

UNIVERSITI TEKNOLOGI MARA

**DEVELOPMENT OF COMPACTION
BEHAVIOUR MODEL FOR LEAD-
CONTAMINATED KAOLIN CLAY
UNDER VARIABLE COMPACTIVE
EFFORTS**

ALIAA AWATIF BINTI OMAR

MSc

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ALIAA AWATIF BINTI OMAR

Thesis submitted in fulfilment
of the requirements for the degree of
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CONFIRMATION BY PANEL OF EXAMINERS

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ABSTRACT

Compaction behaviour significantly influences the performance and stability of earth structures, particularly when soils are subjected to chemical contamination that alters their engineering characteristics. Lead contamination, commonly associated with industrial and construction activities, can modify the physicochemical properties of clay and consequently affect its moisture–density relationship. However, limited systematic studies have evaluated the compaction behaviour of lead-contaminated kaolin clay under multiple compactive efforts within an integrated predictive modelling framework. This study aims to investigate the compaction behaviour of kaolin clay contaminated with 0–4000 mg/L lead nitrate under Reduced, Standard, and Modified Proctor Compaction energies, and to develop empirical models for predicting Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). Laboratory testing was conducted to determine physical properties including Atterberg limits, specific gravity, linear shrinkage, and pH , followed by controlled compaction testing at defined moisture states. The results indicate that increasing lead concentration leads to a moderate increase in moisture demand, while higher compactive effort reduces OMC and increases dry density. Observed variations in plasticity, shrinkage characteristics, and chemical environment were found to be associated with changes in compaction response. Based on statistical correlation and Multiple Linear Regression (MLR) analysis, empirical compaction behaviour models incorporating scaled lead concentration, scaled compactive effort, moisture condition, and dry density indicators were developed and independently validated, demonstrating strong predictive capability. The developed OMC model achieved a coefficient of determination (R^2) of 98.77% during model development and 97.71% during validation, while the MDD model achieved corresponding R^2 values of 95.31% and 93.84%, indicating excellent agreement between the predicted and measured values. The regression structure confirmed that both contamination level and compactive effort exert statistically significant influence on moisture demand for the OMC model. In contrast, the MDD model identified compactive effort as the dominant predictor with strong statistical significance, while lead concentration did not demonstrate a significant influence within the investigated range. Thus, indicate that density development is governed primarily by mechanical compactive energy rather than chemical modification. The developed models provide a practical approach for estimating compaction parameters of lead-contaminated kaolin clay and contribute to improved assessment of contaminated fine-grained soils in geotechnical engineering practice.

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LIST OF SYMBOLS

Symbols

Al_2O_3	Alumina
Ca	Calcium
Cl	Chloride
Cu	Copper
Fe	Iron
K	Potassium
Na	Sodium
Pb^{2+}	Lead Ions
$\text{Pb}(\text{NO}_3)_2$	Lead (II) Nitrate
SiO_2	Silica
X_i	Predictor Variables
Y	Response Variable
Y_i	Measured Value
$\hat{Y}_i$	Predicted Value
$\bar{Y}$	Sample Mean
β_i	Regression Coefficients
ε	Random Error Term
$\mu_{\text{difference}}$	Population Mean Difference between Measured and Predicted Values

LIST OF ABBREVIATIONS

Abbreviations

ANFIS	Adaptive Neuro-Fuzzy Inference System
ANNs	Artificial Neural Networks
ASTM	American Society for Testing and Materials
BS	British Standard
EDL	Electrical Double-Layer
LSBoostRF	Least-Squares Boost Random Forest
LSSVM	Least-Squares Support Vector Machine
LSTM	Long Short-Term Memory
MAE	Mean Absolute Error
MPC	Modified Proctor Compaction
RPC	Reduced Proctor Compaction
SEM	Scanning Electron Microscopy
SPC	Standard Proctor Compaction

LIST OF NOMENCLATURE

Nomenclatures

C	Concentration Pb(NO ₃) ₂ , mg/L
C_scaled	Scaled lead concentration, mg/L
DD	Dry Density, Mg/m ³
E	Compactive Effort, kN-m/m ³
E_scaled	Scaled Compactive Effort, kN-m/m ³ Specific
G _s	Gravity, (No Units)
LL	Liquid Limit, Percentages
LS	Linear Shrinkage, Percentages
MAPE	Mean Absolute Percentage Error, Percentages
MC	Moisture Content, Percentages
MDD	Maximum Dry Density, Mg/m ³
OMC	Optimum Moisture Content, Percentages
PI	Plasticity Index, Percentages
PL	Plastic Limit, Percentages
R ²	Coefficient of Determination, (No Units)
RMSE	Root Mean Square Error, (Depends)
S	Standard Error of Regression, (No Units)
State_code	Moisture State Indicator, (No Units)

CHAPTER 1

INTRODUCTION

1.1 Research Background

Fine grained soils, in particular clays, are the main concern of geotechnical engineers due to their physico-chemical properties which govern their water retaining ability, deformation and load bearing capacity. The parameters such as liquid limit (LL), plastic limit (PL) and plasticity index (PI), specific gravity (G_s), linear shrinkage (LS), pH are inherently associated with the fundamental mineralogy, pore -fluid chemistry and structures of soil and contribute significantly to the compaction, settlement and strength performance of soils in field condition (Hobbs et al., 2018; Tiwari et al., 2014). According to several experimental studies, kaolin-based materials are often preferred in research because it has simple structure of 1:1 kaolinite, moderate plasticity and low swelling behaviour make it an easier interpretation with respect to more active smectitic clays. (Kwon et al., 2023; Zhang et al., 2022). From these studies, kaolin is a practical reference material to investigate how changes in pore fluid composition affect soil properties commonly used in design.

Heavy metal contamination, especially by lead, complicates this situation further. Lead constitutes a significant contamination of industrial waste sludge, mine tailings and urban trash sites. The interaction with clay minerals can alter the surface charge, Electrical Double-Layer (EDL) development and microstructure arrangement (Islam et al., 2016; Liu et al., 2018). In the studies performed by Li et al. (2015) and Du et al. (2015), it comes out that lead, Pb ions, Pb^{2+} are also adsorbed on the clay surfaces or into interlayer sites thus, altering Atterberg limits and pH along with specific gravity and the mechanical and transport response of the soil. Further work on kaolin–bentonite mixtures and sand–clay systems also asserts that lead can enhance aggregation, alter pore-size distributions, and affect consolidation-induced and compression-induced behaviour (Fan et al., 2016; Muththalib & Baudet, 2019; Saeid Nikkhah Nasab & Abdeh Keykha, 2020). These results indicate that the alterations of chemical reactions in response to heavy metals should be considered for evaluating the contaminated ground.

Compaction is one of most common ground improvement methods and still remains fundamental technology for the construction of embankments, road subgrades,

and engineered protection facilities. The classic moisture-density relationship indicates that, for a constant effort of compaction, dry density increases with water content up to an optimum moisture content (OMC) followed by decrease in the same as further increase in water leads to higher void ratios (Di Matteo et al., 2009; Sridharan & Gurtug, 2003). The research on natural and stabilised soils has shown that changes in water content and compaction energy can change OMC and maximum dry density (MDD) as well as the resulting structure and stiffness of compacted soil (Günaydın, 2008; Mohd Yusoff et al., 2017). These observations have been further extended to contaminated and chemically modified soils, in which the process for heavy metals modifying the shape and position of compaction curves has effects on pore-fluid chemistry and fabric (de Campos et al., 2020; Negahdar & Nikghalbpour, 2020; Wen et al., 2023). This study therefore considers how uncontaminated and lead-contaminated kaolin respond to different compactive efforts.

In parallel, other experimental and data-driven models have been developed to predict compaction parameters from basic soil characteristics. Previous studies utilising regression techniques established that OMC and MDD are correlated with Atterberg limits, as well as grain-size characteristics in providing estimates without the full laboratory tests (Bera & Ghosh, 2011; Saikia et al., 2017). Subsequent studies introduced Artificial Neural Networks (ANNs), hybrid soft-computing models, and machine-learning tools were then incorporated for capturing the nonlinear relationships among soil properties, compactive effort and resulting densities (Alavi et al., 2009; Hossein Alavi et al., 2010; Bardhan et al., 2023; Khatti & Grover, 2023; Soltani et al., 2021; Vardhan et al., 2025). However, most of the models have only been developed for uncontaminated or stabilised soils, and contaminant concentration is seldom explicitly used as a predictor. This study therefore aims to develop compaction behaviour model based on lead concentration as well as physical properties and compactive efforts for kaolin clay.

1.2 Problem Statement

The physical properties of kaolin clay are important for determining its response to loading and compaction, but there are few studies on how these properties systematically vary with increasing lead contamination across a specified range of concentrations. From the works of Li et al. (2015), Du et al. (2015) and Fan et al. (2016),

it is observed that lead can influence liquid and plastic limits, specific gravity and pH by surface complexation and ion exchange mechanism. Studies on sand–clay mixtures and contaminated fine-grained soils also indicate that heavy metals can modify physicochemical conditions and thus bring about some measurable changes in consistency limits and pore structure (Negahdar & Nikghalbpour, 2020; Saeid Nikkhah Nasab & Abdeh Keykha, 2020; Zhang et al., 2024). Despite these insights, there is still a lack of focused work on a single kaolin source where the physical properties are characterized across several lead nitrate concentrations in a manner that is directly applicable in compaction analysis and model development.

The effect of lead contamination on compaction behaviour has been investigated less extensively than its influence on index properties or microstructure. According to Karkush and Ali (2020) and de Campos et al. (2020), contamination is also capable of modifying OMC and MDD in clayey soil by changing the interaction between particles and pore water. Other studies on contaminated mixtures and treated soils have shown the compaction response to be sensitive to contaminant content and treatment, but often only in the context of a single compactive effort or a specific range of moisture contents (Negahdar & Nikghalbpour, 2020; Hassanlourad et al., 2024; Motlagh et al., 2025; Zha et al., 2021). Although it is well established that increasing compactive effort generally produces higher MDD and lower OMC, this behaviour has primarily been evaluated under uncontaminated or specific soil conditions and may not fully represent the response of lead-contaminated kaolin. In engineering practice, compacted fill is subjected to different levels of compactive effort depending on construction equipment and project specifications. Therefore, evaluating lead-contaminated kaolin under Reduced, Standard and Modified Proctor compactive efforts is essential to determine whether the conventional compaction response remains applicable under different contamination levels and to provide a more representative dataset for predictive model development. This situation creates a significant research gap because limited systematic laboratory data are available on the compaction behaviour of lead-contaminated kaolin across multiple Proctor-type compactive efforts, thereby restricting the development of predictive models applicable to varying field compaction conditions.

The soil physical properties close to compaction parameters relationships have been explored mainly through studies on uncontaminated soils. For example, Bera and Ghosh (2011) and Saikia et al. (2017) introduced correlations linking between OMC

and MDD with Atterberg limits, while Sridharan and Gurtug (2003) emphasised the role of plasticity in compaction and swelling behaviours. Meanwhile, research on heavy metal–soil systems shows that contamination modifies plasticity, shrinkage and pH , and these changes are accompanied by modifications in microstructure and mechanical behaviour (Du et al., 2015; Liu et al., 2018; Yazdi & Khodaparast, 2025; Wen et al., 2023). There is still limited information on how changes in liquid limit, plasticity index, shrinkage and pH due to association with lead are reflected in OMC–MDD relationship for kaolin.

A further gap exists in empirical and predictive modelling. There have been several studies reported in which compaction parameters have been predicted with good results using neural networks, hybrid intelligence systems and ensemble algorithms, usually with soil properties and compactive effort as inputs (Alavi et al., 2009; Hossein Alavi et al., 2010; Bardhan et al., 2023; Khatti & Grover, 2023; Özçoban et al., 2021; Soltani et al., 2021; Soltani et al., 2024; Vardhan et al., 2025). However, most models discussed by these authors do not explicitly incorporate contaminant concentration and very few for kaolin contaminated with lead nitrate. Thus, there is a need for compaction behaviour model that integrates lead concentration and compactive efforts, calibrated against consistent experimental data.

1.3 Research Objectives

This study aims to develop a compaction behaviour model for lead-contaminated kaolin clay under different compactive efforts. There are four (4) specific objectives highlighted in this study.

- a) To determine the physical properties of non-contaminated and contaminated kaolin clay.
- b) To evaluate the effect of compactive efforts on the optimum moisture content and maximum dry density of kaolin clay under various lead concentrations.
- c) To analyse the relationship between the physical properties and compaction parameters of non-contaminated and lead-contaminated kaolin clay.
- d) To develop a model of compaction behaviour for lead-contaminated kaolin clay under different compactive efforts.

1.4 Scope and Limitation

The first part of this study focuses on determining physical properties of a single commercial kaolin clay in both uncontaminated and lead-contaminated states. Kaolin powder from Kaolin (Malaysia) Sdn. Bhd. is used throughout so that any changes can be attributed to contamination and compaction conditions rather than differences in raw materials. Lead contamination is introduced using Lead (II) Nitrate solutions at concentrations of 0 mg/L, 1000 mg/L, 2000 mg/L, 3000 mg/L, and 4000 mg/L, representing controlled laboratory contamination levels selected to systematically evaluate the influence of increasing lead concentration on the physical properties and compaction behaviour of kaolin clay. The physical characterisation focused mainly on liquid limit, plastic limit, specific gravity, linear shrinkage and *pH*, as these parameters are most directly relevant to compaction behaviour and empirical model development.

The second part of the work deals with laboratory compaction of uncontaminated and contaminated kaolin. Compactive efforts equivalent to Reduced Proctor Compaction (RPC), Standard Proctor Compaction (SPC) and Modified Proctor Compaction (MPC) are adopted to represent a range of energy levels that may be encountered in practice. For each combination of lead concentration and compactive effort, moisture–density behaviour is studied at OMC state and at the state of $OMC \pm 3\%$ to capture both the optimum and neighbouring conditions. All the laboratory testing is conducted at Soil and Environmental Laboratory in Building 1, Faculty of Civil Engineering, UiTM Shah Alam.

The third part of the study is devoted to analysing how changes in physical properties relate to compaction outcomes. The analysis is limited to the measured parameters for this kaolin and the specific range of lead concentrations and compactive efforts considered. No attempt is made to generalise the relationships to other soil types or contaminants without additional data. The correlations developed reflect statistical trends within the dataset rather than fundamental constitutive laws.

The final part of the research develops a compaction behaviour model to predict OMC and MDD as functions of lead concentration and compactive effort a statistical analysis process using Minitab software. This model is calibrated only on data generated in this study, and its validity is restricted to the conditions represented by the tested kaolin, contamination levels and energy ranges. While the modelling framework may

be adaptable, further work would be needed before applying the model directly to other soils or contaminant systems.

1.5 Significance of Study

The influence of lead contamination on the physical properties of kaolin is important for both geotechnical engineering and environmental management. According to Li et al. (2015) and Fan et al. (2016), lead changes the soil surface chemistry and microstructure in clayey soils, while Fijałkowska et al. (2021) and Saeid Nikkhah Nasab and Abdeh Keykha (2020) have shown that alteration in sorption and ion exchange could result in differences of plasticity, specific gravity, pH . The quantified changes through this work between kaolin contaminated with different concentrations of lead nitrate, this study provide a dataset that can support the design and assessment of compacted barriers, covers and fills in contaminated sites.

The work also has implications for compaction practice. This can be also interpreted from the works of Di Matteo et al. (2009) and Mohd Yusoff et al. (2017), that compactive effort and moisture content are key variables in achieving desired densities and stiffness in fine-grained soils. Research by de Campos et al. (2020), Negahdar and Nikghalbpour (2020) and Karkush and Ali (2020), further suggest that contamination changes the way soil reacts to compaction, with potential effects on densification efficiency and post-compaction behaviour. By examining lead-contaminated kaolin under a range of Proctor-type energy levels, this research offers insight that can be used when specifying compaction criteria for contaminated or remediated ground.

From a broader perspective, the analysis of relationships between physical properties and compaction parameters helps clarify how contamination-induced changes in Atterberg limits, shrinkage and pH translate into practical engineering consequences. The work of Bera and Ghosh (2011), Saikia et al. (2017) and Sridharan and Gurtug (2003) shows these parameters can serve as predictors of compaction behaviour in uncontaminated soils. By extending this line of research towards lead-contaminated for kaolin, this study contributes to a more complete understanding of how basic soil tests can be used to anticipate compaction performance in contaminated environments.

Finally, the compaction behaviour model developed in this study is intended to provide a pragmatic tool for predicting OMC and MDD from readily measured inputs. Previous studies have already demonstrated the value of regression and soft-computing approaches for estimating compaction parameters from index properties and compaction energy (Alavi et al., 2009; Hossein Alavi et al., 2010; Bardhan et al., 2023; Khatti & Grover, 2023; Soltani et al., 2021; Vardhan et al., 2025). With the explicit addition of lead concentration as a variable to this model, the model proposed here aims to support more efficient decision-making in projects involving lead-affected kaolin or similar materials, potentially reducing laboratory workload while maintaining a rational basis for compaction control.

1.6 Thesis Outline

This thesis is organised into five (5) chapters. Chapter 1 introduces the background, problem statement, objectives, scope, limitations and significance of the research, and outlines the overall structure of the document. Chapter 2 reviews the relevant literature on kaolin behaviour, heavy metal contamination, compaction theory, the influence of physical properties on compaction, and empirical modelling approaches for predicting compaction parameters. Chapter 3 describes the materials, sample preparation procedures, compaction and index tests, and data analysis methods adopted in this research. Chapter 4 presents and discusses the experimental results on physical properties, compaction behaviour of non-contaminated and lead-contaminated kaolin under variable compactive efforts including the details development and evaluation of the compaction behaviour model for predicting OMC and MDD. Chapter 5 concludes with key findings, limitations and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter presents a comprehensive review of the literature related to the physical characteristics, compaction behaviour and empirical modelling of lead-contaminated kaolin clay. Understanding the interaction between lead contamination and kaolin is essential because contamination can modify the physicochemical characteristics of the soil, which subsequently influence its engineering behaviour, particularly under compaction. Therefore, this chapter reviews previous studies on the mineralogical characteristics of kaolin, the mechanisms governing lead–clay interactions, the influence of lead contamination on the physical properties and compaction behaviour of clay soils, and the relationship between physical properties and compaction parameters. Existing empirical approaches for predicting optimum moisture content (OMC) and maximum dry density (MDD) are also critically reviewed to establish the current state of knowledge.

The literature is organised according to the four research objectives of this study. Section 2.1 discusses the physical characteristics of kaolin and their modification under lead contamination. Section 2.2 reviews the compaction behaviour of uncontaminated and contaminated soils under different compactive efforts. Section 2.3 examines the relationship between physical properties and compaction parameters, while Section 2.4 reviews previous empirical modelling approaches for predicting compaction behaviour. The chapter concludes by identifying the limitations of existing studies and highlighting the research gaps that form the basis for the present investigation

2.1 Physical Characteristics of Kaolin and Their Modification Under Lead Contamination

The physical characteristics of kaolin are fundamental in governing its engineering behaviour and are particularly important when the soil is subjected to heavy metal contamination. Variations in mineralogical composition, physicochemical interactions and index properties influence the response of kaolin to external loading,

including its compaction behaviour. Lead contamination may further modify these characteristics through adsorption, ion exchange and surface complexation mechanisms, resulting in changes to the soil structure and engineering properties. Therefore, this section reviews the mineralogical characteristics of kaolin, the mechanisms of lead–clay interaction, and the influence of lead contamination on the physical properties of kaolin that are directly relevant to the compaction behaviour investigated in this study.

2.1.1 Mineralogical and Basic Index Behaviour of Kaolin

Kaolin has been extensively adopted as a reference material in experimental geotechnical investigations because of its relatively homogeneous mineralogical composition, predictable engineering behaviour and comparatively low mineralogical variability. Unlike naturally deposited soils, which often contain mixed clay minerals and varying proportions of organic matter, commercial kaolin provides a more controlled material for investigating the influence of external factors such as contamination and compactive effort. The engineering behaviour of kaolin is primarily governed by its mineralogical composition and particle arrangement, both of which influence its interaction with water, stress and chemical contaminants. Consequently, understanding the fundamental characteristics of kaolin is essential before evaluating the effects of lead contamination on its physical properties and compaction behaviour.

Kaolin is predominantly composed of kaolinite, a 1:1 aluminosilicate clay mineral consisting of one silica tetrahedral sheet bonded to one alumina octahedral sheet through strong hydrogen bonding (Tiwari et al., 2014; Zhang et al., 2022). This crystal structure restricts interlayer expansion, resulting in relatively low swelling potential, moderate plasticity and greater physicochemical stability than highly expansive clay minerals such as montmorillonite and smectite. Due to these characteristics, kaolin exhibits relatively consistent engineering behaviour and has frequently been selected as a benchmark material for laboratory investigations involving chemical contamination and soil improvement. Kwon et al. (2023) further reported that kaolin possesses a comparatively stable soil fabric during loading, making it particularly suitable for evaluating changes induced by external physicochemical processes rather than inherent mineralogical variability. The platy morphology and aggregated arrangement of

kaolinite particles are illustrated in Figure 2.1, which demonstrates the characteristic particle structure responsible for many of its engineering properties.

