado (2010) investigated the engineering behaviour of tropical residual soils for landfill applications by evaluating their compaction characteristics and hydraulic performance. The study reported that residual soils containing approximately 30–50% fine particles with moderate plasticity developed dense soil fabrics after compaction and achieved hydraulic conductivity values within the range generally accepted for landfill liner applications. Similarly, Kassim et al. (2018) evaluated tropical residual soils as natural landfill barrier materials and concluded that residual soils possessing adequate fines content and moisture-controlled compaction exhibited hydraulic conductivity comparable to compacted natural clay liners. More recently, Adeyemo and Bello (2024) investigated compacted residual soils as hydraulic barrier materials and reported hydraulic conductivity values ranging from 5.14×10^{-8} to 8.73×10^{-8} cm/s, demonstrating that properly compacted residual soils are capable of satisfying the recommended landfill liner criterion. These findings indicate that, despite their inherent geological variability, tropical residual soils can provide hydraulic barrier performance comparable to conventional compacted clay liners when appropriate material selection and compaction procedures are adopted.

Compacted natural clays remain one of the most commonly used landfill liner materials because their high clay mineral content, low void ratio and fine pore structure naturally restrict water movement. The presence of plate-like clay minerals increases

the tortuosity of seepage paths and promotes stronger interparticle bonding after compaction, resulting in consistently low hydraulic conductivity. Shackelford et al. (2016) reviewed the hydraulic performance of compacted clay barrier systems and concluded that fine-grained soils possessing sufficient plasticity and adequate fines content consistently achieved lower hydraulic conductivity than coarse-grained soils due to reduced pore continuity. Similarly, Cortellazzo and Rizzo (2020) reported that well-compacted clay liners commonly achieve hydraulic conductivity values between 1×10^{-9} and 1×10^{-7} cm/s, provided that appropriate moisture control and compaction quality are maintained during construction.

Peat soils, in contrast, generally exhibit poor hydraulic barrier performance because their fibrous structure, high organic matter content and highly compressible nature create large interconnected voids that promote water flow. Unlike mineral soils, peat undergoes substantial long-term settlement and decomposition, which may lead to cracking and increased hydraulic conductivity after construction. Hayashi and Hatakeyama (2020) investigated the hydraulic conductivity characteristics of peat soils using falling-head hydraulic conductivity tests and reported hydraulic conductivity values of approximately 1.7×10^{-6} cm/s, considerably higher than the hydraulic conductivity criterion recommended for landfill liners. The authors concluded that untreated peat is unsuitable for landfill liner applications unless significant stabilisation or modification is undertaken to improve its hydraulic and mechanical performance.

Another material widely adopted in landfill engineering is the bentonite-amended soil. Bentonite is commonly incorporated into natural soils because sodium bentonite possesses a high swelling capacity that enables clay particles to expand upon hydration, filling interconnected pore spaces and substantially reducing hydraulic conductivity. Shackelford et al. (2016) reported that bentonite-amended soils consistently achieved very low hydraulic conductivity due to the formation of a dense swelling clay matrix that effectively restricted seepage. However, Özçoban (2022) investigated the influence of landfill leachate on compacted liner materials and demonstrated that prolonged exposure to chemically aggressive leachate reduced the swelling potential of bentonite through cation exchange, resulting in increased hydraulic conductivity over time. These findings indicate that although bentonite-amended soils provide excellent initial sealing performance, their long-term hydraulic behaviour may depend on the chemical characteristics of the permeating leachate.

2.4.4 Influence of Moisture Condition on Hydraulic Conductivity

The influence of moisture condition on hydraulic conductivity has been widely investigated for compacted clay liners and other fine-grained soils. Bowders and Othman (1993) investigated the relationship between moulding moisture condition and hydraulic conductivity of compacted clay liners by preparing specimens on both the dry and wet sides of the Optimum Moisture Content (OMC). Their study demonstrated that soils compacted dry of the OMC developed larger interconnected macropores because insufficient water limited particle lubrication and restricted particle rearrangement during compaction. Consequently, hydraulic conductivity increased due to greater pore continuity within the compacted soil. Conversely, specimens compacted wet of the OMC formed a denser and more homogeneous soil fabric with fewer interconnected flow paths, resulting in significantly lower hydraulic conductivity. These findings established that moulding moisture condition is one of the principal factors controlling the hydraulic performance of compacted landfill liners, even when identical compaction effort is applied.

Recent studies have further demonstrated that slight variations in moulding moisture content can substantially influence hydraulic conductivity. Adeyemo and Bello (2024) investigated the hydraulic barrier performance of compacted residual soils under four moulding moisture conditions, namely 2% dry of OMC, OMC, 2% wet of OMC and 4% wet of OMC. Their results showed that hydraulic conductivity decreased progressively from the dry side towards 2% wet of the OMC, where the lowest hydraulic conductivity values of approximately 2.0×10^{-8} to 2.6×10^{-8} cm/s were obtained, depending on the soil type investigated. However, when the moulding moisture content increased to 4% wet of the OMC, hydraulic conductivity increased markedly to approximately 3.5×10^{-8} to 4.9×10^{-8} cm/s. The authors attributed this increase to excessive moulding water, which reduced compaction efficiency and produced a less stable soil structure with increased pore continuity. These findings demonstrate that although slight wet-of-optimum compaction improves hydraulic barrier performance, excessive moisture may adversely affect hydraulic conductivity.

Similar observations were reported by Thangamani (2024), who investigated the hydraulic conductivity behaviour of compacted fine-grained soils prepared under dry-of-optimum, optimum and wet-of-optimum moisture conditions. The study demonstrated that hydraulic conductivity progressively decreased as moulding moisture

content approached the wet side of the optimum because additional moisture promoted particle lubrication, improved particle orientation and reduced interconnected pore spaces. Likewise, Osinubi et al. (2012) evaluated the acceptable compaction zone for lateritic soil–bentonite mixtures proposed for landfill liner applications and reported that the lowest hydraulic conductivity was consistently achieved when specimens were compacted approximately 2% to 4% wet of the OMC, confirming that slight wet-side compaction produced the most effective hydraulic barrier performance. Furthermore, Tan et al. (2023) investigated compacted clay liners prepared under different moulding moisture conditions and similarly reported that specimens compacted slightly wet of the OMC consistently exhibited lower hydraulic conductivity than those compacted on the dry side because improved particle lubrication facilitated denser particle packing and reduced the continuity of seepage paths.

The findings reported by previous researchers also support current landfill construction practices. The Crookwell Landfill Detailed Design Technical Specification recommends that compacted soil liners be placed within approximately 0% to +3% of the OMC while achieving at least 95% of the Standard Proctor Maximum Dry Density (Roberts, 2017). This specification recognises that exact laboratory moisture conditions cannot always be maintained under field conditions because rainfall, evaporation and construction activities continuously influence soil moisture. Collectively, previous studies indicate that the optimum moisture range for hydraulic barrier performance generally lies slightly wet of the OMC, although the exact moisture tolerance depends on soil type, mineralogy, fines content, plasticity and compaction effort.

2.5 Relationship of Hydraulic Conductivity with Soil Characteristics

The relationship between soil characteristics and hydraulic conductivity has been widely investigated for compacted clays, residual soils and other fine-grained geomaterials. Albrecht et al. (2006) examined the hydraulic behaviour of compacted soils possessing different plasticity characteristics and mineral compositions and reported that hydraulic conductivity is governed by the interaction between soil gradation, plasticity and compaction condition rather than by individual soil properties alone. Similarly, Shackelford et al. (2016) reviewed numerous laboratory and field investigations involving compacted soil barrier systems and concluded that hydraulic conductivity is controlled by the combined effects of particle size distribution, fines

content, moisture condition and dry density, all of which influence pore continuity within the compacted soil matrix. These studies demonstrate that soil properties should be evaluated collectively because individual parameters are interdependent and contribute simultaneously to the development of hydraulic barrier performance.

The complexity of these relationships becomes more significant for tropical residual soils, whose engineering behaviour varies considerably depending on parent rock, mineralogical composition and degree of weathering. Rahardjo et al. (2013) investigated the engineering behaviour of tropical residual soils and reported that weathering processes substantially modify particle arrangement, mineral composition and pore structure, leading to considerable variability in hydraulic and mechanical behaviour even among soils of similar classification. More recently, Robinson et al. (2022) developed analytical models relating soil porosity, bulk density and hydraulic properties and demonstrated that hydraulic conductivity is strongly influenced by changes in pore structure resulting from variations in density and soil fabric. Their findings highlighted that hydraulic behaviour cannot be accurately interpreted from a single soil property because the interaction between density, pore geometry and particle arrangement governs fluid flow through compacted soils. These observations are particularly relevant to the present study because the investigated residual soils originate from different landfill sites and therefore exhibit different physical characteristics that may influence hydraulic conductivity.

2.5.1 Relationship of Particle Density with Hydraulic Conductivity

Several researchers have demonstrated that the influence of particle density on hydraulic conductivity is primarily associated with changes in soil microstructure. Kholodov et al. (2021) investigated the effects of mineralogy and particle density on pore connectivity in structured soils using laboratory hydraulic testing and microstructural observations. Their study showed that soils containing denser mineral assemblages developed more compact particle arrangements after compaction, resulting in lower pore connectivity and reduced hydraulic conductivity. However, the authors concluded that particle density alone was not the governing parameter, as hydraulic conductivity was controlled by the combined interaction between particle density, particle arrangement and soil fabric. These findings indicate that particle density

contributes indirectly to hydraulic performance through its influence on pore structure development.

Similar observations were reported by Fang et al. (2023), who investigated the influence of mineral composition and soil microstructure on the hydraulic conductivity behaviour of compacted residual soils. Using hydraulic conductivity testing together with microstructural characterisation, the authors reported that residual soils possessing denser mineral compositions produced smaller and less interconnected pore networks after compaction, resulting in lower hydraulic conductivity than soils containing more open soil fabrics. The study further demonstrated that hydraulic conductivity decreased as pore continuity was reduced, confirming that mineral composition and particle density influence hydraulic behaviour through changes in soil fabric rather than through particle density itself.

Quantitative relationships between soil structure and hydraulic conductivity have also been established through analytical modelling. Robinson et al. (2022) developed predictive relationships between porosity, bulk density and hydraulic conductivity using analytical modelling of compacted soils. Their study demonstrated that a reduction in porosity produced a corresponding reduction in hydraulic conductivity because fewer interconnected flow channels remained available for water movement. Likewise, Zhang et al. (2011) developed predictive equations for saturated hydraulic conductivity using measurable soil properties and reported that soils with lower void ratios consistently exhibited lower hydraulic conductivity regardless of soil type. These findings support the concept that hydraulic conductivity is governed primarily by pore geometry, while particle density contributes indirectly through its influence on soil packing efficiency and void ratio.

Evidence from compacted landfill liner studies further supports this relationship. Daniel and Trautwein (1993) investigated the hydraulic conductivity of compacted clay soils prepared under different density conditions and reported that increasing the dry density of compacted specimens significantly reduced hydraulic conductivity from the order of 10^{-7} cm/s to approximately 10^{-8} cm/s, owing to the reduction in interconnected voids created during compaction. Similarly, Benson et al. (2014) evaluated compacted clay liners under controlled laboratory conditions and found that specimens achieving greater particle packing and lower void ratios consistently produced hydraulic conductivity values below the commonly accepted landfill liner criterion of 1×10^{-7} cm/s. Although these studies primarily evaluated the influence of dry density rather than

particle density, they demonstrate the engineering mechanism through which particle density contributes to hydraulic performance by influencing the achievable packing arrangement during compaction.

2.5.2 Relationship of Plasticity and Shrinkage Characteristics with Hydraulic Conductivity

The relationship between plasticity and hydraulic conductivity has been extensively investigated in previous studies. Dolinar (2009) evaluated the hydraulic conductivity of saturated compacted clays possessing different Atterberg limits and developed empirical relationships between Plasticity Index and hydraulic conductivity. The study demonstrated that hydraulic conductivity decreased consistently with increasing Plasticity Index because soils with higher plasticity contained greater proportions of active clay minerals, producing smaller pore openings and more tortuous seepage paths. Hydraulic conductivity values decreased from approximately the order of 10^{-7} cm/s for soils with relatively low Plasticity Index to approximately 10^{-9} cm/s for highly plastic clays, illustrating the strong influence of plasticity on water movement through compacted soils. The author concluded that the Plasticity Index is one of the most reliable index properties for estimating hydraulic conductivity in fine-grained soils, making it an important parameter for landfill liner evaluation.

The beneficial influence of plasticity on hydraulic barrier performance has also been demonstrated in landfill engineering studies. Albrecht et al. (2006) investigated the hydraulic conductivity of compacted natural clay liners with varying plasticity characteristics and mineral compositions. Their laboratory hydraulic conductivity tests showed that soils possessing moderate to high Plasticity Index values consistently achieved hydraulic conductivity values below the commonly accepted landfill liner criterion of 1×10^{-7} cm/s, whereas soils with lower plasticity generally exhibited higher hydraulic conductivity because larger pore channels remained after compaction. Similarly, O'Kelly (2024) reviewed the influence of index properties on the hydraulic conductivity behaviour of fine-grained soils and concluded that moderate plasticity promotes improved particle bonding and more stable pore structures, thereby reducing hydraulic conductivity. However, the review also emphasised that excessively high plasticity may lead to greater shrinkage potential and volume instability during drying,

indicating that an appropriate balance between plasticity and shrinkage characteristics is required for long-term landfill liner performance.

Shrinkage characteristics also play an important role in controlling hydraulic conductivity because they influence the long-term integrity of compacted soil liners under repeated drying and wetting conditions. Hobbs et al. (2019) investigated the shrink–swell behaviour of clay soils and reported that soils exhibiting greater shrinkage potential were more susceptible to desiccation cracking during prolonged drying. The formation of shrinkage cracks produced preferential flow paths that substantially increased hydraulic conductivity, even when the compacted soils initially satisfied landfill liner requirements. Similar observations were reported by Onyelowe et al. (2021), who investigated the shrinkage behaviour of compacted clay modified with rice husk ash and lime. Their study demonstrated that changes in shrinkage characteristics significantly influenced cracking behaviour and hydraulic performance, with specimens exhibiting lower shrinkage potential maintaining more stable soil fabrics and lower hydraulic conductivity throughout drying. These findings indicate that shrinkage behaviour should be evaluated together with plasticity because a soil possessing favourable Plasticity Index values may still experience deterioration in hydraulic performance if excessive shrinkage results in desiccation cracking.

2.5.3 Relationship of Dry Density with Hydraulic Conductivity

The inverse relationship between dry density and hydraulic conductivity has been consistently demonstrated in laboratory investigations. Daniel and Trautwein (1993) evaluated the influence of moulding water content and dry density on the hydraulic conductivity of compacted clay soils by preparing specimens at different compaction conditions. Their study demonstrated that increasing dry density produced a reduction in hydraulic conductivity of approximately one order of magnitude, because denser soil structures contained fewer interconnected macropores available for seepage. The authors concluded that dry density was one of the dominant parameters controlling hydraulic conductivity, particularly when soils were compacted near their optimum moisture condition.

Similar observations were reported by Mbarki et al. (2023), who investigated the hydraulic conductivity of compacted clay liners prepared under different compaction conditions. Laboratory hydraulic conductivity testing showed that

specimens achieving higher dry densities consistently exhibited lower hydraulic conductivity owing to reductions in void ratio and pore connectivity. The study further demonstrated that the influence of dry density became increasingly significant when coupled with appropriate moulding moisture content, indicating that hydraulic conductivity is governed by the combined interaction between soil densification and soil fabric development rather than by density alone.

The relationship between dry density and hydraulic conductivity has also been verified through analytical and experimental investigations involving compacted soils. Robinson et al. (2022) developed analytical models relating bulk density, porosity and hydraulic conductivity and demonstrated that increasing soil density reduced porosity and restricted interconnected flow channels, resulting in progressively lower hydraulic conductivity. Likewise, Matthews et al. (2010) investigated the influence of compaction on water retention, porosity and saturated hydraulic conductivity through laboratory measurements and numerical simulations. Their study demonstrated that increased dry density consistently reduced saturated hydraulic conductivity because improved particle packing produced a denser soil fabric with smaller effective pore diameters and greater flow tortuosity. These findings further confirm that dry density directly governs hydraulic conductivity through modifications of pore geometry within compacted soils. (Mbarki et al., 2023).

2.5.4 Relationship of Compaction Behaviour with Hydraulic Conductivity

The relationship between moulding moisture content and hydraulic conductivity has been extensively investigated in compacted clay liners and residual soils. Daniel and Trautwein (1993) examined the combined influence of moulding moisture content and dry density on the hydraulic conductivity of compacted clay liners by preparing specimens over a range of moisture conditions. Their study demonstrated that specimens compacted slightly wet of the Optimum Moisture Content (OMC) consistently exhibited lower hydraulic conductivity than specimens compacted on the dry side of the OMC because the additional moisture promoted particle lubrication, improved particle orientation and reduced the continuity of interconnected macropores. Hydraulic conductivity decreased by approximately one order of magnitude, illustrating the significant influence of moulding moisture condition on hydraulic barrier

performance. The authors concluded that moisture content is one of the principal parameters controlling the hydraulic behaviour of compacted landfill liners.

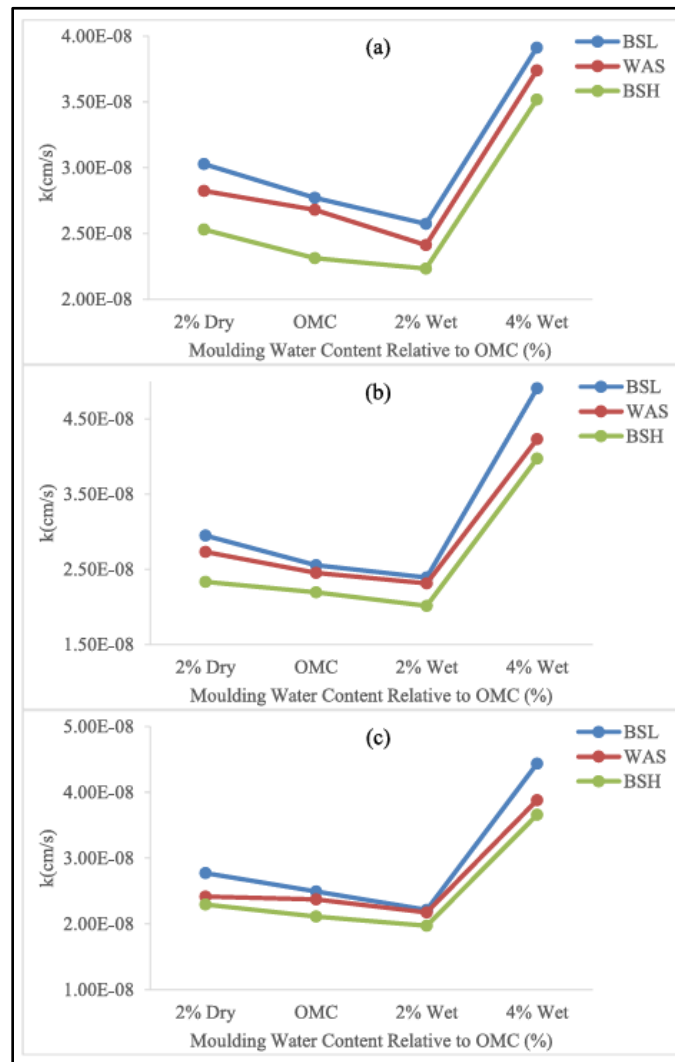


Figure 2.2 Relationship Between Moulding Water Content and Hydraulic Conductivity Under Different Compaction Conditions (Adeyemo and Bello, 2024).

Recent studies have confirmed similar trends for tropical residual soils. Adeyemo and Bello (2024) investigated the hydraulic performance of compacted residual soils by preparing specimens at 2% dry of OMC, OMC, 2% wet of OMC and 4% wet of OMC under controlled laboratory conditions. As presented in Figure 2.1, three different residual soils, namely BSL, WAS and BSH, exhibited consistent hydraulic behaviour despite differences in soil characteristics. Under all three testing conditions shown in Figures 2.1(a), 2.1(b) and 2.1(c), hydraulic conductivity decreased progressively from approximately $(2.3\text{--}3.0) \times 10^{-8}$ cm/s at 2% dry of the OMC to

approximately $(2.0\text{--}2.6) \times 10^{-8}$ cm/s at 2% wet of the OMC, indicating that a slight increase in moulding moisture enhanced particle lubrication, improved particle rearrangement and produced a denser soil fabric with reduced pore connectivity. However, further increasing the moulding moisture to 4% wet of the OMC caused hydraulic conductivity to increase markedly to approximately $(3.5\text{--}4.9) \times 10^{-8}$ cm/s for all three residual soils. The authors attributed this increase to excessive water occupying the soil structure during compaction, which disrupted efficient particle interlocking and resulted in a less stable pore network after saturation. These findings demonstrate that the optimum hydraulic performance of compacted residual soils is achieved within a relatively narrow moisture range slightly wet of the OMC, whereas excessive moulding moisture may adversely affect hydraulic conductivity despite continued compaction.

Similar observations were reported by Osinubi et al. (2012), who evaluated lateritic soil–bentonite mixtures proposed for landfill liner applications by compacting specimens under various moulding moisture conditions. Their study demonstrated that the lowest hydraulic conductivity was consistently achieved when soils were compacted approximately 2% to 4% wet of the OMC, confirming that slight wet-side compaction promoted better particle orientation and reduced pore continuity. Likewise, Tan et al. (2023) investigated compacted clay liners prepared under different moulding moisture conditions and reported that specimens compacted slightly wet of the OMC consistently exhibited lower hydraulic conductivity than those compacted on the dry side because improved particle lubrication facilitated denser particle packing and greater closure of seepage pathways. These findings are consistent with practical landfill engineering specifications, such as the Crookwell Landfill Detailed Design Technical Specification (Roberts, 2017), which recommends placing compacted soil liners within approximately 0% to +3% of the OMC while achieving at least 95% of the Standard Proctor Maximum Dry Density. Collectively, these studies indicate that maintaining moisture content within a controlled range around the OMC is essential for achieving satisfactory hydraulic barrier performance under field conditions. Recent studies have confirmed similar trends for tropical residual soils. Adeyemo and Bello (2024) investigated the hydraulic performance of compacted residual soils by preparing specimens at 2% dry of OMC, OMC, 2% wet of OMC and 4% wet of OMC under controlled laboratory conditions. As presented in Figure 2.1, three different residual soils, namely BSL, WAS and BSH, exhibited consistent hydraulic behaviour despite differences in soil characteristics. Under all three testing conditions shown in Figures

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2.5.5 Statistical Analysis of Hydraulic Conductivity with Soil Characteristics

Previous studies have successfully applied statistical approaches to investigate hydraulic conductivity using measurable soil properties. Ghanbarian et al. (2016) developed statistical scaling relationships from an extensive international soil database to examine the combined influence of soil texture, porosity and particle-size distribution on saturated hydraulic conductivity. Their analysis demonstrated that hydraulic conductivity is governed by the interaction of several soil characteristics rather than by any single parameter, with porosity and soil texture identified as the dominant controlling variables. The authors concluded that multivariable statistical analysis provides a more reliable interpretation of hydraulic conductivity than analysing individual soil properties independently. These findings support the present study, where several physical and compaction properties are evaluated simultaneously to determine their influence on the hydraulic conductivity of compacted residual soils.

Similarly, Waleed et al. (2025) developed regression models to estimate hydraulic conductivity using laboratory-determined soil properties obtained from field investigations. Their study demonstrated that porosity, effective grain size and particle-size distribution significantly influenced hydraulic conductivity and that statistical modelling provided satisfactory agreement between measured and predicted hydraulic conductivity values. The authors concluded that regression analysis offers a practical approach for exploring the relationships between measurable soil properties and hydraulic conductivity while reducing reliance on extensive laboratory hydraulic conductivity testing. These findings further support the application of regression analysis in the present study to investigate the combined influence of physical soil properties and compaction behaviour on hydraulic conductivity.

Statistical relationships between soil density, pore structure and hydraulic conductivity have also been reported in geotechnical engineering studies. Robinson et al. (2022) investigated the influence of porosity and bulk density on hydraulic conductivity using analytical and statistical modelling and demonstrated that reductions in porosity consistently decreased hydraulic conductivity by limiting interconnected flow channels within the soil matrix. Likewise, Zhang et al. (2011) developed predictive relationships between hydraulic conductivity and measurable soil properties, including porosity and bulk density, and reported that these variables could be used to estimate hydraulic conductivity with reasonable engineering accuracy. Collectively, these

studies demonstrate that statistical analysis provides valuable insight into the complex interactions among soil characteristics controlling hydraulic conductivity and offers a practical means of interpreting laboratory results beyond conventional descriptive analysis.

Despite these advantages, previous researchers have emphasised that statistical models should be interpreted cautiously, particularly when developed from relatively small experimental datasets. Kutner et al. (2005) explained that the reliability of regression models depends on the quality, representativeness and variability of the available data, while Montgomery et al. (2021) noted that statistical relationships established from limited datasets should not be extrapolated beyond the experimental conditions under which they were developed without additional validation. These limitations are particularly relevant in laboratory-based geotechnical investigations, where specimen preparation, testing duration and material availability often restrict the number of observations. Consequently, regression models developed in such studies should be interpreted as engineering tools for exploring potential relationships among variables rather than as universally applicable predictive equations.

The statistical analyses are performed using Minitab Statistical Software, which is widely adopted in engineering and quality improvement research because it provides an integrated platform for exploratory data analysis, correlation analysis, regression modelling and model validation within a single analytical environment. According to Minitab LLC (2024), the software is specifically designed to identify relationships among variables, evaluate statistical significance and develop predictive regression models through comprehensive analytical tools. A bibliometric review conducted by Okagbue et al. (2021) further reported that Minitab is one of the statistical software packages most frequently adopted in engineering, manufacturing and materials science research due to its comprehensive statistical capabilities, ease of implementation and suitability for analysing experimental datasets. Consequently, Minitab was selected in the present study to investigate the statistical relationships between soil characteristics and hydraulic conductivity of residual soils from the Tanjung Dua Belas and Air Hitam landfill sites.

2.6 Research Gap

Despite considerable research on soils used for landfill liner applications, the majority of previous studies have focused on conventional liner materials such as marine clay, bentonite-amended soils, peat and lateritic soils, with comparatively limited attention given to tropical residual soils obtained from landfill environments. Existing studies have demonstrated that the engineering behaviour of residual soils is highly dependent on parent material, degree of weathering and mineralogical composition. However, most investigations have characterised residual soils collected from natural slopes, road construction sites or agricultural areas rather than soils obtained directly from landfill environments. Furthermore, previous studies have generally evaluated residual soils under natural conditions without considering that soils collected from landfill sites may exhibit different engineering characteristics owing to prolonged waste disposal activities and possible interaction with landfill leachate. Consequently, the physical properties of residual soils obtained from the Tanjung Dua Belas and Air Hitam landfill sites remain insufficiently documented, limiting the understanding of their suitability as potential landfill liner materials. Therefore, the present study addresses this gap by comprehensively characterising the physical properties of residual soils collected from both landfill sites to evaluate their engineering suitability for landfill liner applications.

Previous investigations have extensively examined the compaction behaviour of fine-grained soils. However, the majority of published studies have focused on determining the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) under controlled laboratory conditions, with comparatively limited consideration of the practical moisture variations encountered during landfill liner construction. International landfill engineering specifications recognise that compacted soil liners are commonly constructed within a narrow moisture tolerance around the OMC to accommodate field conditions. Nevertheless, relatively few studies have evaluated whether these practical moisture ranges are applicable to tropical residual soils obtained from landfill environments. In addition, most investigations have concentrated on conventional clay liner materials rather than locally available residual soils, resulting in limited understanding of how moisture variation influences the compaction behaviour of Malaysian residual soils intended for landfill liner applications. Therefore, the present study addresses this gap by investigating the

compaction behaviour of residual soils from the Tanjung Dua Belas and Air Hitam landfill sites under practical moisture conditions representing dry of optimum, optimum and wet of optimum compaction.

Hydraulic conductivity is widely recognised as the principal engineering criterion governing the performance of landfill liner systems. However, previous hydraulic conductivity studies have predominantly focused on marine clays, bentonite mixtures, engineered clay liners and chemically stabilised soils, whereas comparatively limited information is available for natural tropical residual soils collected from landfill environments. Furthermore, most hydraulic conductivity investigations have evaluated hydraulic conductivity under conventional laboratory conditions without simultaneously considering practical moisture variation and vertical stress representative of landfill loading. As a result, the hydraulic behaviour of Malaysian residual soils obtained from landfill environments remains insufficiently understood, particularly with respect to their suitability as natural hydraulic barrier materials under realistic landfill conditions. Therefore, the present study addresses this gap by evaluating the hydraulic conductivity of residual soils from the Tanjung Dua Belas and Air Hitam landfill sites using the modified oedometer method under different moisture conditions and applied vertical stresses representative of landfill liner applications.

Despite advances in previous studies investigating individual engineering properties of landfill liner materials, physical properties, compaction behaviour and hydraulic conductivity are still frequently evaluated as separate parameters, resulting in a fragmented understanding of the mechanisms governing hydraulic conductivity in compacted residual soils. Although statistical analyses have increasingly been adopted to investigate hydraulic behaviour, relatively few studies have integrated physical soil characteristics, compaction parameters and hydraulic conductivity within a single analytical framework for tropical residual soils intended for landfill liner applications. Consequently, the relative influence of individual soil properties on hydraulic conductivity remains insufficiently understood, limiting the development of practical engineering relationships that can support landfill liner material evaluation. Therefore, the present study addresses this gap by integrating physical properties, compaction behaviour and hydraulic conductivity through statistical correlation and regression analyses using Minitab to explore the relationships between soil characteristics and hydraulic conductivity and to identify the parameters that most significantly influence

the hydraulic performance of residual soils from the Tanjung Dua Belas and Air Hitam landfill sites.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter describes the research methodology adopted to achieve the objectives of this study. It presents the overall experimental programme, including the selection of the landfill sites, soil sampling procedures, laboratory testing methods and statistical analyses used to evaluate the engineering behaviour of the investigated residual soils. The methodology covers the determination of the physical properties, compaction characteristics and hydraulic conductivity of the residual soils obtained from the Tanjung Dua Belas and Air Hitam landfill sites in accordance with the relevant British Standards (BS 1377:1990). The chapter also describes the data analysis procedures performed using Microsoft Excel and Minitab Statistical Software to establish the relationships between hydraulic conductivity and soil characteristics through descriptive statistics, correlation analysis, regression modelling and paired t-test validation. The adopted methodology provides a systematic framework for evaluating the suitability of the investigated residual soils as landfill liner materials and for achieving the four research objectives established in this study.

3.1.1 Soil Methodology Framework

This section describes the methodological framework adopted in this study to systematically investigate the influence of soil characteristics on the hydraulic conductivity behaviour of residual soils obtained from landfill areas for landfill liner applications. The methodology was developed to align with the research objectives by integrating physical properties identification, compaction testing, hydraulic conductivity evaluation and statistical analysis within a structured experimental programme. The overall framework ensures that each stage of the investigation contributes to evaluating the engineering suitability of the investigated residual soils as potential landfill liner materials.

The methodology begins with the collection of residual soil samples from two landfill areas in Selangor, namely Tanjung Dua Belas Landfill and Air Hitam Landfill. These sampling locations were selected to represent residual soils obtained from landfill

areas with different geological and operational conditions. The collected soils were subsequently subjected to laboratory testing for physical properties identification, including Particle Size Distribution (PSD), Particle Density, Atterberg Limits, Linear Shrinkage and *pH*. These tests were conducted to establish the fundamental engineering properties required for soil classification and subsequent evaluation of hydraulic conductivity behaviour.

Following the physical properties identification, compaction testing was performed using the Standard Proctor Test to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of each soil. The compaction parameters obtained from this test were subsequently used to prepare compacted specimens at selected moisture conditions representing dry of optimum, optimum and wet of optimum moisture contents. This procedure enabled the hydraulic conductivity behaviour of the residual soils to be evaluated under practical moisture conditions representative of landfill liner construction.

Hydraulic conductivity evaluation was then conducted using a modified oedometer apparatus. The testing procedure was adapted from the conventional consolidation test by applying incremental vertical loading while maintaining the specimen under confined conditions without unloading. Vertical stresses ranging from 25 kPa to 200 kPa were applied to represent the progressive loading experienced by landfill liner systems as waste accumulates over time. This approach enabled the hydraulic conductivity behaviour of the compacted residual soils to be evaluated under stress conditions representative of field landfill environments.