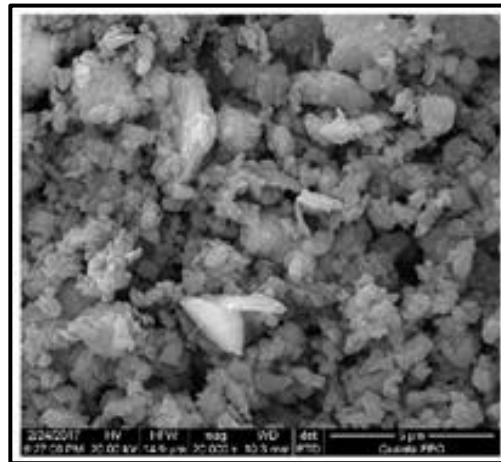


Figure 2.1 SEM Image Showing the Platy Morphology of Kaolinite Particle (Gong et al.,2018)

The mineralogical composition and particle characteristics of kaolin directly influence its engineering performance because they govern particle interaction, pore distribution and water retention behaviour. Zhang et al. (2022) demonstrated that variations in clay mineral content significantly affect the internal soil fabric and mechanical response of geomaterials. Their investigation showed that specimens containing higher clay mineral contents exhibited greater cohesion and a higher proportion of micropores, indicating that relatively small changes in mineralogical composition can alter engineering behaviour through modifications of pore structure and particle arrangement rather than particle size alone. These findings highlight that the engineering response of clay soils is controlled not only by mineral composition but also by the microstructural arrangement developed within the soil matrix. Such observations provide an important theoretical basis for understanding how chemical contaminants may subsequently modify the behaviour of kaolin.

In addition to mineralogical composition, the engineering behaviour of kaolin is commonly evaluated using its basic physical and index properties, including particle size distribution, liquid limit, plastic limit, plasticity index, specific gravity and linear shrinkage. These parameters provide practical indicators of soil consistency, water affinity and volume change behaviour and are widely employed in geotechnical characterisation prior to compaction assessment. The particle size distribution of commercial kaolin reported by Hoo et al. (2024) is presented in Figure 2.2, illustrating

that the material consists predominantly of fine particles within the clay and silt size fractions. This relatively uniform grading contributes to the reproducible engineering behaviour commonly observed in laboratory investigations and provides a consistent basis for evaluating changes caused by chemical contamination rather than variations in soil grading.

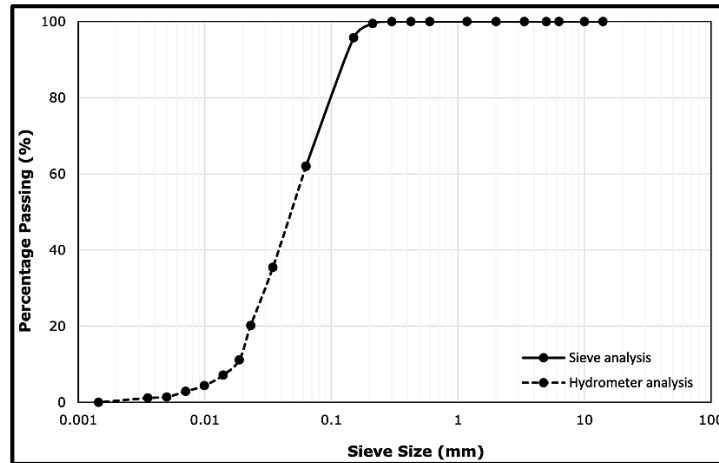


Figure 2.2 Particle Size Distribution of Commercial Kaolin (Hoo et al.,2024)

The basic index properties of kaolin are also closely associated with its particle morphology and physicochemical characteristics. Hoo et al. (2024) reported that kaolin exhibits well-defined Atterberg limits and shrinkage behaviour while remaining sufficiently sensitive to physicochemical modifications introduced by additives or environmental changes. These index properties are particularly important because they reflect changes occurring within the soil structure and therefore provide indirect evidence of modifications in particle interaction and water retention behaviour. Since lead contamination alters the physicochemical environment surrounding clay particles, subsequent changes in liquid limit, plasticity index, specific gravity, linear shrinkage and pH may reasonably be expected and should therefore be systematically evaluated before analysing compaction behaviour.

Microstructural observations further explain the relatively predictable engineering response of kaolin under mechanical loading. Gong et al. (2018) reported that compaction progressively reduces larger interparticle voids and promotes a denser, more homogeneous soil fabric without fundamentally altering the mineralogical structure of kaolinite. Similarly, Zheng et al. (2025) observed that mechanical loading primarily modifies pore distribution and particle contacts rather than changing the

intrinsic mineral composition of the clay. These findings indicate that changes in engineering behaviour are governed predominantly by particle rearrangement and pore redistribution, while the mineralogical framework remains relatively stable. This characteristic is particularly advantageous for laboratory investigations because it enables the effects of lead contamination to be distinguished more clearly from those arising solely from mineralogical variation.

The relatively simple mineralogical composition, stable microstructure and well-defined physical properties make kaolin an appropriate material for investigating the influence of lead contamination on engineering behaviour. Since intrinsic mineralogical variability is comparatively limited, any subsequent changes observed in physical properties and compaction characteristics can be more confidently attributed to physicochemical interactions between lead ions and kaolinite particles rather than differences in the parent soil composition. This provides the necessary foundation for understanding the mechanisms of lead–clay interaction discussed in the following section.

2.1.2 Mechanisms of Lead-Clay Interaction

The engineering behaviour of lead-contaminated clay is governed by a series of physicochemical interactions that occur when dissolved lead (Pb^{2+}) ions come into contact with clay mineral surfaces. These interactions alter the surface chemistry, diffuse double layer (DDL), particle arrangement and pore structure of the soil, ultimately influencing its physical and mechanical properties. The extent of these modifications depends on several factors, including clay mineralogy, contaminant concentration, pore water chemistry, pH and the presence of competing ions or organic compounds.

Adsorption represents the primary mechanism controlling the retention of lead in clay minerals. Owing to their negatively charged surfaces and high specific surface areas, clay minerals provide numerous active sites for Pb^{2+} adsorption. Mao et al. (2022) reported that lead exhibits strong adsorption onto kaolinite, montmorillonite and iron oxides, although the dominant adsorption mechanism varies with environmental conditions such as pH , ionic strength and competing cations. At lower pH values, adsorption generally occurs through electrostatic attraction and surface complexation,

whereas stronger inner-sphere complexes may develop under favourable chemical conditions, thereby reducing lead mobility.

Besides adsorption, cation exchange constitutes another important mechanism governing lead retention in clay. Lead ions can replace naturally occurring exchangeable cations such as Na^+ , Ca^{2+} and Mg^{2+} on clay particle surfaces because of their relatively high valence and affinity for exchange sites. This exchange process alters the ionic composition of the pore fluid and compresses the diffuse double layer surrounding clay particles.

Lead adsorption may also occur through surface complexation reactions. Depending on solution chemistry, particularly pH , lead ions may form either outer-sphere or inner-sphere complexes with clay mineral surfaces. Outer-sphere complexes retain one or more layers of water molecules between the adsorbed ion and the mineral surface and are therefore relatively weak and reversible. In contrast, inner-sphere complexes involve direct chemical bonding between Pb^{2+} ions and surface functional groups without an intervening water layer, producing much stronger adsorption. Saeid Nikkhah Nasab and Abdeh Keykha (2020) reported that acidic environments promote the formation of inner-sphere complexes, thereby strengthening lead adsorption and contributing to diffuse double layer compression. As illustrated in Figure 2.3, inner-sphere complexes involve direct chemical bonding between Pb^{2+} ions and clay surfaces, whereas outer-sphere complexes retain an intervening water layer, resulting in weaker adsorption.

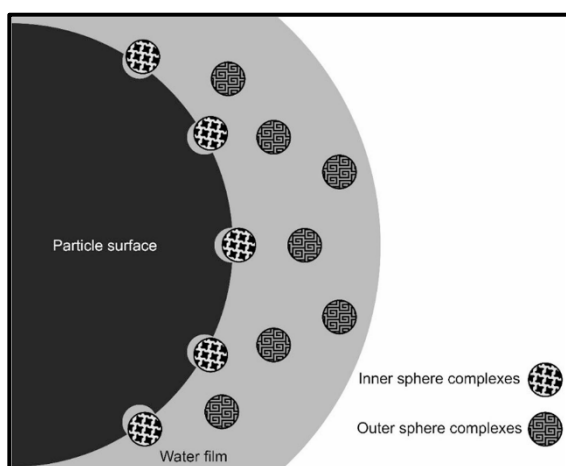


Figure 2.3 Schematic Illustration of Inner-Sphere and Outer-Sphere Adsorption Complexes Formed Between Heavy Metal Ions and Clay Surfaces (Saeid Nikkhah Nasab and Abdeh Keykha, 2020)

The physicochemical interactions between lead ions and clay minerals subsequently induce pronounced microstructural modifications. Compression of the diffuse double layer decreases electrostatic repulsion between adjacent particles, allowing attractive van der Waals forces to become dominant. Consequently, dispersed clay particles progressively transform into flocculated and aggregated structures. Fan et al. (2016) demonstrated that increasing lead concentration changes the sedimentation behaviour of kaolin–calcium bentonite blends from accumulation sedimentation to flocculation–aggregation sedimentation once a threshold lead concentration is exceeded. The SEM observations presented in Figure 2.4 clearly demonstrate the formation of larger particle aggregates following lead contamination, confirming that diffuse double layer compression promotes interparticle attraction and aggregation

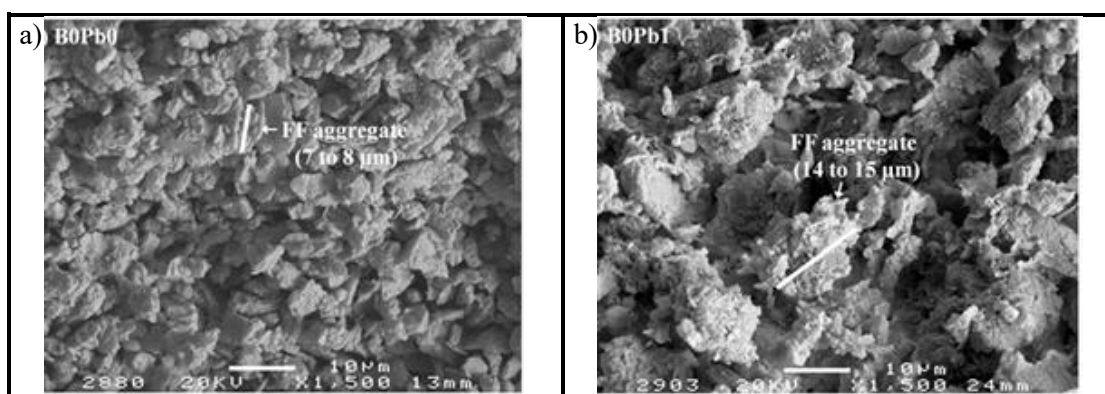


Figure 2.4 Microstructure of Sediments for Kaolin (a) B0Pb0: Pure Kaolin With 0 mmol/L Lead Concentration; (b) B0Pb1: Pure Kaolin With 1 mmol/L Lead Concentration (Fan et al., 2016)

Changes in particle interaction are also reflected by sedimentation behaviour. Fan et al. (2016) reported that kaolin–calcium bentonite blends exhibit accumulation sedimentation at low lead concentrations but progressively transform into flocculation–aggregation sedimentation beyond a threshold lead concentration, reflecting increased interparticle attraction induced by lead adsorption. As illustrated in Figure 2.5, increasing lead concentration promotes the transition from dispersed particle sedimentation to flocculated aggregates, demonstrating the progressive evolution of soil microstructure.

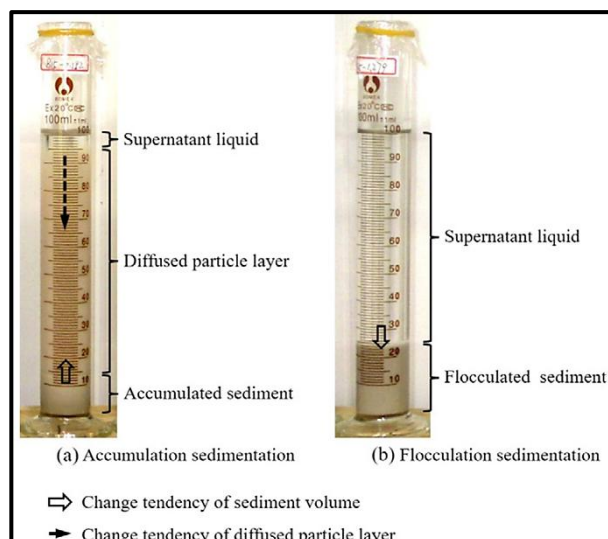


Figure 2.5 Comparison Between Accumulation Sedimentation and Flocculation–Aggregation Sedimentation of Clay Suspensions Under Increasing Lead Concentration (Fan et al., 2016)

The alteration of clay microstructure has significant engineering implications because it governs many macroscopic soil properties. Liu et al. (2018) reported that heavy metal contamination modifies adsorption, complexation and particle interaction processes, thereby affecting contaminant mobility and environmental risk while simultaneously influencing engineering properties such as compressibility, permeability and strength. Likewise, Saeid Nikkhah Nasab and Abdeh Keykha (2020) observed that lead contamination alters pH , Atterberg limits, electrical resistivity and compressibility through changes in pore-water chemistry and particle arrangement, although the magnitude and direction of these changes depend strongly on clay mineralogy.

Fijałkowska et al. (2021) further demonstrated that the presence of polymers such as polyacrylamide modifies lead adsorption on both kaolinite and montmorillonite surfaces by influencing the extent of particle aggregation and heavy metal retention. Their findings highlight that the mechanisms governing lead–clay interaction are not controlled solely by the intrinsic properties of clay minerals but may also be affected by the surrounding chemical environment and the presence of additional organic constituents. Collectively, these studies demonstrate that adsorption, cation exchange, surface complexation and microstructural reorganisation operate simultaneously during lead contamination, forming the fundamental physicochemical processes responsible for changes in the physical and engineering behaviour of contaminated clay.

2.1.3 Effects of Lead on Kaolin Physical Properties

Lead contamination modifies the physical properties of clay through a series of physicochemical interactions involving adsorption, cation exchange, surface complexation and diffuse double layer compression. As discussed in the previous section, these processes alter the electrochemical environment surrounding clay particles, resulting in changes in particle arrangement, pore-water chemistry and interparticle forces. Consequently, measurable engineering properties including the liquid limit, plastic limit, plasticity index, specific gravity, linear shrinkage and pH may vary following lead contamination. Since these physical properties govern soil consistency, workability and compaction behaviour, understanding their response to lead contamination is fundamental for evaluating the engineering performance of contaminated kaolin.

Numerous studies have demonstrated that lead contamination alters the physical properties of clayey soils, however, the reported responses remain inconsistent due to differences in soil mineralogy, contaminant concentration and experimental conditions. Du et al. (2015) observed that lead contamination significantly modified the consistency characteristics of bentonite–sand mixtures through physicochemical interactions between lead ions and clay minerals. Similarly, Li et al. (2015) reported that Pb^{2+} contamination changed both the engineering behaviour and microstructure of kaolin by modifying particle interactions and reducing diffuse double layer thickness. These findings indicate that heavy metal contamination influences clay behaviour primarily through changes in the electrochemical environment rather than solely through physical mixing.

Nevertheless, previous investigations have reported contrasting trends regarding the variation of physical properties. For example, Muththalib and Baudet (2019) reported that heavy metal contamination generally increased the Atterberg limits of several clayey soils owing to enhanced water adsorption associated with changes in mineral surface chemistry. In contrast, Negahdar and Nikghalbpour (2020) observed that lead and zinc contamination produced reductions in the liquid limit, plasticity index and maximum dry density while simultaneously increasing the optimum moisture content of sandy clayey soils, indicating that contaminant-induced particle aggregation reduced soil plasticity. Likewise, Zhang et al. (2024) reported that increasing concentrations of lead and zinc reduced the liquid limit, plasticity index and fine particle

content of clay soils because heavy metal ions compressed the diffuse double layer, promoted particle flocculation and increased particle aggregation, thereby weakening soil fluidity and plasticity.

The contradictory findings reported in previous studies demonstrate that no universal relationship exists between lead concentration and the physical properties of clay. Instead, the observed behaviour depends on several interacting factors, including clay mineralogy, cation valence, contaminant concentration, initial pore-water chemistry and testing methodology. Highly active expansive clays such as bentonite often exhibit different responses from low-swelling kaolinite because their larger specific surface area and higher cation exchange capacity result in stronger physicochemical interactions with heavy metal ions. Furthermore, variations in contamination procedures, curing duration and solution chemistry may alter the degree of adsorption and flocculation, thereby producing different trends in the measured engineering properties. Consequently, direct comparison among previous studies remains difficult despite their common focus on lead contamination.

A summary of the reported effects of lead contamination on the physical properties of clayey soils is presented in Table 2.1. Although the direction of change differs among studies, a common conclusion can be drawn that lead contamination significantly alters soil consistency and engineering behaviour through modifications to the soil microstructure and electrochemical environment. These changes subsequently influence parameters governing compaction, compressibility and strength. Therefore, evaluating the physical properties of contaminated soils remains an essential prerequisite before investigating their compaction characteristics.

Table 2.1

Summary of Previous Studies on the Effects of Lead Contamination on the Physical Properties of Clayey Soils

Study	Soil Type	Pb^{2+} Concentration	LL	PI	Key Observations
Du et al. (2015)	Bentonite–sand backfills (various bentonite contents B5–B15; $Pb(NO_3)_2$ spiked)	0–200 mmol/L ($\approx$ 0–41,000 mg/L equivalent Pb^{2+})	LL decrease with Pb addition (e.g., B5Pb0 = 43.9%; B5Pb200 = 36.4%)	PI decreases with increasing Pb content	Lead contamination lowers pH and reduces plasticity due to cation exchange and flocculation.
Li et al. (2015)	Kaolin clay	0–20,000 mg/L Pb^{2+}	Slight decreasing trend (approx. 42.5% $\rightarrow$ 39%)	PI decreases initially then increase at higher concentrations	LL decreases as Pb causes edge-to-face association; PI trend influenced by microstructure transitions.
Saeid Nikkhah Nasab & Abdeh Keykha (2020)	Kaolin (K) and Bentonite (B)	0, 15,000, 30,000 ppm	K: LL increases (38.8 $\rightarrow$ 41.6%); B: LL decreases (180 $\rightarrow$ 82%)	K slight increase (6.8 $\rightarrow$ 7.5%); B decreases dramatically (115.9 $\rightarrow$ 35.7%)	Impact depends strongly on mineralogy: kaolin shows mild response; bentonite shows large reductions due to collapsed diffuse double layer under Pb^{2+} .

Although previous researchers have investigated lead contamination over a wide range of concentrations, the selected contamination levels differ considerably according to the intended research objectives. For example, Li et al. (2015) investigated lead concentrations up to 20,000 mg/L, while Zhang et al. (2024) evaluated contaminated soils over a concentration range reaching 5000 mg/kg to examine changes in physical properties and microstructure. Higher contaminant concentrations are particularly useful for evaluating adsorption capacity, contaminant transport and long-term

deterioration mechanisms. However, studies focusing on engineering behaviour and empirical model development require a concentration range that permits progressive observation of property changes without introducing excessive physicochemical disturbances.

Accordingly, the present study adopted lead concentrations of 0, 1000, 2000, 3000 and 4000 mg/L to provide a systematic evaluation of the influence of lead contamination on kaolin. The selected concentrations represent equal contamination intervals that enable gradual changes in physical properties and subsequent compaction behaviour to be quantified while remaining comparable with concentration ranges commonly reported in previous laboratory investigations. The use of consistent concentration increments also facilitates statistical comparison and supports the development of empirical prediction models relating contamination level to compaction characteristics.

2.2 Compaction Behaviour of Fine-Grained and Contaminated Soils

Compaction is one of the most important ground improvement processes in geotechnical engineering because it directly influences the engineering performance of compacted soils. By increasing the dry density and reducing the volume of air voids, compaction improves shear strength, stiffness and bearing capacity while reducing compressibility, settlement and hydraulic conductivity. For fine-grained soils, the compaction response is governed not only by the magnitude of the applied compactive effort but also by the interaction between soil particles, pore water and the physicochemical characteristics of the clay minerals. When heavy metal contaminants such as lead are introduced into the soil, these interactions become more complex because contamination modifies the soil fabric and pore-water chemistry, consequently altering the moisture–density relationship. Therefore, understanding both the fundamental principles of soil compaction and the influence of contamination is essential for evaluating the engineering behaviour of lead-contaminated kaolin.

2.2.1 Fundamentals of Compaction in Fine-Grained Soils

Compaction is the mechanical process of densifying soil through the application of external energy, with the primary objective of reducing the volume of air voids while causing minimal changes to the water content. In geotechnical engineering, soil compaction is widely adopted to improve the stability and serviceability of earth structures, including embankments, road foundations, earth dams and engineered fill. The effectiveness of compaction is generally evaluated using two principal parameters, the optimum moisture content (OMC) and maximum dry density (MDD), which are determined through laboratory compaction tests. For a given compactive effort, the relationship between moisture content and dry density produces a characteristic bell-shaped compaction curve, where the dry density increases with increasing moisture content until reaching the OMC before subsequently decreasing with further addition of water (Di Matteo et al., 2009).

Water plays an important role during the compaction process. At relatively low moisture contents, insufficient water restricts particle movement and limits soil densification because interparticle friction remains relatively high. As the moisture content increases, water gradually lubricates the soil particles, allowing them to rearrange into a denser packing configuration under the applied compactive effort. This process continues until the OMC is achieved, where the highest dry density can be obtained for a particular compactive effort. Beyond this point, additional water occupies the available pore spaces and reduces the effectiveness of the applied compactive effort, resulting in a progressive reduction in dry density despite continued compaction. Consequently, both OMC and MDD are governed by the interaction between moisture content and the magnitude of the applied compactive effort.

For fine-grained soils, the compaction mechanism is considerably more complex than that of coarse-grained soils because it is also influenced by physicochemical interactions occurring at the particle level. Sridharan and Gurtug (2003) explained that water serves a dual function during compaction. Besides acting as a lubricant that facilitates particle rearrangement, water also controls the thickness of the diffuse double layer surrounding clay particles, thereby influencing the attractive and repulsive forces between adjacent particles. At moisture contents below the OMC, the diffuse double layer remains relatively thin, and particle movement is restricted, producing a comparatively open soil structure. As the moisture content approaches the

OMC, particle rearrangement becomes more effective owing to improved lubrication and more favourable interparticle interactions. However, excessive water beyond the OMC increases the pore-water content without contributing to further densification, thereby lowering the achievable dry density.

2.2.2 Influence of Compactive Effort and Compaction Method

The compactive effort applied during laboratory and field compaction plays a significant role in determining the moisture–density behaviour of fine-grained soils. Compactive effort represents the amount of mechanical energy transmitted to the soil during compaction and directly influences the degree of particle rearrangement, reduction of air voids and achievable dry density. In general, increasing the compactive effort results in higher MDD and lower OMC because the greater impact energy enables soil particles to achieve a denser packing configuration. Consequently, selecting an appropriate compactive effort is essential for ensuring that laboratory compaction results realistically represent field compaction conditions.

Previous studies have consistently demonstrated that variations in compactive effort significantly influence the engineering behaviour of compacted soils. Lee et al. (2007) reported that specimens prepared using different laboratory compaction methods produced different density characteristics and engineering properties even when compacted at similar moisture contents. The study highlighted that both the magnitude of compactive effort and the method by which the energy is applied contribute to the resulting soil fabric and engineering performance. Similarly, David Suits et al. (2005) demonstrated that mini-compaction procedures produced moisture–density relationships comparable to those obtained from conventional Proctor tests, confirming that the fundamental compaction mechanism remains governed by the interaction between moisture content and compactive effort despite differences in testing procedures.

The principal laboratory compaction methods reported in previous studies and commonly adopted in geotechnical engineering are summarised in Table 2.2. These methods differ primarily in the magnitude of compactive effort applied during testing and are intended to simulate different field compaction conditions.

Table 2.2

Comparison of Common Laboratory Compaction Methods (Shaivan and Sridharan (2020a, 2020b))

Compaction Method	Standard	Compactive Effort, E (kN-m/m³)	Typical Engineering Application
Reduced Proctor Compaction (RPC)	Modified from ASTM D698	360	Low-energy laboratory simulation and research applications
Standard Proctor Compaction (SPC)	ASTM D698	600	General earthworks, embankments and backfill construction
Modified Proctor Compaction (MPC)	ASTM D1557	2700	Highway pavements, airfields and heavily loaded earth structures

The comparison presented in Table 2.2 illustrates that the three Proctor compaction methods represent substantially different levels of compactive effort and are therefore suitable for simulating a wide range of field compaction conditions. Shaivan and Sridharan (2020a) demonstrated that compaction characteristics obtained using reduced and standard Proctor energies exhibited consistent empirical relationships, indicating that variations in compactive effort produced systematic rather than random changes in OMC and MDD. In a subsequent investigation, Shaivan and Sridharan (2020b) further showed that increasing compactive effort not only increased the achievable dry density but also influenced the internal pore structure of compacted soils, resulting in changes to hydraulic conductivity and overall engineering performance. These findings suggest that compactive effort should be regarded as an independent variable that directly governs the physical behaviour of compacted fine-grained soils.

The influence of compactive effort on the moisture–density relationship of kaolin is illustrated in Figure 2.6, which compares the compaction curves obtained under Standard Proctor and Modified Proctor compactive efforts reported by Mohd Yusoff et al. (2017). The figure provides experimental evidence that increasing the compactive effort shifts the compaction curve towards a higher dry density and lower optimum moisture content.

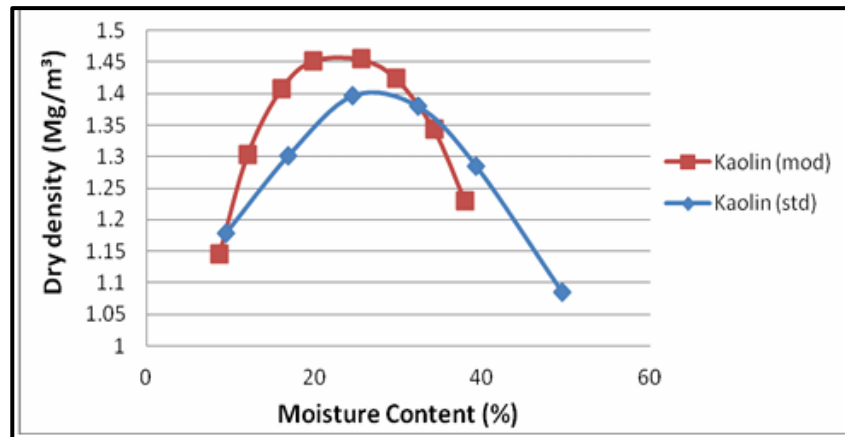


Figure 2.6 Moisture–Density Relationships of Kaolin Under Standard and Modified Proctor Compactive Efforts (Mohd Yusoff et al., 2017)

As shown in Figure 2.6, Mohd Yusoff et al. (2017) reported that increasing the compactive effort from Standard Proctor to Modified Proctor increased the MDD from approximately 1.41 Mg/m³ to 1.46 Mg/m³, representing an increase of approximately 3.6%, while the OMC decreased from approximately 27% to 23%, corresponding to a reduction of approximately 14.8%. These findings confirm that higher compactive efforts enabled greater particle rearrangement and more effective elimination of air voids, thereby producing a denser soil structure with reduced moisture demand. Similar observations were reported by Prasanna et al. (2021), who investigated the influence of different compaction energy levels on fine-grained soils and concluded that higher compactive efforts improved soil densification while simultaneously reducing volumetric shrinkage during drying. Their findings further demonstrate that the effects of compactive effort extend beyond the initial compaction process and continue to influence the subsequent engineering behaviour of compacted soils.

Previous studies consistently demonstrate that compactive effort governs the moisture–density relationship and significantly influences the engineering properties of fine-grained soils. Nevertheless, most published investigations have focused on uncontaminated soils or comparisons between only two compactive effort levels. Limited attention has been given to evaluating contaminated kaolin across multiple Proctor compactive efforts within a single experimental programme. Therefore, the present study adopts Reduced Proctor Compaction (RPC), Standard Proctor Compaction (SPC) and Modified Proctor Compaction (MPC) to represent low, medium and high energy compaction conditions, enabling the influence of compactive effort on the compaction behaviour of lead-contaminated kaolin to be systematically evaluated.

2.2.3 Compaction Behaviour of Contaminated and Lead-Affected Soils

The compaction behaviour of contaminated soils differs from that of uncontaminated soils because the presence of contaminants alters the physicochemical interactions between soil particles and pore water. Heavy metal ions such as lead (Pb^{2+}) modify the diffuse double layer surrounding clay particles through cation exchange, adsorption and flocculation processes, thereby changing the soil fabric and influencing the moisture–density relationship. Consequently, contamination may alter both the OMC and MDD, although the magnitude and direction of these changes depend on factors such as soil mineralogy, contaminant concentration, contamination period and compactive effort.

Previous investigations have consistently demonstrated that lead contamination modifies the compaction characteristics of fine-grained soils through changes in particle arrangement and pore structure. Karkush and Ali (2020) reported that lead nitrate contamination significantly influenced both OMC and MDD of clayey soils, with the observed changes attributed to physicochemical interactions between lead ions and clay minerals. Similarly, Negahdar and Nikghalbpour (2020) showed that lead and zinc contamination altered the moisture–density characteristics of sandy clayey soils by modifying the soil structure and reducing the thickness of the diffuse double layer. These findings suggest that contamination not only affects the engineering behaviour of soils but also changes the compaction response through alterations in interparticle forces.

The influence of lead contamination on the moisture–density relationship is illustrated in Figure 2.7, which presents the compaction curves reported by Karkush and Ali (2020) for uncontaminated and lead-contaminated clay. The figure demonstrates the shift in the compaction curves following lead contamination and provides direct experimental evidence that contamination modifies both OMC and MDD.

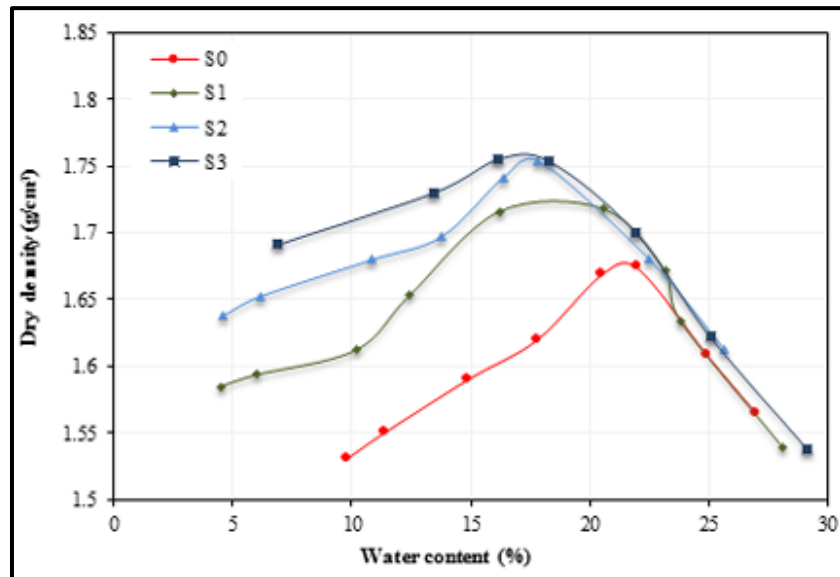


Figure 2.7 Moisture-Density Curve for Uncontaminated (S0) and Lead-Contaminated Clay (S1, S2, S3) (Karkush & Ali, 2020)

As shown in Figure 2.7, increasing the lead concentration from 0 ppm (S0) to 20,000 ppm (S3) progressively shifted the compaction curve, producing an increase in MDD from approximately 1.68 g/cm³ to 1.76 g/cm³, representing an increase of approximately 4.8%, accompanied by a reduction in OMC from approximately 22% to 17%, corresponding to a decrease of approximately 22.7% for the tested clay. Karkush and Ali (2020) explained that Pb^{2+} ions compress the diffuse double layer surrounding clay particles, promoting particle aggregation and reducing the repulsive forces between adjacent particles. This physicochemical modification enables a denser soil structure to develop under compaction, although the overall response remains dependent on the contamination level and soil type.

In addition to conventional compaction characteristics, recent studies have demonstrated that heavy metal contamination influence the mechanical response of compacted soils under different loading conditions. Hassanlourad et al. (2024) reported that the presence of lead altered the stiffness and deformation characteristics of clay-containing soils, while Motlagh et al. (2025) demonstrated that heavy metal contamination modified the cyclic behaviour of fine-grained soils through changes in soil fabric and particle interaction. Although these studies focused primarily on mechanical performance after compaction, their findings collectively support the conclusion that contamination-induced changes in soil structure originate during the compaction process itself and continue to influence the subsequent engineering behaviour of the soil.

Lead contamination influences the compaction behaviour of fine-grained soils through physicochemical interactions that modify particle arrangement, pore structure and moisture–density relationships had been demonstrated in previous studies. However, most published investigations have evaluated contaminated soils under a single compactive effort or focused primarily on environmental remediation and stabilisation. Limited information is available regarding the combined influence of different lead contamination levels and multiple Proctor compactive efforts on the compaction behaviour of kaolin clay. Therefore, a systematic investigation incorporating RPC, SPC and MPC is required to establish the influence of both contamination and compactive effort on OMC and MDD.

2.3 Influence of Physical Soil Properties on Compaction Behaviour

The compaction behaviour of fine-grained soils is governed not only by the magnitude of the applied compactive effort but also by the intrinsic physical properties of the soil. Properties such as Atterberg limits, specific gravity, shrinkage characteristics and pH provide valuable information regarding soil consistency, mineral composition, volume change potential and physicochemical condition, all of which influence the manner in which soil particles respond to compaction. Previous studies have demonstrated that variations in these properties are commonly accompanied by corresponding changes in OMC and MDD, although the magnitude of these changes depends on soil mineralogy, contamination condition and testing procedures. Consequently, understanding the relationship between physical soil properties and compaction behaviour provides an important basis for interpreting the changes observed in lead-contaminated kaolin subjected to different compactive efforts.

2.3.1 Influence of Index Properties on Compaction Behaviour

Among the various physical properties of fine-grained soils, the Atterberg limits remain the most widely adopted indicators for describing soil consistency and its interaction with water. The liquid limit (LL), plastic limit (PL) and plasticity index (PI) collectively describe the range of moisture contents over which clay behaves plastically and therefore provide useful insight into the water demand of soils during compaction.

In general, soils possessing higher liquid limits and plasticity indices exhibit greater water adsorption capacity because of their larger specific surface area and stronger physicochemical attraction between clay particles and pore water. As a result, such soils generally require greater moisture to facilitate particle rearrangement during compaction and consequently tend to exhibit higher OMC together with comparatively lower MDD.

The influence of soil consistency on compaction behaviour has been reported consistently in previous investigations. Bera and Ghosh (2011) demonstrated that soils with increasing liquid limit and plasticity index generally exhibited increasing OMC accompanied by a reduction in MDD, indicating that soil consistency exerts considerable influence on moisture–density behaviour. Similarly, Saikia et al. (2017) reported strong relationships between Atterberg limits and compaction characteristics for a range of fine-grained soils, concluding that changes in consistency properties were consistently accompanied by corresponding changes in compaction response. Sridharan and Gurtug (2003) further explained that these relationships originate from the interaction between clay mineralogy, diffuse double-layer thickness and water adsorption behaviour, which collectively govern the amount of moisture required for effective particle rearrangement during compaction.

The relationships reported by previous researchers are summarised in Table 2.3, which highlights the general influence of Atterberg limits on compaction behaviour observed across different studies.

Table 2.3
General Relationship Between Atterberg Limits and Compaction Behaviour Reported in Previous Studies

Study	Soil Type	Main Findings	Implication for Compaction Behaviour
Bera and Ghosh (2011)	Fine-grained soils	Higher LL and PI associated with higher OMC and lower MDD	Greater water demand during compaction
Saikia et al. (2017)	Clayey soils	Strong correlation between Atterberg limits and compaction characteristics	Soil consistency influences moisture–density relationship
Sridharan and Gurtug (2003)	Fine-grained soils	Clay mineralogy and diffuse double-layer behaviour govern consistency and compaction response	Physicochemical interactions influence particle rearrangement

Table 2.3 demonstrates that, despite differences in soil type and testing conditions, previous studies consistently reported similar trends regarding the influence of Atterberg limits on compaction behaviour. The agreement among these investigations suggests that consistency properties serve as useful indicators for interpreting variations in moisture–density relationships rather than acting as independent controlling variables. This interpretation is particularly relevant for contaminated clayey soils because any physicochemical alteration capable of modifying the Atterberg limits may also influence the moisture requirement necessary to achieve optimum compaction.

In heavy metal-contaminated soils, changes in Atterberg limits have been closely associated with modifications in soil fabric arising from cation exchange and particle aggregation. Du et al. (2015) reported that lead contamination altered the liquid limit and plasticity characteristics of clay–bentonite mixtures through compression of the diffuse double layer and changes in particle arrangement. Similarly, Muththalib and Baudet (2019) observed that heavy metal contamination modified the consistency characteristics of clay mixtures, although the magnitude and direction of change depended on mineral composition and contaminant concentration. These findings indicate that contamination-induced changes in LL, PL and PI should not be considered in isolation but rather as part of the physicochemical processes that ultimately influence compaction behaviour.

2.3.2 Influence of Specific Gravity and Shrinkage Characteristics on Compaction Behaviour

Specific gravity and shrinkage characteristics are important physical properties that contribute to the compaction behaviour of fine-grained soils. While specific gravity represents the density of soil solids and reflects the mineralogical composition of the soil, shrinkage characteristics describe the tendency of compacted soils to undergo volume reduction during drying. Together, these properties provide valuable information regarding the packing efficiency of soil particles, volume stability and the structural changes that occur before and after compaction. Although neither property directly controls the compaction process, both assist in explaining the variations in OMC and MDD observed under different soil conditions.

Specific gravity influences the theoretical dry density that can be achieved

during compaction because soils with denser solid particles generally possess greater potential to attain higher dry densities under similar compactive efforts. Patra et al. (2010) reported that soils exhibiting higher specific gravity generally produced greater maximum dry densities owing to the increased mass of soil solids occupying a given volume. Similarly, Zhang et al. (2022) highlighted that variations in mineralogical composition, particularly the presence of minerals with different particle densities, contribute to differences in dry density behaviour during laboratory compaction. However, these studies also emphasised that the influence of specific gravity should be interpreted together with soil fabric and particle arrangement because the final dry density depends on both particle density and the efficiency of particle packing.

For contaminated soils, changes in specific gravity may arise from physicochemical interactions between heavy metal ions and soil particles. Du et al. (2015) observed that lead contamination altered both the density characteristics and microstructure of clay–bentonite mixtures through cation exchange and particle aggregation, resulting in changes to the packing arrangement of the soil. Similarly, Motlagh et al. (2025) reported that the incorporation of different materials into contaminated fine-grained soils modified both specific gravity and soil structure, thereby influencing the subsequent mechanical behaviour of compacted specimens. These findings suggest that changes in specific gravity associated with contamination should be interpreted together with accompanying microstructural modifications rather than being considered independently.

In addition to specific gravity, shrinkage characteristics provide further insight into the behaviour of compacted fine-grained soils. Linear and volumetric shrinkage describe the reduction in soil volume that occurs during moisture loss and are closely associated with the soil's ability to retain water after compaction. Hobbs et al. (2018) reported that shrinkage behaviour is strongly influenced by the initial soil fabric and moisture condition established during compaction, indicating that soils compacted to different densities may subsequently exhibit different volume change characteristics upon drying. Mohd Nazer and Charles (2022) similarly observed that desiccation crack formation in compacted kaolin is highly dependent on both compaction condition and drying behaviour, demonstrating the close relationship between shrinkage characteristics and the structural condition established during compaction.

The influence of compaction energy on shrinkage behaviour is illustrated in Figure 2.8, which presents the relationship between compactive energy and volumetric

shrinkage for kaolinitic soil reported by Prasanna et al. (2021). The figure demonstrates that increasing the compaction energy consistently reduced the volumetric shrinkage of the compacted specimens regardless of specimen thickness.

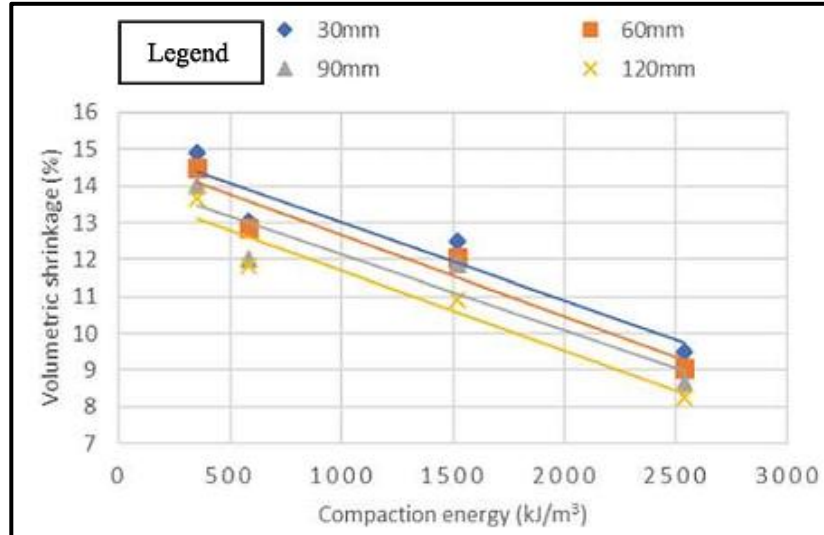


Figure 2.8 Relationship Between Compactive Energy and Volumetric Shrinkage of Kaolinitic Soil (Prasanna et al., 2021)

As shown in Figure 2.8, increasing the compaction energy from approximately 500 kJ/m³ to 2500 kJ/m³ reduced the volumetric shrinkage from approximately 15.0% to 9.5% for the 30 mm specimens, representing a reduction of approximately 36.7%. For the 120 mm specimens, the volumetric shrinkage decreased from approximately 13.5% to 8.2%, corresponding to a reduction of approximately 39.3%. Similar trends were observed for the intermediate specimen thicknesses, indicating that greater compactive effort consistently reduced the susceptibility of compacted soils to post-compaction volume change. Prasanna et al. (2021) attributed this behaviour to the denser particle arrangement produced under higher compactive energies, which reduced the volume of air voids and limited the magnitude of shrinkage during drying.

Specific gravity and shrinkage characteristics provide valuable complementary information for interpreting compaction behaviour. While specific gravity reflects the density potential of the soil solids, shrinkage characteristics indicate the stability of the compacted soil structure during subsequent drying. In the present study, these properties are evaluated together with OMC and MDD to provide a more comprehensive interpretation of the changes in compaction behaviour resulting from lead contamination.

2.3.3 Influence of Soil *pH* on Compaction Behaviour

Soil *pH* is an important physicochemical property that influences the behaviour of fine-grained soils through its effect on mineral stability, surface charge characteristics and the interaction between soil particles and dissolved ions. In contaminated soils, variations in *pH* modify the adsorption, ion exchange and precipitation behaviour of heavy metals, thereby influencing the physicochemical environment surrounding clay particles. These changes may subsequently affect particle arrangement, moisture retention and compaction behaviour. Consequently, although *pH* does not directly determine the compaction characteristics of soils, it provides valuable information for interpreting changes in OMC and MDD resulting from heavy metal contamination.

The importance of *pH* in heavy metal–soil interaction has been widely reported in previous studies. Mao et al. (2022) demonstrated that the adsorption capacity of kaolinite and other clay minerals for Pb^{2+} is strongly dependent on the surrounding *pH*, with lower *pH* conditions generally reducing the availability of negatively charged adsorption sites while altering the dominant sorption mechanisms. Similarly, Fijałkowska et al. (2021) reported that the accumulation and retention of lead ions on clay mineral surfaces varied significantly with *pH* because changes in soil acidity modified both surface charge characteristics and the electrochemical attraction between Pb^{2+} ions and clay particles. These findings indicate that *pH* plays an important role in controlling the physicochemical processes responsible for modifying the engineering behaviour of contaminated soils.