The experimental data obtained from the physical properties identification, compaction testing and hydraulic conductivity evaluation were subsequently analysed to investigate the relationships between soil characteristics and hydraulic conductivity behaviour. Preliminary data processing and graphical presentation were carried out using Microsoft Excel, while statistical analyses were performed using Minitab Statistical Software to explore the relationships between soil properties, compaction behaviour and hydraulic conductivity. The overall methodological framework adopted in this study is presented in Figure 3.1.

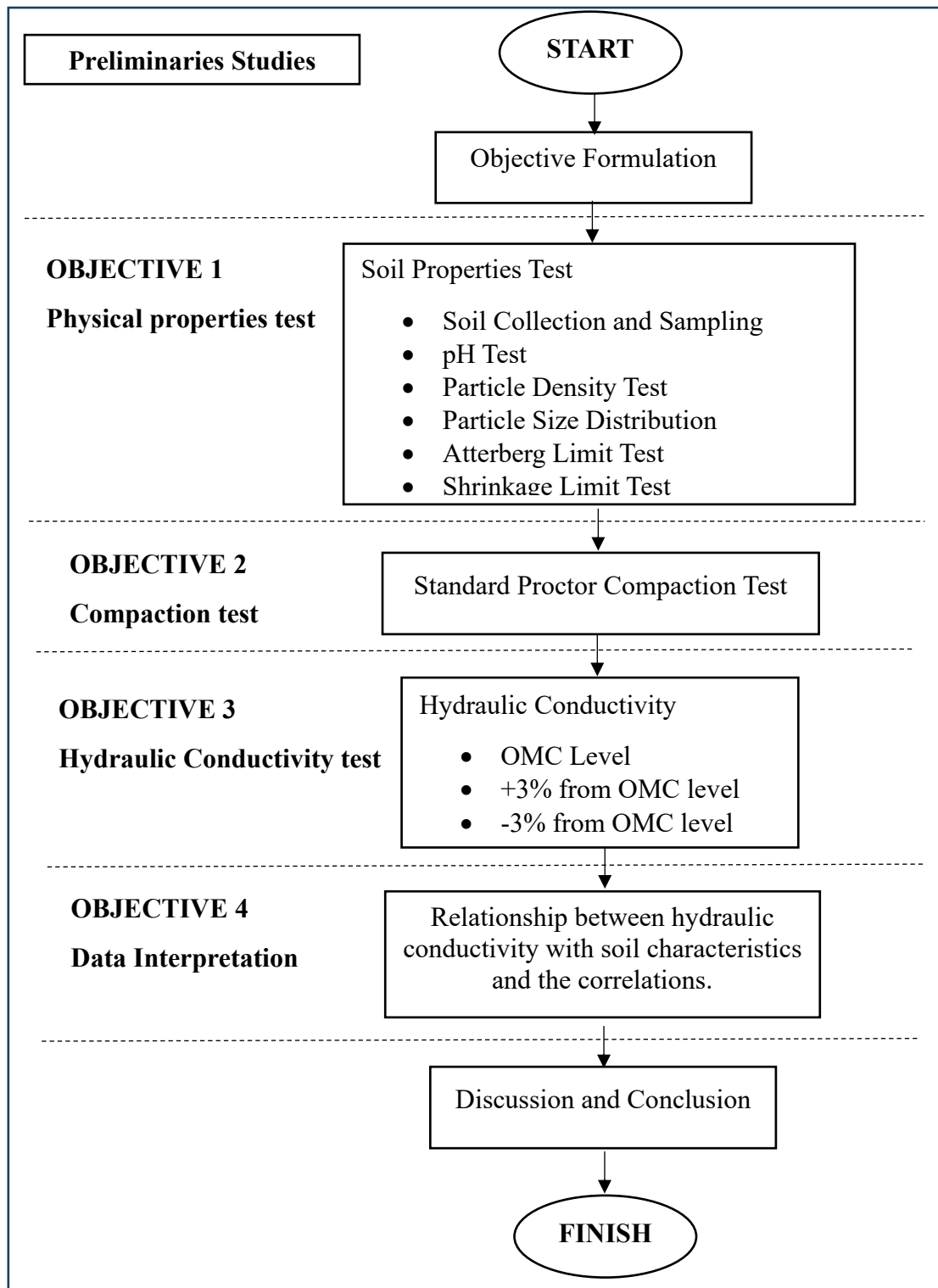


Figure 3.1 Methodological Framework

3.1.2 Soil Collection and Sampling

Figure 3.2 illustrates the location of Tanjung Dua Belas Landfill, situated in Mukim Tanjung Dua Belas, Selangor ($2^{\circ}43'53''\text{N}$, $101^{\circ}36'17''\text{E}$). The landfill is a fully

engineered sanitary landfill with a design capacity of approximately 1,250 tonnes of municipal solid waste per day and has been in operation since 1 January 2010. The facility is owned by the Selangor State Government and operated by Worldwide Holdings Berhad through its environmental services subsidiary, Worldwide Environment Sdn. Bhd. The site was selected because it represents an active sanitary landfill in Selangor where residual soils obtained from the landfill area can be evaluated for their potential use as landfill liner materials. The location of the Tanjung Dua Belas Landfill is presented in Figure 3.2.



Figure 3.2 Location of Tanjung Dua Belas Landfill on Google Maps

Figure 3.3 shows the location of Air Hitam Landfill, located at Persiaran Lestari Perdana, Seri Kembangan, Selangor ($3^{\circ}00'21''\text{N}$, $101^{\circ}66'26''\text{E}$). The landfill commenced operation in November 1995 and has received approximately 6.3 million tonnes of municipal solid waste throughout its operational period. Similar to Tanjung

Dua Belas Landfill, the facility is managed by Worldwide Environment Sdn. Bhd. and incorporates leachate treatment and environmental monitoring systems as part of its landfill management practices. The site was selected to provide a second residual soil source representing a landfill area with different operational history and geological conditions, enabling comparison of the engineering behaviour of residual soils obtained from two landfill environments. The location of the Air Hitam Landfill is shown in Figure 3.3.

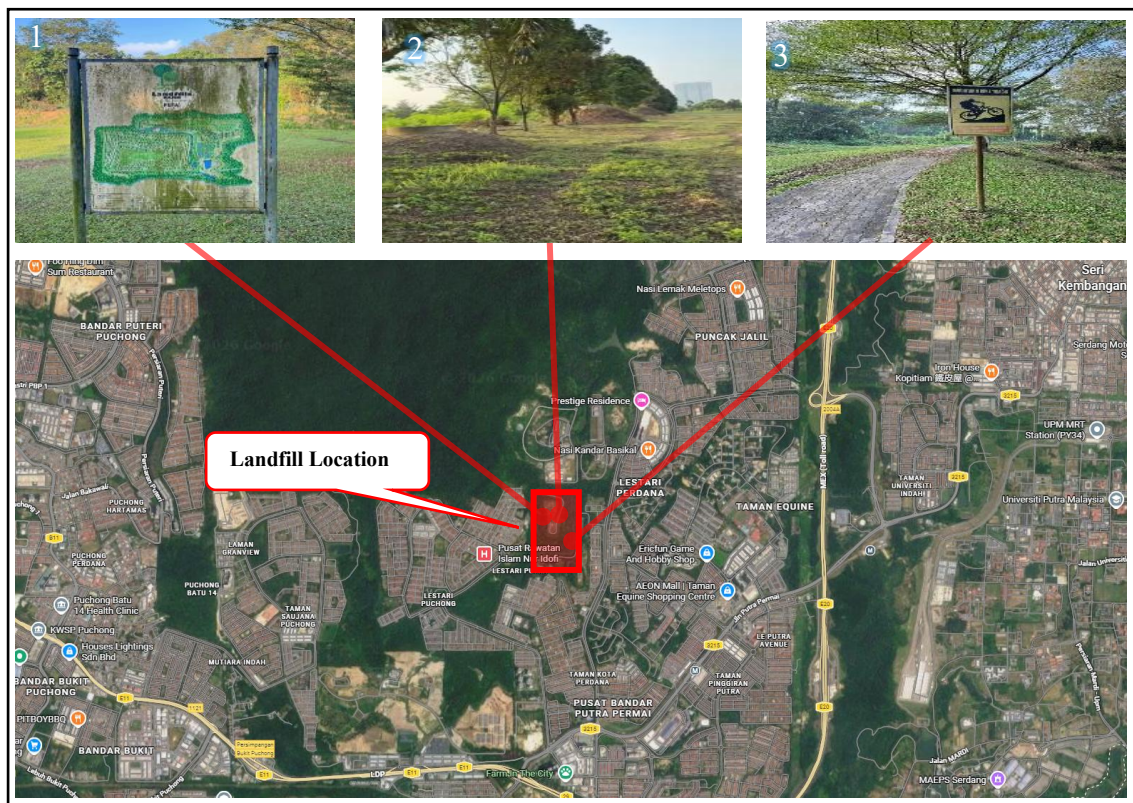


Figure 3.3 Location of Air Hitam Landfill on Google Maps

Soil sampling was carried out at both landfill areas to obtain representative residual soil samples for laboratory testing. Three sampling points were established at each landfill site to account for local variability in soil conditions while maintaining comparable geological conditions within the sampling area. The sampling points were located approximately 5 m apart, providing sufficient spatial coverage without introducing significant variation in site characteristics. At each sampling point, soil was excavated manually using a shovel and hoe at depths ranging from 1.0 m to 1.5 m below the ground surface, as illustrated in Figure 3.4. This sampling depth was selected to

minimise the influence of recently disturbed surface materials and vegetation while obtaining representative subsurface residual soils suitable for laboratory investigation.



Figure 3.4 Extraction of residual soil samples at depths between 1.0-1.5 m.

Approximately 30 kg of residual soil was collected from each sampling point, resulting in approximately 90 kg of soil from each landfill site. As soil samples were obtained from two landfill sites, the total quantity of residual soil collected for this study was approximately 180 kg. The collected samples were immediately placed in sealed sacks to minimise moisture loss and contamination during transportation to the laboratory, as shown in Figure 3.5. The quantity of soil collected was sufficient to complete all laboratory tests specified in this study, including physical properties identification, compaction testing and hydraulic conductivity evaluation. Laboratory testing for each parameter was conducted in triplicate, and the average value was used for subsequent analysis to improve the reliability and consistency of the experimental results.



Figure 3.5 30 kg of Soil Sample Stored in Each Sack

Following field sampling, the soil samples were transported to Makmal Tanah 2, Faculty of Civil Engineering, Universiti Teknologi MARA (UiTM) Shah Alam, for laboratory preparation. The samples were oven-dried for approximately 24 hours at temperatures between 105°C and 110°C in accordance with BS 1377-1:1990 to remove natural moisture before testing. Controlled oven drying ensured a uniform initial moisture condition prior to specimen preparation and subsequent moisture conditioning for laboratory testing. The oven drying process and temperature setting are presented in Figures 3.6 and 3.7, respectively.



Figure 3.6 Oven Drying Process of Soil Sample



Figure 3.7 Temperature Setting of Oven

3.2 Physical Properties

This section presents the determination of the physical properties of the residual soil samples collected from Tanjung Dua Belas Landfill and Air Hitam Landfill. The sampling locations are summarised in Table 3.1. Controlled field sampling procedures were adopted to obtain representative residual soil samples from both landfill areas, ensuring consistency in the laboratory testing programme. The physical properties were determined through laboratory tests, including Particle Density, Atterberg Limits, Linear Shrinkage, Particle Size Distribution (PSD), pH , and Standard Proctor Compaction, all of which were conducted in accordance with BS 1377:1990. The results obtained from these tests provide the fundamental engineering properties required for soil classification and form the basis for the subsequent evaluation of compaction behaviour and hydraulic conductivity. Conducting all tests in accordance with the relevant British Standard ensures the consistency, repeatability and reliability of the experimental results.

Table 3.1
Soil Sampling Locations

Sample Name	Soil Location
T12	Tanjung Dua Belas Sanitary Landfill, Kuala Langat

3.2.1 *pH* Test

The *pH* test was conducted in accordance with BS 1377-3:1990 to determine the *pH* of the residual soil samples collected from the Tanjung Dua Belas and Air Hitam landfill areas. Before testing, the *pH* meter was calibrated using standard buffer solutions of *pH* 4, 7 and 10 to ensure measurement accuracy. The residual soil samples were air-dried, passed through a 2 mm sieve, and prepared using a 1:2.5 soil-to-water ratio by mixing 20 g of soil with 50 mL of distilled water, as summarised in Table 3.2.

Table 3.2
Sample Preparation for *pH* Test

Sample	Weight of Soil (g)	Distilled Water (mL)	Soil-Water Ratio
T12	20	50	1:2.5
AH	20	50	1:2.5

The soil–water mixture was stirred thoroughly to produce a homogeneous suspension and allowed to stand for approximately 1 hour to achieve equilibrium before the *pH* measurement was taken, as shown in Figure 3.8.

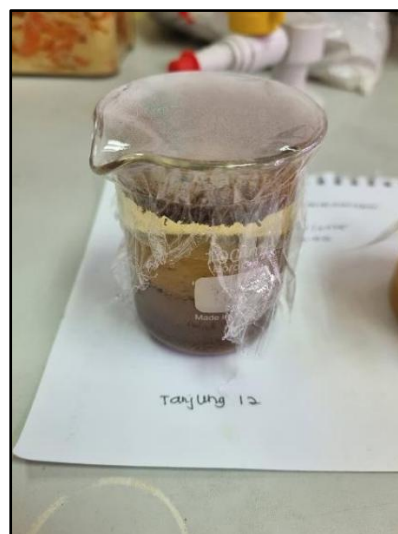


Figure 3.8 Preparation of the Soil–water Suspension for the *pH* test

3.2.2 Particle Density Test

The particle density (ρ_s) and specific gravity (G_s) of the residual soil samples were determined in accordance with BS 1377-2:1990 using the 50 mL Small Pycnometer Method, as shown in Figure 3.9.



Figure 3.9 50mL Small Pycnometer

A 30 g oven-dried residual soil sample was placed into the pycnometer before distilled water was added to the calibration mark, as summarised in Table 3.3.

Table 3.3
Sample Preparation for Particle Density Test

Sample	Weight of Soil (g)	Distilled Water
T12	30	Filled to calibration mark
AH	30	Filled to calibration mark

Following the sample preparation, the pycnometer was partially filled with distilled water and placed in a desiccator for approximately 12 hours to remove entrapped air bubbles, as shown in Figure 3.10. The pycnometer was then filled completely with distilled water, sealed and weighed in accordance with BS 1377-2:1990. To improve the reliability of the measurements, the test was conducted using three separate 50 mL pycnometers, and the average value was reported as the particle density for each residual soil sample.



Figure 3.10 Desiccator Used to Remove Entrapped Air Bubbles

3.2.3 Particle Size Distribution Test

The particle size distribution (PSD) of the residual soil samples was determined in accordance with BS 1377-2:1990 using a combination of wet sieving and hydrometer analysis. Wet sieving was performed to separate the coarse and fine soil fractions prior to mechanical sieving and hydrometer testing.

3.2.3.1 *Wet Sieving Test*

The air-dried residual soil sample was gently disaggregated and placed on a 0.063 mm sieve positioned above a clean collection container. Distilled water was applied while the sample was gently brushed to allow particles finer than 0.063 mm to pass through the sieve, as shown in Figure 3.11.



Figure 3.11 Wet Sieving Process for Separation the Fine Soil Particles

The fine fraction collected in the container was allowed to settle for approximately 1 to 3 days, after which the excess water was removed using a siphoning method, as illustrated in Figure 3.12.



Figure 3.12 Removal of Excess Water Using the Siphoning Method.

The settled fine fraction was oven-dried at 105°C for approximately 24 hours prior to hydrometer analysis. The coarse fraction retained on the sieve was also oven-dried before mechanical sieving. A stack of BS sieves ranging from 2.00 mm to 0.063 mm was arranged in descending order and placed on a mechanical sieve shaker, as

shown in Figure 3.13. The dried coarse fraction was sieved for approximately 10–15 minutes, after which the mass retained on each sieve was recorded. The percentage retained, cumulative percentage retained and percentage passing were subsequently calculated to produce the particle size distribution curve.



Figure 3.13 Mechanical Sieving Arrangement

3.2.3.2 Hydrometer Test

The hydrometer analysis was conducted on the fine fraction passing the 0.063 mm sieve in accordance with BS 1377-2:1990. Approximately 60 g of the oven-dried fine fraction was mixed with a sodium hexametaphosphate dispersing solution prepared in a 1 L measuring cylinder. The suspension was thoroughly shaken to ensure complete dispersion of the soil particles before being placed on a level surface for testing. The prepared soil suspension is shown in Figure 3.14. Hydrometer readings were recorded at 0, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512 and 1028 minutes in accordance with BS 1377-2:1990. The recorded readings were subsequently used to calculate the percentage finer and corresponding particle diameters. The results of the hydrometer analysis were combined with the mechanical sieving results to produce the complete particle size distribution curve for each residual soil sample.



Figure 3.14 Soil Suspensions for Hydrometer Analysis

3.2.4 Atterberg Limit Test

The Atterberg Limits test was conducted in accordance with BS 1377-2:1990 to determine the Liquid Limit (LL), Plastic Limit (PL) and Plasticity Index (PI) of the residual soil samples collected from the Tanjung Dua Belas and Air Hitam landfill areas.

3.2.4.1 Liquid Limit

The Liquid Limit (LL) was determined using the Casagrande apparatus, as shown in Figure 3.15, in accordance with BS 1377-2:1990.



Figure 3.15 Groove Closure using Casagrande Apparatus

Approximately 100 g of air-dried residual soil passing the 425 μm sieve was mixed with distilled water to produce a uniform soil paste, as summarised in Table 3.4.

Table 3.4
Sample Preparation for Liquid Limit Test

Sample	Weight of Soil (g)	Distilled Water (mL)
T12	100	25-40
AH	100	25-40

The Liquid Limit (LL) was determined in accordance with BS 1377-2:1990 using the Casagrande apparatus, as shown in Figure 3.15. The Casagrande method was selected because it remains one of the most widely adopted procedures in geotechnical laboratories and provides results that are directly comparable with previous landfill liner and residual soil studies. Although the cone penetrometer generally offers higher repeatability, the Casagrande apparatus continues to be widely used due to its compatibility with established soil classification systems and long-term geotechnical databases (Marinković et al., 2024). Approximately 100 g of air-dried residual soil passing the 425 μm sieve was mixed with distilled water to produce a uniform soil paste, as summarised in Table 3.4. The prepared soil paste was placed in the Casagrande cup, and a standard groove was formed using the grooving tool. The apparatus was operated until the groove closed over a distance of approximately 13 mm, with target blow counts within the ranges of 15–19, 20–24 and 25–30. After each test, a representative soil

sample was collected for moisture content determination by oven drying at 105–110°C for approximately 24 hours, as shown in Figure 3.16. The moisture contents were plotted against the corresponding number of blows on a semi-logarithmic graph, and the Liquid Limit was obtained as the moisture content corresponding to 25 blows.



Figure 3.16 Liquid Limit Sample after Oven Drying

3.2.4.2 Plastic Limit

The Plastic Limit (PL) was determined in accordance with BS 1377-2:1990 using the residual soil fraction passing the 425 μm sieve. Approximately 20 g of the prepared soil paste was rolled manually on a glass plate until threads approximately 3 mm in diameter were formed, as illustrated in Figure 3.17. When the soil threads began to crumble at this diameter, the material was collected for moisture content determination.



Figure 3.17 Crumbling of Soil Threads During Plastic Limit Determination

The collected soil was weighed before and after oven drying at 105–110°C for approximately 24 hours, as shown in Figure 3.18, and the moisture content was calculated as the Plastic Limit.



Figure 3.18 Plastic Limit Sample After Oven Drying

3.2.4.3 Plasticity Index

The Plasticity Index (PI) was determined in accordance with BS 1377-2:1990 by calculating the difference between the measured Liquid Limit (LL) and Plastic Limit (PL) obtained from the Atterberg limits tests. The calculated PI value was used to evaluate the plasticity characteristics of the residual soil samples and was subsequently incorporated into the analysis of the relationships between soil characteristics and hydraulic conductivity.

3.2.5 Shrinkage Limit Test

The Linear Shrinkage (LS) test was conducted in accordance with BS 1377-2:1990 to determine the shrinkage characteristics of the residual soil samples collected from the Tanjung Dua Belas and Air Hitam landfill areas. Approximately 150 g of air-dried residual soil passing the 425 μm sieve was mixed with distilled water to produce a homogeneous soil paste, as summarised in Table 3.5.

Table 3.5
Sample Preparation for Shrinkage Limit Test

Sample	Weight of Soil (g)	Distilled Water (mL)
T12	150	70-90
AH	150	70-90

The prepared soil paste was carefully placed into the linear shrinkage mould, ensuring that the mould was completely filled without entrapping air. The initial length of the soil specimen (L_0) was recorded before oven drying. The specimens were then oven-dried at 105–110°C for approximately 24 hours, after which the final length (L_d) was measured, as shown in Figure 3.19. The linear shrinkage value for each residual soil sample was subsequently calculated in accordance with BS 1377-2:1990. To improve the reliability of the results, the test was performed in triplicate, and the average linear shrinkage value was used for subsequent analysis.

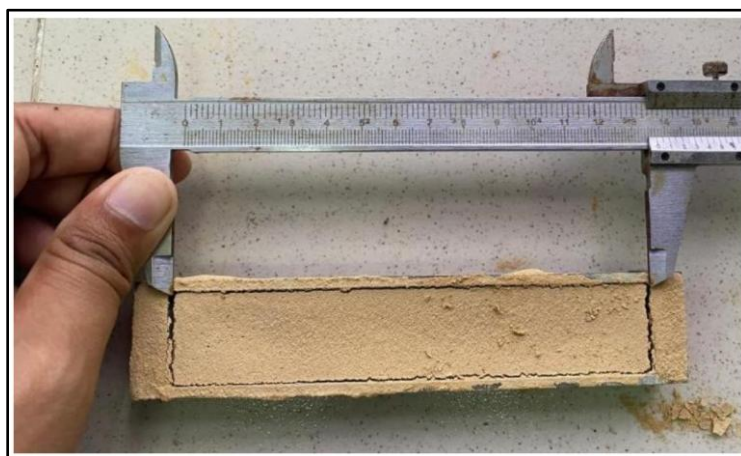


Figure 3.19 Linear Shrinkage Measurement of the Residual Soil After Oven Drying

3.3 Compaction Test

Compaction The compaction test was conducted to establish the relationship between moisture content and dry density of the residual soil samples in order to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). These compaction parameters provide the basis for preparing soil specimens for subsequent hydraulic conductivity testing and are widely used to assess the engineering behaviour of soils intended for landfill liner applications. Previous studies have shown that the degree of compaction significantly influences soil fabric, pore structure and hydraulic conductivity, making the determination of OMC and MDD an essential step in evaluating the performance of compacted soil liners (Kodikara et al., 2018). In this study, the Standard Proctor Compaction Test was conducted in accordance with BS 1377-4:1990 to determine the compaction characteristics of the residual soil samples for subsequent laboratory testing and analysis.

3.3.1 Compaction Sample Preparation

Before compaction testing, the residual soil samples were oven-dried at 105–110°C for approximately 24 hours in accordance with BS 1377-4:1990 to establish a uniform initial moisture condition. The dried soil was then gently disaggregated, passed through a 2 mm sieve, and stored in airtight containers prior to testing to minimise moisture absorption.

Table 3.6
Sample Preparation for Standard Proctor Compaction Test

Sample	Weight of Soil (g)	Water Content (ml)
T12	2500	200 (200 increment)
AH	2500	200 (200 increment)

As summarised in Table 3.6, approximately 2500 g of residual soil was prepared for each compaction test. Distilled water was added incrementally, and the soil was thoroughly mixed after each addition to obtain a series of moisture contents covering the expected compaction range. The prepared specimens were subsequently compacted

to establish the moisture–density relationship and determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of each residual soil sample.

3.3.2 Standard Proctor Compaction Test

The Standard Proctor Compaction Test was conducted in accordance with BS 1377-4:1990 using an automatic Proctor compactor, as shown in Figure 3.20.



Figure 3.20 Automatic Proctor Compactor used for Standard Compaction Test

Approximately 2.5 kg of residual soil passing the 2 mm sieve was used for each compaction trial. The soil was compacted in a standard Proctor mould, shown in Figure 3.21, by placing the material in three equal layers, with each layer compacted in accordance with the requirements of BS 1377-4:1990.



Figure 3.21 Standard Compaction Mould Used for Compaction Test

A series of five compaction trials was performed using progressively increasing moisture contents to establish the moisture–density relationship and determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of each residual soil sample. Upon completion of each compaction trial, the collar was removed and the excess soil was carefully trimmed flush with the top of the mould to maintain a constant specimen volume. The mould containing the compacted soil was then weighed, as illustrated in Figure 3.22.



Figure 3.22 Weighing of Compacted Soil And Mould After Compacted

A representative portion of the compacted specimen was collected after each trial for moisture content determination. The samples were oven-dried at 105–110°C for approximately 24 hours, as shown in Figure 3.23, before calculating the corresponding moisture content for each compaction point.



Figure 3.23 Compacted Soil Sample after Oven Drying for Moisture Content Determination

3.3.3 Determination of OMC and MDD

The bulk density and dry density of each residual soil sample were calculated from the measured mass of the compacted specimen and the known volume of the Standard Proctor mould in accordance with BS 1377-4:1990. The calculated dry density values were then plotted against the corresponding moisture contents to produce the compaction curve for each residual soil sample. The Maximum Dry Density (MDD) was identified as the peak of the compaction curve, while the corresponding moisture content was recorded as the Optimum Moisture Content (OMC). The determined OMC and MDD values were subsequently used to prepare the residual soil specimens for the hydraulic conductivity tests conducted under dry-of-optimum, optimum, and wet-of-optimum moisture conditions.

3.3.4 Determination of Air Void in Compaction Curve

Air void lines of 0%, 5% and 10% were constructed on the compaction curve to compare the experimental compaction results with theoretical air void conditions. The construction of these lines provided an indication of the degree of saturation achieved during compaction and facilitated the interpretation of the compaction characteristics of the residual soil samples. The dry density corresponding to each air void condition was calculated using the measured water content (W) and specific gravity (G_s) obtained from the laboratory tests. The calculated air void lines were subsequently plotted

together with the experimental compaction curve to evaluate the relationship between moisture content and dry density under different theoretical air void conditions. The percentage of air voids (A_v) for each compaction point was calculated using Equation (3.1), adapted from Das and Sobhan (2018).

$$A_v(\%) = \left(1 - \frac{\rho_d(1 + wG_s)}{G_s\rho_w} \right) \times 100 \quad (3.1)$$

Where:

ρ_d = Dry Density (g/cm^3)

ρ_w = Density of water (0.9982 Mg/m^3)

W = Water Content (%)

G_s = Specific Gravity

3.3.5 Moisture Conditioning Relative to OMC

The Optimum Moisture Content (OMC) determined from the Standard Proctor compaction test was used as the reference moisture condition for specimen preparation. Additional specimens were prepared at -3% OMC (dry of optimum) and $+3\%$ OMC (wet of optimum) to evaluate the influence of practical moisture variation on compaction behaviour and hydraulic conductivity. The selected moisture range was adopted based on the Crookwell Landfill Detailed Design Technical Specification, which recommends that compacted clay liner materials be constructed within approximately 0% to $+3\%$ of the OMC while satisfying the specified field compaction requirements (Roberts, 2017). This range is further supported by the findings of Adeyemo and Bello (2024), who investigated the hydraulic conductivity behaviour of compacted residual soils under different moulding moisture conditions. Their study reported that hydraulic conductivity decreased progressively as the moisture content increased from the dry side of optimum to approximately $+2\%$ OMC, indicating improved particle rearrangement and pore closure. However, when the moisture content exceeded approximately $+4\%$ OMC, hydraulic conductivity increased slightly due to changes in soil fabric caused by excess water. Based on these findings, the moisture conditions adopted in the present study (-3% OMC, OMC and $+3\%$ OMC) represent

practical field compaction conditions while remaining within the acceptable construction range recommended for landfill liner applications. The dry density corresponding to each moisture condition was obtained from the compaction curve and subsequently used to prepare specimens for hydraulic conductivity testing. Figure 3.24 illustrates the expected compaction curve showing the dry-of-optimum, optimum, and wet-of-optimum moisture conditions adopted in this study. This procedure enables the influence of practical moisture variation on the hydraulic conductivity behaviour of the residual soils obtained from the Tanjung Dua Belas and Air Hitam landfill areas to be evaluated under controlled laboratory conditions.

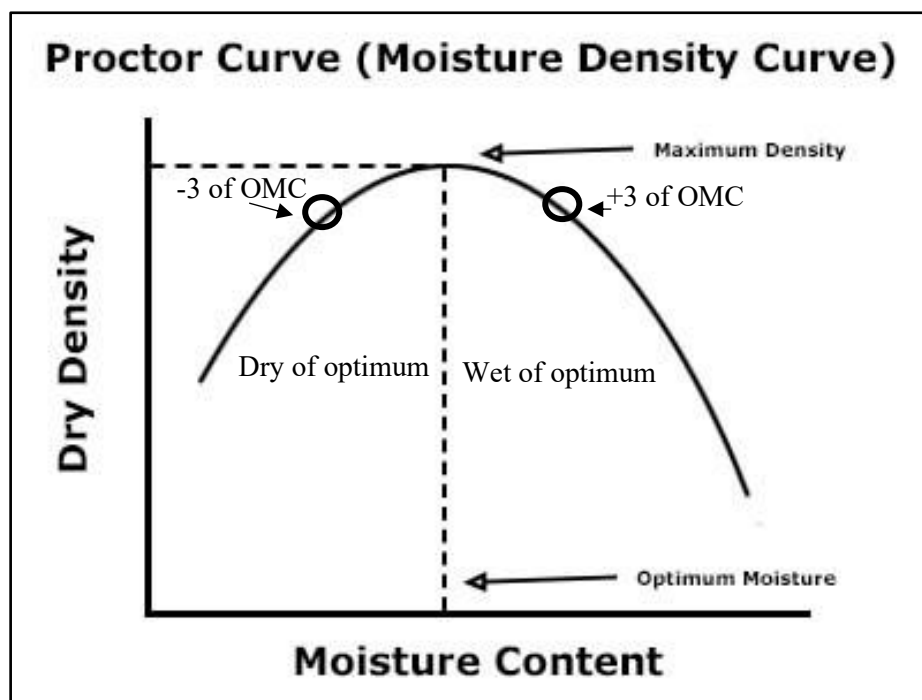


Figure 3.24 Expected Compaction Curve With Moisture Variation

3.4 Hydraulic Conductivity Test

The hydraulic conductivity test was conducted to evaluate the ability of the compacted residual soil samples to transmit water under controlled laboratory conditions. Hydraulic conductivity is one of the principal engineering parameters used to assess the suitability of soils for landfill liner applications because it reflects the effectiveness of the compacted soil in restricting fluid flow. In this study, hydraulic conductivity was determined using a modified oedometer apparatus, which enables hydraulic conductivity to be evaluated under controlled vertical loading conditions representative of those experienced by landfill liners during waste placement.

Oluwapelumi et al. (2022) adopted a similar modified oedometer approach to investigate the stress-dependent hydraulic conductivity of compacted fine-grained soils and demonstrated that the method provides a practical means of evaluating hydraulic conductivity while simulating progressive vertical loading. Accordingly, the modified oedometer test was adopted in the present study to evaluate the hydraulic conductivity behaviour of the compacted residual soils obtained from the Tanjung Dua Belas and Air Hitam landfill areas.

3.4.1 Hydraulic Conductivity Sample Preparation

The residual soil specimens prepared for the hydraulic conductivity test were conditioned at three moisture states based on the Optimum Moisture Content (OMC) obtained from the Standard Proctor Compaction Test, namely dry of optimum (-3% OMC), optimum (OMC) and wet of optimum ($+3\%$ OMC). After the required amount of distilled water was added, each specimen was thoroughly mixed and sealed in plastic bags, as shown in Figure 3.25, to allow uniform moisture distribution throughout the soil mass prior to compaction.



Figure 3.25 Residual Soil Specimens Sealed in Plastic Bags for Moisture Conditioning

The sealed specimens were conditioned for approximately 24 hours to achieve moisture equalisation before compaction and hydraulic conductivity testing. This conditioning period was adopted based on the recommendation of Mitchell and Soga (2005), who reported that approximately 24 hours is generally sufficient for moisture redistribution in compacted fine-grained soils, thereby promoting uniform moisture conditions throughout the specimen. The moisture conditions adopted for the hydraulic

conductivity test are summarised in Table 3.7. A total of 2000 g of residual soil was prepared for each specimen, and the required quantity of distilled water was calculated based on the target moisture content corresponding to the dry-of-optimum, optimum, and wet-of-optimum conditions for each soil.

Table 3.7
Sample Preparation for Hydraulic Conductivity Test

Sample Name	Moisture Condition	MC (%)	Soil (g)	Water(mL)
-3T12	-3%	15.56	2000	311.2
T12	OMC	18.56	2000	371.2
+3T12	+3%	21.56	2000	431.2
-3AH	-3%	8.75	2000	175
AH	OMC	11.75	2000	235
+3AH	+3%	14.75	2000	295

3.4.2 Modified Oedometer Test

The hydraulic conductivity of the compacted residual soil specimens was determined using a modified oedometer apparatus in accordance with BS 1377 Part 5:1990. The testing procedure was adapted from the conventional consolidation test by incorporating a hydraulic conductivity measurement system consisting of a burette, inlet and outlet tubing, and a constant hydraulic head arrangement, following the methodology described by Sawicki et al. (2009) and GeoStru (2024). This modification enables hydraulic conductivity to be evaluated under progressively increasing vertical loads representative of landfill liner conditions. Before specimen preparation, the cutting ring was cleaned and weighed to obtain its initial mass, as shown in Figure 3.26.



Figure 3.26 Initial Weighing of the Empty Cutting Ring

The residual soil was prepared at the target moisture condition based on the Optimum Moisture Content (OMC) obtained from the Standard Proctor compaction test. Additional specimens were prepared at -3% OMC (dry-of-optimum) and $+3\%$ OMC (wet-of-optimum) to represent practical field moisture variations, consistent with the allowable moisture tolerance for compacted clay liners recommended by Roberts (2017). Each specimen was compacted using the Standard Proctor compactor to achieve a uniform density representative of landfill liner construction. The compacted specimen inside the compaction mould is shown in Figure 3.27.

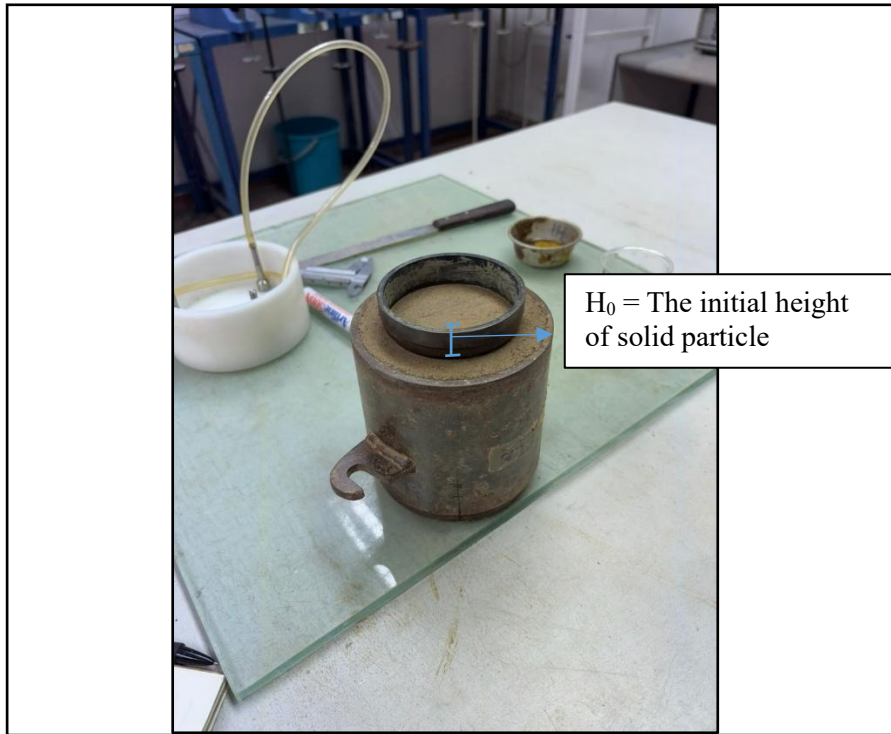


Figure 3.27 Compacted Residual Soil Specimen in the Standard Proctor Mould

Following compaction, the specimen was transferred directly from the compaction mould into the cutting ring using a horizontal extrusion device to preserve the compacted density and minimise disturbance to the soil structure. The extrusion process is illustrated in Figure 3.28, while the extracted soil specimen contained within the cutting ring is shown in Figure 3.29.



Figure 3.28 Horizontal Extrusion of the Compacted Soil into the Cutting Ring



Figure 3.29 Compacted Residual Soil Specimen after Extrusion

After extrusion, excess soil protruding beyond both ends of the cutting ring was carefully trimmed flush with the ring surfaces to produce a specimen with uniform dimensions. The cutting ring containing the trimmed specimen was then weighed to determine the initial specimen mass prior to hydraulic conductivity testing, as shown in Figure 3.30.

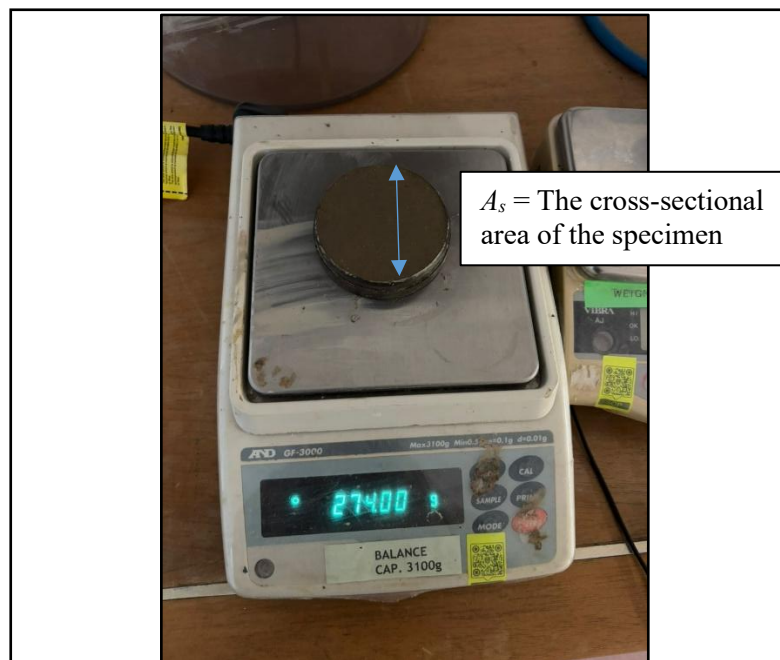


Figure 3.30 Weighing of the Cutting Ring Containing the Soil Specimen

The modified oedometer cell was subsequently assembled by placing porous stones and filter papers above and below the compacted specimen to facilitate uniform water flow during testing. The assembled modified oedometer cell is presented in Figure 3.31.

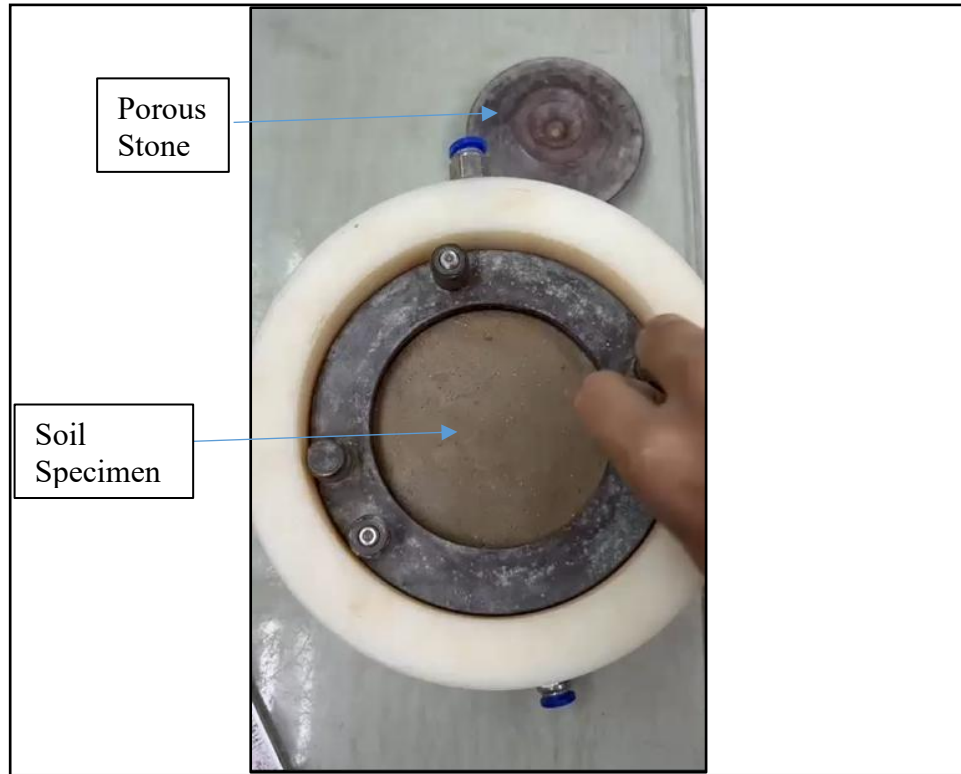


Figure 3.31 Assembly of the Modified Oedometer Cell

The assembled oedometer cell was installed in the consolidation loading frame, and the inlet and outlet tubes were connected to establish the hydraulic flow system. Water was introduced gradually until the specimen became fully saturated before the commencement of hydraulic conductivity testing. The complete installation of the modified oedometer cell is shown in Figure 3.32.

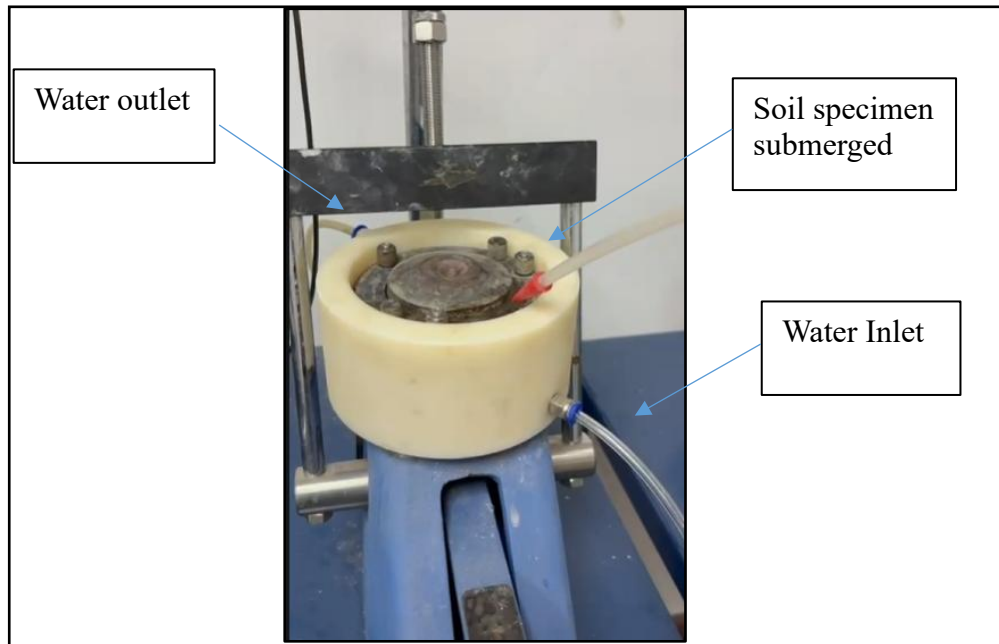
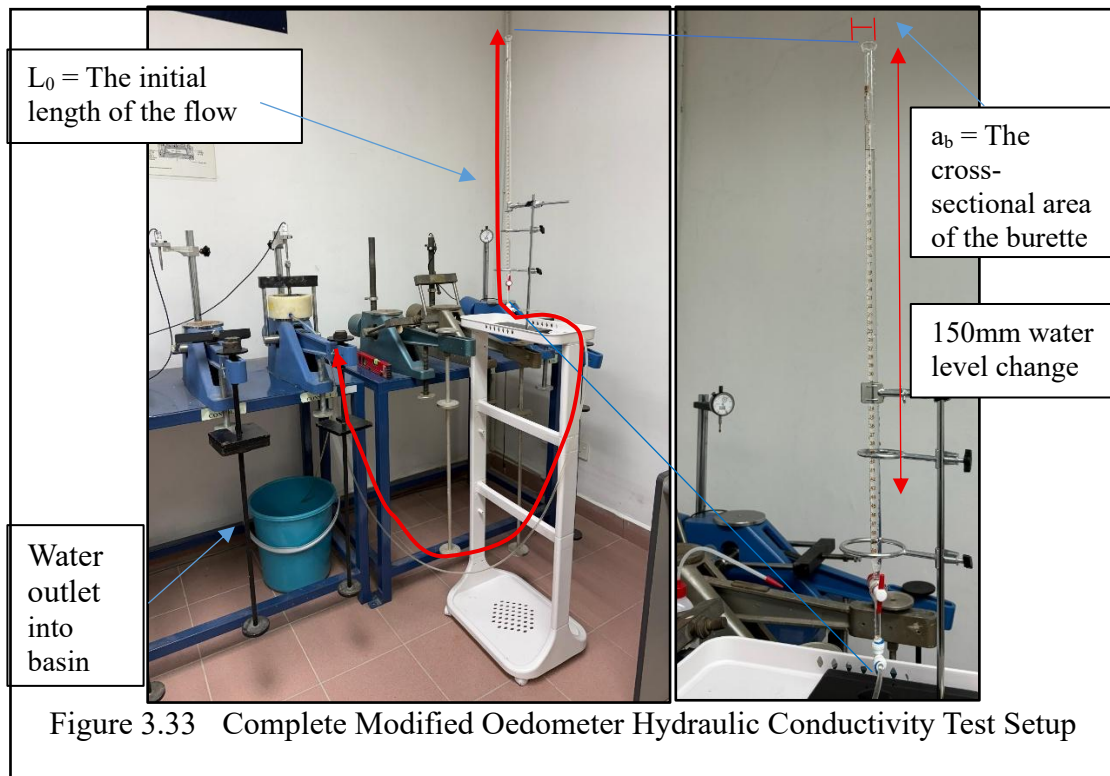


Figure 3.32 Installation of the Modified Oedometer Cell in the Consolidation Frame

A graduated burette was connected to the inlet tubing to provide a constant hydraulic head for the falling-head hydraulic conductivity test. Before each measurement, the burette was completely filled with water to a height of 3000 mm, corresponding to the full length of the burette. Following the procedure recommended by GeoStru (2024), the time required for the water level to fall by 150 mm (from 3000 mm to 2850 mm) was recorded for each loading stage. The complete modified oedometer hydraulic conductivity test arrangement is shown in Figure 3.33.



Vertical loads of 25 kPa, 50 kPa, 100 kPa and 200 kPa were applied sequentially without unloading, following the loading procedure adopted in the conventional consolidation test. These incremental loads simulate the progressively increasing overburden pressure imposed on landfill liners during waste placement. At each loading stage, the time required for the hydraulic head to decrease by 150 mm was recorded and subsequently used in the hydraulic conductivity calculation. The application of incremental loading is illustrated in Figure 3.34.

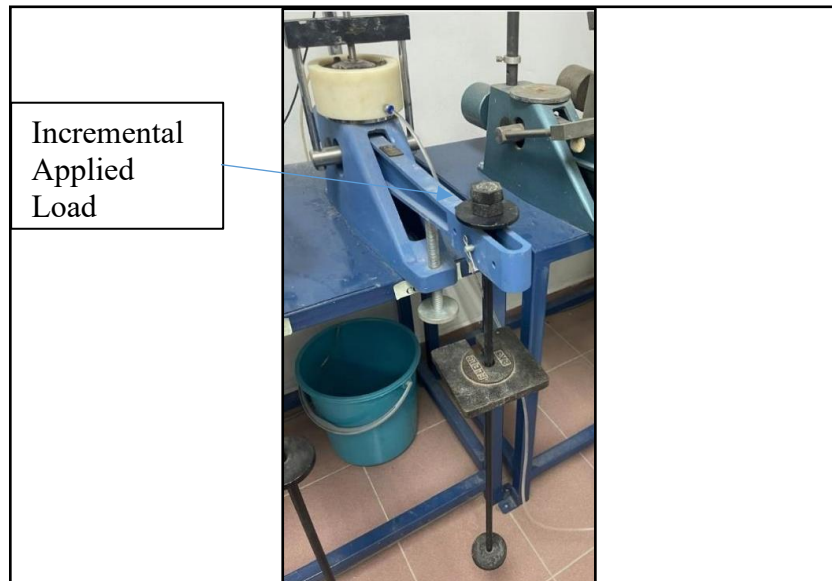


Figure 3.34 Application of Incremental Vertical Loads During the Modified Oedometer Test

Upon completion of the hydraulic conductivity test, the specimen was removed from the cutting ring and oven dried at 105–110°C for approximately 24 hours to determine its final moisture content and dry mass. The dried specimen was subsequently weighed for verification of the hydraulic conductivity calculations. The oven-drying and final weighing procedures are shown in Figure 3.35.



Figure 3.35 Oven Drying and Final Weighing of the Tested Soil Specimen

3.4.3 Hydraulic Conductivity Analysis

The hydraulic conductivity (k) of each compacted residual soil specimen was calculated in accordance with BS 1377-5:1990 using the hydraulic head, flow time,

specimen dimensions and burette dimensions recorded during the modified oedometer test. The hydraulic conductivity was determined using Equation (3.2), which was adapted from BS 1377-5:1990 and the hydraulic conductivity calculation procedure described by GeoStru (2023) for oedometer-based hydraulic conductivity analysis. The required parameters were obtained directly from the experimental measurements recorded at each applied vertical load increment throughout the hydraulic conductivity test. The hydraulic conductivity was determined using Equation (3.2)

$$k = [H_0 - \delta H] \left(\frac{a_b}{A_s} \right) \left(\frac{\log_e \frac{L_0}{L_t}}{t_t - t_0} \right) (10^{-2}) \quad (3.2)$$

Where:

H_0 = The initial height of solid particle (cm)

δH = The final height of solid particle (cm)

a_b = The cross-sectional area of the burette (cm²)

A_s = The cross-sectional area of the specimen (cm²)

L_0 = The initial length of the flow path (mm)

L_t = The current length of the flow path t_t (mm)

t_t = The initial time corresponding to the reading L_0 (sec)

t_0 = The subsequent time corresponding to the reading L_t (sec)

3.5 Analysis of Relationship between Hydraulic Conductivity with Soil Characteristics

All experimental results obtained from the laboratory tests were analysed to evaluate the relationships between the physical properties, compaction characteristics and hydraulic conductivity of the residual soil samples. Initial data processing was carried out using Microsoft Excel, where the experimental data were organised into tables and graphs for comparison and preliminary interpretation. Graphical analysis was used to illustrate the relationships between hydraulic conductivity and the investigated soil characteristics, including particle size distribution, particle density, Atterberg limits, linear shrinkage, dry density and moisture condition. Microsoft Excel is commonly used in geotechnical studies for organising laboratory datasets and supporting preliminary data interpretation (Waleed et al., 2025).

Further statistical analyses were performed using Minitab to evaluate the relationships between the measured soil characteristics and hydraulic conductivity. Prior to the statistical analyses, a normality test was conducted to determine whether the experimental data satisfied the assumptions required for parametric statistical methods (Montgomery et al., 2021). Correlation analysis was subsequently performed to determine the strength and direction of the relationships between the investigated variables, while regression analysis was used to explore possible relationships between soil characteristics and hydraulic conductivity. In addition, paired t-tests were carried out to evaluate whether statistically significant differences existed between the hydraulic conductivity values obtained under the different moisture conditions. The statistical procedures adopted in this study followed established statistical approaches commonly applied in engineering data analysis (Kutner et al., 2005).

The combined graphical and statistical analyses were used to identify the soil characteristics that most strongly influenced hydraulic conductivity and to compare the hydraulic conductivity behaviour of the residual soils obtained from the Tanjung Dua Belas and Air Hitam landfill areas. The outcomes of these analyses supported the evaluation of the suitability of the investigated residual soils for landfill liner applications and addressed the fourth research objective of this study.

3.5.1 Relationship of Particle Density with Hydraulic Conductivity

The relationship between particle density and hydraulic conductivity was evaluated to examine the influence of particle density on the hydraulic conductivity behaviour of the residual soil samples. The particle density values obtained from the specific gravity test were analysed together with the corresponding hydraulic conductivity values determined at the optimum moisture content (OMC). Scatter plots and trendlines were developed using Microsoft Excel to illustrate the relationship between particle density and hydraulic conductivity. The resulting relationship was interpreted by examining the trend of the plotted data to evaluate the influence of particle density on the hydraulic conductivity behaviour of the residual soils obtained from the Tanjung Dua Belas and Air Hitam landfill areas.

3.5.2 Relationship of Plasticity and Shrinkage Characteristics with Hydraulic Conductivity

The relationship between the Atterberg limits, comprising the Liquid Limit (LL), Plastic Limit (PL) and Plasticity Index (PI), together with the Linear Shrinkage (LS), and hydraulic conductivity was evaluated to examine the influence of the measured plasticity and shrinkage characteristics on the hydraulic conductivity behaviour of the residual soil samples. The LL, PL, PI and LS values obtained from the laboratory tests were analysed together with the corresponding hydraulic conductivity values determined at the Optimum Moisture Content (OMC). Scatter plots and trendlines were developed using Microsoft Excel to illustrate the relationships between the measured index properties and hydraulic conductivity. The resulting relationships were interpreted by examining the trend of the plotted data to evaluate the influence of the plasticity and shrinkage characteristics on the hydraulic conductivity behaviour of the residual soils obtained from the Tanjung Dua Belas and Air Hitam landfill areas.

3.5.3 Relationship of Compaction with Hydraulic Conductivity

The relationship between compaction behaviour and hydraulic conductivity was evaluated to examine the influence of dry density and moisture condition on the hydraulic conductivity behaviour of the residual soil samples. The dry density values obtained at the dry-of-optimum (-3% OMC), optimum (OMC) and wet-of-optimum ($+3\%$ OMC) moisture conditions were analysed together with the corresponding hydraulic conductivity values determined under the same compaction conditions. Scatter plots and trendlines were developed using Microsoft Excel to illustrate the relationships between dry density and hydraulic conductivity, as well as between moisture condition and hydraulic conductivity. The resulting relationships were interpreted by examining the trend of the plotted data to evaluate the influence of compaction behaviour on the hydraulic conductivity of the residual soils obtained from the Tanjung Dua Belas and Air Hitam landfill areas.

3.5.4 Minitab Normality Analysis of Hydraulic Conductivity with soil characteristics

Prior to the statistical analyses, the distribution of the experimental data was evaluated using Minitab Statistical Software (Minitab LLC, 2023) to determine whether the measured soil characteristics and hydraulic conductivity datasets exhibited an approximately normal distribution. A total of 24 hydraulic conductivity observations obtained from the modified oedometer tests, together with their corresponding soil characteristics, including moisture content, air void, maximum dry density and applied vertical load, were entered into the software for statistical evaluation. Descriptive statistical analysis was first performed to summarise each variable by determining the mean, median, minimum value, maximum value, standard deviation, skewness and kurtosis, providing an overview of the distribution characteristics and variability of the experimental dataset prior to further statistical analyses (Montgomery et al., 2021).

The normality of the dataset was subsequently assessed by examining the skewness and kurtosis values generated by Minitab. Skewness evaluates the degree of symmetry of the data distribution, whereas kurtosis describes the degree of peakedness or flatness relative to a normal distribution (Kim, 2013). Following the recommendations of George and Mallery (2010), datasets with skewness and kurtosis values between -2 and $+2$ were considered to exhibit an approximately normal distribution. The outcome of the normality assessment was then used to verify the suitability of the dataset for subsequent Pearson correlation analysis, regression analysis and paired t-test, which assume that the analysed variables satisfy the normality requirement for parametric statistical analyses (Montgomery et al., 2021).

3.5.5 Minitab Correlation Analysis of Hydraulic Conductivity with soil characteristics

Pearson correlation analysis was performed using Minitab Statistical Software (Minitab LLC, 2023) to evaluate the linear relationships between hydraulic conductivity and the measured soil characteristics. A total of 24 hydraulic conductivity observations obtained from the modified oedometer tests, together with their corresponding soil characteristics, including moisture content, air void, maximum dry density and applied vertical load, were used in the analysis. The analysis was conducted to determine the

strength and direction of the relationships between hydraulic conductivity and the investigated physical and compaction properties.

The Pearson correlation coefficient (r) was used to quantify the degree of linear association between the investigated variables. Correlation coefficient values range from -1 to $+1$, where values approaching $+1$ indicate a strong positive linear relationship, values approaching -1 indicate a strong negative linear relationship, and values close to 0 indicate little or no linear relationship between the variables (Schober et al., 2018). The statistical significance of each correlation was evaluated using the corresponding p-value generated by Minitab. A p-value less than 0.05 was considered to indicate a statistically significant linear relationship between the investigated variables at the 95% confidence level (Montgomery et al., 2021). The Pearson correlation analysis was subsequently used to identify the soil characteristics that exhibited statistically significant relationships with hydraulic conductivity before further empirical regression modelling.

3.5.6 Minitab Regression Analysis of Hydraulic Conductivity with soil characteristics

Regression Analysis was performed using Minitab Statistical Software (Minitab LLC, 2023) to explore the relationships between hydraulic conductivity and the measured soil characteristics. The analysis was conducted to develop empirical regression equations describing the relationships between hydraulic conductivity and the selected physical and compaction properties obtained from the laboratory tests. A total of 24 hydraulic conductivity observations obtained from the modified oedometer tests were used in the regression analysis. The dataset was divided into two groups, whereby the 12 observations from the Tanjung Dua Belas (T12) residual soil were used as the model development (analysis) dataset to establish the regression equations, while the remaining 12 observations from the Air Hitam (AH) residual soil were reserved as an independent validation dataset to evaluate the predictive capability of the developed models.

Regression modelling was used to evaluate the extent to which variations in the measured soil characteristics could explain the corresponding variations in hydraulic conductivity. The explanatory capability of the regression model was evaluated using the coefficient of determination (R^2), which represents the proportion of the variation

in hydraulic conductivity explained by the independent variables included in the regression model (Montgomery et al., 2021). Higher R^2 values indicate that a larger proportion of the variability in hydraulic conductivity is explained by the selected soil characteristics, whereas lower R^2 values suggest that a greater proportion of the variability may be attributed to factors not included in the regression model (Kutner et al., 2005). The regression coefficients were further evaluated to determine the direction and relative influence of each soil characteristic on hydraulic conductivity. The developed regression equations and their corresponding R^2 values were subsequently interpreted to identify the soil characteristics that contributed most to the observed hydraulic conductivity behaviour of the investigated residual soils before being evaluated using the independent validation dataset.

3.5.7 Minitab Paired t-Test Analysis of Hydraulic Conductivity

Paired t-test analysis was performed using Minitab Statistical Software (Minitab LLC., 2023) to evaluate the predictive capability of the empirical regression models developed from the regression analysis. The regression equations established using the 12 experimental hydraulic conductivity observations from the Tanjung Dua Belas (T12) residual soil were subsequently applied to the corresponding independent variables of the 12 Air Hitam (AH) residual soil observations to generate predicted hydraulic conductivity values. These predicted values were then plotted against the experimentally measured hydraulic conductivity values obtained from the modified oedometer tests to evaluate the agreement between the predictive model and the laboratory results. The comparison plots also provide the corresponding coefficient of determination (R^2), which indicates how closely the predicted hydraulic conductivity values follow the trend of the measured values.

The paired t-test was subsequently performed to determine whether a statistically significant difference existed between the measured and predicted hydraulic conductivity values. The statistical significance of the comparison was evaluated using the corresponding p-value generated by Minitab. Following the principles of hypothesis testing described by Montgomery et al. (2021), a p-value greater than 0.05 indicates that no statistically significant difference exists between the measured and predicted hydraulic conductivity values at the 95% confidence level, suggesting that the developed empirical regression model provides an acceptable representation of the

experimental hydraulic conductivity data. Therefore, the R^2 value and the paired t-test p-value were interpreted together to evaluate both the predictive capability and the statistical agreement of the developed empirical regression models.

CHAPTER 4

RESULTS & DISCUSSION

4.1 Introduction

This chapter presents and discusses the results obtained from the laboratory testing and statistical analyses conducted on the residual soils collected from the Tanjung Dua Belas and Air Hitam landfill sites. The findings are organised according to the four research objectives established for this study, beginning with the evaluation of the physical properties, followed by the assessment of compaction behaviour, hydraulic conductivity performance, and the relationship between hydraulic conductivity and soil characteristics. The experimental results are interpreted with reference to the relevant engineering principles, landfill liner requirements and findings reported in previous studies to evaluate the suitability of the investigated residual soils for landfill liner applications. Statistical analyses using Microsoft Excel and Minitab Statistical Software are also presented to establish the relationships between soil characteristics and hydraulic conductivity, including descriptive statistics, Pearson correlation analysis, regression modelling, and paired t-test validation. The integration of the laboratory and statistical analyses provides a comprehensive understanding of the engineering behaviour of the investigated residual soils and supports the achievement of the four research objectives of this study.

4.2 Physical Properties

The physical properties of the residual soils obtained from the Tanjung Dua Belas and Air Hitam landfill areas were evaluated to establish the fundamental characteristics influencing their suitability as landfill liner materials. These properties govern the soil behaviour during compaction, moisture retention and hydraulic conductivity, all of which are critical to the performance of compacted soil liners. The laboratory tests included particle size distribution, particle density, Atterberg limits and linear shrinkage, which collectively provide information on soil composition, grading, plasticity and volume change behaviour. According to Nikbakht et al. (2023), soils suitable for landfill liner applications should possess a high proportion of fine particles, adequate plasticity, low hydraulic conductivity and sufficient compaction capability to

form a dense soil structure with limited pore connectivity, thereby restricting leachate migration. The physical property results presented in this section provide the basis for interpreting the compaction behaviour and hydraulic conductivity performance of the investigated residual soils. These results are subsequently used to evaluate the suitability of the Tanjung Dua Belas and Air Hitam residual soils for landfill liner applications.

4.2.1 *pH* Values

The *pH* values of the residual soil samples collected from Tanjung Dua Belas (T12) and Air Hitam (AH) were measured in triplicate, and the average values were calculated to ensure the reliability and consistency of the measurements. The T12 soil recorded *pH* values of 2.96, 2.79 and 2.69, giving an average *pH* of 2.81, whereas the AH soil recorded *pH* values of 3.70, 3.66 and 3.60, with an average of 3.65, as presented in Table 4.1. Both residual soils exhibit strongly acidic conditions, with the T12 soil showing greater acidity than the AH soil. The close agreement between the repeated measurements indicates good repeatability of the test and suggests that the collected samples possess consistent chemical characteristics.

Table 4.1
Tanjung Dua Belas and Air Hitam *pH* Result

Sample	T12	AH
<i>pH</i> Value	2.81	3.65

The acidic nature of both residual soils is likely associated with the landfill environment, where the decomposition of municipal solid waste generates organic acids and acidic leachate that may infiltrate the underlying soil. In addition, the buffering capacity of tropical residual soils is generally limited, allowing acidic conditions to persist within the subsurface. The lower *pH* observed in the T12 soil may indicate a greater degree of acidification within the sampled area, possibly resulting from local variations in waste composition, decomposition processes or prolonged interaction with landfill leachate. Similar findings have been reported in previous landfill studies. Ahmad et al. (2018) reported that soils surrounding Malaysian landfill sites commonly exhibit *pH* values ranging from 3 to 5, which were attributed to continuous leachate

infiltration and the production of organic acids during waste decomposition. Wdowczyk et al. (2021) similarly reported that leachate generated during the early stages of landfill operation typically exhibits acidic characteristics, with pH values generally ranging from 3.7 to 6.5. Comparable acidic soil conditions were also observed by Adeyemo and Bello (2024), who reported pH values below 4.0 for residual soils collected from an active municipal landfill following prolonged exposure to landfill leachate. The pH values obtained for both T12 and AH therefore fall within the range reported for residual soils influenced by active landfill environments, supporting the representativeness of the sampled residual soils for the present investigation.