The influence of *pH* extends beyond contaminant adsorption and also affects the engineering performance of compacted soils. Wang et al. (2022) investigated cement-stabilised lead-contaminated soils subjected to long-term erosion and observed that changes in *pH* were accompanied by modifications in hydration products and microstructure, which subsequently influenced the mechanical performance and durability of the compacted specimens. Likewise, Das and Bharat (2021) reported that acidic leachates reduced the engineering performance of compacted clay liners by altering the physicochemical condition of the soil matrix, thereby affecting hydraulic conductivity and structural integrity. Roy and Mishra (2024) further demonstrated that variations in chemical environment influenced the long-term behaviour of compacted clay barriers through changes in mineral interaction and pore structure. Collectively,

these studies suggest that pH should be considered an important indicator for interpreting changes in the engineering behaviour of contaminated fine-grained soils. The influence of pH on lead adsorption reported by previous researchers is summarised in Table 2.4, which highlights the general relationship between soil acidity, lead retention and engineering behaviour.

Table 2.4
General Influence of Soil pH on Lead–Soil Interaction and Compaction Behaviour Reported in Previous Studies

Study	Main Observation	Implication for Compaction Behaviour
Mao et al. (2022)	Lead adsorption by kaolinite is strongly pH dependent.	Changes in pH modify surface charge characteristics and particle interaction.
Fijałkowska et al. (2021)	Lead accumulation on clay minerals varies with pH and adsorption conditions.	Variations in pH influence physicochemical processes governing soil fabric.
Wang et al. (2022)	pH changes alter hydration products and microstructure in lead-contaminated soils.	Microstructural modification contributes to changes in engineering behaviour after compaction.
Das and Bharat (2021)	Acidic conditions affect hydraulic and engineering performance of compacted clay liners.	Chemical environment influences the stability of compacted soils.
Roy and Mishra (2024)	Long-term performance of compacted clay barriers depends on chemical interactions within the soil matrix.	Soil chemistry contributes to the durability and behaviour of compacted clay.

Table 2.4 demonstrates that, although previous studies have investigated pH primarily from the perspective of contaminant retention and environmental performance, they consistently recognise that changes in soil acidity influence the physicochemical environment governing particle interaction and soil structure. These physicochemical modifications may subsequently contribute to variations in compaction behaviour, particularly in contaminated fine-grained soils where adsorption and cation exchange occur simultaneously.

In the present study, pH is measured for uncontaminated and lead-contaminated kaolin to evaluate the changes in soil acidity associated with increasing lead

concentration. Rather than considering pH as a direct controlling variable for OMC and MDD, the measured pH values are interpreted together with the Atterberg limits, specific gravity and linear shrinkage to provide a more comprehensive explanation of the compaction behaviour observed under different contamination levels and compactive efforts.

2.4 Empirical Modelling of Compaction Parameters

The prediction of soil compaction parameters has received increasing attention in geotechnical engineering owing to the need to reduce laboratory testing while maintaining reliable estimates of engineering behaviour. Traditionally, OMC and MDD have been determined through laboratory Proctor compaction tests, which remain the standard approach for evaluating compaction characteristics. However, laboratory testing is often time-consuming, labour-intensive and costly, particularly when numerous soil types, contamination levels and compactive efforts are investigated. Consequently, considerable research has focused on developing empirical and predictive models capable of estimating compaction parameters from measurable soil properties and experimental variables.

2.4.1 Conventional Empirical Regression Models

Empirical regression models represent one of the earliest and most widely adopted approaches for predicting the compaction characteristics of soils. These models establish mathematical relationships between measurable soil properties and compaction parameters, allowing OMC and MDD to be estimated without performing extensive laboratory compaction tests. Compared with advanced computational techniques, empirical regression models offer several practical advantages, including mathematical simplicity, ease of implementation and direct interpretation of the contribution of each independent variable. Consequently, regression-based approaches continue to be extensively applied in geotechnical engineering, particularly where experimental datasets are relatively limited and explicit predictive equations are required for engineering design.

Among the earliest studies, Bera and Ghosh (2011) developed multiple

regression equations to predict OMC and MDD for fine-grained soils using readily measurable index properties, including liquid limit, plasticity index, specific gravity and compaction energy. Their study demonstrated that the inclusion of several physical soil properties significantly improved prediction accuracy compared with single-variable relationships, indicating that compaction behaviour results from the combined influence of soil consistency, mineralogical characteristics and applied compactive effort. The developed regression equations exhibited high coefficients of determination, demonstrating that multiple linear regression provides a reliable and statistically sound method for estimating compaction characteristics from experimental soil data.

Similarly, Saikia et al. (2017) investigated the relationship between Atterberg limits and compaction characteristics for fine-grained soils and reported that both OMC and MDD exhibited strong correlations with liquid limit and plasticity characteristics. The authors concluded that regression equations developed using index properties provide sufficiently accurate preliminary estimates of compaction characteristics while substantially reducing the amount of laboratory testing required during site investigation and preliminary design. Their findings further demonstrated that consistency properties influence the moisture demand of fine-grained soils during compaction, thereby providing a practical basis for empirical model development.

While many early regression models focused on fine-grained cohesive soils, Patra et al. (2010) demonstrated that similar empirical approaches could also be successfully applied to granular materials. Their investigation established regression relationships between relative density, median particle size, compaction energy and density characteristics for clean sands, indicating that regression modelling is applicable across different soil classifications provided that appropriate explanatory variables are selected. Collectively, these investigations established regression analysis as one of the fundamental tools for predicting soil compaction behaviour and demonstrated that the selection of physically meaningful predictor variables is essential for obtaining reliable predictive equations.

The application of regression modelling has subsequently expanded to include modified and blended geomaterials. Soltani et al. (2021) developed empirical regression models to predict the compaction characteristics of fine-grained soils stabilised with tyre-derived aggregates using an extensive experimental database compiled from published studies. Unlike earlier regression models that relied solely on conventional index properties, their predictive equations incorporated the compaction characteristics

of the parent soil together with the specific gravity ratio between soil and tyre-derived aggregates. The proposed models were evaluated using several statistical performance indicators and validated through Bland–Altman analysis, demonstrating close agreement between predicted and measured values over the investigated range of soil conditions. The study concluded that regression models provide practical engineering tools capable of reducing laboratory testing while maintaining acceptable prediction accuracy for preliminary design and material evaluation.

The principal characteristics of conventional empirical regression models reported in previous studies are summarised in Table 2.5, which compares the predictor variables and major findings of representative investigations.

Table 2.5
Summary of Conventional Empirical Regression Models for Predicting Compaction Parameters

Study	Soil Type	Model Type	Predictor Variables	Predicted Parameters	Major Findings
Bera and Ghosh (2011)	Fine-grained soils	Multiple Linear Regression (MLR)	LL, PI, specific gravity, compaction energy	OMC, MDD	Multiple regression successfully predicted compaction characteristics with high statistical reliability.
Saikia et al. (2017)	Clayey soils	Regression Analysis	Atterberg limits	OMC, MDD	Strong relationships observed between consistency properties and compaction behaviour.
Patra et al. (2010)	Clean sands	Regression Analysis	Relative density, median grain size, compaction energy	Density characteristics	Regression applicable to granular soils when appropriate predictor variables are selected.

Soltani et al. (2021)	Fine- grained soils blended with tyre- derived aggregates	Multiple Linear Regression (MLR)	Parent soil compaction properties, specific gravity ratio	OMC, MDD	Regression models showed good agreement with laboratory data and were successfully validated using Bland–Altman analysis.
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Table 2.5 demonstrates that conventional empirical regression models have progressively evolved from simple correlations to multiple-variable predictive equations capable of representing increasingly complex soil systems. Despite differences in soil type and material composition, these studies consistently indicate that Multiple Linear Regression (MLR) remains one of the most practical modelling techniques because it produces explicit mathematical equations, allows rigorous statistical evaluation and provides transparent interpretation of the contribution of each independent variable. Nevertheless, most existing models have been developed using uncontaminated soils or mechanically modified geomaterials, whereas regression models incorporating contamination variables remain limited. This limitation provides the basis for adopting MLR in the present study to develop statistically validated empirical models relating OMC and MDD to the principal experimental variables governing the compaction behaviour of lead-contaminated kaolin clay.

2.4.2 Multiple Linear Regression for Geotechnical Model Development

Selecting an appropriate modelling technique is essential for developing predictive equations that are both statistically reliable and practically applicable in geotechnical engineering. Among the various statistical approaches available, MLR remains one of the most widely adopted methods because it establishes explicit mathematical relationships between one dependent variable and several independent variables while allowing the statistical significance of each variable to be quantitatively evaluated. Unlike simple regression, which considers only a single explanatory variable, MLR simultaneously accounts for the combined influence of multiple variables and therefore provides a more comprehensive representation of engineering behaviour. Owing to its transparency, computational simplicity and ease of

interpretation, MLR continues to be extensively applied in geotechnical engineering for developing empirical prediction models based on laboratory experimental data.

Previous studies have demonstrated that MLR provides reliable prediction accuracy for a wide range of geotechnical applications when appropriate predictor variables are selected. Bera and Ghosh (2011) successfully developed regression equations relating OMC and MDD to several physical soil properties, showing that multiple explanatory variables produced more accurate predictions than individual correlations. Similarly, Saikia et al. (2017) demonstrated that combining several consistency properties within a regression framework improved the estimation of compaction characteristics across different fine-grained soils. Soltani et al. (2021) further extended this approach by incorporating both parent soil compaction characteristics and the specific gravity ratio of tyre-derived aggregates into regression equations for predicting OMC and MDD. Their study demonstrated that MLR can effectively model complex geotechnical behaviour while maintaining relatively simple mathematical expressions that are suitable for practical engineering applications.

The successful application of MLR depends not only on the selection of suitable predictor variables but also on the adoption of an appropriate statistical model development procedure. Md Diah et al. (2012) proposed a comprehensive regression modelling framework consisting of data preparation, descriptive statistical analysis, variable screening, regression model development and independent model validation. The authors emphasised that reliable predictive equations should not be evaluated solely by their coefficient of determination but also through statistical significance testing, residual analysis and validation using independent datasets. Such procedures minimise model bias, improve prediction reliability and ensure that the developed equations possess sufficient statistical robustness for practical application.

The general procedure adopted for statistical regression model development reported by Md Diah et al. (2012) is summarised in Figure 2.9, illustrating the sequential process from data preparation to model validation. The figure highlights that regression modelling involves considerably more than fitting an equation to experimental data and requires systematic statistical evaluation before a predictive model can be considered reliable.

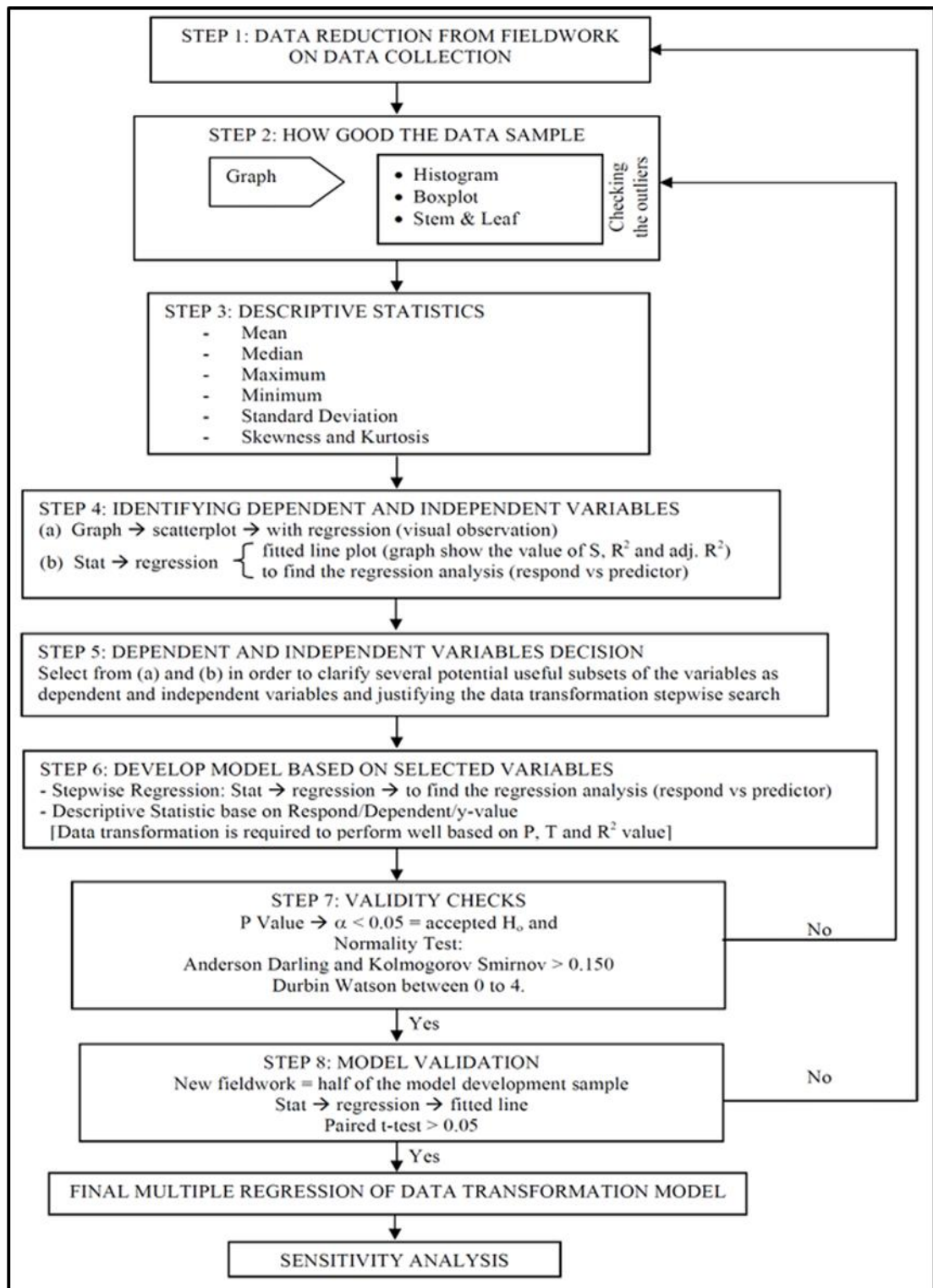


Figure 2.9 General Framework for Regression Model Development and Validation (Md Diah et al., 2012)

As illustrated in Figure 2.9, regression modelling requires systematic evaluation at each stage to ensure that the developed model satisfies the required statistical assumptions. Following model calibration, statistical performance is commonly assessed using the coefficient of determination (R^2), adjusted coefficient of

determination (Adjusted R^2), predicted coefficient of determination (Predicted R^2), standard error of estimate and significance testing of the regression coefficients. Residual analysis is subsequently performed to verify that the residuals satisfy the assumptions of normality, randomness and constant variance, thereby confirming that the mathematical relationship adequately represents the experimental observations. Finally, validation using an independent dataset is recommended to evaluate the predictive capability of the developed model beyond the calibration dataset and to minimise the possibility of overfitting.

Several statistical software packages are available for implementing MLR; however, Minitab has become one of the most widely adopted platforms for regression analysis in engineering research because it provides comprehensive statistical procedures within an integrated environment. In addition to developing regression equations, Minitab enables automated variable significance testing, analysis of variance (ANOVA), residual diagnostics, multicollinearity assessment and prediction analysis, thereby facilitating systematic evaluation of model performance. Md Diah et al. (2012) demonstrated that the integration of these statistical procedures within Minitab enables researchers to develop predictive models that satisfy recognised statistical requirements while maintaining straightforward interpretation of the resulting regression equations.

Although recent developments in artificial intelligence have introduced increasingly sophisticated prediction algorithms, MLR continues to offer several important advantages for laboratory-based geotechnical investigations. Unlike machine learning models that often require large datasets and extensive computational optimisation, MLR performs effectively with relatively small experimental datasets commonly generated through laboratory testing. Furthermore, the resulting regression equations explicitly quantify the contribution of each independent variable, allowing engineers to directly interpret the physical significance of the developed relationships. This level of interpretability is particularly important in geotechnical engineering, where understanding the influence of each experimental variable is often as important as achieving high prediction accuracy.

2.4.3 Artificial Intelligence and Machine Learning Approaches

Recent advances in computational intelligence have significantly expanded the application of predictive modelling in geotechnical engineering. Compared with

conventional empirical regression models, artificial intelligence (AI) and machine learning (ML) techniques are capable of modelling highly complex and nonlinear relationships among multiple variables without requiring predefined mathematical equations. These approaches learn directly from experimental datasets through iterative optimisation processes and have therefore become increasingly popular for predicting various engineering properties of soils, including compaction characteristics. The growing availability of computational resources and large experimental databases has further accelerated the application of AI-based models in geotechnical engineering research.

Among the earliest applications of artificial intelligence to compaction prediction, Alavi et al. (2009) employed Radial Basis Function (RBF) neural networks to estimate the OMC and MDD of stabilised soils. The developed RBF model achieved correlation coefficients of approximately 0.959 for MDD and 0.951 for OMC during testing, outperforming the Gene Expression Programming (GEP) model evaluated in the same study. The authors concluded that neural network models were capable of successfully capturing the nonlinear interactions among soil properties and stabilising agents while providing excellent prediction accuracy over a wide range of experimental conditions.

Subsequently, Hossein Alavi et al. (2010) further investigated artificial neural network techniques by developing Multilayer Perceptron (MLP) models for predicting compaction characteristics of chemically stabilised soils. Their study demonstrated that MLP networks effectively represented complex nonlinear relationships between multiple soil variables and compaction parameters while maintaining high prediction accuracy. The authors further reported that neural network models consistently outperformed conventional regression equations when sufficiently large and representative datasets were available for model training.

The development of machine learning techniques has continued rapidly in recent years. Bardhan et al. (2023) proposed a hybrid prediction model combining the Adaptive Neuro-Fuzzy Inference System (ANFIS) with an Improved Grey Wolf Optimiser (IGWO) to estimate OMC and MDD. The hybrid optimisation procedure significantly improved prediction performance compared with conventional ANFIS by optimising the membership function parameters and reducing prediction error. Their findings demonstrated that hybrid machine learning models provide powerful tools for modelling highly nonlinear geotechnical datasets when adequate training data are

available.

Similarly, Khatti and Grover (2023) compared several modern machine learning algorithms, including Least-Squares Support Vector Machine (LSSVM), Long Short-Term Memory (LSTM) and Least-Squares Boost Random Forest (LSBoostRF) for predicting compaction characteristics. Among the evaluated models, LSSVM produced the highest prediction performance, with testing correlation coefficients exceeding 0.99 together with RMSE values of approximately 0.017 g/cm³ for MDD and 0.607% for OMC, indicating excellent agreement between predicted and measured values. The comparative study demonstrated that the selection of an appropriate machine learning algorithm plays an important role in determining prediction performance, particularly when modelling complex engineering datasets containing nonlinear relationships.

Artificial intelligence has also been successfully applied to other geotechnical prediction problems beyond compaction characteristics. Özçoban et al. (2021) compared Multiple Linear Regression (MLR), Artificial Neural Networks (ANN) and Support Vector Machines (SVM) for predicting the permeability behaviour of compacted clay soils containing nanomaterials. Although all three techniques produced satisfactory prediction accuracy, the study reported that SVM achieved the highest overall prediction performance, followed closely by ANN. Nevertheless, the authors noted that MLR remained advantageous because the developed regression equations were considerably easier to interpret and required substantially fewer computational resources than the machine learning models.

Artificial intelligence and machine learning techniques generally achieve excellent prediction performance, particularly when large experimental datasets and highly nonlinear relationships are involved. Nevertheless, these approaches commonly require extensive computational training, optimisation of numerous model parameters and specialised expertise during model development. Moreover, the resulting predictive models often operate as black-box algorithms, making it difficult to directly interpret the influence of individual input variables on the predicted response. In contrast, MLR provides explicit mathematical equations that can be readily interpreted, statistically evaluated and independently validated using established statistical procedures. For laboratory-based geotechnical investigations involving relatively small experimental datasets, this transparency represents an important advantage because it allows the contribution and statistical significance of each independent variable to be quantitatively assessed while maintaining straightforward implementation.

2.5 Identified Research Gap

The literature shows that kaolin is a convenient reference material for geotechnical research, that lead contamination significantly alters soil properties and microstructure, and that compaction behaviour depends on both energy and moisture conditions. However, several gaps are apparent when the findings are considered together. First, while many authors have examined lead sorption and microstructural changes in clayey soils, there is limited systematic data on how the physical properties of a single kaolin source vary across a controlled range of lead nitrate concentrations in a way that is directly compatible with compaction testing (Du et al., 2015; Fan et al., 2016; Mao et al., 2022). Second, although studies on contaminated soils have reported changes in compaction behaviour, only a few have considered multiple Proctor-type compactive efforts for lead-contaminated kaolin (Karkush & Ali, 2020; Negahdar & Nikghalbpour, 2020; de Campos et al., 2020).

Third, existing correlations between physical properties and compaction parameters have been developed mainly for uncontaminated soils, and they do not explicitly account for contamination-induced changes in plasticity, specific gravity, shrinkage or pH (Bera & Ghosh, 2011; Saikia et al., 2017; Sridharan & Gurtug, 2003). The validity of these relationships for lead-contaminated kaolin has not been fully established. Finally, empirical and soft-computing models for predicting OMC and MDD have rarely been extended to include heavy metal concentration and compactive effort simultaneously, particularly for kaolin-based systems (Alavi et al., 2009; Hossein Alavi et al., 2010; Bardhan et al., 2023; Khatti & Grover, 2023; Soltani et al., 2024). This study is designed to address these gaps by generating new experimental data on physical properties and compaction behaviour of lead-contaminated kaolin under several compactive energy levels and by developing compaction behaviour model that integrates lead concentration and compactive efforts.