4.2.2 Particle Density

The particle density values of the residual soils collected from Tanjung Dua Belas (T12) and Air Hitam (AH) are presented in Table 4.2. The measurements were determined using the small pycnometer method, and the measured specific gravity values were converted to particle density using the density of water at room temperature (0.9982 Mg/m^3). The specific gravity of the T12 residual soil was 2.227, corresponding to a particle density of 2.223 Mg/m^3 , whereas the AH residual soil recorded a specific gravity of 2.482, corresponding to a particle density of 2.478 Mg/m^3 . These results indicate that the AH residual soil possesses a higher particle density than the T12 residual soil. The reported values represent the average of three pycnometer measurements for each residual soil sample. The close agreement among the repeated measurements indicates good repeatability of the test and confirms the reliability of the particle density test. The higher particle density observed for the AH residual soil suggests the presence of relatively denser mineral constituents or a lower proportion of organic matter compared with the T12 residual soil.

Table 4.2
Tanjung Dua Belas and Air Hitam Particle Density Result

Sample	Specific Gravity	Particle Density (Mg/m^3)
T12	2.277	2.223
AH	2.482	2.478

Variations in particle density are primarily influenced by differences in mineral composition and organic matter content. Mineral constituents with relatively high specific gravity, such as iron-bearing minerals, generally increase particle density, whereas organic matter lowers the overall particle density because of its comparatively lower density (Ruehlmann et al., 2020). The lower particle density recorded for the T12 residual soil may therefore indicate a greater degree of weathering or a higher proportion of organic constituents than the AH residual soil. Such variations are commonly observed in tropical residual soils because weathering intensity and local geological conditions influence the composition and density of soil particles.

Particle density also provides a useful indication of the mineralogical characteristics of soils when compared with values commonly reported for natural clay minerals used in landfill liner applications. Clay minerals such as kaolinite and illite generally exhibit particle densities ranging from approximately 2.60 to 2.80 Mg/m³, depending on their mineralogical composition (Mitchell & Soga, 2005). Both residual soils investigated in the present study exhibit particle densities below this range, with the T12 residual soil showing the lowest value (2.223 Mg/m³). This suggests that the investigated residual soils contain weathered mineral constituents and possibly a greater proportion of lighter materials than relatively pure clay minerals. Nevertheless, both soils remain within the range commonly reported for tropical residual soils, where mineral weathering and local geological conditions produce lower particle density values than those observed for pure clay minerals (Rahardjo et al., 2004).

4.2.3 Particle Size Distribution

The particle size distribution results for the residual soil samples obtained from Tanjung Dua Belas and Air Hitam are presented in Figure 4.1, which illustrates the grading curves over a particle size range of 0.001 mm to 10 mm on a logarithmic scale. The grading curves provide information on the proportions of clay, silt and sand within each soil and are commonly used to evaluate soil classification, gradation characteristics and engineering behaviour. Particle size distribution influences several important engineering properties, including compaction behaviour, pore structure and hydraulic conductivity. In general, soils containing a greater proportion of fine particles are capable of forming denser soil matrices with smaller interconnected pore spaces after compaction, making them more suitable for landfill liner applications.

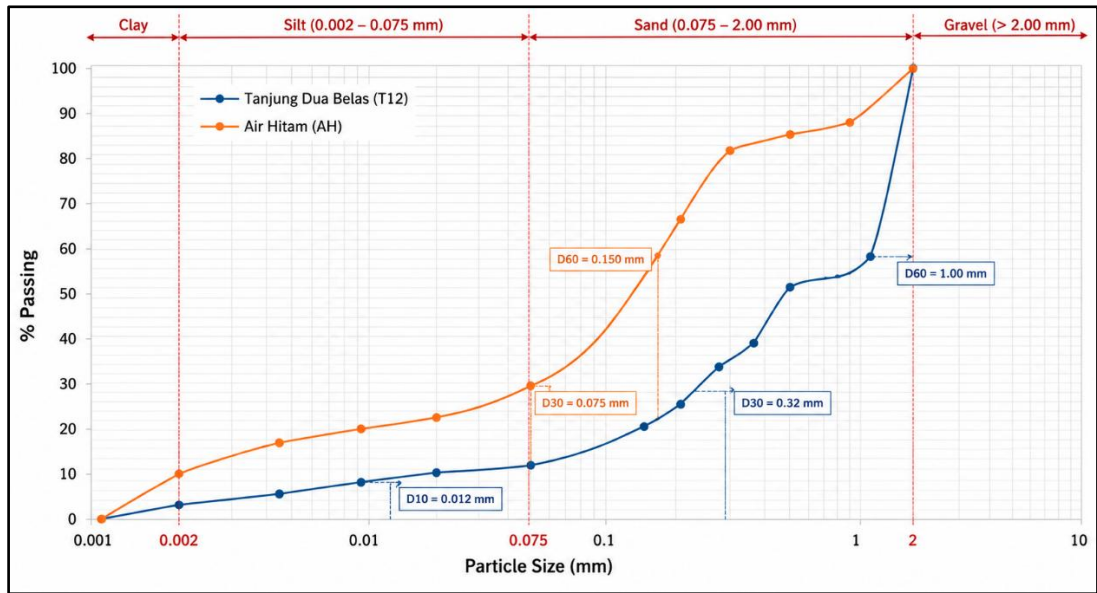


Figure 4.1 Particle Size Distribution Curves

Table 4.3 summarises the particle size distribution characteristics of both residual soils. The Tanjung Dua Belas soil consists of 86% sand, 10% silt and 4% clay, whereas the Air Hitam soil contains 70% sand, 20% silt and 10% clay. Although both soils are dominated by sand-sized particles, the Air Hitam soil contains a greater proportion of fine particles (30%) than the Tanjung Dua Belas soil (14%), indicating a relatively finer overall grading. This difference is also reflected by the characteristic particle diameters. The Air Hitam soil records $D_{60} = 0.150$ mm, $D_{30} = 0.075$ mm and $D_{10} = 0.002$ mm, whereas the Tanjung Dua Belas soil records larger characteristic diameters of $D_{60} = 1.000$ mm, $D_{30} = 0.320$ mm and $D_{10} = 0.012$ mm. The smaller characteristic particle sizes observed in the Air Hitam soil indicate a finer grading, which generally promotes the development of smaller pore spaces after compaction.

The gradation coefficients further distinguish the grading characteristics of the two soils. The coefficient of uniformity (C_u) is 83.33 for Tanjung Dua Belas and 75.00 for Air Hitam, indicating that both soils possess a wide range of particle sizes. However, the coefficient of gradation (C_g) values of 8.53 and 18.75, respectively, fall outside the range typically associated with well-graded soils. According to the Unified Soil Classification System (USCS), well-graded sands generally satisfy $C_u \geq 6$ and $1 \leq C_g \leq 3$ (ASTM D2487, 2017). Although both soils satisfy the uniformity requirement, their C_g values indicate that the particle size distributions are not continuously graded throughout the entire size range. Based on the particle size distribution alone, both

residual soils are therefore classified as Silty SAND, with sand representing the dominant fraction and silt acting as the secondary component.

Table 4.3
Tanjung Dua Belas and Air Hitam Particle Size Distribution Summary

	T12	AH
Gravel (%)	0	0
Sand (%)	86	70
Silt (%)	10	20
Clay (%)	4	10
D60 (mm)	1.000	0.150
D30 (mm)	0.320	0.075
D10 (mm)	0.012	0.002
Cu	83.33	75.00
Cg	8.53	18.75
Soil Classification	Silty SAND	Silty SAND

The grading characteristics obtained in this study are consistent with observations reported for tropical residual soils used in landfill engineering. Yang et al. (2024) reported that increasing fine particle content enhances water retention because finer particles increase the specific surface area and reduce pore sizes within the soil matrix. Similarly, Adeyemo and Bello (2024) observed that residual soils containing approximately 25–35% fines (clay and silt combined) achieved lower hydraulic conductivity after compaction than soils with lower fine contents, highlighting the importance of fine particles in improving barrier performance. In the present study, the Air Hitam residual soil contains 30% fines, whereas the Tanjung Dua Belas soil contains 14% fines, suggesting that the Air Hitam soil has greater potential to develop a denser soil structure during compaction. Nevertheless, particle size distribution alone is insufficient to determine landfill liner suitability because hydraulic performance is also influenced by plasticity, compaction characteristics and moisture condition. These aspects are therefore evaluated in the subsequent sections before the overall suitability of both residual soils as landfill liner materials is assessed.

4.2.4 Atterberg Limit

The Atterberg limit values of the residual soils collected from Tanjung Dua Belas (T12) and Air Hitam (AH) are presented in Table 4.4. The T12 residual soil recorded a Liquid Limit (LL) of 39.83% and a Plastic Limit (PL) of 16.85%, resulting in a Plasticity Index (PI) of 22.98%. The AH residual soil recorded a lower LL of 24.14% and PL of 10.75%, producing a PI of 13.39%. Based on the Casagrande Plasticity Chart, the fine fraction of the T12 residual soil is classified as CI (Clay of Intermediate Plasticity), whereas the AH residual soil is classified as CL (Clay of Low Plasticity). The reported values represent the average of repeated laboratory measurements, indicating good repeatability of the Atterberg Limit Tests.

Table 4.4
Tanjung Dua Belas and Air Hitam Atterberg Limit Result

Sample	Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)	Soil Classification
T12	39.83%	16.85%	22.98%	CI (Clay of Intermediate Plasticity)
AH	24.14%	10.75%	13.39%	CL (Clay of Low Plasticity)

The higher plasticity index of the T12 residual soil indicates that its fine fraction exhibits greater plastic behaviour than that of the AH residual soil. Although the particle size distribution shows that the AH residual soil contains a higher proportion of clay-sized particles (10%) than the T12 residual soil (4%), the T12 soil exhibits a considerably higher plasticity index. This demonstrates that soil plasticity is governed not only by the quantity of clay-sized particles but also by the mineralogical composition and activity of the fine fraction, which influence the interaction between soil particles and water (Mitchell & Soga, 2005).

The Atterberg limit results obtained in this study are consistent with the ranges commonly reported for compacted clay liners used in landfill engineering. Daniel (1993) reported that soils used as compacted landfill liners typically exhibit Plasticity Index values between approximately 10% and 30%, while the Liquid Limit generally exceeds 20–30%, with many successful compacted liner soils exhibiting Liquid Limit values between 30% and 60%. The T12 residual soil (LL = 39.83%, PI = 22.98%) falls comfortably within these commonly reported ranges, whereas the AH residual soil (LL

= 24.14%, PI = 13.39%) satisfies the lower end of the recommended plasticity range. Similar observations were reported by Adeyemo and Bello (2024), who found that residual soils exhibiting Plasticity Index values of approximately 20–30% generally achieved lower hydraulic conductivity after compaction because the higher plasticity promoted improved particle bonding and reduced pore connectivity. These findings suggest that the T12 residual soil possesses favourable plasticity characteristics for landfill liner applications, whereas the AH residual soil may require more careful compaction control to achieve comparable hydraulic performance.

4.2.5 Linear Shrinkage

The linear shrinkage values of the residual soils obtained from Tanjung Dua Belas (T12) and Air Hitam (AH) are presented in Table 4.5. The T12 residual soil recorded a linear shrinkage of 6.61%, whereas the AH residual soil recorded a substantially lower value of 1.14%. These results indicate that the T12 residual soil undergoes greater volume reduction during drying than the AH residual soil. The marked difference in shrinkage behaviour reflects variations in the plasticity and mineralogical characteristics of the fine fraction rather than solely the proportion of clay-sized particles.

Table 4.5
Tanjung Dua Belas and Air Hitam Linear Shrinkage Result

Sample	Linear Shrinkage (%)
T12	6.61
AH	1.14

The higher linear shrinkage exhibited by the T12 residual soil is consistent with its higher Liquid Limit (39.83%) and Plasticity Index (22.98%), indicating that the fine fraction possesses greater plasticity and a stronger capacity to retain absorbed water before drying. Although the particle size distribution shows that the AH residual soil contains a greater proportion of clay-sized particles than the T12 residual soil, its considerably lower plasticity results in much smaller volume changes during drying. This observation demonstrates that shrinkage behaviour is governed primarily by the

plasticity and activity of the fine fraction, rather than by the percentage of clay-sized particles alone (Mitchell & Soga, 2005).

Comparable shrinkage values have been reported in previous studies of compacted fine-grained soils. Onyelowe et al. (2021) reported linear shrinkage values of approximately 12.2% for compacted clay soils evaluated under laboratory conditions, indicating substantially greater shrinkage than that observed for both residual soils in the present study. Similarly, Adeyemo and Bello (2024) reported that residual soils exhibiting relatively low linear shrinkage maintained satisfactory dimensional stability after compaction, reducing the likelihood of desiccation cracking under controlled laboratory conditions. The T12 residual soil, with a linear shrinkage of 6.61%, and the AH residual soil, with 1.14%, therefore exhibit comparatively low shrinkage when compared with values commonly reported for compacted clay soils. The very low shrinkage recorded for the AH residual soil indicates excellent dimensional stability during drying, whereas the moderate shrinkage of the T12 residual soil reflects its greater plasticity while remaining well below values commonly associated with excessive shrinkage of highly plastic clays. These characteristics are advantageous for landfill liner applications because excessive shrinkage may increase the likelihood of desiccation cracking during prolonged drying periods.

4.3 Compaction Result

The compaction characteristics of the residual soils obtained from Tanjung Dua Belas and Air Hitam were evaluated to determine their ability to achieve dense soil structures suitable for landfill liner applications. The compaction behaviour of fine-grained soils is governed by the interaction between moisture content, compactive effort and soil characteristics, which collectively influence dry density and pore structure development. Variations in moulding water content affect particle rearrangement, lubrication and pore distribution, thereby influencing the engineering behaviour of compacted soils. Recent studies have demonstrated that compacting residual soils at or slightly wet of the Optimum Moisture Content (OMC) promotes improved particle rearrangement and reduced hydraulic conductivity, making moisture control an important consideration in landfill liner construction (Adeyemo & Bello, 2024). In this study, the Standard Proctor compaction test was conducted to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of both residual soils,

providing the basis for subsequent hydraulic conductivity testing under controlled moisture conditions.

4.3.1 Sampling of Compaction

The compaction curve for the Tanjung Dua Belas soil is presented in Figure 4.2, illustrating the relationship between dry density and moisture content together with the corresponding air void lines of 0%, 5% and 10%. The compaction curve exhibits the characteristic bell-shaped relationship between moisture content and dry density. The dry density increases progressively with increasing moisture content until reaching a maximum dry density of 1.50 Mg/m^3 at an optimum moisture content of 18.56%, after which the dry density decreases as additional water occupies the pore spaces and reduces the achievable dry density. The relatively broad compaction curve indicates that the soil can be compacted over a wider range of moisture contents before reaching its optimum condition. Such behaviour is commonly associated with soils exhibiting greater plasticity and stronger moisture sensitivity. Although the particle size distribution indicates that the Tanjung Dua Belas soil contains a relatively high proportion of sand-sized particles, its compaction behaviour resembles that of a more plastic soil. This response suggests that compaction behaviour is influenced not only by particle size distribution but also by the characteristics of the fine fraction, including soil fabric, particle arrangement and plasticity, which govern moisture–density relationships during compaction. The air void lines further illustrate the compaction behaviour by showing that the measured dry densities progressively approach theoretical saturation conditions as moisture content increases.

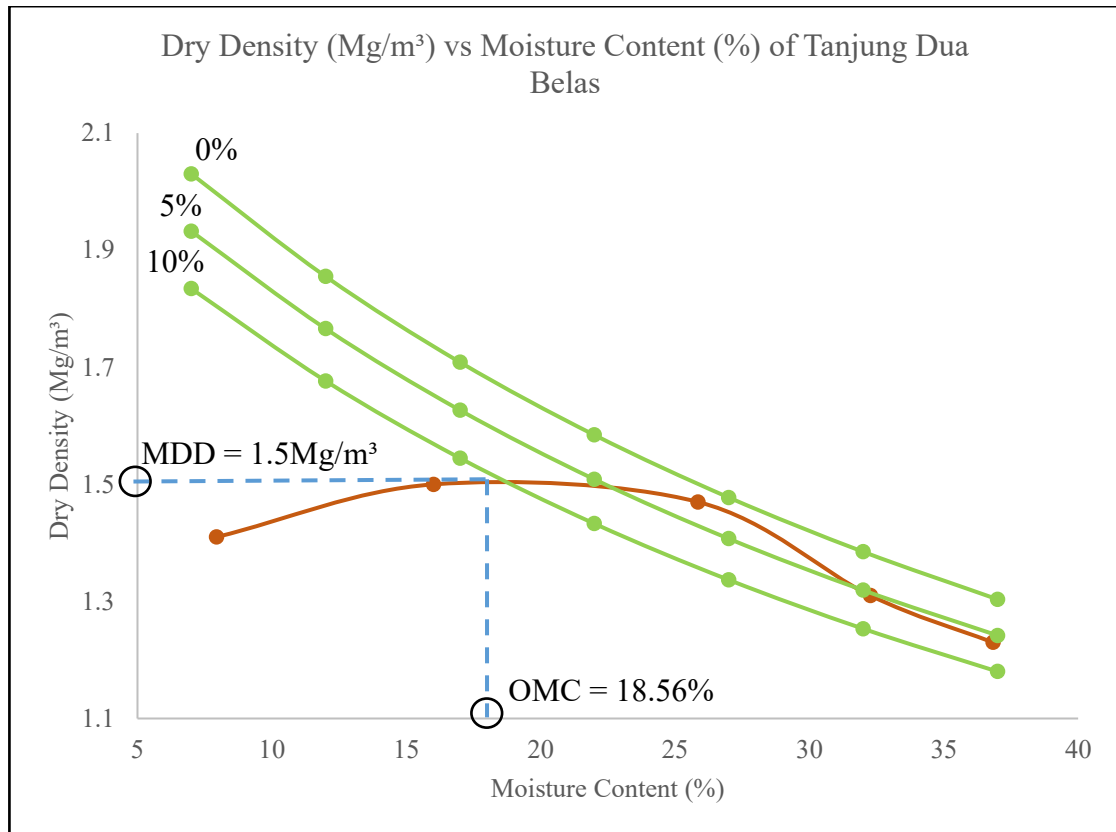


Figure 4.2 Compaction Curve of Tanjung Dua Belas

The Air Hitam soil exhibits a steeper compaction curve than the Tanjung Dua Belas soil, reaching a maximum dry density of 1.88 Mg/m^3 at an optimum moisture content of 11.75%. The narrower shape of the compaction curve indicates that the soil attains maximum densification within a relatively small range of moisture contents. This behaviour is consistent with soils containing a higher proportion of coarse particles and lower plasticity, where efficient particle rearrangement occurs with comparatively less water. This observation agrees well with the particle size distribution results presented in Section 4.1.3, which show that Air Hitam contains a greater proportion of sand-sized particles than finer fractions. Consequently, the soil requires less moisture to achieve maximum compaction and develops a higher dry density than the Tanjung Dua Belas soil. The air void reference lines further demonstrate that the compacted specimens approach lower air void conditions near the optimum moisture content, indicating efficient particle packing during compaction.

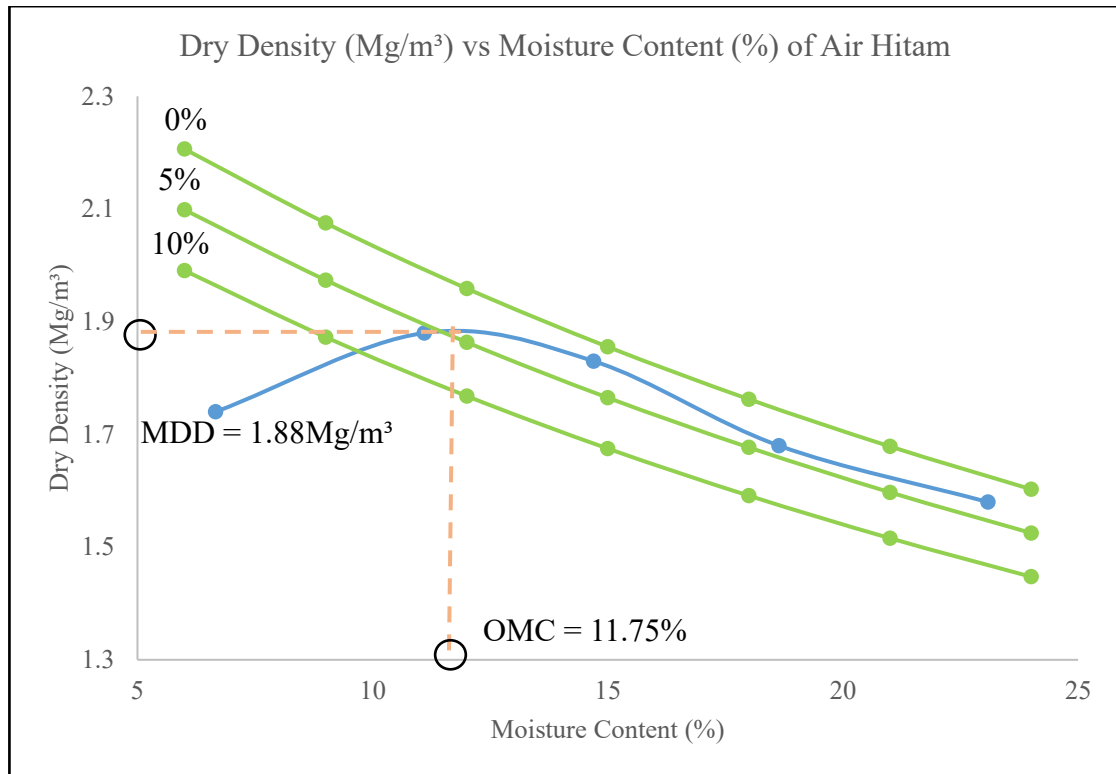


Figure 4.3 Compaction Curve of Air Hitam

A direct comparison between the compaction behaviour of both soils is presented in Figure 4.4, where the compaction curves of Tanjung Dua Belas and Air Hitam are plotted together. The comparison highlights the distinct differences in moisture–density response between the two soils. Air Hitam achieves a higher maximum dry density at a lower optimum moisture content, reflecting the more efficient packing of its comparatively coarser soil particles during compaction. In contrast, the Tanjung Dua Belas soil requires a higher moisture content to attain its maximum dry density and exhibits a broader compaction curve. Although this response is commonly associated with more plastic soils, it differs from the particle size distribution results, which indicate that Tanjung Dua Belas contains a larger proportion of sand-sized particles. This difference suggests that compaction behaviour is governed by the combined effects of particle size distribution, plasticity and soil structure rather than particle size distribution alone.

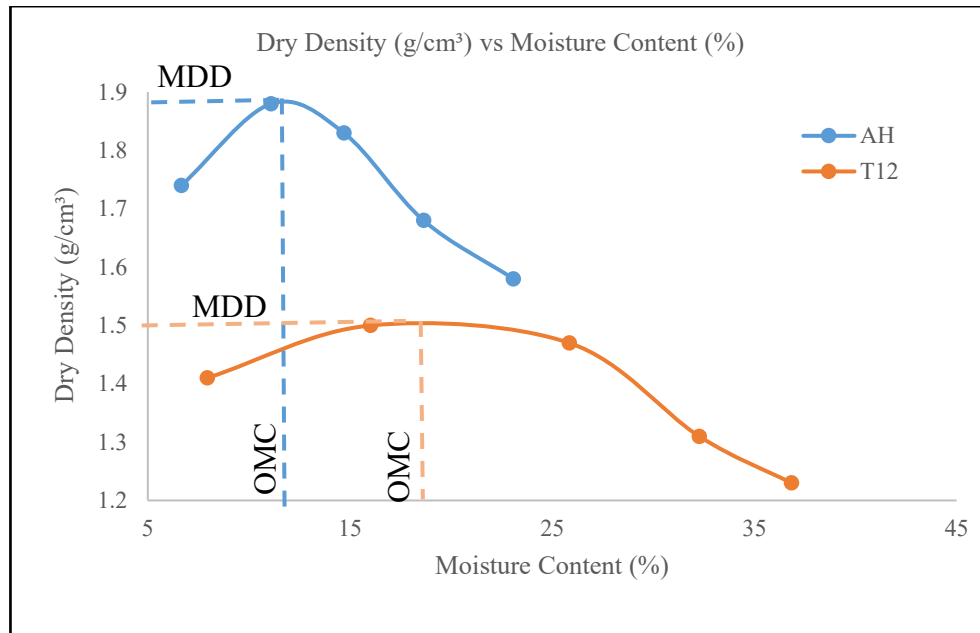


Figure 4.4 Comparison of Compaction Curves for Tanjung Dua Belas and Air Hitam

The compaction parameters summarised in Table 4.6 provide the basis for evaluating the engineering performance of both soils and are subsequently used in the hydraulic conductivity analyses. The maximum dry density and optimum moisture content obtained from the Standard Proctor compaction tests also serve as the reference conditions for preparing specimens at optimum, dry-of-optimum (-3% OMC) and wet-of-optimum ($+3\%$ OMC) moisture contents for the modified oedometer hydraulic conductivity tests.

Table 4.6
Tanjung Dua Belas and Air Hitam Compaction Result

Sample	Maximum Dry Density (Mg/m ³)	Optimum Moisture Content (%)
T12	1.50	18.56
AH	1.88	11.75

4.3.2 Moisture Variation around Optimum Moisture Content

The influence of moisture variation on compaction behaviour is evaluated at moisture contents corresponding to 3% below the Optimum Moisture Content (-3% OMC) and 3% above the Optimum Moisture Content ($+3\%$ OMC). This moisture range

represents practical field compaction conditions, where achieving the exact optimum moisture content is often difficult during landfill liner construction. Previous studies have shown that compacting cohesive soils within approximately $\pm 3\%$ of the optimum moisture content provides adequate moisture control while minimising changes in density and hydraulic performance (Roberts, 2017; Adeyemo & Bello, 2024). Evaluating soil behaviour within this range therefore provides a more realistic assessment of the sensitivity of compacted landfill liner soils to field moisture variations.

The influence of moisture variation on the Tanjung Dua Belas soil is illustrated in Figure 4.5. The maximum dry density of 1.50 Mg/m^3 occurs at an optimum moisture content of 18.56%, while slight reductions in dry density are observed when the soil is compacted under both dry-of-optimum and wet-of-optimum conditions. This behaviour reflects the typical response of cohesive soils, where insufficient moisture under dry-of-optimum conditions limits particle lubrication and restricts particle rearrangement, whereas excessive moisture under wet-of-optimum conditions increasingly occupies the pore spaces and reduces effective particle contact during compaction. The air void percentage decreases progressively from the dry-of-optimum condition towards the wet-of-optimum condition, indicating that increasing moisture content promotes more efficient particle rearrangement and reduces the volume of entrapped air within the compacted soil structure. The boundaries at -3% OMC and $+3\%$ OMC define the practical moisture range adopted for the subsequent hydraulic conductivity tests, enabling the influence of moisture deviation from the optimum condition on dry density and air void development to be evaluated under conditions representative of field compaction practices, as shown in Figure 4.5.

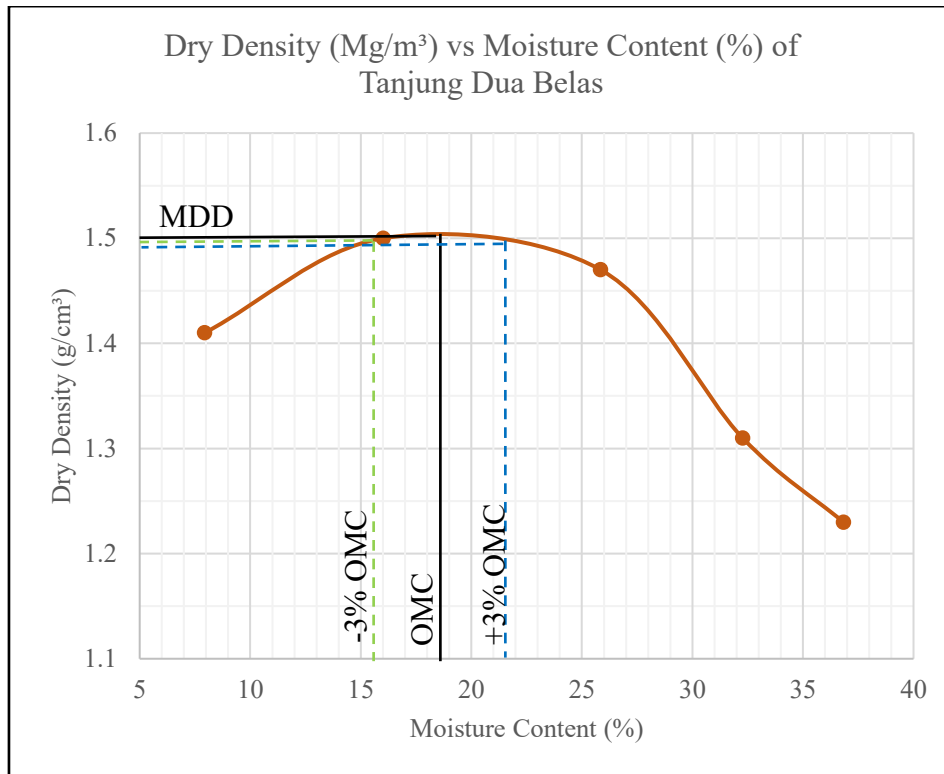


Figure 4.5 Compaction Curve of Tanjung Dua Belas under Moisture Variation around the Optimum Moisture Content

The influence of moisture variation on the Air Hitam soil is illustrated in Figure 4.6. The maximum dry density of 1.88 Mg/m^3 occurs at an optimum moisture content of 11.75%, while slightly lower dry densities are obtained under both dry-of-optimum and wet-of-optimum conditions. Compared with the Tanjung Dua Belas soil, the steeper compaction curve indicates that Air Hitam achieves maximum densification within a narrower moisture range and is therefore more sensitive to variations in moulding water content during compaction. Similar to the Tanjung Dua Belas soil, the air void percentage decreases progressively with increasing moisture content, reflecting improved particle rearrangement and a reduction in the volume of entrapped air within the compacted soil matrix. The -3% OMC and $+3\%$ OMC boundaries represent the moisture conditions selected for subsequent hydraulic conductivity testing and illustrate the influence of moisture variation on the compaction response of the Air Hitam soil, as shown in Figure 4.6.

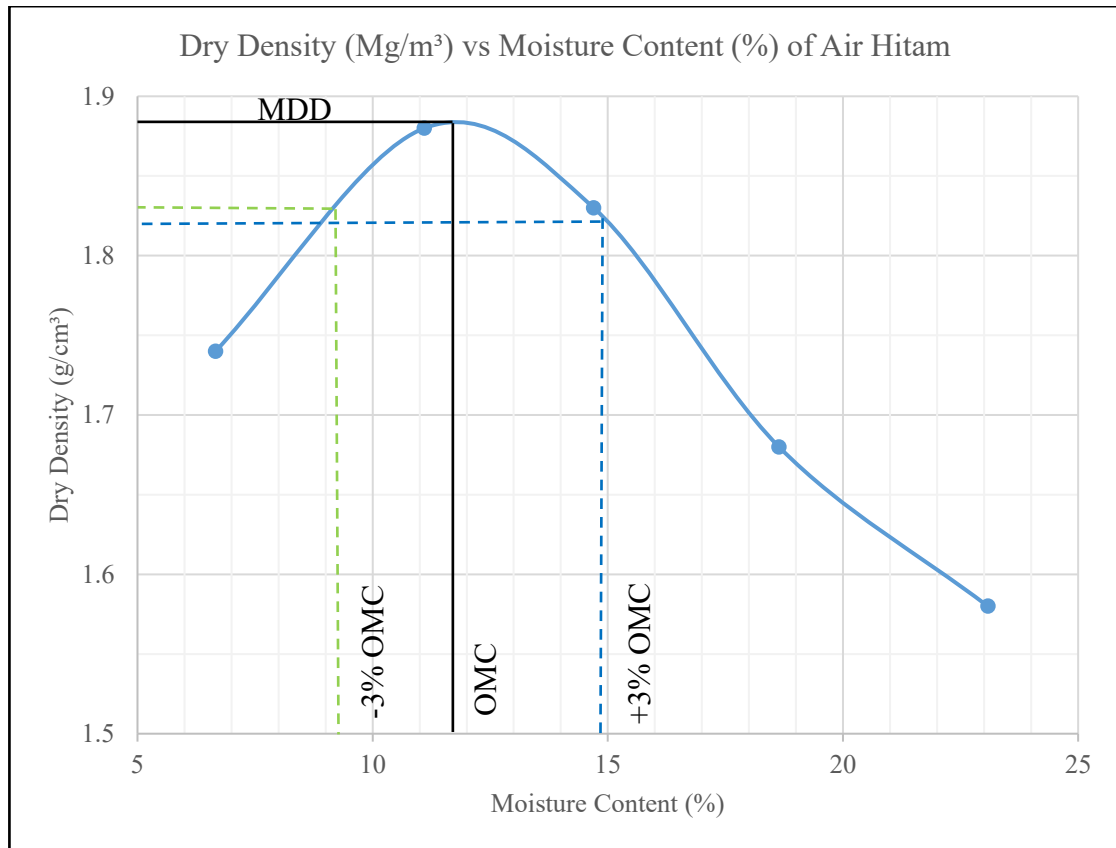


Figure 4.6 Compaction Curve of Air Hitam under Moisture Variation around the Optimum Moisture Content

A quantitative comparison of the moisture variation conditions for both soils is presented through the corresponding moisture content, dry density and air void percentages. These values allow the compaction behaviour under dry-of-optimum, optimum and wet-of-optimum conditions to be evaluated systematically, as summarised in Table 4.7.

Table 4.7
Moisture Variation Conditions with Corresponding Dry Density and Air Void Percentage

Sample Name	Moisture condition	Moisture Content (%)	Dry Density (Mg/m ³)	Air Void (%)
-3T12	-3% OMC	15.56	1.49	11.21
T12	OMC	18.56	1.5	6.15
+3T12	+3% OMC	21.56	1.48	2.92
-3AH	-3% OMC	8.75	1.84	9.63
AH	OMC	11.75	1.88	1.99

+3AH	+3% OMC	14.75	1.81	0.20
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The results presented in Table 4.7 show that both soils achieve their maximum dry density at the optimum moisture content, with slight reductions in density under both dry-of-optimum and wet-of-optimum conditions. This behaviour is characteristic of compacted cohesive soils, where insufficient water limits particle lubrication during dry-side compaction, whereas excessive water occupies part of the void space and reduces the achievable dry density during wet-side compaction. The corresponding reduction in air void content with increasing moisture content indicates progressively improved particle rearrangement and denser soil packing. Similar observations are reported by Benson et al. (1999), who demonstrated that relatively small deviations from the optimum moisture content alter soil fabric and pore continuity, thereby influencing hydraulic conductivity. More recent studies by Mbarki et al. (2023) and Adeyemo and Bello (2024) further confirm that compaction moisture remains one of the primary factors controlling the hydraulic conductivity behaviour of compacted landfill liner soils. Consequently, evaluating moisture variation around the optimum moisture content provides a realistic basis for assessing field compaction performance, where exact optimum moisture conditions are rarely achieved during landfill liner construction.

4.3.3 Dry Density Result

The dry density results further demonstrate the contrasting compaction behaviour of the residual soils obtained from Tanjung Dua Belas and Air Hitam. The Tanjung Dua Belas residual soil exhibits a broader compaction curve, achieving a Maximum Dry Density (MDD) of 1.50 Mg/m³ at an Optimum Moisture Content (OMC) of 18.56%. The broader moisture–density relationship indicates that the soil requires a higher moisture content to achieve maximum densification and maintains relatively stable dry density over a wider range of moisture conditions. In contrast, the Air Hitam residual soil exhibits a steeper compaction curve, reaching a Maximum Dry Density of 1.88 Mg/m³ at an Optimum Moisture Content of 11.75%. This behaviour indicates that the soil achieves maximum densification within a narrower moisture range, reflecting more efficient particle packing during compaction. The observed difference is consistent with the lower plasticity of the Air Hitam residual soil and its greater

proportion of sand-sized particles identified from the particle size distribution analysis. When compacted outside the optimum moisture condition, both soils exhibit slight reductions in dry density. The Tanjung Dua Belas residual soil records dry densities of 1.49 Mg/m^3 at -3% OMC and 1.48 Mg/m^3 at $+3\%$ OMC, whereas the Air Hitam residual soil records 1.84 Mg/m^3 and 1.81 Mg/m^3 under the corresponding moisture conditions, indicating that maximum densification is achieved only near the optimum moisture content.

Previous studies report similar compaction behaviour, where soils exhibiting higher plasticity generally achieve lower maximum dry density while requiring higher optimum moisture content because greater amounts of water are needed to lubricate soil particles and facilitate particle rearrangement during compaction (Soltani et al., 2024). Abdullah et al. (2024) similarly reported that increasing the proportion of coarse particles within fine-grained soils increased the achievable maximum dry density while reducing the corresponding optimum moisture content. These observations are consistent with the present study, where the Tanjung Dua Belas residual soil exhibits a higher Plasticity Index (22.98%) together with a lower maximum dry density and higher optimum moisture content than the Air Hitam residual soil.

Maximum dry density is an important parameter for evaluating landfill liner performance because increasing soil density generally reduces void ratio and pore connectivity, thereby restricting water flow through the compacted soil. Benson et al. (1999) demonstrated that increasing compaction density substantially reduces hydraulic conductivity by producing a denser soil structure with fewer interconnected pores. Similar findings were reported by Mbarki et al. (2023), who confirmed that dry density remains one of the dominant factors controlling the hydraulic performance of compacted clay barriers. Rather than relying on a fixed target value, the required maximum dry density depends on soil type, mineralogical composition and the specified compaction criteria. In the present study, the Air Hitam residual soil achieved a higher Maximum Dry Density of 1.88 Mg/m^3 , indicating a greater degree of particle packing under the applied compactive effort than the Tanjung Dua Belas residual soil. Although the Tanjung Dua Belas residual soil achieved a lower Maximum Dry Density of 1.50 Mg/m^3 , it also exhibited a higher plasticity and broader moisture tolerance during compaction. Therefore, the suitability of both residual soils for landfill liner applications should be evaluated together with their hydraulic conductivity behaviour rather than based solely on maximum dry density.

4.3.4 Moisture Content Result

The optimum moisture content (OMC) values of 18.56% for the Tanjung Dua Belas residual soil and 11.75% for the Air Hitam residual soil further demonstrate the contrasting compaction behaviour of the two soils. The higher optimum moisture content of the Tanjung Dua Belas residual soil indicates that a greater amount of water is required to achieve maximum densification during compaction. Although the particle size distribution shows that the Air Hitam residual soil contains a higher proportion of fine particles, the Atterberg limit results indicate that the Tanjung Dua Belas residual soil exhibits greater plasticity. This suggests that the compaction behaviour is governed not only by particle size distribution but also by the plasticity and characteristics of the fine fraction, which influence particle interaction and the amount of water required to facilitate particle rearrangement during compaction. In contrast, the lower optimum moisture content of the Air Hitam residual soil indicates that maximum dry density can be achieved with comparatively less water, reflecting more efficient particle packing under the applied compactive effort.

When the moisture content deviates from the optimum condition, the compaction behaviour of both residual soils changes noticeably. Under dry-of-optimum conditions (-3% OMC), insufficient moisture limits particle lubrication and restricts particle rearrangement, resulting in slightly lower dry densities. Conversely, under wet-of-optimum conditions ($+3\%$ OMC), excess water increasingly occupies the pore spaces and reduces effective particle contact during compaction, also leading to lower dry densities. Consequently, both residual soils achieve their maximum dry density only at the optimum moisture content, demonstrating the importance of moisture control during field compaction.

These observations are consistent with the findings of Soltani et al. (2024), who reported that soils exhibiting higher plasticity generally require higher optimum moisture contents because additional water is needed to facilitate particle rearrangement during compaction. Similarly, Kodikara et al. (2018) observed that soils compacted at higher moisture contents showed improved particle rearrangement but became more sensitive to moisture variation around the optimum condition. The broader compaction curve exhibited by the Tanjung Dua Belas residual soil therefore indicates greater tolerance to moisture variation while simultaneously requiring more careful moisture control to achieve maximum dry density. In contrast, the steeper compaction curve of

the Air Hitam residual soil indicates that optimum compaction is achieved within a narrower moisture range, making its compaction response more sensitive to deviations from the optimum moisture content. Understanding the optimum moisture content is therefore essential for ensuring that residual soils are compacted under appropriate moisture conditions to achieve favourable engineering performance and low hydraulic conductivity in landfill liner applications.

4.3.5 Air Void Percentage

The air void percentage provides additional insight into the internal structure of the compacted residual soils and the effectiveness of particle packing during compaction. Air void content represents the proportion of air-filled voids remaining within the compacted soil structure and is closely related to both dry density and moisture content. For both residual soils examined in this study, the air void percentage decreases progressively as the moisture content increases from the dry-of-optimum condition towards the wet-of-optimum condition. The Tanjung Dua Belas residual soil exhibits an air void content of 11.21% at -3% OMC, which decreases to 6.15% at the Optimum Moisture Content (OMC) and further to 2.92% at +3% OMC. A similar trend is observed for the Air Hitam residual soil, where the air void percentage decreases from 9.63% at -3% OMC to 1.99% at OMC and 0.20% at +3% OMC.

The progressive reduction in air void percentage demonstrates the important role of moisture during compaction. Under dry-of-optimum conditions, insufficient water limits particle lubrication, restricting particle rearrangement and resulting in greater volumes of entrapped air within the compacted soil structure. As the moisture content increases towards the optimum condition, water facilitates particle movement and promotes closer particle packing, thereby reducing the volume of entrapped air. Under wet-of-optimum conditions, the degree of saturation continues to increase and the remaining air-filled voids become progressively smaller. However, excessive water beyond the optimum moisture content reduces the efficiency of compactive effort because part of the applied energy is dissipated in compressing pore water rather than further densifying the soil skeleton (Mitchell & Soga, 2005). Consequently, although the air void percentage continues to decrease, the dry density no longer increases beyond the optimum moisture content.

The observed reduction in air void percentage with increasing moisture content agrees well with previous investigations of compacted soils used for landfill liner applications. Mbarki et al. (2023) reported that moisture-controlled compaction significantly influences soil fabric development by reducing entrapped air and improving particle arrangement, thereby contributing to lower hydraulic conductivity. Similarly, Benson et al. (1999) demonstrated that compacting cohesive soils near the optimum moisture content produces denser soil structures with fewer interconnected air-filled voids, resulting in reduced hydraulic conductivity. In landfill liner systems, minimising air-filled voids is important because interconnected air voids may increase pore continuity and create preferential pathways for leachate migration. The results obtained in this study demonstrate a substantial reduction in air void percentage as both residual soils are compacted from the dry-of-optimum to the wet-of-optimum condition, indicating progressively improved particle packing and pore closure. These observations further support the importance of maintaining appropriate moisture conditions during compaction to achieve dense soil structures capable of providing effective hydraulic barrier performance.

4.4 Hydraulic Conductivity

Hydraulic conductivity is evaluated to determine the ability of the residual soils obtained from Tanjung Dua Belas and Air Hitam to restrict water flow when compacted under controlled moisture and loading conditions. As a key performance parameter for landfill liner materials, hydraulic conductivity is governed by soil structure, pore connectivity and the degree of compaction achieved during placement. Variations in moisture content relative to the Optimum Moisture Content (OMC) and the application of vertical loading can modify the arrangement of soil particles and pore continuity, thereby influencing the hydraulic conductivity of compacted soils (Mitchell & Soga, 2005). Rowe et al. (2012) reported that the hydraulic performance of compacted clay liners is controlled not only by soil characteristics but also by construction-related factors such as moulding water content, compaction conditions and the applied stress history. Accordingly, the hydraulic conductivity results obtained in this study are evaluated under dry-of-optimum (-3% OMC), optimum, and wet-of-optimum ($+3\%$ OMC) moisture conditions together with applied vertical loads ranging from 25 kPa to 200 kPa. This approach enables the combined influence of moisture condition and

loading on hydraulic conductivity behaviour to be assessed under conditions representative of landfill liner systems. The findings provide the basis for evaluating the suitability of the investigated residual soils for landfill liner applications.

4.4.1 Hydraulic Conductivity at Optimum Moisture Content

Hydraulic conductivity at the Optimum Moisture Content (OMC) was evaluated to examine the influence of applied vertical loading on the hydraulic performance of the compacted residual soils. As the applied vertical load increased from 25 kPa to 200 kPa, the hydraulic conductivity of both residual soils decreased progressively, indicating that increasing stress promoted further compression of the soil structure, reduced pore continuity and restricted water flow through the compacted specimens. At 25 kPa, the Air Hitam residual soil recorded a hydraulic conductivity of 3.074×10^{-8} cm/s, which decreased to 1.472×10^{-8} cm/s at 200 kPa. Similarly, the hydraulic conductivity of the Tanjung Dua Belas residual soil decreased from 4.195×10^{-8} cm/s at 25 kPa to 2.900×10^{-8} cm/s at 200 kPa. These results demonstrate that increasing vertical loading enhances the hydraulic performance of both residual soils by reducing interconnected pore spaces and limiting the flow paths available for water movement. The relationship between applied vertical load and hydraulic conductivity is presented in Figure 4.7.

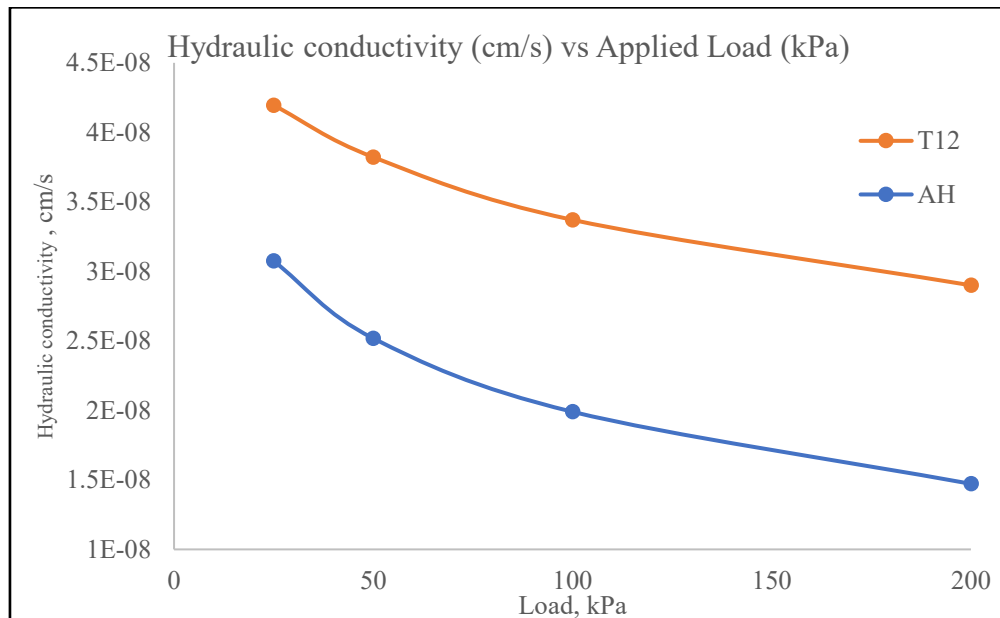


Figure 4.7 Hydraulic Conductivity (cm/s) vs Applied Load (kPa) at OMC

The hydraulic conductivity values presented in Table 4.8 show a consistent reduction with increasing applied vertical load for both residual soils. Throughout the loading range, the Air Hitam residual soil exhibits lower hydraulic conductivity than the Tanjung Dua Belas residual soil. This behaviour is attributed to the combined influence of its higher Maximum Dry Density (1.88 Mg/m^3), greater proportion of clay-sized particles (10%), and lower optimum moisture content, which together promote a denser soil structure with reduced pore connectivity. In contrast, although the Tanjung Dua Belas residual soil exhibits higher plasticity, its lower Maximum Dry Density (1.50 Mg/m^3) and smaller clay-sized fraction (4%) contribute to comparatively higher hydraulic conductivity under the same loading conditions.

Table 4.8
Hydraulic conductivity of Soil Sample at OMC

Load (kPa)	Hydraulic Conductivity, k (cm/s)	
	Sample AH	Sample T12
25	3.074×10^{-8}	4.195×10^{-8}
50	2.518×10^{-8}	3.822×10^{-8}
100	1.990×10^{-8}	3.371×10^{-8}
200	1.472×10^{-8}	2.900×10^{-8}

The stress-dependent hydraulic conductivity behaviour observed in this study agrees with previous geotechnical investigations. Hamdi et al. (2013) reported that increasing vertical stress progressively reduces hydraulic conductivity by compressing the soil skeleton, decreasing void ratio and restricting the continuity of flow channels within compacted cohesive soils. Similar observations were reported by Mesri and Olson (2014), who demonstrated that increasing effective stress modifies soil fabric and reduces pore space, resulting in lower hydraulic conductivity under loading conditions comparable to those experienced by landfill liners. More recently, Adeyemo and Bello (2024) reported a similar reduction in hydraulic conductivity with increasing vertical loading for compacted tropical residual soils used in landfill barrier applications.

The hydraulic conductivity values obtained in this study were also compared with the hydraulic conductivity criterion commonly adopted for compacted landfill liners. The United States Environmental Protection Agency (US EPA, 1993)

recommends a maximum hydraulic conductivity of 1×10^{-7} cm/s to provide effective leachate containment, and the same performance criterion is adopted in the Malaysian Technical Guidelines for Sanitary Landfills issued by the Ministry of Housing and Local Government (KPKT). All hydraulic conductivity values obtained for both residual soils remain below this recommended limit throughout the applied loading range. Furthermore, the Air Hitam residual soil consistently exhibits lower hydraulic conductivity than the Tanjung Dua Belas residual soil under identical loading conditions, indicating superior hydraulic barrier performance. These findings demonstrate that both residual soils satisfy the hydraulic conductivity requirement for landfill liner applications, with the Air Hitam residual soil exhibiting the most favourable hydraulic performance among the two investigated materials.

4.4.2 Hydraulic Conductivity under Wet-of-Optimum Conditions

Hydraulic conductivity under wet-of-optimum conditions (+3% OMC) was evaluated to examine the influence of compaction at a moisture content slightly above the Optimum Moisture Content (OMC) on the hydraulic performance of the residual soils. Compaction under wet-of-optimum conditions commonly occurs during field construction because maintaining the exact optimum moisture content is often difficult. Additional moisture promotes particle lubrication and facilitates particle rearrangement during compaction, resulting in a denser soil structure with improved contact between particles. The hydraulic conductivity of both residual soils decreases progressively with increasing applied vertical load under wet-of-optimum conditions. The Air Hitam residual soil records a hydraulic conductivity of 2.722×10^{-8} cm/s at 25 kPa, which decreases to 1.241×10^{-8} cm/s at 200 kPa. Similarly, the hydraulic conductivity of the Tanjung Dua Belas residual soil decreases from 3.438×10^{-8} cm/s at 25 kPa to 2.386×10^{-8} cm/s at 200 kPa. The continued reduction in hydraulic conductivity with increasing vertical loading indicates that applied stress further compresses the compacted soil structure, reducing pore continuity and restricting water flow even when the soils are compacted under moisture conditions slightly above the optimum moisture content. The relationship between applied vertical load and hydraulic conductivity under wet-of-optimum conditions is presented in Figure 4.8.

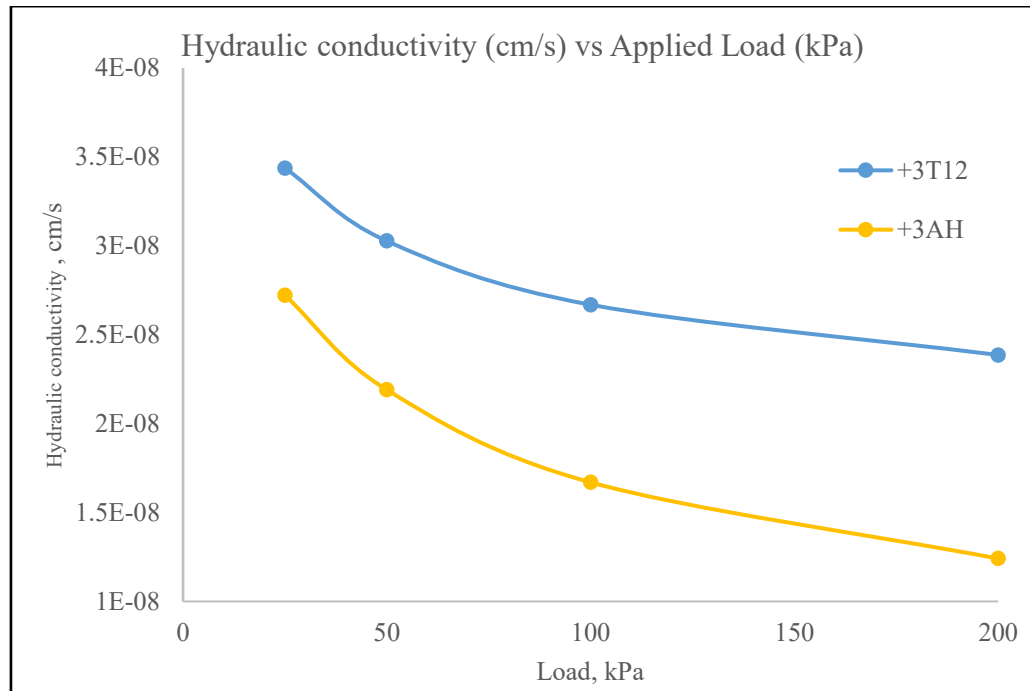


Figure 4.8 Hydraulic Conductivity (cm/s) vs Applied Load (kPa) at +3% OMC

The hydraulic conductivity values presented in Table 4.9 remain consistently within the order of 10^{-8} cm/s throughout the applied loading range for both residual soils. Compared with the results obtained at the optimum moisture condition, compaction under wet-of-optimum conditions continues to produce very low hydraulic conductivity values, indicating that the additional moisture does not adversely affect the hydraulic barrier performance of either residual soil. Instead, the presence of slightly higher moisture during compaction promotes improved particle contact and reduced pore connectivity, thereby maintaining a dense soil structure capable of restricting water flow.

Table 4.9
Hydraulic conductivity of Soil Sample at +3 OMC

Load (kPa)	Hydraulic Conductivity, k (cm/s)	
	Sample AH	Sample T12
25	2.722 × 10 ⁻⁸	3.438 × 10 ⁻⁸
50	2.190 × 10 ⁻⁸	3.028 × 10 ⁻⁸
100	1.670 × 10 ⁻⁸	2.669 × 10 ⁻⁸
200	1.241 × 10 ⁻⁸	2.386 × 10 ⁻⁸

The hydraulic conductivity behaviour observed under wet-of-optimum conditions agrees well with previous investigations of compacted landfill liner materials. Benson et al. (2014) reported that compacting cohesive soils slightly wet of optimum promotes improved particle orientation and reduces the continuity of interconnected pores, thereby enhancing the sealing performance of compacted soil liners. Similarly, Mbarki et al. (2023) demonstrated that compacting soils within a controlled moisture range above the optimum moisture content maintains low hydraulic conductivity because the additional moisture facilitates improved particle rearrangement and pore closure. Comparable observations were reported by Adeyemo and Bello (2024), who found that tropical residual soils compacted at +3% OMC consistently achieved hydraulic conductivity values suitable for landfill liner applications.

The hydraulic conductivity values obtained in this study remain within the order of 10^{-8} cm/s, which is well below the maximum hydraulic conductivity criterion of 1×10^{-7} cm/s recommended by the United States Environmental Protection Agency (US EPA, 1993) and adopted in the Malaysian Technical Guidelines for Sanitary Landfills. These results demonstrate that compaction under wet-of-optimum conditions provides effective hydraulic barrier performance while satisfying the hydraulic conductivity requirement for landfill liner materials. This finding also indicates that slight increases in moisture content above the optimum condition do not compromise the hydraulic performance of the investigated residual soils, provided that adequate compaction is achieved.

4.4.3 Hydraulic Conductivity under Dry-of-Optimum Conditions

Hydraulic conductivity under dry-of-optimum conditions (−3% OMC) was evaluated to examine the influence of compaction at a moisture content slightly below the Optimum Moisture Content (OMC) on the hydraulic performance of the residual soils. Compaction under dry-of-optimum conditions commonly produces a more aggregated soil structure because insufficient moisture limits particle lubrication and restricts particle rearrangement during compaction. Consequently, larger interconnected pores remain within the compacted soil structure, resulting in higher hydraulic conductivity than that observed under optimum and wet-of-optimum conditions. The hydraulic conductivity of both residual soils decreases progressively

with increasing applied vertical load under dry-of-optimum conditions. The Air Hitam residual soil records a hydraulic conductivity of 4.082×10^{-8} cm/s at 25 kPa, which decreases to 2.068×10^{-8} cm/s at 200 kPa. Similarly, the hydraulic conductivity of the Tanjung Dua Belas residual soil decreases from 4.764×10^{-8} cm/s at 25 kPa to 3.257×10^{-8} cm/s at 200 kPa. Although increasing vertical loading continues to reduce hydraulic conductivity by compressing the soil structure and decreasing pore continuity, both residual soils consistently exhibit higher hydraulic conductivity than those compacted under optimum and wet-of-optimum moisture conditions. This behaviour indicates that the initial soil fabric developed during dry-of-optimum compaction cannot be completely eliminated by the applied loading. The relationship between applied vertical load and hydraulic conductivity under dry-of-optimum conditions is presented in Figure 4.9.

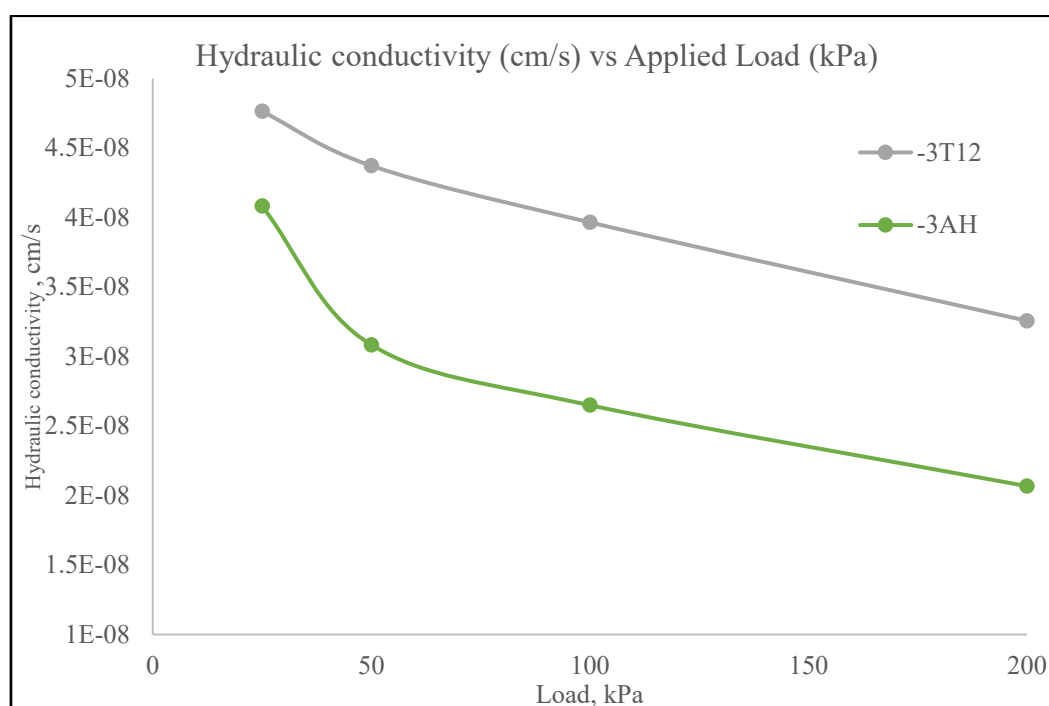


Figure 4.9 Hydraulic Conductivity (cm/s) vs Applied Load (kPa) at -3% OMC

The hydraulic conductivity values presented in Table 4.10 remain within the order of 10^{-8} cm/s throughout the applied loading range for both residual soils. However, the hydraulic conductivity values are consistently higher than those obtained under the optimum and wet-of-optimum moisture conditions. This observation demonstrates that compaction below the optimum moisture content produces a less

efficient particle arrangement, resulting in greater pore continuity and consequently higher hydraulic conductivity.

Table 4.10
Hydraulic conductivity of Soil Sample at -3 OMC

Load (kPa)	Hydraulic Conductivity, k (cm/s)	
	Sample AH	Sample T12
25	4.082 x10 ⁻⁸	4.764 x10 ⁻⁸
50	3.084 x10 ⁻⁸	4.373 x10 ⁻⁸
100	2.650 x10 ⁻⁸	3.965 x10 ⁻⁸
200	2.068 x10 ⁻⁸	3.257 x10 ⁻⁸

The hydraulic conductivity behaviour observed under dry-of-optimum conditions agrees well with previous investigations of compacted fine-grained soils. Benson et al. (1999) reported that compacted clay liner soils moulded on the dry side of optimum moisture content develop an aggregated soil fabric containing relatively large interconnected pores, resulting in higher hydraulic conductivity than soils compacted at or above the optimum moisture content. Similarly, Almasoudi (2023) reported that insufficient moisture during compaction restricts particle rearrangement and prevents complete pore closure, leading to higher hydraulic conductivity even after the application of vertical loading. Comparable behaviour was observed by Adeyemo and Bello (2024) for compacted tropical residual soils, where specimens compacted below the optimum moisture content consistently exhibited higher hydraulic conductivity than those compacted under optimum and wet-of-optimum conditions, despite satisfying the hydraulic conductivity requirement for landfill liner applications.

Although the hydraulic conductivity values obtained under dry-of-optimum conditions are higher than those measured under the optimum and wet-of-optimum moisture conditions, all measured values remain below the maximum hydraulic conductivity criterion of 1×10^{-7} cm/s recommended by the United States Environmental Protection Agency (US EPA, 1993) and adopted in the Malaysian Technical Guidelines for Sanitary Landfills. These findings indicate that compaction under dry-of-optimum conditions is still capable of satisfying the hydraulic conductivity requirement for landfill liner materials. However, compared with the optimum and wet-

of-optimum conditions, dry-of-optimum compaction produces a less favourable soil structure for restricting water flow, highlighting the importance of appropriate moisture control during landfill liner construction.

4.4.4 Comparison of Hydraulic Conductivity under Different Moisture Conditions

A comparison of hydraulic conductivity under different moisture conditions provides a comprehensive evaluation of how compaction moisture influences the hydraulic performance of the investigated residual soils. The combined effects of moulding moisture content and applied vertical load on hydraulic conductivity are presented in Figure 4.10. For both residual soils, hydraulic conductivity consistently decreases as the compaction condition changes from dry-of-optimum to optimum and subsequently to wet-of-optimum at each applied vertical load. The dashed lines represent the Tanjung Dua Belas residual soil, whereas the solid lines represent the Air Hitam residual soil, allowing direct comparison of the hydraulic conductivity behaviour of both soils under identical moisture and loading conditions.