2.6 Summary of the Chapter

This chapter has reviewed work on kaolin clay, lead–soil interaction, compaction behaviour of fine-grained and contaminated soils, the influence of physical properties on compaction and modelling of compaction parameters. The discussion highlighted that kaolin provides a suitable baseline material, that lead contamination

can significantly modify its physical and microstructural characteristics, and that compactive effort and moisture conditions jointly shape compaction response. Studies were also reviewed that link Atterberg limits, specific gravity, shrinkage and pH with OMC and MDD, and demonstrate the potential of regression and machine-learning methods for predicting compaction parameters.

The review identified several gaps, particularly the lack of systematic data on lead-contaminated kaolin across multiple compactive efforts and the absence of models that explicitly incorporate lead concentration alongside with compactive effort. These gaps motivate the experimental and modelling work presented in the following chapters. Chapter 3 describes the materials, testing procedures and analytical methods used to generate the dataset required to address these issues.

CHAPTER 3

RESEARCH METHODOLOGY

3.0 Introduction

This chapter describes the research methodology adopted to achieve the objectives of this study. The methodology comprises material selection, specimen preparation, laboratory testing, experimental data analysis and empirical model development. Laboratory investigations were conducted to determine the physical properties and compaction behaviour of uncontaminated and lead-contaminated kaolin clay under different contamination levels and compactive efforts. The experimental programme was designed in accordance with relevant British Standards (BS) and ASTM standards to ensure consistency, repeatability and reliability of the test results.

The methodology was structured to correspond directly with the research objectives. The first objective involved determining the physical properties of kaolin subjected to different lead contamination concentrations. The second objective evaluated the compaction behaviour of contaminated kaolin using Reduced Proctor Compaction (RPC), Standard Proctor Compaction (SPC) and Modified Proctor Compaction (MPC). The third objective examined the relationships between the measured physical properties and compaction parameters through correlation analysis, while the fourth objective developed empirical Multiple Linear Regression (MLR) models for predicting optimum moisture content (OMC) and maximum dry density (MDD) using the principal experimental variables. The overall research framework and detailed experimental procedures adopted throughout this study are presented in the following sections.

3.1 Experimental Work for Physical Properties of Kaolin Clay

The first objective of this study was to determine the physical properties of kaolin clay contaminated with Lead (II) Nitrate ($Pb(NO_3)_2$) at five (5) different contamination concentrations, namely 0, 1000, 2000, 3000 and 4000 mg/L. The measured physical properties were subsequently used to evaluate the influence of lead contamination on the engineering characteristics of kaolin clay and to provide the

fundamental dataset required for subsequent compaction and modelling analyses. This section presents the overall research framework, materials employed, selection of physical property tests and the experimental procedures adopted to determine the physical properties of both uncontaminated and lead-contaminated kaolin clay.

3.1.1 Research Framework and Experimental Design

The overall research framework was developed to systematically achieve the four research objectives while ensuring that the experimental programme remained logically organised and scientifically consistent. Rather than following a purely sequential procedure, the methodology comprised two (2) complementary experimental components that were conducted independently before being integrated during the subsequent data analysis stage. The first component focused on determining the physical properties of uncontaminated and lead-contaminated kaolin clay, whereas the second component evaluated the compaction behaviour of the same material under different compactive efforts. The findings obtained from these two experimental components were subsequently integrated to establish the relationships between physical soil properties and compaction behaviour before being utilised for empirical model development. The overall research framework adopted in this study is illustrated in Figure 3.1.

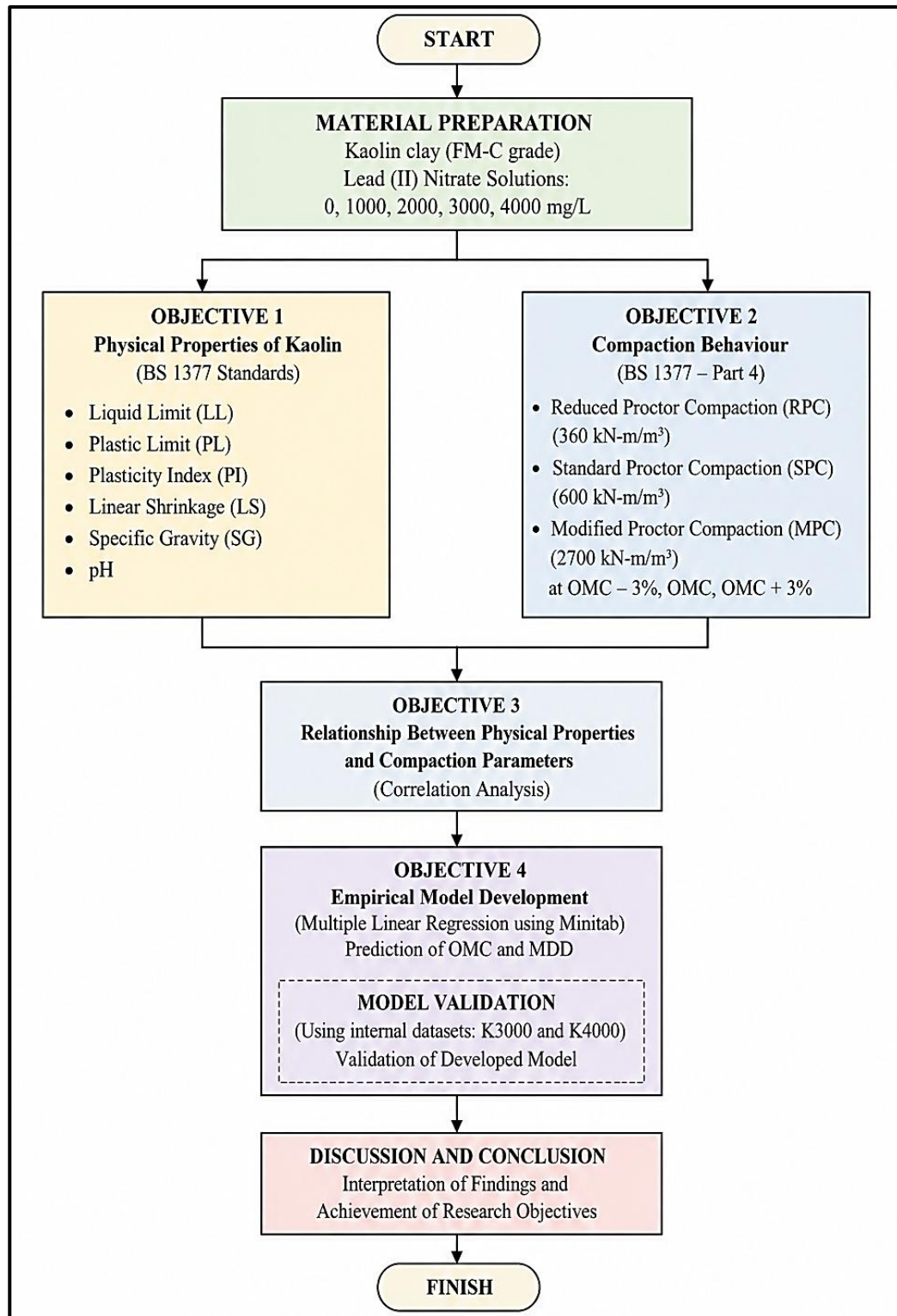


Figure 3.1 A General Framework of This Study

Figure 3.1 demonstrates that Objectives 1 and 2 were conducted independently because the determination of physical properties and compaction behaviour required different laboratory testing procedures. The outputs from these two (2) experimental components were subsequently combined in Objective 3 to evaluate the relationships between physical soil properties and compaction parameters through correlation

analysis. The resulting dataset then formed the basis for Objective 4, in which empirical Multiple Linear Regression (MLR) models were developed and internally validated prior to the interpretation of the research findings and formulation of the study conclusions.

The experimental programme considered five (5) lead contamination concentrations of 0, 1000, 2000, 3000 and 4000 mg/L using Lead (II) Nitrate ($Pb(NO_3)_2$), together with three (3) compactive efforts comprising Reduced Proctor Compaction (RPC), Standard Proctor Compaction (SPC) and Modified Proctor Compaction (MPC), representing low-, medium- and high-energy compaction conditions, respectively. These compactive efforts are consistent with established laboratory compaction standards and previous investigations on energy-dependent soil behaviour (Shaivan & Sridharan, 2020b; Lee et al., 2007). For each combination of contamination concentration and compactive effort, specimens were prepared at three (3) moisture states, OMC – 3%, OMC and OMC + 3%, thereby producing a comprehensive experimental matrix for subsequent analysis and empirical model development. The complete experimental matrix adopted in this study is presented in Table 3.1.

Table 3.1
Experimental Matrix of Contamination Levels and Compactive Efforts

	Sample	Concentration $Pb(NO_3)_2$, C (mg/L)	Compactive Effort, E	State Moisture Content
1	K0 _{RPC}	0	RPC (360 kN-m/m ³)	OMC-3%, OMC, OMC +3%
2	K0 _{SPC}	0	SPC (600 kN-m/m ³)	OMC-3%, OMC, OMC +3%
3	K0 _{MPC}	0	MPC (2700 kN-m/m ³)	OMC-3%, OMC, OMC +3%
4	K1000 _{RPC}	1000	RPC (360 kN-m/m ³)	OMC-3%, OMC, OMC +3%
5	K1000 _{SPC}	1000	SPC (600 kN-m/m ³)	OMC-3%, OMC, OMC +3%
6	K1000 _{MPC}	1000	MPC (2700 kN-m/m ³)	OMC-3%, OMC, OMC +3%
7	K2000 _{RPC}	2000	RPC (360 kN-m/m ³)	OMC-3%, OMC, OMC +3%
8	K2000 _{SPC}	2000	SPC (600 kN-m/m ³)	OMC-3%, OMC, OMC +3%
9	K2000 _{MPC}	2000	MPC (2700 kN-m/m ³)	OMC-3%, OMC, OMC +3%

10	K3000 _{RPC}	3000	RPC (360 kN-m/m ³)	OMC-3%, OMC, OMC +3%
11	K3000 _{SPC}	3000	SPC (600 kN-m/m ³)	OMC-3%, OMC, OMC +3%
12	K3000 _{MPC}	3000	MPC (2700 kN-m/m ³)	OMC-3%, OMC, OMC +3%
13	K4000 _{RPC}	4000	RPC (360 kN-m/m ³)	OMC-3%, OMC, OMC +3%
14	K4000 _{SPC}	4000	SPC (600 kN-m/m ³)	OMC-3%, OMC, OMC +3%
15	K4000 _{MPC}	4000	MPC (2700 kN-m/m ³)	OMC-3%, OMC, OMC +3%

3.1.2 Materials and Specimen Preparation

The kaolin clay used in this work was supplied as FM-C grade, with a mineralogical composition dominated by kaolinite, consisting primarily of alumina ($Al_2O_3 \approx 35\%$) and silica ($SiO_2 \approx 50\%$). Table 3.2 shows the physical properties and chemical composition obtained from Kaolin (Malaysia) Sdn. Bhd. The low activity and simple one-to-one layered structure of kaolinite, as discussed by Mao et al. (2022) and Hoo et al. (2024), makes it an ideal reference material for geotechnical studies because its behaviour is sensitive but not excessively reactive to chemical changes. Kaolin's low surface charge and high structural uniformity support-controlled examination of contaminant soil interactions, facilitating clearer attribution of observed behavioural changes to lead contamination rather than to mineralogical complexity. Figure 3.2 shows kaolin clay grade FM-C.

Table 3.2
Physical Properties and Chemical Composition of Kaolin Clay Grade FM-C Based on Supplier's Datasheet

Physical Properties (In-house Test Method)	
Moisture Content	$\leq 2.5\%$
<i>pH</i> (30% Solid)	5.0 ± 1.0
Brightness	$78.0\% \pm 3\%$
325 Mesh Residue	$\leq 0.2\%$
Average Particle Size	$3.0\mu \pm 0.5\mu$
Chemical Composition (XRF Test Method)	
Aluminium (Al_2O_3)	$35.0\% \pm 3.0\%$
Silica (SiO_2)	$50.0\% \pm 3.0\%$
Loss on Ignition @ 1025 °C	$13.0\% \pm 2.0\%$



Figure 3.2 Kaolin Clay FM-C (a) A Pallet of Kaolin Received From Supplier (b) White Kaolin Clay

Lead (II) nitrate ($Pb(NO_3)_2$) was selected as the contaminant in this study due to its high solubility and complete dissociation in water, ensuring consistent availability of Pb^{2+} ions during testing. Numerous studies have used $Pb(NO_3)_2$ to simulate lead contamination because it produces stable ionic behaviour suitable for soil–contaminant interaction research (Karkush & Ali, 2020; Fan et al., 2016). Solutions of 0, 1000, 2000, 3000, and 4000 mg/L were prepared using analytical-grade reagent $Pb(NO_3)_2$ in powdery form, dissolved in distilled water. The mass of powder reagent required in preparing the solution is calculated using equation in (3.1). This analytical reagent of $Pb(NO_3)_2$ is from R&M Chemicals with specification as shown in Table 3.3. Figure 3.3 shows the Lead (II) nitrate substance used in this study.

$$\text{Mass of } Pb(NO_3)_2 = \frac{\text{Concentration } Pb(NO_3)_2}{\text{Molecular weight Pb}} \times \text{Molecular weight } Pb(NO_3)_2 \quad (3.1)$$

Table 3.3

Properties and Specification of Lead (II) Nitrate Substance

Properties Lead (II) Nitrate	
Type of reagent	Analytical Reagent (Substance)
Formula	N_2O_6Pb
Molecular weight $Pb(NO_3)_2$	331.21 g/mol
Molecular weight Pb	207.20 g/mol
Specification:	
Assay (Complexometry)	Min. 99.5%
<i>pH</i> (5%, water)	3.0 ---- 5.0
Insoluble matter	Max. 0.005%
Chloride (<i>Cl</i>)	Max. 0.0005%
Calcium (<i>Ca</i>)	Max. 0.01%
Copper (<i>Cu</i>)	Max. 0.0005%
Iron (<i>Fe</i>)	Max. 0.0005%
Potassium (<i>K</i>)	Max. 0.002%
Sodium (<i>Na</i>)	Max. 0.002%

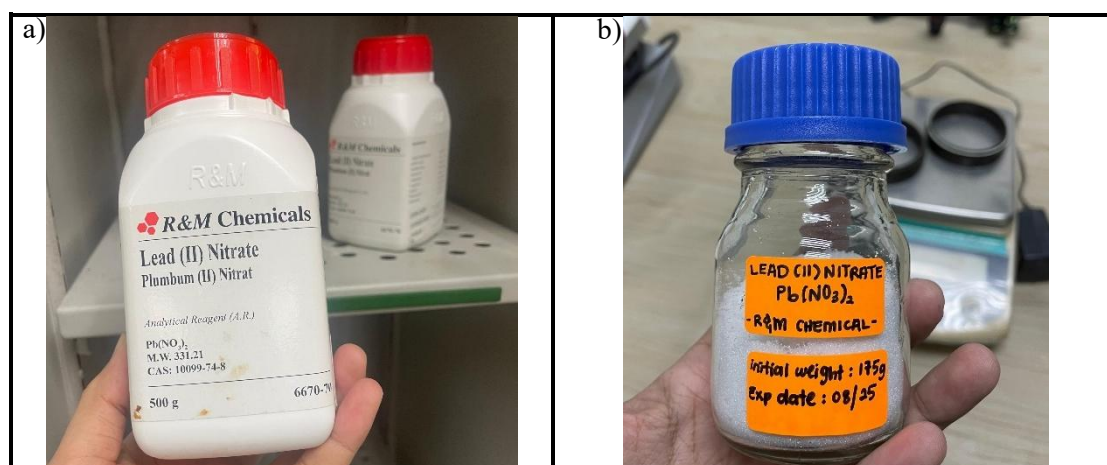


Figure 3.3 Lead (II) Nitrate Substance (a) Original Packaging Received From Supplier (b) Repacking in Small Airtight Glass Bottle for Small Amount Used

Concentration levels of lead-contaminant were chosen based on previous works that examined similar contamination ranges and their effects on soil microstructure and compaction response (Du et al., 2015; Negahdar & Nikghalbpour, 2020). Figure 3.4 shows the process in preparation for different concentration of Lead (II) Nitrate solution.



Figure 3.4 Preparation $Pb(NO_3)_2$ Solution (a) Weighted the Substance Based on Concentration (b) Dissolved the Substance Using 1000 mL Volumetric Flask (c) Stored the Solution in Glass Bottle With Proper Labelling (d) Keep the Glass Bottle in Specific Rack for Chemical Substances

Kaolin was thoroughly mixed with the appropriate lead solutions to ensure uniform moisture distribution. The mixing process followed practices recommended in earlier studies dealing with heavy-metal contaminated soils (Motlagh et al., 2025; Yazdi & Khodaparast, 2025). The soil–solution mixture was allowed to equilibrate for a duration of 24 hours before testing to ensure all the clay mineral have enough time to mix and react with lead contaminant. Figure 3.5 shows the preparation process of non-contaminated and lead-contaminated kaolin clay.



Figure 3.5 Preparation Sample (a) Weighted Kaolin Clay (b) Gradually Added Solution to the Soil (c) Mixed the Sample Until Well Mixed (d) Sealed Sample in Double Layers of Matte-Black Plastic Bag

Prepared samples were sealed in double layers of matte-black plastic bag before being store in storage box as shown in Figure 3.6 to prevent moisture loss and contamination. Storage conditions adhered to standard laboratory practices. For lead-contaminated samples, handling procedures aligned with recommendations for hazardous materials management, as outlined in the safety data sheet for $Pb(NO_3)_2$.



Figure 3.6 Sample Being Stored in Storage Box

3.1.3 Liquid Limit and Plastic Limit

Liquid Limit (LL) and Plastic Limit (PL) were determined using the cone penetration method, following BS 1377-2. This method was selected because cone-based LL values show lower operator variability and more repeatable penetration–strength relationships compared to Casagrande cup results, a point also highlighted by Hobbs et al. (2018). Figure 3.7 shows the cone penetrometer used in this study. For each contamination level, three (3) to four (4) LL points were prepared to define the penetration–water content curve, from which LL was interpolated at 20 mm penetration. The PL was determined using the rolling method, ensuring consistency with British Standard (BS) requirements.

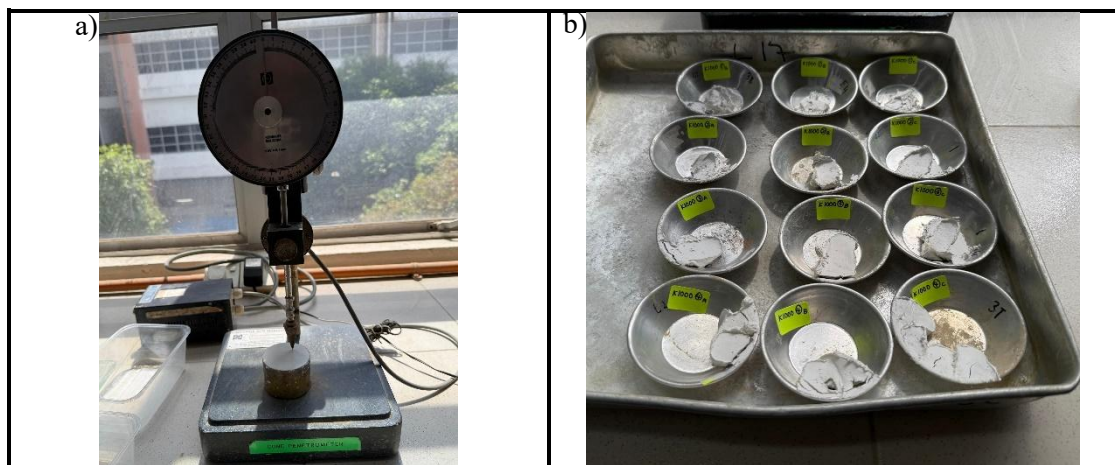


Figure 3.7 Cone Penetration Test (a) Setup Apparatus Using Cone Penetrometer (b) Sample From Each LL Points to be Oven-Dried

3.1.4 Specific Gravity Determination

The Specific Gravity (G_s) of each non-contaminated and contaminated sample was determined using a 50 mL pycnometer, following BS 1377-2 as shown in Figure 3.8. specific gravity is affected by the presence of heavy metals due to partial occupation of interparticle spaces by high-density cations (Ganesan et al., 2024; De Campos et al., 2020). Temperature corrections were applied to ensure measurement consistency.



Figure 3.8 Specific Gravity Test (a) Sample Filled in 50 mL Pycnometer (b) Pycnometer Filled With Solution Until Almost Full (c) Pycnometer Left in Desiccator to Remove Air Bubbles (d) Pycnometer Filled With Solution Until Full and the Weight Were Recorded

3.1.5 Linear Shrinkage Test

Linear Shrinkage (LS) was measured according to BS 1377-2 by filling linear shrinkage moulds with soil paste near the liquid limit and allowing them to dry under controlled laboratory conditions using oven as shown in Figure 3.9. Measuring linear shrinkage is important because shrinkage behaviour is sensitive to physicochemical changes induced by Pb^{2+} adsorption (Kamil Kayabali, 2013; Kumar & Mohini, 2020), which subsequently influences compaction response.