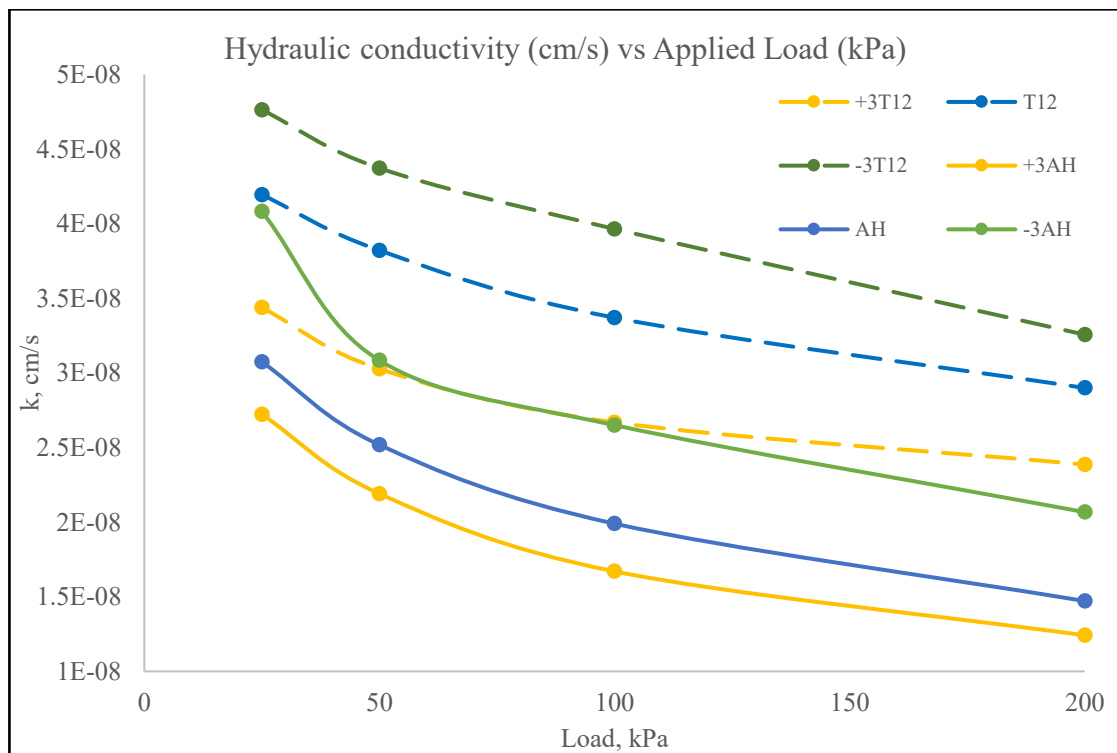


Figure 4.10 Comparison of Hydraulic Conductivity (cm/s) versus Applied Load (kPa) under different Moisture Content (%)

The hydraulic conductivity values summarised in Table 4.11 further demonstrate the combined influence of moisture condition and applied vertical loading on hydraulic conductivity. For both residual soils, hydraulic conductivity decreases progressively as the applied vertical load increases under all three moisture conditions, confirming that increasing effective stress reduces pore continuity and restricts water flow through the compacted soil structure. At each applied load, the highest hydraulic conductivity is consistently observed under the dry-of-optimum condition, followed by the optimum condition, whereas the wet-of-optimum condition produces the lowest hydraulic conductivity. This trend remains consistent throughout the applied loading range from 25 kPa to 200 kPa for both residual soils.

At the maximum applied load of 200 kPa, the Air Hitam residual soil records hydraulic conductivity values of 2.068×10^{-8} cm/s, 1.472×10^{-8} cm/s and 1.241×10^{-8} cm/s under the dry-of-optimum, optimum and wet-of-optimum conditions, respectively. Similarly, the Tanjung Dua Belas residual soil records hydraulic conductivity values of 3.257×10^{-8} cm/s, 2.900×10^{-8} cm/s and 2.386×10^{-8} cm/s under the corresponding moisture conditions. These results demonstrate that compaction under wet-of-optimum conditions consistently produces the lowest hydraulic conductivity for both residual soils. Furthermore, the Air Hitam residual soil consistently exhibits lower hydraulic conductivity than the Tanjung Dua Belas residual soil under all moisture conditions and loading stages. This behaviour is attributed to the combined influence of its higher Maximum Dry Density, greater clay-sized particle content, and the denser soil structure developed during compaction, which collectively reduce pore connectivity and restrict water flow more effectively than the Tanjung Dua Belas residual soil.

Table 4.11
Summary of Hydraulic Conductivity Result with different Moisture Content (%)

Sample Name	Moisture Content (%)	Hydraulic Conductivity, k (cm/s)			
		At 25kPa Load	At 50kPa Load	At 100kPa Load	At 200kPa Load
-3AH (cm/s)	8.75	4.081×10^{-8}	3.084×10^{-8}	2.650×10^{-8}	2.067×10^{-8}
AH (cm/s)	11.75	3.074×10^{-8}	2.518×10^{-8}	1.990×10^{-8}	1.472×10^{-8}
+3AH (cm/s)	14.75	2.722×10^{-8}	2.190×10^{-8}	1.670×10^{-8}	1.241×10^{-8}
-3T12 (cm/s)	15.56	4.763×10^{-8}	4.372×10^{-8}	3.965×10^{-8}	3.256×10^{-8}
T12 (cm/s)	18.56	4.194×10^{-8}	3.821×10^{-8}	3.370×10^{-8}	2.899×10^{-8}

+3T12(cm/s)	21.56	3.438 x10 ⁻⁸	3.027 x10 ⁻⁸	2.669 x10 ⁻⁸	2.386 x10 ⁻⁸
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The observed hydraulic conductivity behaviour agrees well with previous investigations of compacted landfill liner materials. Benson et al. (1999) reported that compacted clay liner soils moulded on the dry side of optimum moisture content develop an aggregated soil fabric with relatively large interconnected pores, resulting in higher hydraulic conductivity than soils compacted at or above the optimum moisture content. Conversely, soils compacted on the wet side of optimum develop a more dispersed soil fabric with reduced pore continuity, producing lower hydraulic conductivity. Similar observations were reported by Benson et al. (2014), who demonstrated that compacting cohesive soils slightly wet of optimum enhances particle rearrangement and improves hydraulic barrier performance by reducing interconnected pore spaces. Mbarki et al. (2023) likewise confirmed that hydraulic conductivity systematically decreases as moulding moisture content increases from the dry-of-optimum to the wet-of-optimum condition within the recommended compaction moisture tolerance.

Comparable behaviour has also been reported for tropical residual soils used as landfill liner materials. Adeyemo and Bello (2024) investigated lateritic residual soils containing approximately 18–30% clay and 35–50% silt, and reported that specimens compacted at +2% to +3% above the optimum moisture content consistently achieved lower hydraulic conductivity than specimens compacted at or below the optimum moisture content while maintaining hydraulic conductivity within the order of 10⁻⁸ cm/s under simulated landfill loading conditions. Similarly, Almasoudi (2023) investigated compacted clayey soils used as hydraulic barrier materials and observed that specimens compacted on the dry side of optimum exhibited higher hydraulic conductivity because incomplete particle rearrangement produced larger interconnected pores that could not be completely eliminated by subsequent loading. These findings closely agree with the behaviour observed in the present study, where the lowest hydraulic conductivity is consistently achieved under wet-of-optimum compaction conditions for both investigated residual soils.

4.4.5 Summary of Hydraulic Conductivity and Soil Characteristics Result

An overall summary of the key physical and engineering properties of the residual soils obtained from Tanjung Dua Belas (T12) and Air Hitam (AH) is presented in Table 4.12, providing an integrated comparison of their characteristics relevant to landfill liner applications. Since the physical properties remain unchanged regardless of the compaction moisture condition, the representative hydraulic conductivity corresponds to specimens compacted at the Optimum Moisture Content (OMC) and subjected to the maximum applied vertical load of 200 kPa, representing the highest stress condition considered in the present study and simulating the long-term overburden stress acting on landfill liner systems following continuous waste placement (Rowe et al., 2004).

Table 4.12
Summary of Soil Characteristics and Hydraulic Conductivity for T12 and AH

	T12	AH
<i>pH</i>	2.81	3.65
Particle Density (Mg/m³)	2.223	2.478
Particle Distribution (%)	Gravel: 0	Gravel: 0
	Sand: 86	Sand: 70
	Silt: 10	Silt: 20
	Clay: 4	Clay: 10
	C _u : 83.33	C _u : 75.00
	C _g : 8.53	C _g : 18.75
Soil Classification	Silty SAND	Silty SAND
USCS Classification	CI (Clay of Intermediate Plasticity)	CL (Clay of Low Plasticity)
Plastic Limit (%)	16.85	10.75
Liquid Limit (%)	39.83	24.14
Plasticity Index (%)	22.98	13.39
Optimum Moisture Content (%)	18.56	12.15
Maximum Dry Density (g/cm³)	1.5	1.88

Air Void (%)	6.12	1.99
Representative Hydraulic Conductivity at OMC and 200 kPa (cm/s)	2.899×10^{-8}	1.416×10^{-8}

Both residual soils exhibit strongly acidic conditions, with Tanjung Dua Belas recording a lower pH (2.81) than Air Hitam (3.65). The stronger acidity observed in the Tanjung Dua Belas residual soil may reflect greater exposure to acidic landfill leachate or more advanced waste decomposition processes. Nevertheless, both residual soils satisfy the hydraulic conductivity criterion for landfill liners, indicating that the measured acidity does not adversely affect their hydraulic barrier performance under the tested conditions.

Differences in particle density indicate variations in mineral composition between the two residual soils. The Air Hitam residual soil records a higher particle density (2.478 Mg/m^3) than the Tanjung Dua Belas residual soil (2.223 Mg/m^3), suggesting a denser mineralogical composition that contributes to improved particle packing during compaction. The particle size distribution analysis classifies both residual soils as Silty SAND, although the Air Hitam residual soil contains a greater proportion of clay-sized particles (10%) and silt (20%) than the Tanjung Dua Belas residual soil (4% clay and 10% silt). These differences indicate that the Air Hitam residual soil contains a larger proportion of fine particles capable of contributing to improved pore filling during compaction.

The Atterberg limit results reveal contrasting plasticity characteristics. Based on the plasticity chart, the Tanjung Dua Belas residual soil is classified as CI (Clay of Intermediate Plasticity), whereas the Air Hitam residual soil is classified as CL (Clay of Low Plasticity). Although the Air Hitam residual soil contains a greater proportion of clay-sized particles, the higher Plasticity Index of the Tanjung Dua Belas residual soil (22.98%) indicates greater plasticity and moisture sensitivity, suggesting that soil behaviour is influenced not only by the quantity of clay-sized particles but also by their mineralogical characteristics.

The compaction characteristics also differ considerably. The Tanjung Dua Belas residual soil requires a higher Optimum Moisture Content (18.56%) to achieve maximum densification, whereas the Air Hitam residual soil reaches its optimum

condition at 11.75% while achieving a considerably higher Maximum Dry Density (1.88 Mg/m^3) than the Tanjung Dua Belas residual soil (1.50 Mg/m^3). This denser compacted structure is reflected by the lower air void percentage recorded for the Air Hitam residual soil (1.99%) compared with 6.15% for the Tanjung Dua Belas residual soil.

The combined influence of these physical and engineering characteristics is reflected in the representative hydraulic conductivity measured at the Optimum Moisture Content under an applied vertical load of 200 kPa. The Air Hitam residual soil records a lower hydraulic conductivity ($1.472 \times 10^{-8} \text{ cm/s}$) than the Tanjung Dua Belas residual soil ($2.900 \times 10^{-8} \text{ cm/s}$). The lower hydraulic conductivity achieved by the Air Hitam residual soil is attributed to its higher particle density, greater clay-sized particle content, higher maximum dry density and lower air void percentage, all of which contribute to the formation of a denser soil structure with reduced pore connectivity.

Overall, both residual soils satisfy the hydraulic conductivity requirement of $\leq 1 \times 10^{-7} \text{ cm/s}$ recommended for landfill liner materials. However, the Air Hitam residual soil exhibits superior engineering performance because it develops a denser compacted structure and consistently achieves lower hydraulic conductivity than the Tanjung Dua Belas residual soil. These findings demonstrate that hydraulic barrier performance is governed by the combined influence of soil composition, plasticity, compaction characteristics and soil structure rather than by a single soil property alone.

4.5 Relationship of Hydraulic Conductivity with the Soil Characteristics

The relationship between hydraulic conductivity and the measured soil characteristics is analysed to identify the factors influencing the hydraulic performance of the residual soils obtained from Tanjung Dua Belas and Air Hitam. Microsoft Excel is first used to graphically evaluate the direct relationships between hydraulic conductivity and the measured soil characteristics, including particle density, particle size distribution, pH , Atterberg limits, linear shrinkage and compaction characteristics. Subsequently, Minitab Statistical Software (Minitab LLC, 2023) is used to perform normality assessment, correlation analysis, regression analysis and paired t-test analysis to quantitatively evaluate the relationships between hydraulic conductivity and the investigated soil characteristics. This combined analytical approach provides a comprehensive understanding of the factors governing hydraulic conductivity and

supports the evaluation of the suitability of the investigated residual soils for landfill liner applications.

4.5.1 Relationship of Hydraulic Conductivity and Particle Density

Figure 4.11 illustrates the relationship between hydraulic conductivity (k) and particle density for the investigated residual soils. Since particle density is an intrinsic soil property that remains unchanged regardless of the compaction moisture condition, the representative hydraulic conductivity values used in this comparison correspond to specimens compacted at the Optimum Moisture Content (OMC) and subjected to the maximum applied vertical load of 200 kPa. This loading condition represents the highest vertical stress applied during the modified oedometer test and simulates the increased overburden stress acting on landfill liner systems following progressive waste placement (Rowe et al., 2004).

The plotted data show particle density values ranging from approximately 2.223 Mg/m³ for the Tanjung Dua Belas residual soil to 2.478 Mg/m³ for the Air Hitam residual soil. The corresponding hydraulic conductivity decreases from 2.900×10^{-8} cm/s for the Tanjung Dua Belas residual soil to 1.472×10^{-8} cm/s for the Air Hitam residual soil. These results indicate an inverse relationship between particle density and hydraulic conductivity, whereby soils possessing higher particle density tend to exhibit lower hydraulic conductivity. This behaviour suggests that denser mineral particles promote a more compact soil structure during compaction, resulting in reduced pore continuity and greater resistance to water flow.

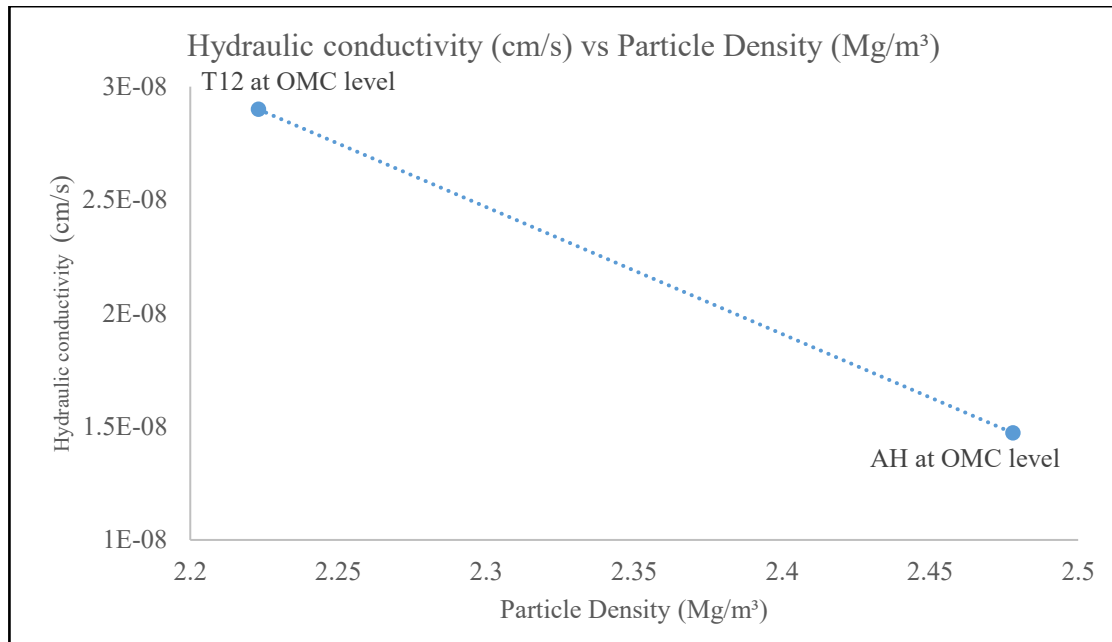


Figure 4.11 Relationship of Hydraulic Conductivity (cm/s) with Particle Density (Mg/m³)

The observed relationship agrees with previous studies investigating the influence of particle density on soil hydraulic behaviour. Zhao et al. (2021) investigated the hydraulic conductivity of compacted fine-grained soils by developing a hydraulic conductivity model based on the equivalent hydraulic diameter. Their study demonstrated that hydraulic conductivity is governed not only by void ratio and particle size distribution but also by particle density, specific gravity and dry density, all of which influence the effective pore size available for water flow. Similarly, Hamdi et al. (2013) investigated compacted clay soils subjected to increasing vertical stress and reported that soils with higher particle density and denser packing developed lower void ratios and reduced pore connectivity, resulting in lower hydraulic conductivity. These findings are consistent with the present study, where the Air Hitam residual soil, having the higher particle density (2.478 Mg/m³), also records the lowest hydraulic conductivity (1.472×10^{-8} cm/s) among the two investigated soils.

The results therefore indicate that particle density contributes to the hydraulic performance of compacted residual soils by influencing the compacted soil structure and pore continuity. However, particle density should not be considered independently because hydraulic conductivity is also affected by other interacting factors, including clay-sized particle content, plasticity, maximum dry density and air void percentage.

Consequently, the hydraulic behaviour of landfill liner materials is governed by the combined influence of these soil characteristics rather than by particle density alone.

4.5.2 Relationship of Hydraulic Conductivity with Plasticity and Shrinkage Characteristics

Figure 4.12 illustrates the relationship between hydraulic conductivity and the measured plasticity and shrinkage characteristics of the investigated residual soils. Since the Liquid Limit (LL), Plastic Limit (PL), Plasticity Index (PI) and Linear Shrinkage (LS) are intrinsic soil properties that remain unchanged regardless of the compaction moisture condition, the hydraulic conductivity values used in this comparison correspond to specimens compacted at the Optimum Moisture Content (OMC) under the maximum applied vertical load of 200 kPa. The OMC condition is selected because it represents the standard compaction condition for evaluating the engineering properties of compacted soils, while the maximum applied load of 200 kPa represents the highest vertical stress adopted in the modified oedometer test, simulating the overburden pressure acting on landfill liner materials following progressive waste placement (Rowe et al., 2004). Using the hydraulic conductivity values obtained under these conditions enables direct comparison with the measured plasticity and shrinkage characteristics without the influence of varying compaction moisture conditions.

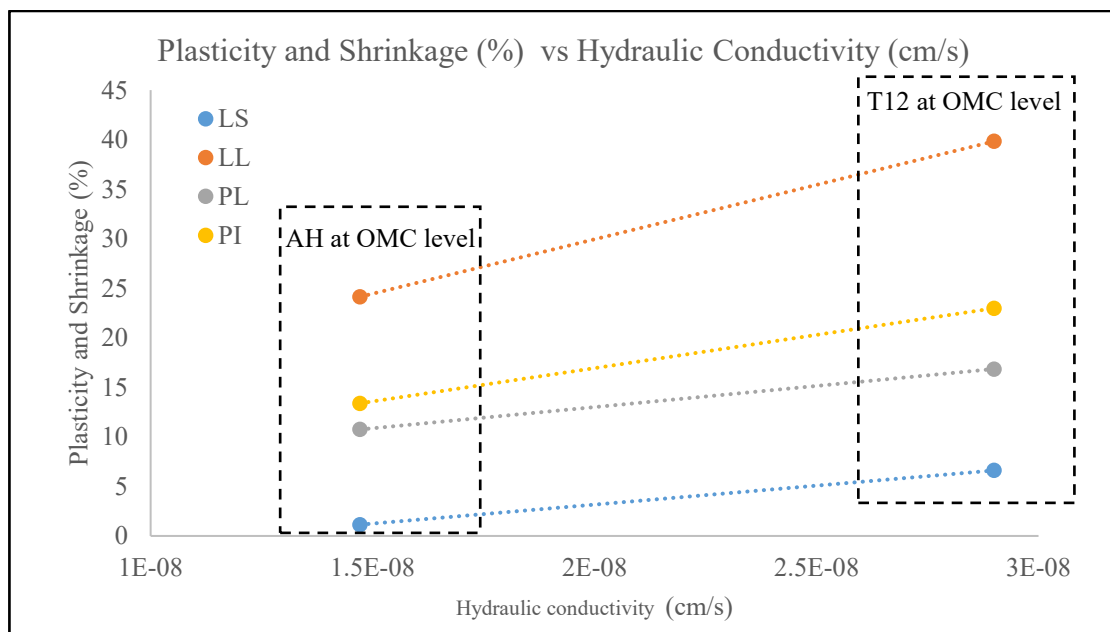


Figure 4.12 Relationship of Plasticity and Shrinkage (%) vs Hydraulic Conductivity (cm/s)

The results indicate that the Tanjung Dua Belas residual soil exhibits higher Liquid Limit (39.83%), Plastic Limit (16.85%) and Plasticity Index (22.98%) than the Air Hitam residual soil, while also recording a higher hydraulic conductivity of 2.900×10^{-8} cm/s compared with 1.472×10^{-8} cm/s. However, this relationship should not be interpreted as indicating that increasing plasticity directly increases hydraulic conductivity. Benson et al. (1999) reported that the Atterberg limits are useful indicators of soil consistency and workability but should not be used independently to predict hydraulic conductivity because the hydraulic conductivity of compacted soils is governed primarily by the compacted soil structure and the dry density achieved during compaction. Rowe et al. (2012) further explained that the hydraulic performance of compacted landfill liners depends on the combined influence of clay mineralogy, compaction density, moulding water content and soil fabric rather than on the Atterberg limits alone. In the present study, although the Tanjung Dua Belas residual soil exhibits higher plasticity characteristics, it also records a lower Maximum Dry Density (1.50 Mg/m^3) and a higher Air Void percentage (6.15%) than the Air Hitam residual soil. These characteristics produce a comparatively less dense compacted soil structure with greater pore connectivity, resulting in the higher hydraulic conductivity observed in this study.

In contrast, the relationship between Linear Shrinkage and hydraulic conductivity is consistent with the observed results. The Tanjung Dua Belas residual soil records a higher Linear Shrinkage value (6.61%) than the Air Hitam residual soil (1.14%) and similarly exhibits higher hydraulic conductivity. Albrecht and Benson (2001) reported that soils with greater shrinkage potential are more susceptible to volumetric changes during drying, increasing the likelihood of shrinkage cracking and the formation of preferential flow paths. Consequently, soils exhibiting greater shrinkage behaviour may develop higher pore continuity, which contributes to increased hydraulic conductivity. The higher Linear Shrinkage value recorded for the Tanjung Dua Belas residual soil therefore supports the comparatively higher hydraulic conductivity measured in the present study.

4.5.3 Relationship of Hydraulic Conductivity and Maximum Dry Density

Figure 4.13 illustrates the relationship between hydraulic conductivity and the Maximum Dry Density (MDD) of the investigated residual soils. Since the MDD

represents the maximum density achieved during the Standard Proctor compaction test, the hydraulic conductivity values used in this comparison correspond to specimens compacted at the Optimum Moisture Content (OMC) and subjected to the maximum applied vertical load of 200 kPa. The OMC condition represents the standard compaction condition for achieving the maximum dry density of each soil, while the applied load of 200 kPa represents the highest vertical stress adopted in the modified oedometer test, simulating the overburden pressure acting on landfill liner systems following progressive waste placement (Rowe et al., 2004). Using the hydraulic conductivity values obtained under these conditions enables direct comparison between the maximum compacted density achieved by each soil and its corresponding hydraulic conductivity.

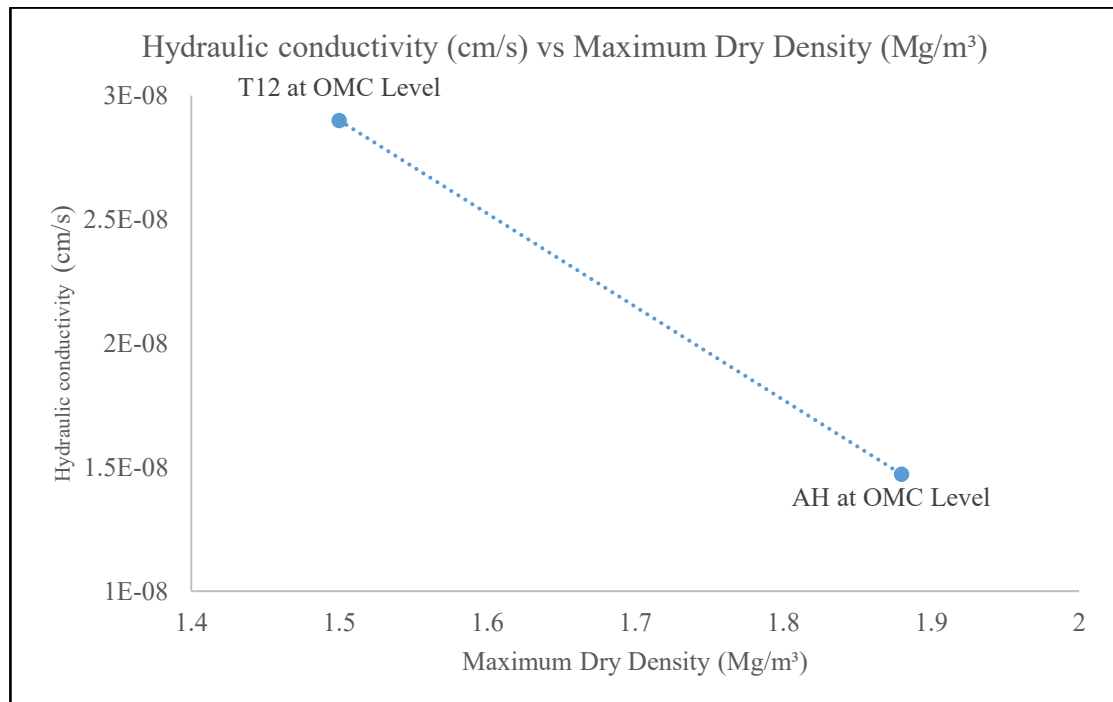


Figure 4.13 Relationship of Hydraulic Conductivity (cm/s) with MDD (Mg/m³)

The results show that the Air Hitam residual soil achieves a higher Maximum Dry Density (1.88 Mg/m^3) than the Tanjung Dua Belas residual soil (1.50 Mg/m^3), while simultaneously recording a lower hydraulic conductivity of $1.472 \times 10^{-8} \text{ cm/s}$ compared with $2.900 \times 10^{-8} \text{ cm/s}$ for the Tanjung Dua Belas residual soil. These results demonstrate an inverse relationship between Maximum Dry Density and hydraulic conductivity, whereby soils achieving higher dry density generally exhibit lower hydraulic conductivity. A higher Maximum Dry Density indicates more efficient

particle packing during compaction, producing a denser soil structure with reduced void ratio and lower pore connectivity, thereby restricting the flow of water through the compacted soil matrix.

The observed relationship is consistent with previous studies on compacted landfill liner soils. Benson et al. (1999) investigated compacted clay liners under different compaction conditions and reported that increasing dry density significantly reduced hydraulic conductivity by producing a denser soil structure with fewer interconnected pores. Hamdi et al. (2013) similarly found that compacted clay soils subjected to higher dry densities exhibited lower hydraulic conductivity due to reduced void ratio and improved particle contact. More recently, Mbarki et al. (2023) demonstrated that achieving a high Maximum Dry Density during compaction is essential for developing low-hydraulic conductivity clay barriers for landfill applications. These findings agree well with the present study, where the Air Hitam residual soil achieved the highest Maximum Dry Density and correspondingly recorded the lowest hydraulic conductivity.

4.5.4 Relationship of Hydraulic Conductivity and Moisture Content

Figure 4.14 illustrates the relationship between hydraulic conductivity and the moisture conditions adopted during compaction, comprising the dry of optimum (-3% OMC), Optimum Moisture Content (OMC) and wet of optimum ($+3\%$ OMC) for the investigated residual soils. Since the comparison evaluates the influence of compaction moisture on hydraulic conductivity, the hydraulic conductivity values used correspond to specimens subjected to the maximum applied vertical load of 200 kPa, representing the highest loading condition adopted in the modified oedometer test and simulating the overburden pressure developed under progressive landfill waste placement (Rowe et al., 2004). Using the hydraulic conductivity values obtained under the same loading condition enables direct evaluation of the influence of compaction moisture on hydraulic conductivity behaviour.

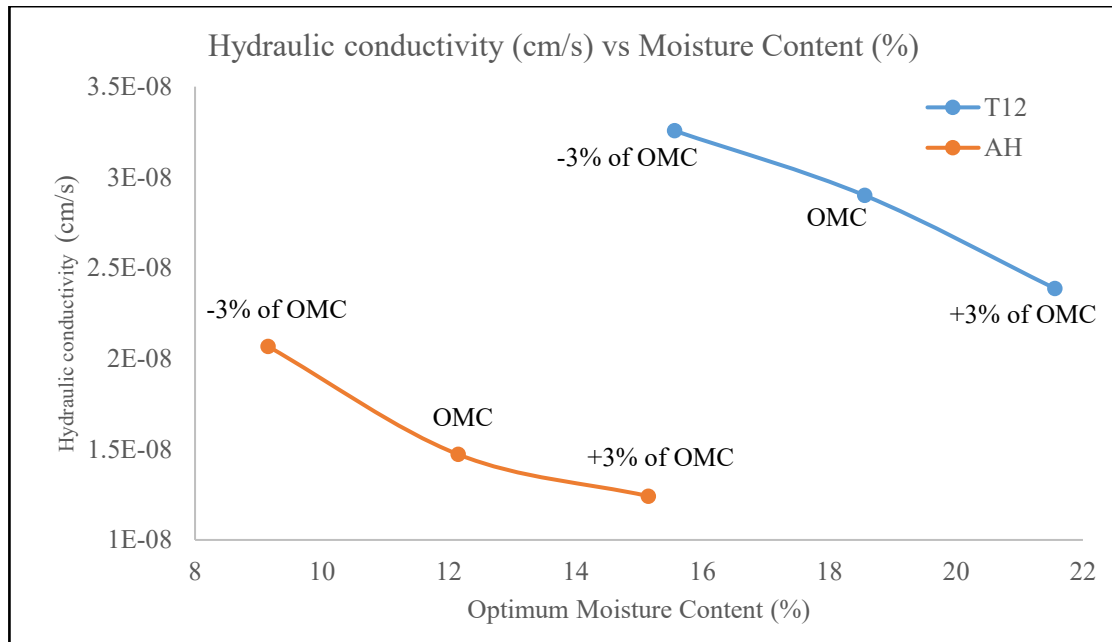


Figure 4.14 Relationship of Hydraulic Conductivity (cm/s) with Moisture Content (%)

The results indicate that hydraulic conductivity decreases progressively as the compaction moisture condition changes from dry of optimum (-3% OMC) to Optimum Moisture Content (OMC) and subsequently to wet of optimum ($+3\%$ OMC) for both residual soils. The Air Hitam residual soil consistently records lower hydraulic conductivity than the Tanjung Dua Belas residual soil throughout the evaluated moisture range, reflecting its higher Maximum Dry Density and lower Air Void content shown in figure 4.15. The observed trend demonstrates that increasing the moulding water content within the allowable moisture tolerance promotes improved particle rearrangement during compaction, resulting in reduced pore continuity and lower hydraulic conductivity.

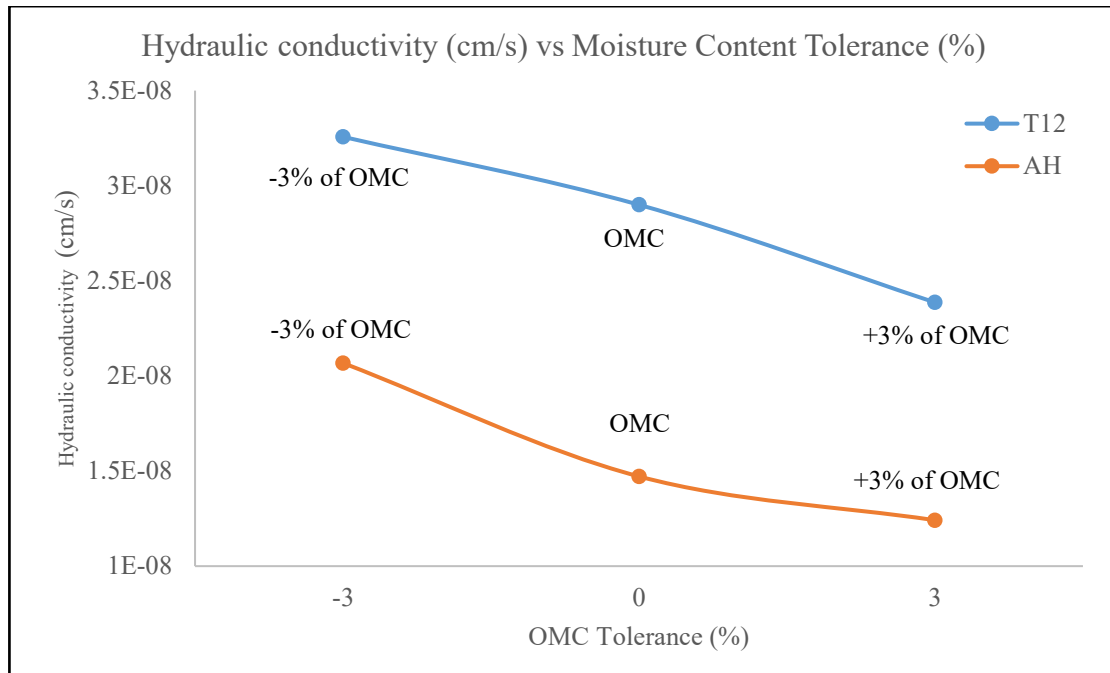


Figure 4.15 Relationship of Hydraulic Conductivity (cm/s) and Moisture Condition (%)

The relationship observed in this study agrees with previous investigations on compacted landfill liner materials. Benson et al. (1999) investigated compacted clay liner soils prepared under different moulding water contents and reported that specimens compacted at or slightly wet of optimum consistently achieved lower hydraulic conductivity because of improved soil fabric and reduced macropore continuity. Benson et al. (2014) similarly demonstrated, through laboratory testing of compacted clay barriers, that wet of optimum compaction produced lower hydraulic conductivity than dry of optimum compaction even when comparable dry densities were achieved. Adeyemo and Bello (2024) also reported comparable behaviour for tropical residual soils evaluated as landfill liner materials, where hydraulic conductivity decreased progressively from dry of optimum to wet of optimum conditions while remaining within the order of 10^{-8} cm/s.

From an engineering perspective, these findings demonstrate that controlling compaction moisture is essential during landfill liner construction. In practice, achieving the exact Optimum Moisture Content is often difficult because the moulding water content may be influenced by rainfall, evaporation, solar exposure, material stockpiling, transportation, construction delays and field mixing operations. The observed reduction in hydraulic conductivity under wet of optimum compaction therefore provides engineers with a practical moisture tolerance range that can still

achieve satisfactory hydraulic performance under field conditions. Throughout the evaluated moisture range, both residual soils maintain hydraulic conductivity values below the maximum value of 1×10^{-7} cm/s specified by the United States Environmental Protection Agency (EPA, 1993), which is also adopted in the Malaysian Guidelines for Sanitary Landfill Design and Operation issued by the Ministry of Housing and Local Government (KPKT) for compacted landfill liner materials. These findings demonstrate that both soils satisfy the required hydraulic conductivity criterion within the evaluated moisture tolerance range.

4.5.5 Normally Distributed Analysis of Hydraulic Conductivity and Soil Characteristics

Statistical analysis was performed using Minitab Statistical Software (Minitab LLC, 2023) to evaluate the relationships between hydraulic conductivity and the measured soil characteristics. A total of 24 hydraulic conductivity values obtained from the modified oedometer hydraulic conductivity tests were entered into the software. These values were generated from two residual soil samples, namely Tanjung Dua Belas (T12) and Air Hitam (AH), tested under three compaction moisture conditions (-3% OMC, OMC and $+3\%$ OMC) and four applied vertical loads (25, 50, 100 and 200 kPa). The corresponding soil properties, including moisture content, air void, maximum dry density and applied load, were incorporated into the dataset to evaluate their relationships with hydraulic conductivity. The variables included in the statistical analysis are summarised in Table 4.13.

Table 4.13
Input Variables for Minitab Statistical Analysis

Number	Sample Name	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	D ₆₀ (mm)	D ₃₀ (mm)	D ₁₀ (mm)	Cu	C _g	Classification	PH	G _s	SL	LL	PL	PI	Classification	w	Av	Pd	load	k
1	-T12	0	86	10	4	1	0.32	0.012	83.33	8.53	Silty SAND	2.81	2.277	6.61	39.83	16.85	22.98	Clay of intermediate plasticity	15.56	11.219	1.49	25	4.76E-08
2	-T12	0	86	10	4	1	0.32	0.012	83.33	8.53	Silty SAND	2.81	2.277	6.61	39.83	16.85	22.98	Clay of intermediate plasticity	15.56	11.219	1.49	50	4.37E-08
3	-T12	0	86	10	4	1	0.32	0.012	83.33	8.53	Silty SAND	2.81	2.277	6.61	39.83	16.85	22.98	Clay of intermediate plasticity	15.56	11.219	1.49	100	3.97E-08
4	-T12	0	86	10	4	1	0.32	0.012	83.33	8.53	Silty SAND	2.81	2.277	6.61	39.83	16.85	22.98	Clay of intermediate plasticity	15.56	11.219	1.49	200	3.28E-08
5	T12	0	86	10	4	1	0.32	0.012	83.33	8.53	Silty SAND	2.81	2.277	6.61	39.83	16.85	22.98	Clay of intermediate plasticity	18.56	6.115	1.5	25	4.19E-08
6	T12	0	86	10	4	1	0.32	0.012	83.33	8.53	Silty SAND	2.81	2.277	6.61	39.83	16.85	22.98	Clay of intermediate plasticity	18.56	6.115	1.5	50	3.82E-08
7	T12	0	86	10	4	1	0.32	0.012	83.33	8.53	Silty SAND	2.81	2.277	6.61	39.83	16.85	22.98	Clay of intermediate plasticity	18.56	6.115	1.5	100	3.37E-08
8	T12	0	86	10	4	1	0.32	0.012	83.33	8.53	Silty SAND	2.81	2.277	6.61	39.83	16.85	22.98	Clay of intermediate plasticity	18.56	6.115	1.5	200	2.9E-08
9	+T12	0	86	10	4	1	0.32	0.012	83.33	8.53	Silty SAND	2.81	2.277	6.61	39.83	16.85	22.98	Clay of intermediate plasticity	21.56	2.919	1.48	25	3.44E-08
10	+T12	0	86	10	4	1	0.32	0.012	83.33	8.53	Silty SAND	2.81	2.277	6.61	39.83	16.85	22.98	Clay of intermediate plasticity	21.56	2.919	1.48	50	3.03E-08
11	+T12	0	86	10	4	1	0.32	0.012	83.33	8.53	Silty SAND	2.81	2.277	6.61	39.83	16.85	22.98	Clay of intermediate plasticity	21.56	2.919	1.48	100	2.67E-08
12	+T12	0	86	10	4	1	0.32	0.012	83.33	8.53	Silty SAND	2.81	2.277	6.61	39.83	16.85	22.98	Clay of intermediate plasticity	21.56	2.919	1.48	200	2.39E-08
13	-AH	0	70	20	10	0.15	0.075	0.002	75	18.75	Silty SAND	3.65	2.482	1.14	24.14	10.75	13.39	Clay of low plasticity	8.75	9.604	1.84	25	4.08E-08
14	-AH	0	70	20	10	0.15	0.075	0.002	75	18.75	Silty SAND	3.65	2.482	1.14	24.14	10.75	13.39	Clay of low plasticity	8.75	9.604	1.84	50	3.08E-08
15	-AH	0	70	20	10	0.15	0.075	0.002	75	18.75	Silty SAND	3.65	2.482	1.14	24.14	10.75	13.39	Clay of low plasticity	8.75	9.604	1.84	100	2.65E-08
16	-AH	0	70	20	10	0.15	0.075	0.002	75	18.75	Silty SAND	3.65	2.482	1.14	24.14	10.75	13.39	Clay of low plasticity	8.75	9.604	1.84	200	2.07E-08
17	AH	0	70	20	10	0.15	0.075	0.002	75	18.75	Silty SAND	3.65	2.482	1.14	24.14	10.75	13.39	Clay of low plasticity	11.75	1.989	1.88	25	3.07E-08
18	AH	0	70	20	10	0.15	0.075	0.002	75	18.75	Silty SAND	3.65	2.482	1.14	24.14	10.75	13.39	Clay of low plasticity	11.75	1.989	1.88	50	2.52E-08
19	AH	0	70	20	10	0.15	0.075	0.002	75	18.75	Silty SAND	3.65	2.482	1.14	24.14	10.75	13.39	Clay of low plasticity	11.75	1.989	1.88	100	1.99E-08
20	AH	0	70	20	10	0.15	0.075	0.002	75	18.75	Silty SAND	3.65	2.482	1.14	24.14	10.75	13.39	Clay of low plasticity	11.75	1.989	1.88	200	1.47E-08
21	+AH	0	70	20	10	0.15	0.075	0.002	75	18.75	Silty SAND	3.65	2.482	1.14	24.14	10.75	13.39	Clay of low plasticity	14.75	0.198	1.81	25	2.72E-08
22	+AH	0	70	20	10	0.15	0.075	0.002	75	18.75	Silty SAND	3.65	2.482	1.14	24.14	10.75	13.39	Clay of low plasticity	14.75	0.198	1.81	50	2.19E-08
23	+AH	0	70	20	10	0.15	0.075	0.002	75	18.75	Silty SAND	3.65	2.482	1.14	24.14	10.75	13.39	Clay of low plasticity	14.75	0.198	1.81	100	1.67E-08
24	+AH	0	70	20	10	0.15	0.075	0.002	75	18.75	Silty SAND	3.65	2.482	1.14	24.14	10.75	13.39	Clay of low plasticity	14.75	0.198	1.81	200	1.24E-08

Descriptive statistical analysis was first performed to summarise the characteristics of the experimental dataset before conducting further statistical analyses. The descriptive statistics comprise the mean, standard deviation, minimum value, median, maximum value, skewness and kurtosis, as presented in Table 4.14. These statistical measures provide an overview of the central tendency, variability and distribution pattern of each variable, allowing the overall behaviour of the experimental data to be evaluated prior to correlation and regression analyses. Montgomery et al. (2021) described descriptive statistical analysis as an essential preliminary procedure for understanding the characteristics of experimental datasets before applying inferential statistical techniques.

Table 4.14
Summary of Descriptive Statistics

Variable	Mean	StDev	Min	Median	Max	Skewness	Kurtosis
Moisture Content (w)	18.56	2.558	15.56	18.56	21.56	0	-1.65
Air Void (A_v)	6.75	3.57	2.92	6.12	11.22	0.31	-1.65
Dry Density, (ρ_d)	1.49	0.0085	1.48	1.49	1.5	0	-1.65
Applied Load, (Load)	93.8	70	25	75	200	0.75	-1.01
Hydraulic Conductivity, (K (E10 ⁻⁸))	3.514	0.723	2.387	3.404	4.764	0.18	-0.82

The descriptive statistics presented in Table 4.14 summarise the characteristics of the experimental dataset prior to further statistical analysis. The analysed variables exhibit different numerical ranges according to their respective engineering properties. For example, the applied vertical load varies from 25 kPa to 200 kPa, while the hydraulic conductivity ranges from 2.387×10^{-8} cm/s to 4.764×10^{-8} cm/s, reflecting the variation produced under different compaction moisture conditions and applied loading during the modified oedometer test. Likewise, the moisture content, air void and maximum dry density vary according to the physical characteristics of the investigated residual soils. According to Montgomery et al. (2021), descriptive statistical analysis provides a preliminary summary of experimental datasets by describing their central tendency, variability and distribution characteristics before applying inferential statistical analyses.

Assessment of data normality was subsequently performed using the skewness and kurtosis values obtained from the descriptive statistics. Skewness measures the degree of symmetry of the data distribution, whereas kurtosis describes the degree of peakedness or flatness relative to a normal distribution. Kim (2013) explained that skewness and kurtosis are widely used to assess the normality of experimental datasets prior to applying parametric statistical analyses because they provide numerical indicators of distribution shape. George and Mallery (2010) recommended that datasets with skewness and kurtosis values between -2 and $+2$ can generally be considered approximately normally distributed for parametric statistical analysis. Razali and Wah (2011), in their comparative evaluation of statistical normality tests, also emphasised that verifying the normality of experimental data is an essential prerequisite before applying parametric statistical techniques because it improves the reliability and validity of subsequent statistical interpretations. Based on Table 4.14, the skewness values range from 0.00 to 0.75, while the kurtosis values range from -1.65 to -0.82 . Since all values fall within the acceptable range of -2 to $+2$, the analysed variables are considered to exhibit approximately normal distributions. The dataset is therefore suitable for subsequent Pearson correlation analysis, regression analysis and paired t-test, which assume that the analysed variables satisfy the normality requirement for parametric statistical analysis (Montgomery et al., 2021).

4.5.6 Pearson Correlation Analysis between Hydraulic Conductivity and Soil Characteristics

Pearson correlation analysis is performed to evaluate the strength, direction and statistical significance of the relationships between hydraulic conductivity and the selected soil characteristics. The Pearson correlation coefficient (r) is adopted to quantify the degree of linear association between two variables, with values ranging from -1 to $+1$. Positive correlation coefficients indicate that both variables change in the same direction, whereas negative correlation coefficients indicate that one variable increases while the other decreases. Correlation coefficients with values closer to ± 1 represent stronger linear relationships, while coefficients approaching 0 indicate weak or negligible relationships (Schober et al., 2018). The statistical significance of each relationship is evaluated using the P-value, where a P-value lower than the significance level ($\alpha = 0.05$) indicates that the null hypothesis can be rejected and that a statistically

significant relationship exists between the analysed variables (Montgomery et al., 2021). Pearson correlation analysis has been widely adopted in geotechnical engineering studies to evaluate relationships among soil properties and to identify the engineering parameters that most strongly influence soil behaviour (Akinwumi et al., 2016).

Table 4.15
Pairwise Pearson Correlations

Variable 1	Variable 2	Pearson Correlation, <i>r</i>	P value	Interpretation
K (1×10^{-8})	<i>W</i>	-0.713	0.009	Strong negative, statistically significant
K (1×10^{-8})	<i>A_v</i>	0.699	0.011	Strong positive, statistically significant
K (1×10^{-8})	ρ_d	0.408	0.188	Moderate positive, not statistically significant
K (1×10^{-8})	Load	-0.67	0.017	Strong negative, statistically significant

The Pearson correlation results indicate that moisture content, air void and applied load exhibit statistically significant relationships with hydraulic conductivity, whereas the relationship between hydraulic conductivity and dry density is not statistically significant at the 95% confidence level. A strong negative correlation is observed between hydraulic conductivity and moisture content ($r = -0.713$, $P = 0.009$), indicating that hydraulic conductivity decreases as the moulding moisture content increases. This finding agrees with the compaction behaviour observed in the present study, where specimens compacted at +3% OMC consistently produced lower hydraulic conductivity than specimens compacted at OMC and -3% OMC. Increasing the moulding moisture content improves particle lubrication during compaction, allowing soil particles to rearrange more efficiently and reducing pore continuity within the compacted soil structure. Similar observations are reported by Benson et al. (2014), who investigated compacted clay liner materials for landfill applications and demonstrated that specimens compacted slightly wet of optimum consistently developed lower

hydraulic conductivity because improved soil fabric reduced the continuity of macropores.

Hydraulic conductivity also exhibits a strong positive correlation with air void content ($r = 0.699$, $P = 0.011$), indicating that hydraulic conductivity increases as the air void percentage increases. This relationship reflects the influence of pore structure on water movement, where larger air void contents provide more continuous flow paths through the compacted soil matrix. Consequently, reducing air voids through effective compaction contributes directly to lower hydraulic conductivity and improved hydraulic barrier performance. A similar relationship was reported by Mbarki et al. (2023), who evaluated compacted clay barrier materials under different moisture conditions and concluded that air void ratio is one of the primary parameters governing hydraulic conductivity because it directly controls pore connectivity and soil microstructure.

The relationship between maximum dry density and hydraulic conductivity shows a moderate positive correlation ($r = 0.408$), although the relationship is not statistically significant ($P = 0.188$). This statistical result should not be interpreted as indicating that increasing dry density increases hydraulic conductivity. Instead, the limited number of representative maximum dry density values available in the present study reduces the statistical significance of the correlation. From an engineering perspective, the experimental results clearly demonstrate that the Air Hitam soil, which achieves the higher maximum dry density, consistently records lower hydraulic conductivity than the Tanjung Dua Belas soil. This observation agrees with the findings of Hamdi et al. (2013), who investigated compacted clay soils under different stress conditions and reported that increasing dry density generally reduces pore connectivity and hydraulic conductivity by producing a denser soil fabric.

Applied vertical load exhibits a strong negative correlation with hydraulic conductivity ($r = -0.670$, $P = 0.017$), indicating that hydraulic conductivity decreases as the applied vertical stress increases. Increasing vertical loading compresses the compacted soil matrix, decreases the void ratio and limits pore continuity, thereby restricting the movement of water through the specimen. This behaviour is consistent with the modified oedometer results obtained in the present study, where hydraulic conductivity decreases progressively from 25 kPa to 200 kPa for both residual soils. Similar stress-dependent hydraulic conductivity behaviour has been reported by Hamdi et al. (2013), who observed that increasing vertical stress on compacted clay soils

progressively reduced hydraulic conductivity through compression of the soil structure and closure of interconnected pores.

Overall, the Pearson correlation analysis confirms that moisture content, air void content and applied vertical load are the dominant factors influencing hydraulic conductivity in the investigated residual soils. The statistical findings are consistent with the experimental observations and demonstrate that hydraulic conductivity is governed primarily by the combined effects of compaction moisture condition, pore structure development and applied loading rather than by any individual soil property alone. These results further support the suitability of the investigated residual soils for landfill liner applications when appropriate moisture control and compaction procedures are adopted.

4.5.7 Regression Analysis of Hydraulic Conductivity and Soil Characteristics

Regression Analysis was performed to develop empirical equations capable of predicting hydraulic conductivity from selected soil characteristics. The regression models were established using 12 experimental observations obtained from the Tanjung Dua Belas (T12) residual soil, which served as the model development dataset. The dataset comprised hydraulic conductivity measurements obtained under three compaction moisture conditions (-3% OMC, OMC and $+3\%$ OMC) and four applied vertical loads (25, 50, 100 and 200 kPa), resulting in twelve experimental observations. The remaining 12 observations obtained from the Air Hitam (AH) residual soil were reserved as an independent validation dataset, where the measured soil properties were substituted into the developed regression equations to predict hydraulic conductivity. The predicted hydraulic conductivity values were subsequently compared with the experimentally measured values obtained from the modified oedometer tests to evaluate the predictive capability of the developed equations. The use of separate model development and validation datasets is widely recommended in predictive modelling because it provides a more objective assessment of model reliability and reduces the possibility of overfitting the regression equations (Hastie et al., 2009).

Quadratic polynomial regression was adopted because preliminary scatter plots generated using Minitab indicated that the relationships between hydraulic conductivity and the investigated soil characteristics exhibited nonlinear trends rather than simple linear behaviour. Engineering properties such as moisture content, dry density, air void

and applied vertical load commonly influence hydraulic conductivity through complex interactions involving particle rearrangement, soil fabric development and pore structure evolution during compaction. Consequently, a second-order polynomial regression provides a more appropriate representation of these nonlinear relationships than a simple linear regression model (Montgomery et al., 2021). The resulting empirical regression equations together with their corresponding coefficients of determination (R^2) are presented in Table 4.16.

Table 4.16
Empirical Modelling in Predicting k value

Equation No.	Equation	R^2
1	$k \text{ (E-08)} = 3.769 - 0.02389 \text{ load} + 0.000065 \text{ load}^2$	0.66
2	$k \text{ (E-8)} = 2.002 + 0.3413 A_v - 0.01383 A_v^2$	0.51
3	$k \text{ (E-8)} = 4.00 + 0.156 w - 0.00963 w_2$	0.49
4	$k \text{ (E-8)} = -19222 + 25772 P_d - 8637 P_d^2$	0.48

The predictive capability of each regression equation was evaluated using the coefficient of determination (R^2), which represents the proportion of variation in hydraulic conductivity explained by the independent variable. An R^2 value approaching 1.0 indicates that the regression model explains a greater proportion of the observed variation and therefore possesses higher explanatory capability, whereas values approaching 0 indicate limited explanatory capability (Hair et al., 2019). Regression Analysis has been widely applied in geotechnical engineering to establish predictive relationships between measurable soil properties and engineering performance when extensive laboratory testing is impractical. Das and Sobhan (2018) explained that regression models are commonly used to estimate engineering behaviour from measurable soil parameters, while Chapuis (2012), in a comprehensive review of hydraulic conductivity prediction for natural soils, demonstrated that empirical regression models provide practical tools for estimating hydraulic conductivity based on soil characteristics when supported by reliable laboratory measurements.

Among the investigated variables, applied vertical load produced the highest explanatory capability ($R^2 = 0.66$), indicating that approximately 66% of the variation in hydraulic conductivity can be explained by changes in applied load alone. This

finding confirms that vertical stress is the most influential individual parameter within the present dataset and agrees with the hydraulic conductivity results presented in Section 4.3, where increasing vertical load consistently reduced hydraulic conductivity through progressive compression of the soil matrix and reduction of interconnected pore spaces. The regression model developed using air void demonstrates a moderate explanatory capability ($R^2 = 0.51$), indicating that approximately 51% of the variation in hydraulic conductivity is associated with changes in air void content. This observation supports the physical interpretation that reducing air-filled voids improves particle packing and limits continuous flow paths, thereby reducing hydraulic conductivity.

The regression equations developed using moisture content ($R^2 = 0.49$) and maximum dry density ($R^2 = 0.48$) exhibit low to moderate explanatory capability, suggesting that although these parameters influence hydraulic conductivity, they do not independently govern hydraulic conductivity behaviour. Instead, their effects are strongly coupled with other engineering properties such as air void, applied stress and soil fabric. Similar observations were reported by Benson et al. (1999), who investigated compacted clay liner soils for landfill applications and demonstrated that hydraulic conductivity is controlled by the combined interaction between moulding water content, achieved dry density and soil structure rather than by a single parameter alone. Likewise, Mbarki et al. (2023), in their investigation of compacted clay barrier materials, concluded that hydraulic conductivity is governed by the combined effects of moisture condition, dry density and applied stress because these factors collectively control pore connectivity and soil microstructure. The regression analysis therefore demonstrates that hydraulic conductivity is best interpreted as the combined response of multiple interacting soil characteristics rather than the influence of any single engineering property.

4.5.8 Validation of the Empirical Regression Models Using Paired t-Test

The empirical regression models developed in Section 4.5.7 were further evaluated using a paired t-test to assess whether the predicted hydraulic conductivity values differed significantly from the corresponding experimentally measured values. In this study, the regression equations were developed using twelve observations obtained from the Tanjung Dua Belas (T12) residual soil, representing the model

development dataset. The remaining twelve observations obtained from the Air Hitam (AH) residual soil were reserved as an independent validation dataset. Separating the experimental data into model development and validation datasets is a common practice in predictive modelling because it enables the predictive capability of the developed equations to be evaluated using independent observations rather than the data used during model development (Hastie et al., 2009). Similar regression-based predictive modelling approaches have been adopted in geotechnical engineering. Khalid et al. (2024) developed empirical relationships between compaction characteristics and hydraulic conductivity of bentonite-amended residual soils for landfill liner applications to evaluate hydraulic performance using measurable engineering properties. Although their study did not employ a paired t-test, it demonstrates the application of regression models as practical engineering prediction tools for landfill liner assessment.

Unlike the coefficient of determination (R^2), which evaluates how well a regression equation fits the model development dataset, the paired t-test evaluates whether the predicted values produced by the developed equation are statistically comparable with independent experimental observations. Consequently, both statistical methods complement one another, where R^2 measures the explanatory capability of the regression model, whereas the paired t-test evaluates its predictive consistency when applied to independent data (Montgomery et al., 2021). The regression model relating hydraulic conductivity to applied vertical load was first evaluated using the independent validation dataset. Figure 4.16 compares the experimentally measured hydraulic conductivity values with those predicted using the quadratic regression equation developed from the Tanjung Dua Belas dataset. The predicted values closely follow the overall decreasing trend of the measured hydraulic conductivity as the applied vertical load increases. This agreement indicates that the regression equation successfully captures the stress-dependent hydraulic conductivity behaviour observed experimentally. Although minor deviations between the predicted and measured values remain, the overall prediction pattern demonstrates that the applied load is an important predictor of hydraulic conductivity because increasing vertical stress progressively compresses the soil structure, reduces pore continuity and decreases hydraulic conductivity.

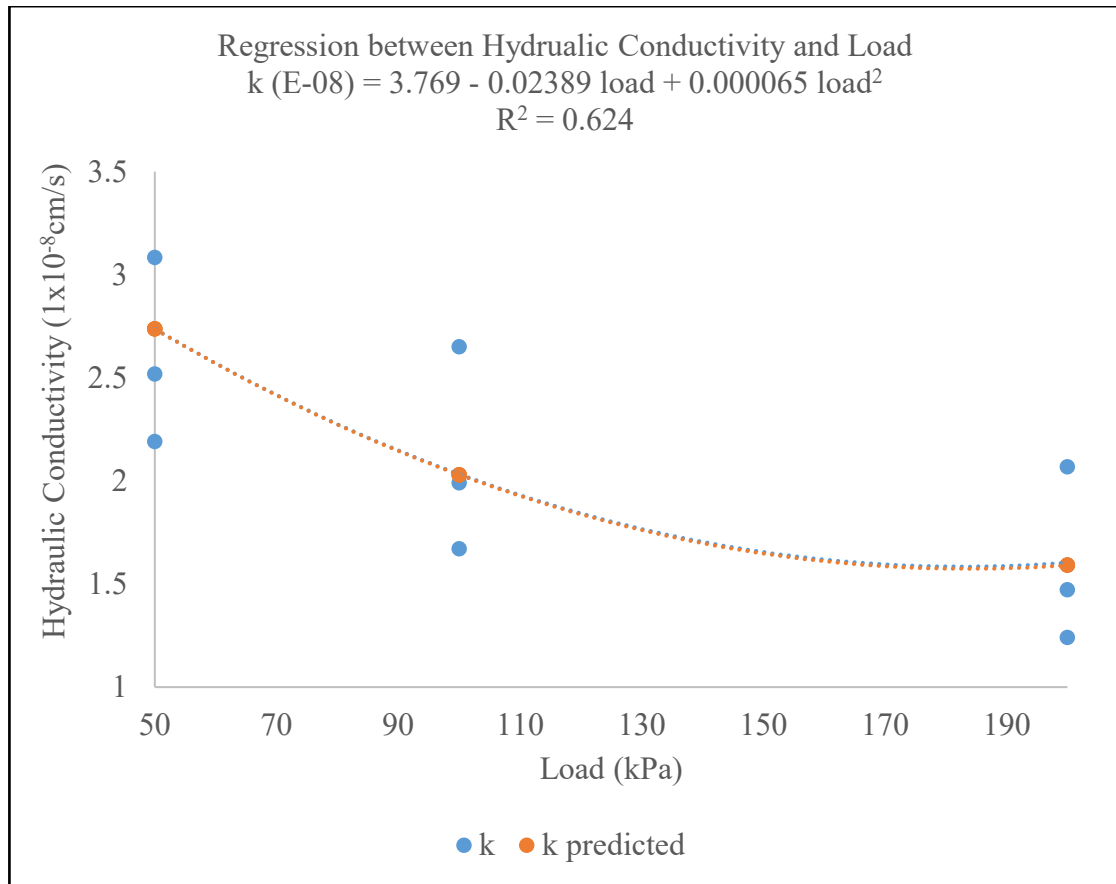


Figure 4.16 Validation of the Load-Based Regression Model Using Measured and Predicted k

A similar validation was performed for the regression model relating hydraulic conductivity to air void percentage, as presented in Figure 4.17. The predicted hydraulic conductivity values generally follow the same increasing trend as the measured values with increasing air void percentage. However, compared with the applied load model, a greater degree of scatter is observed between the predicted and measured values. This behaviour is consistent with the regression analysis, where the air void model produced a lower coefficient of determination ($R^2 = 0.512$) than the applied load model ($R^2 = 0.624$). The results therefore suggest that although air void influences hydraulic conductivity through its effect on pore connectivity, additional factors such as particle arrangement, moisture condition and dry density also contribute to the observed hydraulic conductivity behaviour.

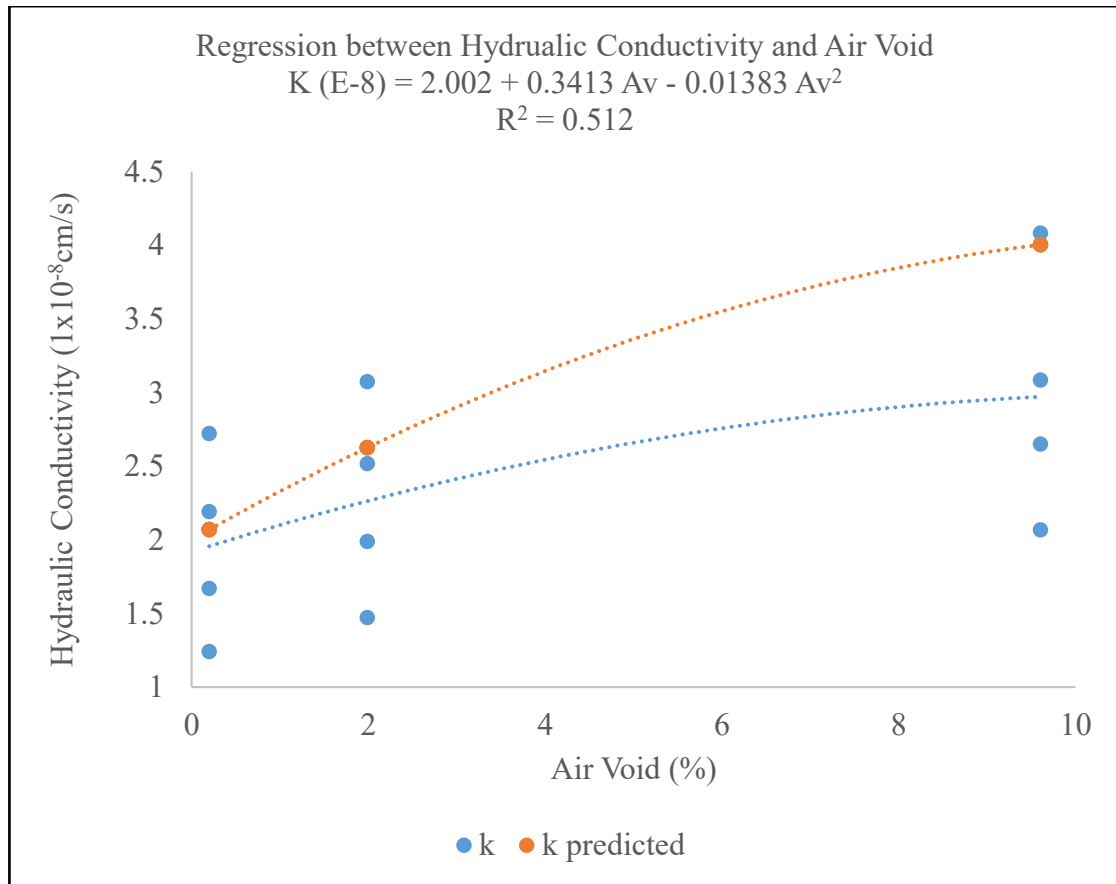


Figure 4.17 Validation of the Air Void-Based Regression Model Using Measured and Predicted k

The statistical comparison between the measured and predicted hydraulic conductivity values is summarised in Table 4.17 using the paired t-test.

Table 4.17
P Value using t Paired Test

Equation No.	Equation	P Value
1	$k (1 \times 10^{-8}) \text{ cm/s} = 3.769 - 0.02389 \text{ load} + 0.000065 \text{ load}^2$	0.975
2	$k (1 \times 10^{-8}) \text{ cm/s} = 2.002 + 0.3413 A_v - 0.01383 A_v^2$	0.05

The paired t-test evaluates whether the mean difference between the predicted and experimentally measured hydraulic conductivity values is statistically significant. At the 95% confidence level, a p-value greater than 0.05 indicates that no statistically significant difference exists between the predicted and measured values, suggesting that the developed regression equation can represent the experimental observations with acceptable accuracy (Montgomery et al., 2021). Both regression equations satisfy this

criterion. The applied load model records a p-value of 0.975, indicating excellent agreement between the predicted and measured hydraulic conductivity values. The air void model produces a p-value of 0.050, which lies exactly at the selected significance level. Although this result still satisfies the acceptance criterion adopted in this study, it indicates comparatively lower predictive consistency than the applied load model. This observation agrees with the corresponding R^2 values, where the applied load model explains a greater proportion of the variation in hydraulic conductivity than the air void model.

It should be noted that the paired t-test only evaluates whether statistically significant differences exist between the predicted and measured values and does not independently quantify the overall prediction error of the regression model. Therefore, the paired t-test should be interpreted together with the coefficient of determination (R^2), which describes the explanatory capability of the regression equation. Based on the present results, the developed equations should be regarded as preliminary empirical relationships that describe the observed experimental behaviour rather than fully validated predictive models.