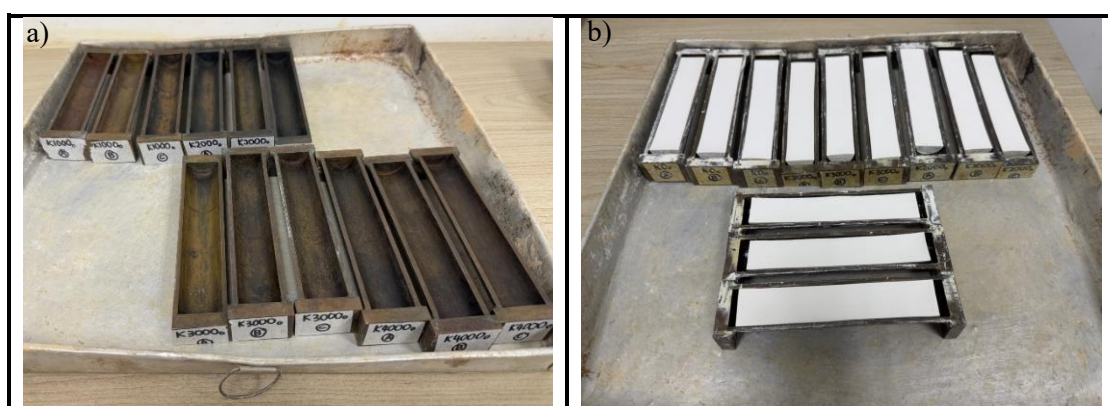


Figure 3.9 Linear Shrinkage Test (a) Linear Shrinkage Mould (b) Oven-Dried Samples of Linear Shrinkage Test

3.1.6 *pH* Measurement

Soil *pH* was determined following BS 1377-3. The soil slurry was left to stand for 24 hours before measurement, as required by the standard (minimum of 8 hours), to ensure proper equilibrium between soil particles and pore water before being test using *pH* meter. Figure 3.10 shows the *pH* test conducted for non-contaminated and contaminated samples. This step is necessary because *pH* strongly influences ion exchange behaviour and Pb^{2+} adsorption, as demonstrated in studies by Fijałkowska et al. (2021) and Zha et al. (2021).

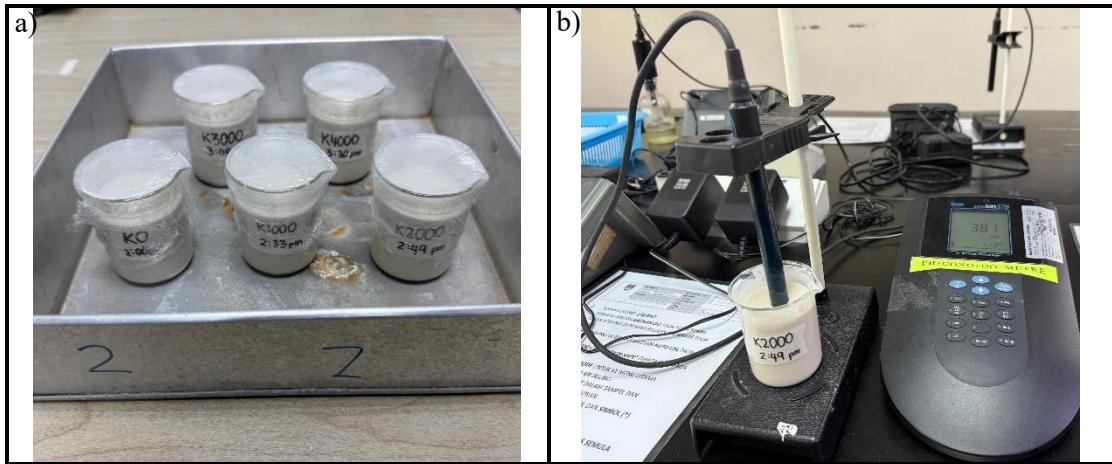


Figure 3.10 *pH* test (a) Samples Slurry Left for 24 hours (b) Tested Using *pH* Meter

3.1.7 Standards, Replicates and Data Reduction

All tests in Section 3.1 were conducted in triplicate. Mean values and standard deviations were calculated, and any reading showing abnormal deviation was retested. Physical test results will further be summarised in Chapter 4.

3.2 Compaction Behaviour Under Reduced, Standard and Modified Proctor Energies

The second objective examines how lead contamination affects the compaction response of kaolin clay under three (3) different compactive efforts, Reduced Proctor Compaction (RPC), Standard Proctor Compaction (SPC) and Modified Proctor Compaction (MPC). This section outlines the rationale for selecting these methods and describes the procedures adopted to determine the optimum moisture content (OMC) and maximum dry density (MDD) for each contamination level. The same experimental procedures were consistently repeated for all five (5) lead contamination concentrations of 0, 1000, 2000, 3000 and 4000 mg/L to ensure that any observed differences in compaction behaviour were solely attributable to variations in lead contamination rather than differences in testing methodology.

3.2.1 Selection of Compactive Efforts

The adoption of RPC, SPC and MPC energies allows examination of soil

behaviour across a practical spectrum of field compaction scenarios ranging from lightly compacted embankments to heavily compacted structural fills. The selected energies of 360 kN-m/m³ (RPC), 600 kN-m/m³ (SPC) and 2700 kN-m/m³ (MPC) reflect industry-recognised compaction efforts endorsed by ASTM D698 and ASTM D1557.

According to Shaivan and Sridharan (2020a), reduced-energy Proctor tests provide valuable insight into the sensitivity of fine-grained soils to compactive effort variations, especially for materials whose densification behaviour is strongly controlled by moisture and clay–water interaction mechanisms. Meanwhile, Lee et al. (2007) noted that differences in rammer mass and drop height can influence the orientation of clay particles, thereby modifying the achievable densification.

Using all three (3) efforts in this study provides a more complete understanding of how kaolin contaminated with Pb^{2+} responds to different compaction scenarios, enabling meaningful comparison and supporting compaction behaviour model development later in Chapter 4. Table 3.4 shows the comparison between all compactive efforts used in this research field.

Table 3.4
Comparison of RPC-SPC-MPC Based on ASTM

Test	Rammer (kg)	Falling height (m)	No. of blows	No. of layers	Compactive effort, E (kN-m/m ³)
RPC	2.5	0.305	15	3	360.0
SPC	2.5	0.305	25	3	600.0
MPC	4.5	0.457	25	5	2700.0

3.2.2 Sample Preparation and Moisture Conditioning

Before each compaction test, the soil mixtures were adjusted to several moisture contents spanning the dry and wet sides of the anticipated OMC. Moisture conditioning is critical because even small moisture gradients can significantly alter compaction outcomes, especially in clays where water acts as both a lubricant and a structural agent (Tiwari et al., 2014). The mixture was remixed thoroughly before each mould filling to reduce variability. This practice follows recommendations by Di Matteo et al. (2009), who emphasised the importance of consistent moisture conditioning for developing reliable compaction curves. Figure 3.11 shows apparatus used in conducting the Proctor compaction test.



Figure 3.11 Apparatus for Compaction Test (a) Compaction Mould (b) Rammer for RPC and SPC (c) Rammer for MPC (d) Mechanical Compaction Machine

3.2.3 Proctor Compaction Procedures

Compaction was carried out by placing soil in three (3) layers for RPC and SPC while five (5) layers for MPC and applying the appropriate number of blows per layer (15 or 25 blows). Each compacted specimen was trimmed flush with the mould to obtain an accurate volume. Part of the full procedures for Proctor compaction can be seen in Figure 3.12. The mass of the mould–soil system was measured immediately after compaction to minimise moisture loss. Using ASTM-based procedures ensures that the data can be compared directly with findings reported by previous research on contaminated or chemically modified clays (e.g., Zheng et al., 2019; Hoo et al., 2024). The identical compaction procedure was repeated for each lead contamination concentration and compactive effort throughout the experimental programme to ensure consistency and comparability of the results.



Figure 3.12 Procedures of Compaction Test (a) Measured Diameter of the Compaction Mould (b) Measured Height of the Compaction Mould (c) Weighted Compaction Mould With Base (d) Samples for Each Repeated Test of Compaction

3.2.4 Determination of OMC and MDD

Dry density values were calculated using the measured bulk density and corresponding water content obtained after oven drying. The moisture–density relationship for each contamination level and compactive effort was plotted to determine the OMC and MDD. The compaction curves were fitted using smooth and best-fit functions to minimise experimental scatter which is a practice widely adopted in studies modelling Proctor behaviour (Di Matteo et al., 2009; Günaydın, 2008). The resulting OMC–MDD points form the foundational dataset for Objectives 3 and 4.

3.2.5 Post-Compaction Measurements

The water content of each compacted specimen was subsequently determined using oven drying at 105°C. Figure 3.13 shows some post-compaction procedures. This step verifies the accuracy of moisture conditioning and mitigates deviation in reported dry density. Any specimen showing unexpected moisture deviation was retested to maintain dataset reliability.



Figure 3.13 Post-Compaction Procedures (a) Oven-Dried Samples for 24 hours at 105°C (b) Recorded the Weight of Dried Samples

3.2.6 Summary of Compaction Data Structure

All final OMC and MDD values were tabulated for each combination of contamination level and compactive effort. Dry density vs moisture content curves were plotted for all conditions. These curves allow direct observation of shifts in compaction behaviour caused by lead contamination. For example, several studies have shown that Pb^{2+} can compress the diffuse double layer, modify particle arrangement and thereby affect the densification response (Du et al., 2015; Fan et al., 2016). These structured datasets form the basis for subsequent analysis and regression modelling.

3.3 Correlations Analysis Between Physical Properties and Compaction Response

This objective focuses on identifying how physical properties of contaminated kaolin relate to its compaction behaviour. The analysis is intentionally carried out relying on Excel-based graphical interpretation to preserve transparency and reduce overfitting.

3.3.1 Comparative Behaviour Across Energies and Pb Concentrations

Comparisons will be made between K0 and contaminated specimens at the same compactive effort, as well as across energies for the same contamination level. This dual comparison helps distinguish whether observed trends stem primarily from contamination or from compactive effort. Previous works, such as Negahdar and Nikghalbpour (2020), demonstrated that heavy metals influence densification behaviour differently depending on input energy.

3.3.2 Development of Variables for Correlation

To identify meaningful trends, complete datasets of LL, PL, Plasticity Index (PI), Gs, LS, *pH*, Pb concentration, OMC and MDD were compiled. These variables were selected based on their physicochemical relevance and established influence on soil moisture sensitivity and densification potential (Saikia et al., 2017; Ganesan et al., 2024).

3.3.3 Correlation Tools and Graph Types

Analytical focus was on visual and statistical relationships. The following graph types will be included in Chapter 4:

- **Scatter Plots:** For relationships such as: OMC vs LL, MDD vs LL, OMC vs PI, MDD vs PI, MDD vs Gs, OMC vs LS, OMC vs *pH*-value, MDD vs *pH*-value, Normalised OMC vs *Pb* concentration, and Normalised MDD vs *Pb* concentration. These graphs reveal directionality and strength of correlations.

- **Grouped Scatter Plots:** Overlaying RPC, SPC and MPC trends to observe energy-sensitive correlations.

If any trendline shows low correlation, this will also be discussed openly, as identifying weak relationships helps refine model development. Irregular points are cross-checked against original laboratory logs. Only confirmed anomalies are excluded, ensuring that the compaction behaviour model in Chapter 4 is based on reliable data.

3.4 Empirical Model Development for Predicting OMC and MDD

This section describes the systematic modelling framework adopted to develop empirical predictive equations for optimum moisture content and maximum dry density of lead-contaminated kaolin clay subjected to different compactive efforts. The modelling approach integrates theoretical understanding of compaction behaviour with multiple regression analysis and independent validation to ensure both statistical robustness and engineering interpretability.

3.4.1 Model Concept and Theoretical Basis

The development of the compaction behaviour model was grounded in the fundamental principle that moisture–density behaviour is governed by the interaction between soil contamination level, and applied compactive energy. In compacted fine-grained soils, OMC reflects the moisture condition required to achieve maximum particle rearrangement, whereas MDD represents the resulting packing efficiency under a given compactive effort. The introduction of Lead (II) Nitrate modifies the physicochemical environment of the clay matrix, potentially influencing double-layer thickness, interparticle forces, and water affinity.

Previous modelling studies by Alavi et al. (2009) and Hossein Alavi et al. (2010) demonstrated that compaction characteristics can be reasonably predicted using soil index properties and additive content. Consistent with these findings, the present study hypothesises that OMC and MDD can be expressed as functions of lead concentration and compactive effort within the investigated range. In general form, the multiple linear regression model adopted in this study can be expressed as in (3.2).

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon \quad (3.2)$$

Where Y represents the response variable (OMC or MDD), X_i denotes the predictor variables, β_i are regression coefficients, and ε is the random error term. This formulation allows quantitative evaluation of the relative contribution of each governing parameter while maintaining physical interpretability.

3.4.2 Data Preparation and Partitioning Strategy

A consolidated dataset was developed comprising all contamination levels (K0–K4000), compactive efforts (RPC, SPC, MPC), and moisture states (OMC–3%, OMC, OMC+3%). However, to ensure rigorous model evaluation, a two-stage modelling design was implemented. The partitioning strategy adopted for model development and validation is summarised in Table 3.5. The dataset was divided according to contamination level to ensure that independent data were available for model validation while maintaining sufficient observations for model calibration. Accordingly, 27 datasets were used for regression model development, whereas the remaining 18 datasets were reserved exclusively for independent model validation.

Table 3.5
Dataset Partitioning Adopted for Empirical Model Development

Purpose	Contamination Level	Compactive Effort	Moisture State	Total Dataset
Model development (Training)	K0, K1000, K2000	RPC, SPC, MPC	OMC – 3%, OMC, OMC + 3%	27
Model validation	K3000, K4000	RPC, SPC, MPC	OMC – 3%, OMC, OMC + 3%	18
Overall dataset	K0–K4000	RPC, SPC, MPC	OMC – 3%, OMC, OMC + 3%	45

Data corresponding to K0, K1000, and K2000 were used for model development as training dataset, while K3000 and K4000 were reserved as sensitive validation data. The calibration dataset comprised contamination levels ranging from 0 to 2000 mg/L, whereas the higher contamination levels of 3000 and 4000 mg/L were reserved for

independent validation. This partitioning strategy was intentionally adopted to evaluate the capability of the developed models to predict compaction behaviour beyond the calibration range using unseen datasets. Since the highest contamination levels represent more severe contamination conditions, they provide a more rigorous assessment of model robustness than random partitioning of the experimental data.

This partitioning strategy ensures that model performance was not evaluated using data involved in coefficient estimation, thereby reducing overfitting risk and strengthening predictive credibility. To enhance numerical stability while preserving interpretability, lead concentration and compactive effort were scaled as in (3.3) and (3.4).

$$C_{\text{scaled}} = \frac{C}{1000} \quad (3.3)$$

$$E_{\text{scaled}} = \frac{E}{1000} \quad (3.4)$$

Where C is lead concentration (mg/L) and E is compactive energy (kN-m/m³). No further transformations were applied in order to maintain physical meaning of regression coefficients. The overall modelling and validation workflow adopted in this study is illustrated in Figure 3.14. The workflow summarises the complete procedure implemented for empirical model development, beginning with the preparation and partitioning of the experimental dataset, followed by variable scaling, exploratory analysis, MLR model development, statistical evaluation, independent model validation and the formulation of the final empirical models. This workflow was developed for the present study to ensure that the empirical model development procedure remained systematic, statistically robust and consistent with the research objectives.

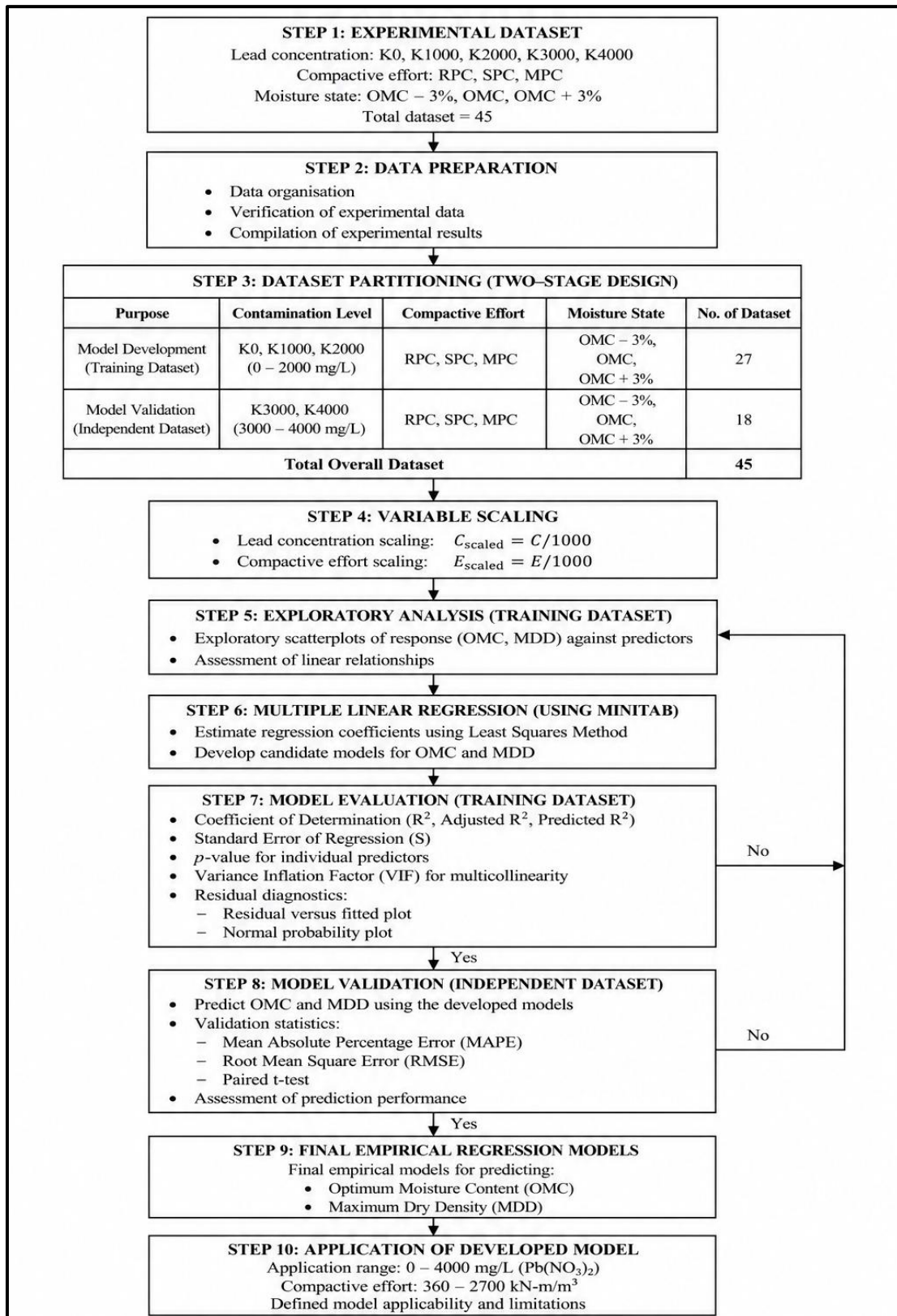


Figure 3.14 Proposed Modelling and Validation Workflow for Model Development Adopted in This Study

3.4.3 Regression Modelling in Minitab

Multiple regression analysis was performed using Minitab to quantify the influence of contamination level and compactive effort on OMC and MDD. Model development followed a structured procedure involving first, initial exploratory scatterplot analysis to examine linear trends. Second, estimation of regression coefficients using the least squares method. Third, evaluation of statistical adequacy using coefficient of determination (R^2), adjusted R^2 , predicted R^2 , standard error of regression (S), p-values of individual predictors, Variance Inflation Factor (VIF), and residual diagnostic plots. The coefficient of determination is defined as in (3.5).

$$R^2 = 1 - \frac{\sum(Y_i - \hat{Y}_i)^2}{\sum(Y_i - \bar{Y})^2} \quad (3.5)$$

Where Y_i is the measured value, $\hat{Y}_i$ is the predicted value, and $\bar{Y}$ is the sample mean. Model refinement was conducted only when statistically necessary, ensuring that physically meaningful predictors were retained even if marginally insignificant, in accordance with applied engineering modelling principles.

3.4.4 Model Validation Using Sensitive Dataset

Independent model validation was conducted using K3000 and K4000 data, which were excluded during model calibration. The predictive accuracy of the developed models was assessed using Mean Absolute Percentage Error (MAPE) in (3.6), Root Mean Square Error (RMSE) in (3.7), and paired t-test to evaluate systematic bias. The null hypothesis for validation is in (3.8).

$$MAPE = \frac{1}{n} \sum \left| \frac{Y_i - \hat{Y}_i}{Y_i} \right| \times 100 \quad (3.6)$$

$$RMSE = \sqrt{\frac{1}{n} \sum (Y_i - \hat{Y}_i)^2} \quad (3.7)$$

$$H_0: \mu_{\text{difference}} = 0 \quad (3.8)$$

Where $\mu_{\text{difference}}$ represents the population mean difference between measured and predicted values. This validation framework ensures that the compaction behaviour models demonstrate not only high explanatory power but also stable extrapolation behaviour beyond the calibration range.

3.4.5 Presentation of Final Model and Application Scope

The final empirical equations derived from regression analysis will be presented in explicit mathematical form in Chapter 4. These equations are applicable to kaolin clay with similar mineralogical characteristics and within the tested contamination range of 0–4000 mg/L and compactive energies of 360–2700 kN-m/m³. It is acknowledged that model applicability may be limited by variations in clay mineralogy, ion valency effects, or boundary conditions not investigated in this study.

3.5 Quality Assurance, Calibration and Error Control

To ensure reliability of experimental data used for modelling, all instruments were calibrated in accordance with relevant BS and ASTM standards. The cone penetration apparatus was verified prior to Atterberg limit testing, pycnometer calibration was conducted using distilled water, and rammer mass and drop height were checked before compaction testing.

Lead–soil mixtures were prepared under controlled laboratory conditions with consistent mixing procedures to minimise variability in moisture distribution. Replicate testing was performed to reduce experimental uncertainty. Environmental factors such as room humidity and temperature were monitored to prevent systematic bias. These quality control measures enhance confidence in the dataset used for regression modelling.

3.6 Summary of the Chapter

This chapter has presented the methodological framework adopted to investigate the physical and compaction behaviour of lead-contaminated kaolin clay and to develop models predicting OMC and MDD. A two-stage modelling strategy incorporating calibration and independent model validation were established to ensure predictive reliability. The used of multiple regression analysis, combined with statistical performance metrics and rigorous quality control, ensures that the resulting models were both statistically robust and physically interpretable. The following chapter presents and discusses the experimental results and model development outcomes.

CHAPTER 4

RESULTS AND DISCUSSION

4.0 Introduction

This chapter presents and discusses the experimental results obtained from the laboratory programme described in Chapter 3. The findings are organised according to the research objectives to provide a systematic interpretation of the effects of lead (Pb^{2+}) contamination and compactive effort on the engineering behaviour of kaolin clay. The chapter begins with the evaluation of the physical properties of uncontaminated and lead-contaminated kaolin, followed by the analysis of compaction characteristics under Reduced Proctor Compaction (RPC), Standard Proctor Compaction (SPC), and Modified Proctor Compaction (MPC). Subsequently, the relationships between contamination level, compactive effort, and moisture condition are examined to establish the mechanisms governing compaction behaviour. Finally, empirical multiple linear regression (MLR) models for predicting optimum moisture content (OMC) and maximum dry density (MDD) are developed and validated based on the experimental results.

4.1 Physical Properties of Uncontaminated and Lead-Contaminated Kaolin

Section 4.1 presents the physical properties of uncontaminated and lead-contaminated kaolin obtained from laboratory testing. The physical properties were determined for five Pb^{2+} contamination concentrations, namely 0, 1000, 2000, 3000, and 4000 mg/L, to evaluate the influence of lead contamination on the fundamental characteristics of the soil. Since these properties are inherent to the soil–contaminant system, they remain unchanged regardless of the compactive effort or moisture condition adopted during the subsequent compaction tests. The measured physical properties provide the basis for interpreting the compaction behaviour and model development presented in the following sections.

4.1.1 Liquid Limit and Plastic Limit

The liquid limit (LL) of the uncontaminated kaolin is 71%, while the plastic limit (PL) is 38%, resulting in a plasticity index (PI) of 33%. These values classify the soil as a high-plasticity clay and are consistent with kaolinite-rich materials reported in earlier studies (Hobbs et al., 2018; Zaini et al., 2024). With the introduction of lead contamination, the LL increases to 75% at 1000 mg/L and reaches a maximum value of 84% at 2000 mg/L before decreasing slightly to 78% at 3000 mg/L and 74% at 4000 mg/L, as summarised in Table 4.1.

Table 4.1
Atterberg Limits of Uncontaminated and Contaminated Kaolin Clay

Sample	LL (%)	PL (%)	PI (%)
K0	71	38	33
K1000	75	37	38
K2000	84	42	42
K3000	78	39	39
K4000	74	39	35

A similar trend is observed for the PL, which increases from 38% in the uncontaminated state to 42% at 2000 mg/L and subsequently stabilises at 39% for both 3000 and 4000 mg/L. As a consequence, the PI increases from 33% to a peak value of 42% at 2000 mg/L before decreasing to 35% at 4000 mg/L. Figure 4.1 further illustrates that both LL and PL exhibit a similar non-linear trend with increasing Pb^{2+} concentration, with the highest values occurring at 2000 mg/L.

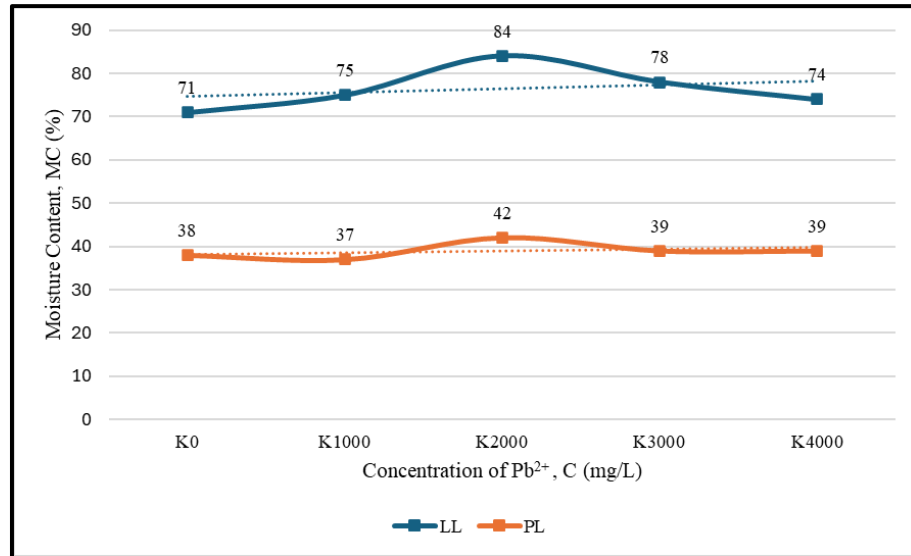


Figure 4.1 Liquid Limit and Plastic Limit vs Concentration of Pb^{2+}

This non-linear variation suggests that moderate Pb^{2+} concentrations initially enhance water adsorption and interparticle interactions, leading to higher consistency limits. At higher contamination levels, however, structural rearrangement and possible precipitation or flocculation processes may reduce the effective thickness of the diffuse double layer, resulting in a reduction in LL and PI. Similar behaviour which characterised by an initial increase in plasticity followed by stabilisation or a slight decline at higher heavy-metal concentrations, has been reported for bentonite and sand–clay mixtures contaminated with lead and other metals (Muththalib & Baudet, 2019; Negahdar & Nikghalbpour, 2020; Saeid Nikkhah Nasab & Abdeh Keykha, 2020).

4.1.2 Specific Gravity and Linear Shrinkage

The specific gravity of the uncontaminated kaolin is 2.50 and increases to 2.57 at 1000 mg/L and 2.56 at 2000 mg/L before declining slightly to 2.55 and 2.51 at 3000 and 4000 mg/L, respectively, as shown in Table 4.2. The initial increase in G_s is consistent with partial occupation of pore spaces and clay particle surfaces by relatively dense Pb^{2+} ions, a phenomenon that has also been observed in other studies on heavy-metal-contaminated clays and sands (De Campos et al., 2020; Ganesan et al., 2024; Hassanlourad et al., 2024). The subsequent reduction at higher concentrations may be attributed to microstructural rearrangement and increased internal voids caused by particle aggregation.

Linear shrinkage exhibits a trend similar to that of plasticity. LS increases from

7.69% in the uncontaminated soil to 8.26% at 1000 mg/L and reaches a maximum of 8.85% at 2000 mg/L before decreasing to 8.47% at 3000 mg/L and 7.98% at 4000 mg/L. This behaviour, presented in Table 4.2 and the corresponding variation of G_s and LS with Pb^{2+} concentration is illustrated in Figure 4.2, which shows that both parameters follow a similar trend, increasing at low to moderate contamination levels before decreasing at higher concentrations. That indicates shrinkage potential is closely linked to plasticity changes induced by lead contamination. The increase in LS up to 2000 mg/L reflects greater volumetric sensitivity to moisture loss, which is characteristic of soils with higher plasticity indices (Kamil Kayabali, 2013; Hobbs et al., 2018; Prasanna et al., 2021). The reduction in LS at the highest contamination level again suggests the development of a more aggregated soil fabric with reduced effective shrinkage.

Table 4.2
Specific Gravity and Linear Shrinkage of Kaolin Clay at Various Lead-Contamination

Sample	G_s	LS (%)
K0	2.50	7.69
K1000	2.57	8.26
K2000	2.56	8.85
K3000	2.55	8.47
K4000	2.51	7.98

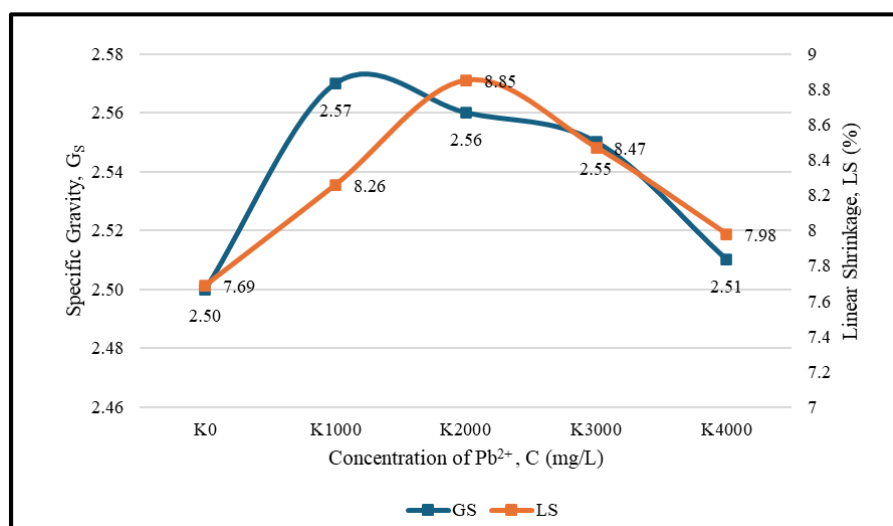


Figure 4.2 Specific Gravity and Linear Shrinkage vs Concentration of Pb^{2+}

4.1.3 *pH* Evolution with Lead Concentration

The *pH* value of the uncontaminated kaolin slurry is 5.43, indicating a slightly acidic condition that is typical of kaolin-based soils (Das & Bharat, 2021; Mohd Nazer & Charles, 2022). Upon the introduction of lead nitrate, the *pH* decreases sharply to approximately 3.8–3.9 for all contaminated samples, with a slight further decline as Pb^{2+} concentration increases from 1000 to 4000 mg/L, as summarised in Table 4.3. The overall reduction of about 1.6 pH units reflects the acidic nature of nitrate-based lead solutions and is consistent with reported behaviour for $Pb(NO_3)_2$ -contaminated clays (Karkush & Ali, 2020; Fijałkowska et al., 2021; Zha et al., 2021). Figure 4.3 shows that the pH decreases markedly following lead contamination before remaining relatively stable between 1000 and 4000 mg/L.

Table 4.3
pH-value of Non-contaminated and Contaminated Kaolin Clay

Sample	<i>pH</i> -value
K0	5.43
K1000	3.83
K2000	3.82
K3000	3.81
K4000	3.79

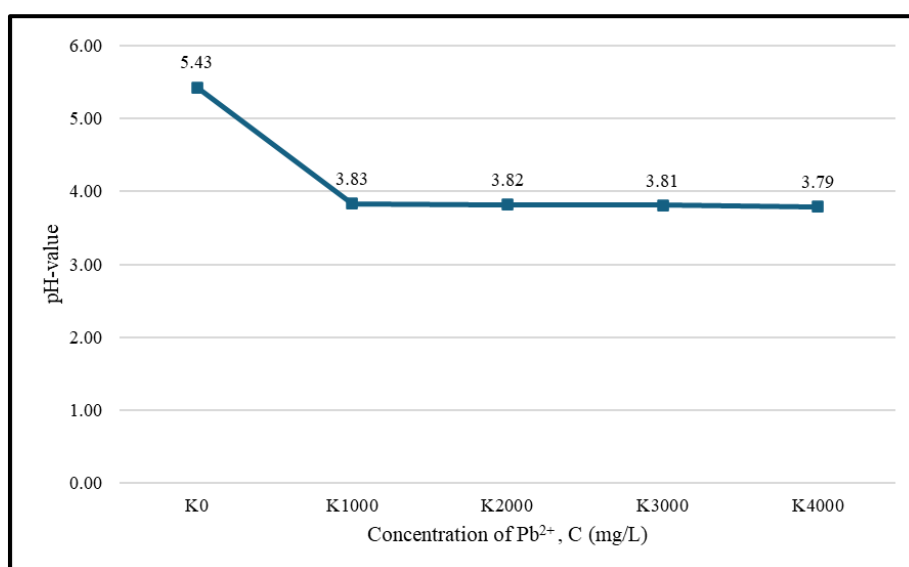


Figure 4.3 *pH*-value vs Concentration of Pb^{2+}

This pronounced acidification enhances the potential for cation exchange, dissolution processes, and reorganisation of surface complexes within the clay matrix. Several studies have demonstrated that pH plays a critical role in controlling Pb^{2+} sorption behaviour, flocculation tendencies, and clay microfabric, which is consistent with the coupled changes in plasticity and shrinkage observed in this study (Mao et al., 2022; Zhang et al., 2024; Yazdi & Khodaparast, 2025).

4.1.4 Summary of Physical Behaviour

Overall, the physical properties indicate that lead contamination initially increases water affinity, plasticity, and shrinkage potential, with maximum effects observed at approximately 2000 mg/L, followed by a modest decline at 4000 mg/L. This behaviour is consistent with a transition from enhanced diffuse double-layer interactions at low to moderate contamination levels to a more aggregated and flocculated soil structure at higher concentrations (Du et al., 2015; Li et al., 2015; Muththalib & Baudet, 2019). The observed variations in LL, PL, PI, G_s, LS, and pH collectively demonstrate that Pb^{2+} contamination alters the physicochemical characteristics of kaolin, which subsequently influence its compaction behaviour. These findings provide the foundation for interpreting the variations in OMC and MDD discussed in the following sections. These trends summarised in Table 4.4.

Table 4.4
Physical Properties of Kaolin Clay at Different Lead-Contamination

Sample	LL (%)	PL (%)	PI (%)	G _s	LS (%)	pH -value
K0	71	38	33	2.50	7.69	5.43
K1000	75	37	38	2.57	8.26	3.83
K2000	84	42	42	2.56	8.85	3.82
K3000	78	39	39	2.55	8.47	3.81
K4000	74	39	35	2.51	7.98	3.79

4.2 Compaction Behaviour Under Reduced, Standard and Modified Proctor Energies

This section discusses the compaction behaviour of kaolin–lead mixtures subjected to three (3) compactive efforts, namely Reduced Proctor Compaction (RPC, $360 \text{ kN}\cdot\text{m}/\text{m}^3$), Standard Proctor Compaction (SPC, $600 \text{ kN}\cdot\text{m}/\text{m}^3$), and Modified Proctor Compaction (MPC, $2700 \text{ kN}\cdot\text{m}/\text{m}^3$). The behaviour is evaluated at three (3) moisture states of OMC–3%, OMC, and OMC+3%. The OMC values reported for each contamination level and compactive effort correspond to the moisture contents at which the MDD was obtained from the respective Proctor compaction curves. The OMC–3% and OMC+3% conditions represent dry-of-optimum and wet-of-optimum states respectively and are included to characterise the complete moisture–density relationship of lead-contaminated kaolin across different contamination levels and compactive efforts.

4.2.1 Effect of Compactive Effort on OMC and MDD

Across all lead-contamination levels, an increase in compactive effort results in a systematic reduction in optimum moisture content and a corresponding increase in maximum dry density. Focusing on the optimum condition, the OMC decreases by approximately 3.5–3.6% points when the compactive effort increases from RPC to MPC, while the MDD increases by about $0.12 \text{ Mg}/\text{m}^3$, equivalent to an increase of roughly 8–9% in dry density.

A detailed observation of the compaction results shows that, at RPC ($360 \text{ kN}\cdot\text{m}/\text{m}^3$), the kaolin mixtures require the highest moisture contents to reach optimum compaction. The OMC values at this energy level range from approximately 29.47% for the uncontaminated soil (K0) to about 29.86% for the highest contamination level (K4000). This indicates that relatively higher moisture is required to facilitate particle lubrication and rearrangement when the applied compactive energy is low. When the compactive effort increases to SPC ($600 \text{ kN}\cdot\text{m}/\text{m}^3$), a noticeable reduction in OMC occurs for all contamination levels. For instance, the OMC for K0 decreases from 29.47% to 28.46%, while the OMC for K4000 decreases from 29.86% to approximately 28.96%. The decline in OMC at this stage indicates that the increased compactive

energy assists in achieving closer particle packing with reduced dependence on moisture for lubrication.

A further increase in compactive effort to MPC ($2700 \text{ kN}\cdot\text{m}/\text{m}^3$) produces the lowest optimum moisture contents for all mixtures. Under this high energy level, the OMC for K0 decreases further to 25.93%, while the OMC for K4000 decreases to 26.28%. The consistent downward slope of the graph in Figure 4.4 therefore illustrates that higher compactive energies allow the soil particles to be rearranged more effectively with less water required to facilitate compaction.

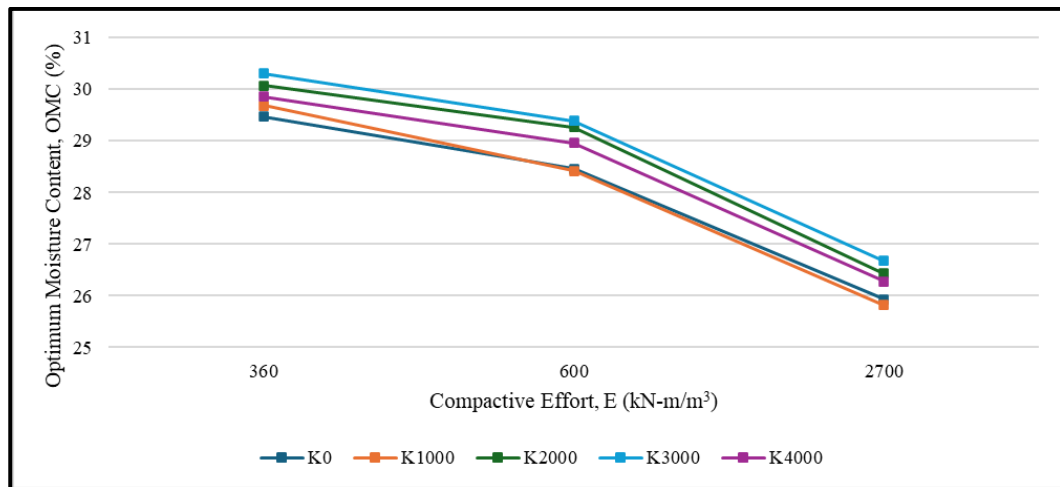


Figure 4.4 Effect of Compactive Efforts for Each Concentration on OMC

In contrast to the decreasing OMC trend, the maximum dry density increases with increasing compactive effort, as illustrated in Figure 4.5. At RPC, the MDD values range between approximately $1.352 \text{ Mg}/\text{m}^3$ and $1.367 \text{ Mg}/\text{m}^3$, depending on the contamination level. When the compactive effort increases to SPC, the MDD values increase to around $1.383\text{--}1.398 \text{ Mg}/\text{m}^3$, reflecting improved particle packing due to the higher compactive energy. The highest dry densities are obtained under MPC, where MDD values reach approximately $1.474 \text{ Mg}/\text{m}^3$ for K0 and $1.485 \text{ Mg}/\text{m}^3$ for K4000. The upward trend observed in the curves therefore demonstrates that higher compactive energy compresses the soil structure more effectively, resulting in greater dry density.

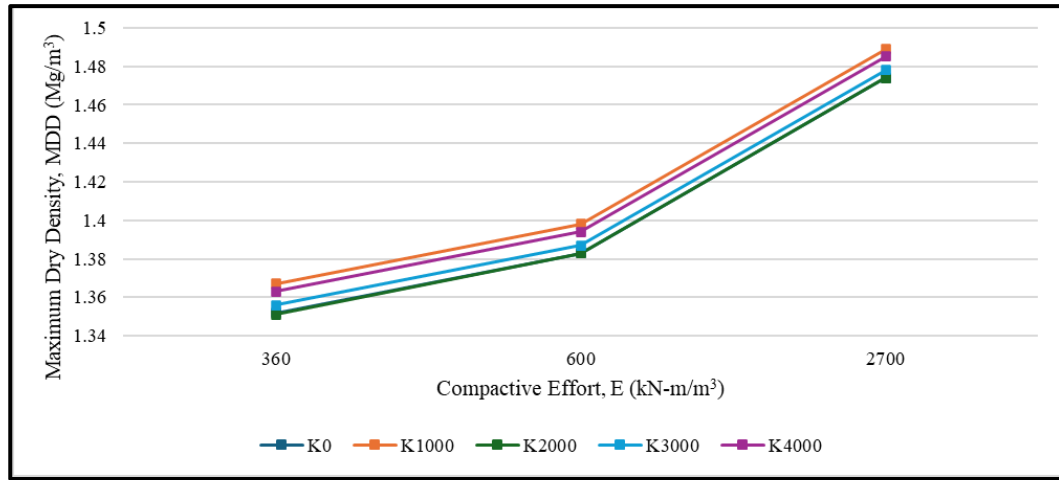


Figure 4.5 Effect of Compactive Efforts for Each Concentration on MDD

The observed reduction in OMC and corresponding increase in MDD with increasing compactive effort demonstrate that compactive energy is the dominant factor governing the densification behaviour of lead-contaminated kaolin. As the applied energy increases from RPC (360 kN·m/m³) to MPC (2700 kN·m/m³), greater impact forces enable soil particles to overcome interparticle friction more effectively, producing a denser particle arrangement while requiring less water to facilitate particle lubrication. Consequently, higher dry densities are achieved at progressively lower optimum moisture contents. Similar trends were reported by Mohd Yusoff et al. (2017), who observed that increasing compactive effort consistently reduced OMC while increasing MDD for compacted fine-grained soils. Likewise, Shaivan and Sridharan (2020a, 2020b) demonstrated that the moisture–density relationship remains fundamentally governed by compactive effort despite changes in soil type and compaction energy. The present findings therefore indicate that although lead contamination modifies the absolute values of OMC and MDD, it does not alter the fundamental influence of compactive effort on the compaction mechanism.