4.5.9 Derivation of a Predictive Hydraulic Conductivity Model from the Regression Analysis

The regression analysis identifies air void percentage (A_v) as one of the significant engineering parameters influencing hydraulic conductivity. Since air void is not measured directly but is calculated from other measurable soil properties, the developed regression equation can be further expressed in terms of dry density (ρ_d), water content (w), specific gravity (G_s) and water density (ρ_w). This derivation allows the predictive hydraulic conductivity model to be formulated using soil properties that are routinely determined during laboratory compaction testing.

The empirical regression model obtained from the Minitab analysis is expressed as

$$k = 2.002 + 0.3413 A_v - 0.01383 A_v^2$$

Where the air void percentage is determined using Equation (3.1):

$$A_v = \left[1 - \frac{\rho_d (1+w G_s)}{G_s \rho_w} \right] \times 100$$

Substituting Equation (3.1) into the regression equation produces the predictive hydraulic conductivity model shown in Equation (4.1):

$$k = 2.002 + 0.3413 \left[1 - \frac{\rho_d (1+w G_s)}{G_s \rho_w} \times 100 \right] - 0.01383 \left[1 - \frac{\rho_d (1+w G_s)}{G_s \rho_w} \times 100 \right]^2 \quad (4.1)$$

Where:

ρ_d = Dry Density (Mg/m³)

ρ_w = Density of water (0.9982 Mg/m³)

W = Water Content (%)

G_s = Specific Gravity

The derived equation enables hydraulic conductivity to be estimated directly from routinely measured laboratory parameters without first calculating the air void percentage separately. Consequently, only the dry density, water content and specific gravity of the compacted soil are required to generate a preliminary estimate of hydraulic conductivity. The predictive model developed in this study is intended as a preliminary engineering assessment tool rather than a replacement for conventional laboratory hydraulic conductivity testing. Hydraulic conductivity tests using the modified oedometer apparatus require specimen preparation, saturation, incremental loading and continuous monitoring, making the testing procedure relatively time-consuming. In contrast, the proposed equation enables a rapid preliminary estimation of hydraulic conductivity immediately after the compaction properties have been determined. Such empirical prediction models are commonly developed in geotechnical engineering to provide preliminary estimates of engineering behaviour before detailed laboratory verification is completed (Shackelford et al., 2016). Similar approaches have been adopted by Benson et al. (2014), who demonstrated that compaction-related parameters can be used to establish practical empirical relationships for estimating the hydraulic performance of compacted clay liners.

Although the regression model does not provide a perfect prediction of hydraulic conductivity, the coefficient of determination obtained for the air void model ($R^2 = 0.512$) indicates that approximately 51.2% of the observed variation in hydraulic conductivity is explained by the derived equation. According to Montgomery et al. (2021), regression models with moderate explanatory capability remain useful for engineering prediction provided that their limitations are clearly recognised and the

models are applied within the range of the experimental data used for their development. Therefore, the proposed equation should be regarded as a preliminary predictive model suitable for estimating hydraulic conductivity during the early stages of landfill liner assessment or preliminary design, while the final hydraulic conductivity should continue to be verified using laboratory hydraulic conductivity testing before engineering implementation.

CHAPTER 5

CONCLUSION

5.1 Introduction

This section presents the conclusions drawn from the findings discussed in Chapter 4 based on the four research objectives established for this study. The conclusions are organised according to each research objective to provide a systematic evaluation of the physical properties, compaction behaviour, hydraulic conductivity performance and the relationship between hydraulic conductivity and soil characteristics of the residual soils obtained from the Tanjung Dua Belas and Air Hitam landfill sites. The findings provide a comprehensive assessment of the engineering behaviour of the investigated residual soils and their suitability for use as landfill liner materials.

5.1.1 Physical Properties of the Residual Soils

The first research objective was successfully achieved by determining the physical properties of the residual soils obtained from the Tanjung Dua Belas and Air Hitam landfill sites. The results indicate that both soils are classified as Silty SAND, although the Air Hitam soil contains a higher proportion of fines (30%) than the Tanjung Dua Belas soil (14%). The Air Hitam soil also records a higher particle density of 2.478 Mg/m³ compared with 2.223 Mg/m³ for the Tanjung Dua Belas soil. Based on the Atterberg limit results, the Tanjung Dua Belas soil is classified as CI (Clay of Intermediate Plasticity) with a Liquid Limit of 39.83%, Plastic Limit of 16.85% and Plasticity Index of 22.98%, whereas the Air Hitam soil is classified as CL (Clay of Low Plasticity) with corresponding values of 24.14%, 10.75% and 13.39%, respectively. The linear shrinkage values of 6.61% for Tanjung Dua Belas and 1.14% for Air Hitam further indicate differences in the volumetric change characteristics of the two soils. Overall, the measured physical properties are generally within or close to the ranges commonly reported for soils used as compacted landfill liner materials. These findings provide a comprehensive understanding of the physical characteristics of the investigated residual soils and confirm that the first research objective, which is to

determine the physical properties of the residual soils from the Tanjung Dua Belas and Air Hitam landfill sites, has been successfully achieved.

5.1.2 Compaction Behaviour of the Residual Soils

The second research objective was successfully achieved by evaluating the compaction behaviour of the residual soils under different moisture conditions. The results show that the Air Hitam soil achieved a higher Maximum Dry Density (MDD) of 1.88 Mg/m^3 at an Optimum Moisture Content (OMC) of 11.75%, whereas the Tanjung Dua Belas soil recorded an MDD of 1.50 Mg/m^3 at an OMC of 18.56%. These results indicate that the Air Hitam soil requires less water to achieve maximum compaction and is capable of developing a denser compacted structure than the Tanjung Dua Belas soil. Both soils exhibited only slight changes in dry density when compacted within the adopted moisture tolerance range of -3% OMC and $+3\%$ OMC, demonstrating stable compaction behaviour under varying moisture conditions. The air void content also decreased progressively with increasing moisture content, reducing from 11.21% to 2.92% for the Tanjung Dua Belas soil and from 9.63% to 0.20% for the Air Hitam soil, indicating improved particle rearrangement and more effective pore closure during compaction. Overall, the compaction results demonstrate that both residual soils are capable of forming dense and stable compacted structures under controlled moisture conditions, with the higher maximum dry density achieved by the Air Hitam soil indicating greater compaction efficiency. These findings provide a comprehensive understanding of the compaction behaviour of the investigated residual soils and confirm that the second research objective, which is to evaluate the compaction behaviour of the residual soils under different moisture conditions, has been successfully achieved.

5.1.3 Hydraulic Conductivity Performance of the Residual Soils

The third research objective was successfully achieved by evaluating the hydraulic conductivity performance of the residual soils under different moisture conditions. The results demonstrate that hydraulic conductivity decreases progressively with increasing applied vertical load for both residual soils, indicating that higher loading promotes greater soil densification and reduces pore connectivity. Under optimum moisture content, the hydraulic conductivity of the Air Hitam soil decreased

from 3.074×10^{-8} cm/s at 25 kPa to 1.472×10^{-8} cm/s at 200 kPa, while the Tanjung Dua Belas soil decreased from 4.195×10^{-8} cm/s to 2.899×10^{-8} cm/s over the same loading range. Moisture condition also influenced the hydraulic behaviour, where both soils consistently recorded the highest hydraulic conductivity under -3% OMC, followed by OMC, while the lowest values were obtained under $+3\%$ OMC, demonstrating that compaction slightly wet of optimum produced the most effective hydraulic barrier. At the maximum applied vertical load of 200 kPa, the hydraulic conductivity values ranged from 1.241×10^{-8} cm/s to 2.067×10^{-8} cm/s for the Air Hitam soil and from 2.386×10^{-8} cm/s to 3.256×10^{-8} cm/s for the Tanjung Dua Belas soil across the evaluated moisture conditions. All measured hydraulic conductivity values remained below the maximum hydraulic conductivity criterion of 1×10^{-7} cm/s recommended by the United States Environmental Protection Agency (US EPA, 1993) and adopted by the Department of Environment (DOE) Malaysia for compacted landfill liner materials, confirming that both investigated residual soils possess suitable hydraulic barrier performance when properly compacted. These findings provide a comprehensive understanding of the hydraulic conductivity behaviour of the investigated residual soils and confirm that the third research objective, which is to evaluate the hydraulic conductivity performance of the residual soils under different moisture conditions, has been successfully achieved.

5.1.4 Relationship between Hydraulic Conductivity and Soil Characteristics

The fourth research objective was successfully achieved by establishing the relationship between hydraulic conductivity and the selected soil characteristics through graphical analysis using Microsoft Excel and statistical analysis using Minitab Statistical Software. The graphical analysis demonstrated that hydraulic conductivity generally decreased with increasing particle density, maximum dry density and moisture content, while decreasing air void content resulted in lower hydraulic conductivity. Pearson correlation analysis further confirmed that moisture content ($r = -0.713$, $P = 0.009$) and air void ($r = 0.699$, $P = 0.011$) exhibited statistically significant relationships with hydraulic conductivity. Regression Analysis identified air void as one of the most influential parameters governing hydraulic conductivity because it incorporates the combined effects of dry density, moisture content and specific gravity. Consequently, a preliminary empirical hydraulic conductivity prediction model was

successfully developed using these measurable soil properties. Validation using the paired t-test demonstrated acceptable agreement between the predicted and measured hydraulic conductivity values, indicating that the developed model can be used as a preliminary estimation tool for hydraulic conductivity while awaiting the results of the more time-consuming laboratory hydraulic conductivity test. These findings establish the relationship between hydraulic conductivity and the investigated soil characteristics and confirm that the fourth research objective of this study has been successfully achieved.

5.2 Recommendations

Future studies are recommended to expand the scope of soil sampling to strengthen the reliability and broader applicability of the findings obtained in this study. The present investigation is limited to residual soils collected from the Tanjung Dua Belas and Air Hitam landfill sites. Incorporating soil samples from additional landfill facilities within the Klang Valley, such as Jeram, Bukit Tagar and Sungai Sedu, would enable a more comprehensive comparison of residual soils developed under different geological formations and environmental conditions. Variations in mineral composition, fines content and natural moisture conditions may influence the compaction behaviour and hydraulic conductivity of landfill liner materials. A larger dataset would also improve the robustness of the statistical analyses, allowing stronger relationships to be established between soil characteristics and hydraulic conductivity while enhancing the reliability and generalisability of the developed empirical prediction model.

Further investigation is also recommended to evaluate a wider range of compaction moisture tolerances. The present study focuses on moisture conditions of -3% OMC, OMC and $+3\%$ OMC, which represent the moisture tolerance commonly adopted for landfill liner construction. Future research could investigate smaller moisture intervals, such as $\pm 1\%$ and $\pm 2\%$ OMC, together with wider tolerances such as $\pm 4\%$ OMC, to provide a more detailed assessment of the sensitivity of hydraulic conductivity to moisture variation. Such investigations would assist in identifying the critical moisture range at which hydraulic conductivity begins to increase significantly and could contribute towards the development of improved field compaction guidelines for engineered landfill liner construction.

Future research is recommended to incorporate Soil-Water Characteristic Curve (SWCC) analysis to provide a more comprehensive understanding of the influence of moisture conditions on hydraulic conductivity. While the present study evaluates hydraulic conductivity under different moulding moisture conditions, SWCC analysis would enable the determination of the water retention behaviour and matric suction characteristics of compacted residual soils over a wider range of moisture contents. Integrating SWCC with hydraulic conductivity testing would strengthen the interpretation of unsaturated flow behaviour and improve the understanding of the relationship between moisture condition, soil suction and hydraulic conductivity. Such information could support the development of more reliable compaction control guidelines and enhance the hydraulic performance assessment of landfill liner materials.

Finally, further research should evaluate the long-term engineering performance of compacted residual soils under landfill operating conditions. Additional laboratory investigations, including one-dimensional consolidation and Unconfined Compressive Strength (UCS) tests, are recommended to evaluate settlement characteristics, deformation resistance and the potential development of shrinkage or loading-induced cracking throughout the service life of the landfill liner. Integrating these mechanical assessments with hydraulic conductivity evaluation would provide a more comprehensive understanding of the long-term durability and serviceability of compacted residual soils, thereby supporting the development of more reliable and sustainable landfill liner systems.

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APPENDICES

APPENDIX 1

Table of *pH* Test Result

	TG12	Air Hitam
1	2.96	3.7
2	2.79	3.66
3	2.69	3.6
Avg.	2.81	3.65

APPENDIX 2

Table of Particle Density Test Result

	Sample No.				
	Test Meth	Small Pycnometer (50ml)			
Soil Sample		Tanjung Dua Belas		Air Hitam	
Density bottle no	#	1	2	1	2
mass of density bottle + stopper (g)	m1	38.66	41.54	40.38	40.6
mass of density bottle + stopper + dry soil (g)	m2	51.63	56.18	53.93	54.49
mass of density bottle + stopper + dry soil + water (g)	m3	145.48	149.825	148.38	148.475
mass of density bottle + stopper +dry soil + water (g)	m4	138.38	141.71	140.27	140.2
mass of dry soil used (g)	m2-m1	12.97	14.64	13.55	13.89
mass of water to fill density bottle (g)	m3-m2	93.85	93.645	94.45	93.985
specific gravity of soil	m4-m1	99.72	100.17	99.89	99.6
	Gs	2.20954	2.243678	2.490809	2.473731
AVERAGE SPECIFIC GRAVITY OF SOIL	Average G	2.226609097		2.482269951	
AVERAGE PARTICLE DENSITY OF SOIL	ps	2.222601201		2.477801865	
specific gravity, $G_s = (m_2 - m_1) / [(m_4 - m_1) - (m_3 - m_2)]$					
particle density, $p_w = G_s p_w$ where $p_w = 0.9982$					
$p_w = G_s \text{ (mg/m}^3\text{)}$					

APPENDIX 3

Table of Wet Sieving and Hydrometer Test Result for Air Hitam

Sieve No.	Sieve size (mm)	Mass of Sieve (g)	Mass of sieve + soil retained (g)	Soil weight retained (g)	Soil retained (%)	Cum. Soil retained (%)	Cum. Percentage finer (%)
							100
	2	361.88	413.6	51.72	10.59	10.59	89.41
	1.8	349.66	364.24	14.58	2.98	13.57	86.43
	0.6	332.23	351.33	19.10	3.91	17.48	82.52
	0.425	324.01	339.81	15.80	3.23	20.72	79.28
	0.3	327.97	379.17	51.20	10.48	31.20	68.80
	0.212	332.34	395.19	62.85	12.87	44.07	55.93
	0.15	325.3	436.63	111.33	22.79	66.86	33.14
	0.063	312.49	469.27	156.78	32.10	98.96	1.04
	Pan	377.77	382.86	5.09	1.04	100.00	0.00

Time (min)		
0	1.03	1.027
1	1.03	1.027
2	1.03	1.027
4	1.03	1.027
8	1.0285	1.0255
16	1.027	1.024
32	1.025	1.022
64	1.023	1.02
128	1.021	1.018
256	1.018	1.015
572	1.0135	1.0105
1024	1.012	1.009

APPENDIX 4

Table of Wet Sieving and Hydrometer Test Result for Tanjung 12

Sieve No.	Sieve size (mm)	Mass of Sieve (g)	Mass of sieve + soil retained (g)	Soil weight retained (g)	Soil retained (%)	Cum. Soil retained (%)	Cum. Percentage finer (%)
						0	100
	2	381.41	486.60	105.19	38.26	38.26	61.74
	1.8	340.06	363.68	23.62	8.59	46.85	53.15
	0.6	337.73	369.12	31.39	11.42	58.26	41.74
	0.425	376.50	394.74	18.24	6.63	64.90	35.10
	0.3	330.23	343.66	13.43	4.88	69.78	30.22
	0.212	336.25	353.17	16.92	6.15	75.93	24.07
	0.15	333.12	358.88	25.76	9.37	85.30	14.70
	0.063	265.80	305.80	40.00	14.55	99.85	0.15
	Pan	258.47	258.88	0.41	0.15	100.00	0.00

Time (min)		
0	1.0265	1.0235
1	1.0255	1.0225
2	1.025	1.022
4	1.0235	1.0205
8	1.0215	1.0185
16	1.02	1.017
32	1.018	1.015
64	1.016	1.013
128	1.0145	1.0115
256	1.013	1.01
572	1.01	1.007
1024	1.009	1.006

APPENDIX 5

Table of Liquid Limit Test Result

	Air Hitam			Tanjung 12		
Trial no.	1	2	3	4	5	6
No. of blows	33	24	27	35	29	18
Wt. of Container, g	16.50	14.00	18.10	13.90	13.70	13.50
Wt. of Container + wet soil, g	27.80	29.30	32.20	24.40	23.60	26.50
Wt. of Container + dry soil, g	25.70	26.30	29.50	21.60	20.90	22.60
Wt. of water, g	2.10	3.00	2.70	2.80	2.70	3.90
Wt. of dry soil, g	9.20	12.30	11.40	7.70	7.20	9.10
Water content, %	22.83	24.39	23.68	36.36	37.50	42.86

APPENDIX 6

Table of Plastic Limit Test Result

	Air Hitam			Tanjung 12		
Trial no.	1	2	3	4	5	6
Wt. of Container, g	13.76	16.53	16.57	23.50	23.49	16.59
Wt. of Container + wet soil, g	23.25	25.24	25.54	31.32	33.70	23.20
Wt. of Container + dry soil, g	22.23	24.37	24.79	30.17	32.16	22.31
Wt. of water, g	1.02	0.87	0.75	1.15	1.54	0.89
Wt. of dry soil, g	8.47	7.84	8.22	6.67	8.67	5.72
Water content, %	12.04	11.10	9.12	17.24	17.76	15.56
Avg. Water content, %	10.75			16.85		

APPENDIX 7

Table of Shrinkage Limit Test Result

Sample	Initial Length, L_0 (cm)	Final Length, L_d (cm)	Linear Shrinkage (%)
AH	13.92	13.72	1.44%
TG	13.92	13.00	6.61%

Landfill Site	Mass Before Oven (g)	Mass After Oven (g)	Moisture Content (%)
Air Hitam (AH)	303.90	292.41	3.93%
Tanjung 12 (TG12)	351.24	330.75	6.20%

APPENDIX 8

Table of Compaction Test Result for Air Hitam

Air Hitam

MOISTURE CONTENT				
TRIAL	Wet (g)	Dry (g)	Tin (g)	w (%)
1	101.18	96.35	23.88	6.66
2	98.56	91.1	23.89	11.10
3	87.46	78.04	13.97	14.70
4	122.41	105.79	16.61	18.64
5	137.85	115.14	16.73	23.08

WET BULK DENSITY				
TRIAL	M1 (kg)	M2 (kg)	V (m ³)	ρ (kg/m ³)
1	3.74	1.89	0.00	1857.82
2	3.965	1.89	0.00	2083.77
3	3.985	1.89	0.00	2103.86
4	3.88	1.89	0.00	1998.41
5	3.83	1.89	0.00	1948.20

ρ_d : Dry density [$\rho/(1+w/100)$]

RESULTS			
TRIAL	w (%)	ρ (kg/m ³)	ρ _d (g/cm ³)
1	6.66	1857.82	1.74
2	11.10	2083.77	1.88
3	14.70	2103.86	1.83
4	18.64	1998.41	1.68
5	23.08	1948.20	1.58

APPENDIX 9

Table of Compaction Test Result for Tanjung 12

Tanjung Dua Belas

MOISTURE CONTENT				
TRIAL	Wet (g)	Dry (g)	Tin (g)	w (%)
1	55.86	53.57	24.74	7.94
2	57.17	51.61	16.91	16.02
3	55.73	49.36	24.72	25.85
4	58.15	47.31	13.72	32.27
5	59.13	46.91	13.73	36.83

WET BULK DENSITY				
TRIAL	M ₁ (kg)	M ₂ (kg)	V (m ³)	ρ (kg/m ³)
1	3.41	1.89	0.00	1526.43
2	3.62	1.89	0.00	1737.31
3	3.73	1.89	0.00	1847.78
4	3.615	1.89	0.00	1732.29
5	3.565	1.89	0.00	1682.08

RESULTS			
TRIAL	w (%)	ρ (kg/m ³)	ρ _d (g/cm ³)
1	7.94	1526.43	1.41
2	16.02	1737.31	1.50
3	25.85	1847.78	1.47
4	32.27	1732.29	1.31
5	36.83	1682.08	1.23

APPENDIX 10

Hydraulic Conductivity Result from Modified Oedometer Test for Air Hitam at OMC

One Dimensional Consolidation Properties (Oedometer)			
+			
Client	HARIS	Lab Ref	
Project		Job	AH
Borehole		Sample	AH
Test Details			
Standard	BS 1377: Part 5: 1990: Clause 3	Particle Density	2.48 Mg/m ³
Sample Type	Core sample	Lab Temperature	0.0 deg.C
Sample Depth	0.00 m		
Sample Description			
Variations from Procedure	None		
Specimen Details			
Specimen Reference	A	Description	
Depth within Sample	0.00 mm	Orientation within Sample	
Specimen Mass	175.59 g	Condition	Natural Moisture
Specimen Height	20.00 mm	Preparation	
Comments			
Test Apparatus			
Ring Number	1	Ring Diameter	74.00 mm
Ring Height	20.00 mm	Ring Weight	118.01 g
Lever Ratio	10.00: 1		
Height of Solid Particles	13.78 mm	Swelling Pressure	0.0 kPa

APPENDIX 11

Hydraulic Conductivity Result from Modified Oedometer Test for Air Hitam at +3 of OMC

One Dimensional Consolidation Properties (Oedometer)			
Client	HARIS	Lab Ref	
Project		Job	+3AH
Borehole		Sample	+3AH
Test Details			
Standard	BS 1377: Part 5: 1990 - Clause 3	Particle Density	2.48 Mg/m ³
Sample Type	Core sample	Lab Temperature	0.0 deg.C
Sample Depth	0.00 m		
Sample Description			
Variations from Procedure	None		
Specimen Details			
Specimen Reference	A	Description	
Depth within Sample	0.00 mm	Orientation within Sample	
Specimen Mass	182.89 g	Condition	Natural Moisture
Specimen Height	20.00 mm	Preparation	
Comments			
Test Apparatus			
Ring Number	0	Ring Diameter	75.00 mm
Ring Height	20.00 mm	Ring Weight	115.30 g
Lever Ratio	10.00: 1		
Void's Ratio Vs Applied Pressure			
Height of Solid Particles	14.64 mm	Swelling Pressure	0.0 kPa

APPENDIX 12

Hydraulic Conductivity Result from Modified Oedometer Test for Air Hitam at - 3 of OMC

One Dimensional Consolidation Properties (Oedometer)				ELE International
Client	HARIS	Lab Ref		
Project		Job	-3AH	
Borehole		Sample	-3AH	

Test Details			
Standard	BS 1377: Part 5: 1990: Clause 3	Particle Density	2.48 Mg/m ³
Sample Type	Core sample	Lab Temperature	0.0 deg.C
Sample Depth	0.00 m		
Sample Description			
Variations from Procedure	None		

Specimen Details			
Specimen Reference	A	Description	
Depth within Sample	0.00 mm	Orientation within Sample	
Specimen Mass	160.35 g	Condition	Natural Moisture
Specimen Height	20.00 mm	Preparation	
Comments			

Test Apparatus			
Ring Number	0	Ring Diameter	75.00 mm
Ring Height	20.00 mm	Ring Weight	109.57 g
Lever Ratio	10.00: 1		

Void's Ratio Vs Applied Pressure

Height of Solid Particles	13.26 mm	Swelling Pressure	0.0 kPa
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APPENDIX 13

Hydraulic Conductivity Result from Modified Oedometer Test for Tanjung 12 at OMC

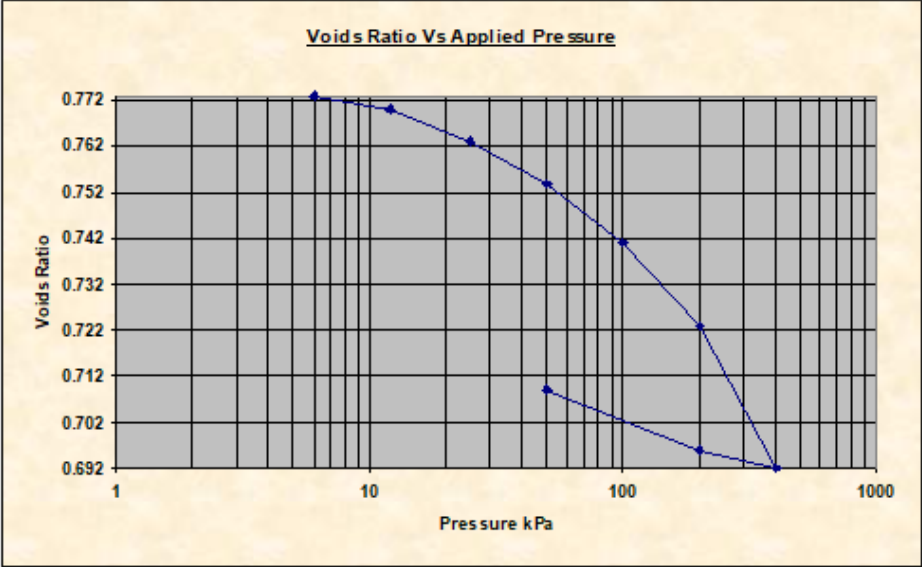
One Dimensional Consolidation Properties (Oedometer)			
			
Client	HARIS	Lab Ref	
Project		Job	T12
Borehole		Sample	T12

Test Details			
Standard	BS 1377: Part 5: 1990: Clause 3	Particle Density	2.22 Mg/m ³
Sample Type	Core sample	Lab Temperature	0.0 deg.C
Sample Depth	0.00 m		
Sample Description			
Variations from Procedure	None		

Specimen Details			
Specimen Reference	A	Description	
Depth within Sample	0.00 mm	Orientation within Sample	
Specimen Mass	149.86 g	Condition	Natural Moisture
Specimen Height	20.00 mm	Preparation	
Comments			

Test Apparatus			
Ring Number	1	Ring Diameter	74.00 mm
Ring Height	20.00 mm	Ring Weight	115.20 g
Lever Ratio	10.00: 1		

Void's Ratio Vs Applied Pressure



Height of Solid Particles	11.28 mm	Swelling Pressure	0.0 kPa
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ELE International
Page 1 of 1

APPENDIX 14

Hydraulic Conductivity Result from Modified Oedometer Test for Tanjung 12 at +3 of OMC

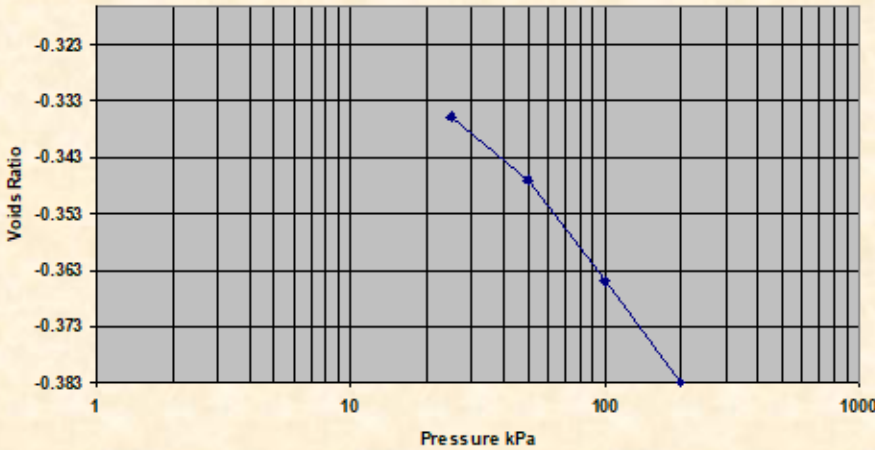
One Dimensional Consolidation Properties (Oedometer)				
Client	HARIS	Lab Ref		
Project		Job	+3T12	
Borehole		Sample	+3T12	

Test Details			
Standard	BS 1377: Part 5: 1990: Clause 3	Particle Density	2.22 Mg/m ³
Sample Type	Core sample	Lab Temperature	0.0 deg.C
Sample Depth	0.00 m		
Sample Description			
Variations from Procedure	None		

Specimen Details			
Specimen Reference	A	Description	
Depth within Sample	0.00 mm	Orientation within Sample	
Specimen Mass	216.35 g	Condition	Natural Moisture
Specimen Height	20.00 mm	Preparation	
Comments			

Test Apparatus			
Ring Number	0	Ring Diameter	75.00 mm
Ring Height	20.00 mm	Ring Weight	109.47 g
Lever Ratio	10.00 : 1		

Voids Ratio Vs Applied Pressure



Height of Solid Particles	12.25 mm	Swelling Pressure	0.0 kPa
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APPENDIX 15

Hydraulic Conductivity Result from Modified Oedometer Test for Tanjung 12 at -3 of OMC

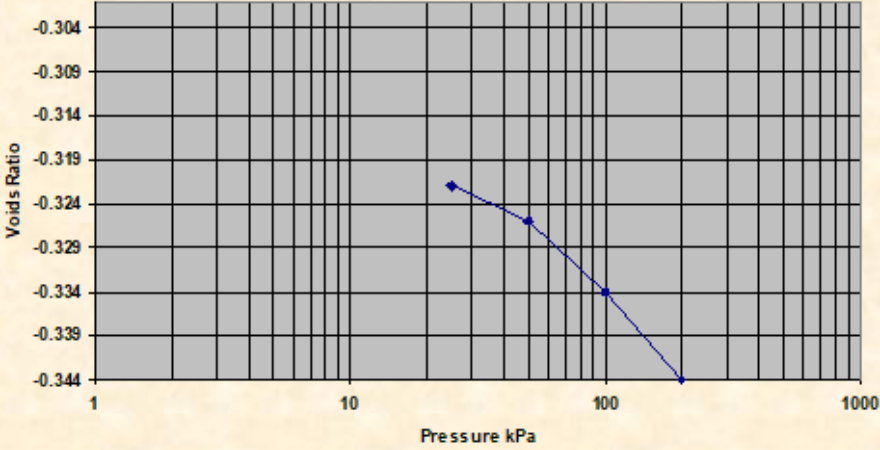
One Dimensional Consolidation Properties (Oedometer)				
Client	HARIS	Lab Ref		
Project		Job	-3T12	
Borehole		Sample	-3T12	

Test Details			
Standard	BS 1377: Part 5: 1990: Clause 3	Particle Density	2.22 Mg/m ³
Sample Type	Core sample	Lab Temperature	0.0 deg.C
Sample Depth	0.00 m		
Sample Description			
Variations from Procedure	None		

Specimen Details			
Specimen Reference	A	Description	
Depth within Sample	0.00 mm	Orientation within Sample	
Specimen Mass	191.37 g	Condition	Natural Moisture
Specimen Height	20.00 mm	Preparation	
Comments			

Test Apparatus			
Ring Number	0	Ring Diameter	75.00 mm
Ring Height	20.00 mm	Ring Weight	115.30 g
Lever Ratio	10.00: 1		

Void's Ratio Vs Applied Pressure



Height of Solid Particles	11.23 mm	Swelling Pressure	0.0 kPa
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AUTHOR'S PROFILE



Haris Assiddiq Bin Khairul Anuar obtained a Diploma in Civil Engineering (2021) from Universiti Teknologi MARA (UiTM) Cawangan Johor, Kampus Pasir Gudang, and a Bachelor of Civil Engineering (Hons.) (2023) from Universiti Teknologi MARA (UiTM) Shah Alam. In 2025, he obtained the Certificate of Registration as a Graduate Engineer from the Board of Engineers Malaysia (BEM). He is currently pursuing a Master of Science in Civil Engineering at Universiti Teknologi MARA (UiTM) Shah Alam. His research focuses on landfill performance in relation to soil properties and hydraulic conductivity behaviour, particularly the effects of compaction characteristics and moisture content on the engineering performance of landfill cover soils.

LIST OF PUBLICATIONS

- Mukri, M., **Anuar, H.A.K.**, Khalid, N., Omar, A. A., Assessment of Properties and the Influence on Compaction Characteristics, Settlement Behaviour, and Hydraulic Conductivity at Tanjung Dua Belas and Air Hitam Landfills. (2026). International Journal of Latest Technology in Engineering, Management & Applied Science.
- Mukri, M., Safingi, S., Rahman, A.S.A., **Anuar, H.A.K.** Microstructural Mechanisms And Hydraulic Performance Of Pressmud-Modified Marine Clay. (2026). EnCon UNIMAS.