4.2.2 Influence of Moisture State (OMC–3%, OMC, OMC+3%)

At each compactive effort and contamination level, the maximum dry density consistently occurs at the optimum moisture content, with slightly lower dry densities recorded at OMC–3% and OMC+3%. For instance, under SPC at a Pb^{2+} concentration of 2000 mg/L, the dry density increases from 1.371 Mg/m³ at OMC–3% to 1.383 Mg/m³ at OMC, before decreasing to 1.369 Mg/m³ at OMC+3%. Similar behaviour is observed across RPC and MPC conditions, as summarised in Table 4.5.

Table 4.5

Moisture Content and Dry Density for RPC, SPC and MPC at Different Moisture State in Compaction

	Moisture state	K0	K1000	K2000	K3000	K4000
RPC	OMC -3% - MC (%)	26.47	26.68	27.07	27.31	26.86
	DD (Mg/m ³)	1.343	1.348	1.340	1.331	1.342
	OMC - MC (%)	29.47	29.68	30.07	30.31	29.86
	DD (Mg/m ³)	1.352	1.367	1.351	1.356	1.363
	OMC +3% - MC (%)	32.47	32.68	33.07	33.31	32.86
	DD (Mg/m ³)	1.344	1.349	1.338	1.337	1.349
SPC	OMC -3% - MC (%)	25.46	25.42	26.27	26.39	25.96
	DD (Mg/m ³)	1.373	1.376	1.371	1.373	1.368
	OMC - MC (%)	28.46	28.42	29.27	29.39	28.96
	DD (Mg/m ³)	1.383	1.398	1.383	1.387	1.394
	OMC +3% - MC (%)	31.46	31.42	32.27	32.39	31.96
	DD (Mg/m ³)	1.374	1.379	1.369	1.367	1.380
MPC	OMC -3% - MC (%)	22.93	22.82	23.43	23.68	23.28
	DD (Mg/m ³)	1.466	1.471	1.460	1.463	1.467
	OMC - MC (%)	25.93	25.82	26.43	26.68	26.28
	DD (Mg/m ³)	1.474	1.489	1.474	1.478	1.485
	OMC +3% - MC (%)	28.93	28.82	29.43	29.68	29.28
	DD (Mg/m ³)	1.465	1.473	1.459	1.457	1.470

The reduction in dry density observed on both sides of the optimum moisture condition reflects the fundamental mechanism governing soil compaction. At the dry-of-optimum condition (OMC–3%), insufficient water is available to lubricate the clay particles, resulting in relatively high interparticle friction that restricts particle rearrangement during compaction. Consequently, larger air voids remain within the compacted soil, producing lower dry density values. Conversely, at the wet-of-optimum condition (OMC+3%), excess pore water begins to occupy part of the soil volume and prevents further densification because water is substantially less compressible than air under the applied compactive effort. Although additional moisture reduces particle friction, it simultaneously increases the volume occupied by pore water, thereby reducing the achievable dry density. Similar moisture-dependent compaction behaviour has been consistently reported by Sridharan and Gurtug (2003), Di Matteo et al. (2009) and Prasanna et al. (2021), confirming that the optimum moisture content represents the condition at which lubrication is sufficient to maximise particle rearrangement without excessive pore-water interference.

First, under RPC conditions as shown in Figure 4.6, the compaction curves show relatively broad peaks occurring within the moisture range of approximately 29–30%, depending on the contamination level. The curves exhibit a typical bell-shaped pattern, where dry density increases gradually as moisture content approaches the optimum point and decreases after exceeding the optimum moisture content. The lower compactive energy associated with RPC results in relatively flatter compaction curves, indicating that moisture plays a greater role in facilitating particle rearrangement. As a result, the differences between dry-of-optimum and wet-of-optimum densities are relatively small, and higher moisture contents are required to achieve effective particle lubrication and compaction.

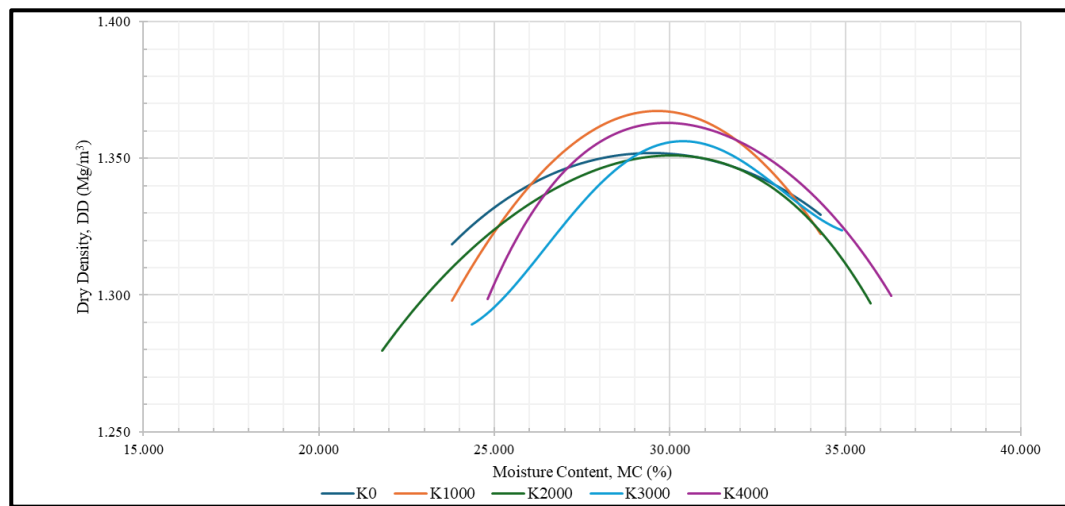


Figure 4.6 Compaction Curve for RPC

Next, under Standard Proctor Compaction (SPC) conditions, the compaction curves become slightly steeper and more clearly defined compared with RPC as illustrated in Figure 4.7. The peak dry densities occur at moisture contents around 28–29%, reflecting the reduction in optimum moisture content associated with higher compactive effort. The steeper shape of the curves indicates that soil particles are compacted more efficiently under SPC, resulting in a more pronounced difference between densities obtained at dry-of-optimum and wet-of-optimum conditions. This behaviour demonstrates that increasing compactive energy enhances particle packing and reduces the dependence on moisture for achieving maximum dry density.

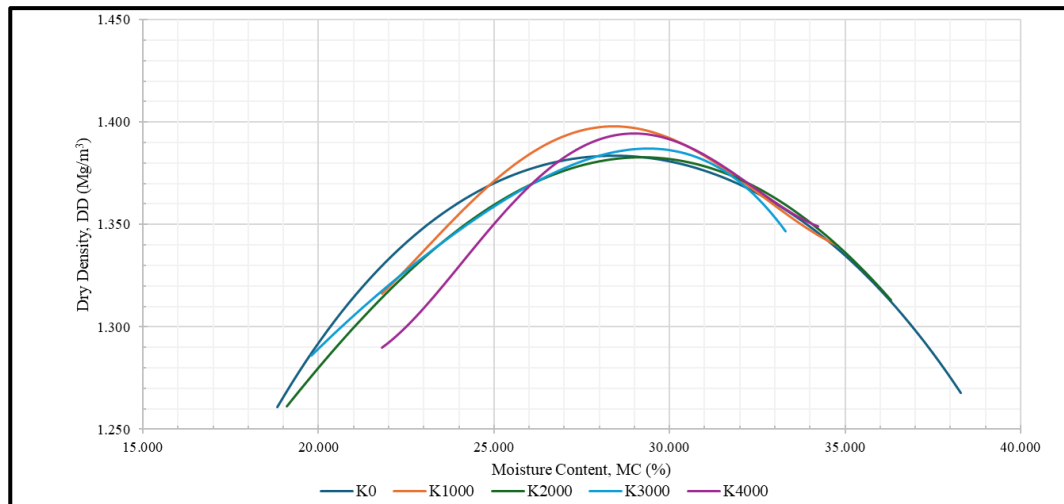


Figure 4.7 Compaction Curve for SPC

While under Modified Proctor Compaction (MPC) conditions, the compaction curves exhibit the highest peak densities and the lowest optimum moisture contents among all compactive efforts as in Figure 4.8. The optimum moisture contents are generally located within the range of 25–27%, while the peak dry densities approach 1.47–1.49 Mg/m^3 . The curves also appear narrower and steeper, indicating that soil densification becomes increasingly sensitive to moisture variation at high compactive energy levels. At this stage, the higher compactive effort allows soil particles to be compressed into a denser structure, resulting in greater dry densities even at lower moisture contents.

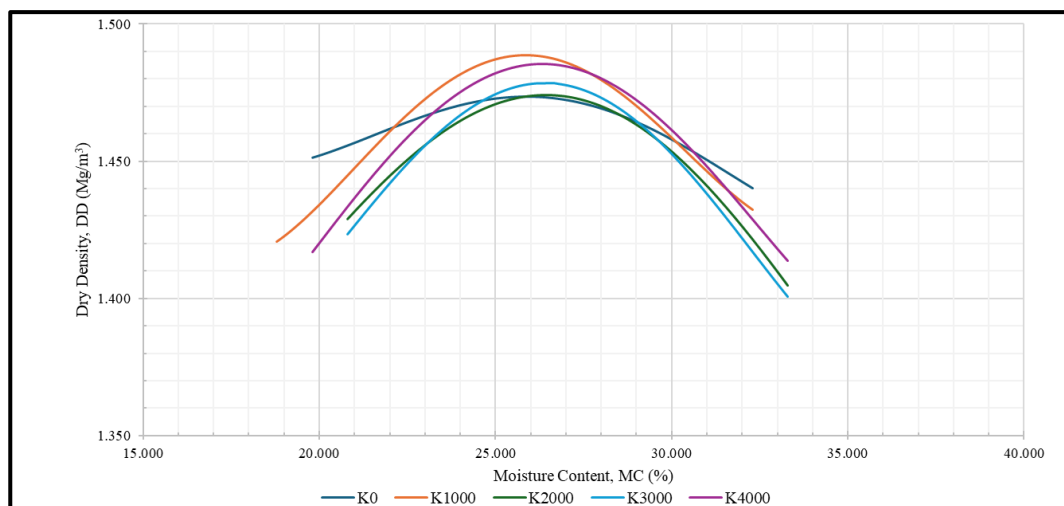


Figure 4.8 Compaction Curve for MPC

Comparison of the RPC, SPC and MPC compaction curves further demonstrates that increasing compactive effort not only shifts the compaction curves towards lower moisture contents and higher dry densities but also produces progressively steeper

curves around the optimum condition. This indicates that soils compacted under higher energies become increasingly sensitive to relatively small variations in moisture content. Consequently, moisture control becomes more critical when higher compactive efforts are applied in engineering practice to ensure that field compaction is performed close to the optimum condition.

4.2.3 Effect of Lead Concentration on OMC and MDD at Optimum

When considering only the optimum conditions, the influence of lead concentration on compaction behaviour becomes more apparent. Under RPC conditions, the optimum moisture content increases from 29.47% for uncontaminated kaolin (K0) to 30.31% at 3000 mg/L, before decreasing slightly to 29.86% at 4000 mg/L. A similar trend is observed under SPC, where OMC increases from 28.46% to 29.39%, and under MPC, where OMC increases from 25.93% to 26.68%. These observations suggest that moderate levels of lead contamination slightly increase the moisture requirement needed to achieve maximum dry density. The relationship between OMC, MDD, and Pb^{2+} concentration for all compactive efforts is summarised in Table 4.6 and illustrated in Figure 4.9.

Table 4.6
Optimum Moisture Content and Maximum Dry Density Under Various Concentration of Lead Contamination in Kaolin Clay for All Compactive Efforts

Sample	RPC		SPC		MPC	
	OMC (%)	MDD (Mg/m ³)	OMC (%)	MDD (Mg/m ³)	OMC (%)	MDD (Mg/m ³)
K0	29.47	1.352	28.46	1.383	25.93	1.474
K1000	29.68	1.367	28.42	1.398	25.82	1.489
K2000	30.07	1.351	29.27	1.383	26.43	1.474
K3000	30.31	1.356	29.39	1.387	26.68	1.478
K4000	29.86	1.363	28.96	1.394	26.28	1.485

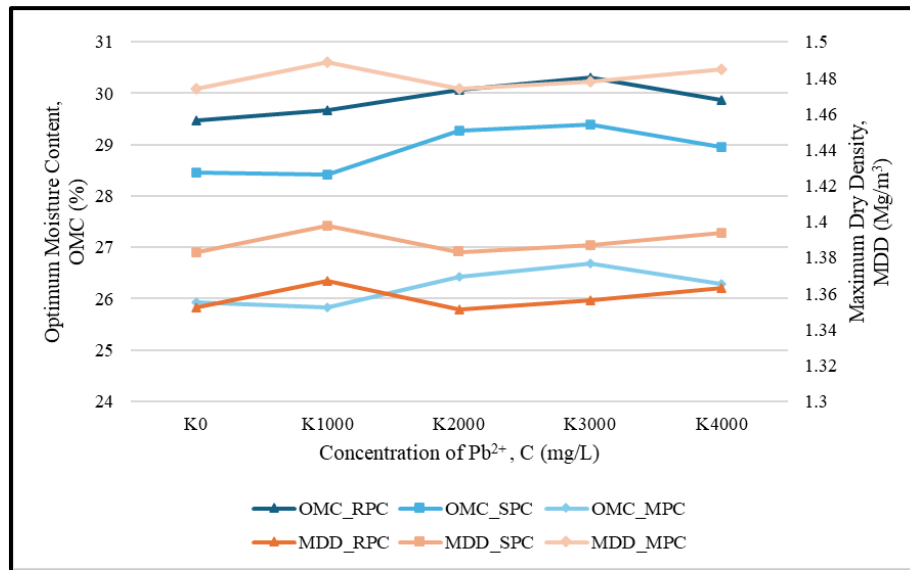


Figure 4.9 OMC and MDD vs Concentration of Pb^{2+}

The experimental results demonstrate that lead contamination produces a measurable but comparatively modest influence on the compaction characteristics of kaolin. For all three compactive efforts, OMC increases slightly from the uncontaminated condition to intermediate contamination levels before decreasing marginally at 4000 mg/L, whereas MDD exhibits only small fluctuations throughout the investigated concentration range. The increase in OMC may be attributed to the physicochemical interaction between Pb^{2+} ions and clay particles, which modifies diffuse double-layer behaviour, interparticle attraction and water adsorption characteristics. These interactions increase the amount of water required to achieve efficient particle rearrangement during compaction, particularly at intermediate contamination levels. However, at higher lead concentrations, increased particle aggregation and flocculation reduce the effective surface area available for water adsorption, resulting in the slight reduction in OMC observed at 4000 mg/L.

The relatively small variation in MDD compared with OMC suggests that lead contamination primarily influences the moisture requirement for compaction rather than the ultimate packing efficiency of the compacted soil. Similar observations were reported by Du et al. (2015), who demonstrated that lead contamination modified the microstructure and water-particle interactions of clay-bentonite mixtures through cation exchange and compression of the diffuse double layer. Muththalib and Baudet (2019) likewise reported that heavy-metal contamination altered the consistency and compaction behaviour of clay mixtures, although the magnitude of the changes depended on contaminant concentration and soil mineralogy. The trends obtained in the

present study therefore agree with previous investigations, indicating that contamination modifies the moisture–density relationship while preserving the overall compaction mechanism governed by applied compactive effort.

4.2.4 Overall Compaction Behaviour

Overall, the compaction results demonstrate that the fundamental energy–moisture–density relationship of kaolin clay is preserved in the presence of lead contamination. Compactive effort remains the dominant factor governing dry density, while lead contamination introduces secondary modifications to optimum moisture content and maximum dry density. The modest yet consistent shifts in OMC and MDD with increasing Pb^{2+} concentration, particularly within the range of 2000–3000 mg/L, reflect the combined influence of increased plasticity, reduced pH , and microstructural reorganisation of clay particles.

Comparison of the experimental results indicates that compactive effort exerts a substantially greater influence on compaction behaviour than lead contamination. Increasing the compactive effort from RPC to MPC reduced the OMC by approximately 3.5% points while increasing the MDD by approximately 0.12 Mg/m³ across all contamination levels. In contrast, increasing the lead concentration from 0 to 4000 mg/L produced variations of generally less than 1% point in OMC and approximately 0.01–0.02 Mg/m³ in MDD. These observations demonstrate that although lead contamination modifies the moisture–density relationship through physicochemical interactions, the magnitude of its influence remains secondary to that of compactive effort. Therefore, within the investigated contamination range, compactive effort represents the principal governing parameter controlling the compaction behaviour of lead-contaminated kaolin clay.

These interactions are consistent with mechanisms reported in previous studies on heavy-metal-contaminated clays (Du et al., 2015; Li et al., 2015; Karkush & Ali, 2020; Muththalib & Baudet, 2019). The overall compaction behaviour across all contamination levels and compactive efforts is illustrated in Figure 4.10, which combines the compaction curves for all mixtures and compaction energies.

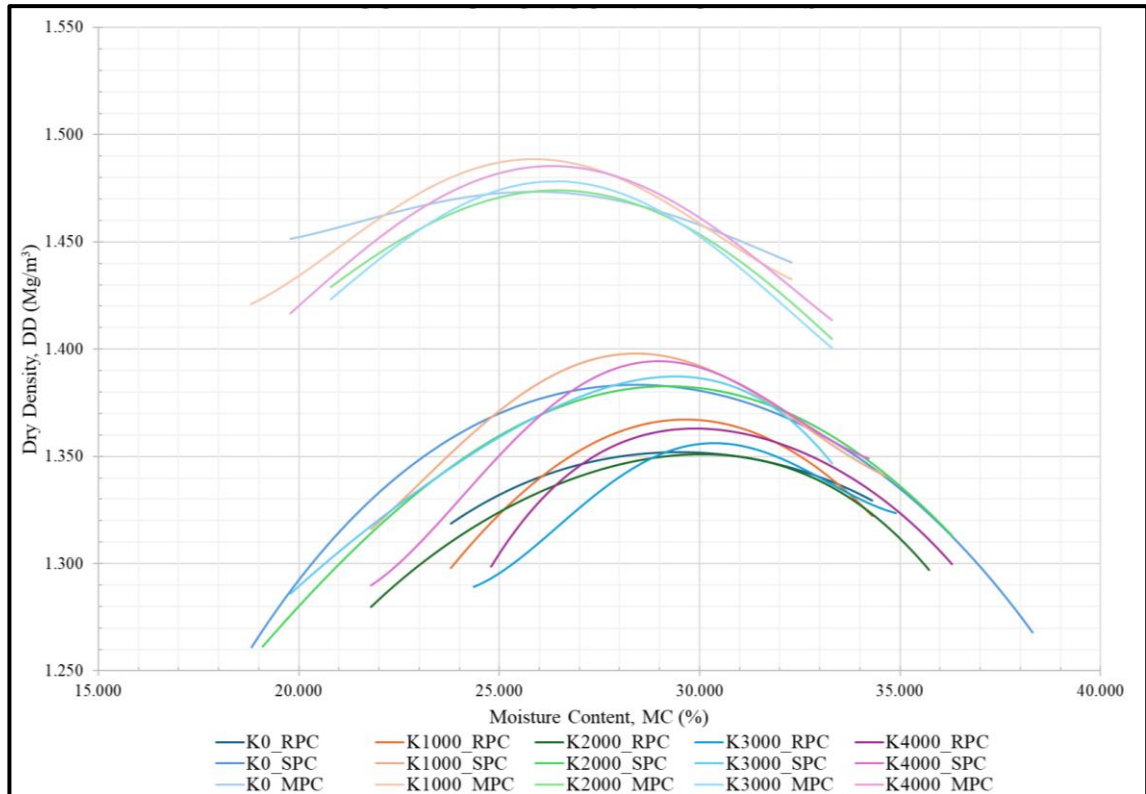


Figure 4.10 Compaction Curve Across all Contamination and Compactive Effort

For completeness, the individual compaction curves and corresponding compaction datasets for each contamination level under RPC, SPC, and MPC are provided in the Appendix, allowing a more detailed examination of the compaction behaviour for each experimental condition.

4.3 Relationships Between Physical Properties and Compaction Response

Objective 3 examines the relationships between the physical properties of lead-contaminated kaolin and its compaction response. To isolate the influence of the measured physical properties from the effect of varying compactive effort, only the Standard Proctor Compaction (SPC) results are considered in this analysis. Since liquid limit, plasticity index, specific gravity, linear shrinkage and pH are intrinsic properties of the soil–contaminant system, fixing the compactive effort enables the observed variations in optimum moisture content (OMC) and maximum dry density (MDD) to be interpreted primarily as responses to physicochemical changes induced by lead contamination. The relationships are presented using graphical analyses to facilitate direct visual interpretation and to establish the mechanisms governing the observed compaction behaviour before empirical model development in Objective 4.

4.3.1 Influence of Plasticity on OMC and MDD

Changes in plasticity characteristics with increasing lead concentration are reflected in the compaction response of the kaolin clay by examining the relationships between liquid limit and both optimum moisture content and maximum dry density under SPC conditions. As shown in Figure 4.11, the OMC generally increases as LL increases from 71% for K0 to 78% for K3000, where the OMC reaches its highest value of 29.39%. This indicates that soils exhibiting higher liquid limit require more water to reach the condition at which maximum dry density can be achieved. The graph also shows that the relationship is not perfectly linear. Although K2000 records the highest LL value of 84%, its corresponding OMC is 29.27%, which is slightly lower than that of K3000. Similarly, K1000, with LL of 75%, records an OMC of 28.42%, which is lower than both K4000 and K3000. This pattern suggests that while LL exerts an important influence on moisture demand, the relationship is moderated by other concurrent changes in the soil system, including plasticity index, shrinkage behaviour, and chemical environment. Nevertheless, the overall tendency of increased OMC with increasing LL remains evident, especially when comparing the uncontaminated specimen with the intermediate contaminated states.

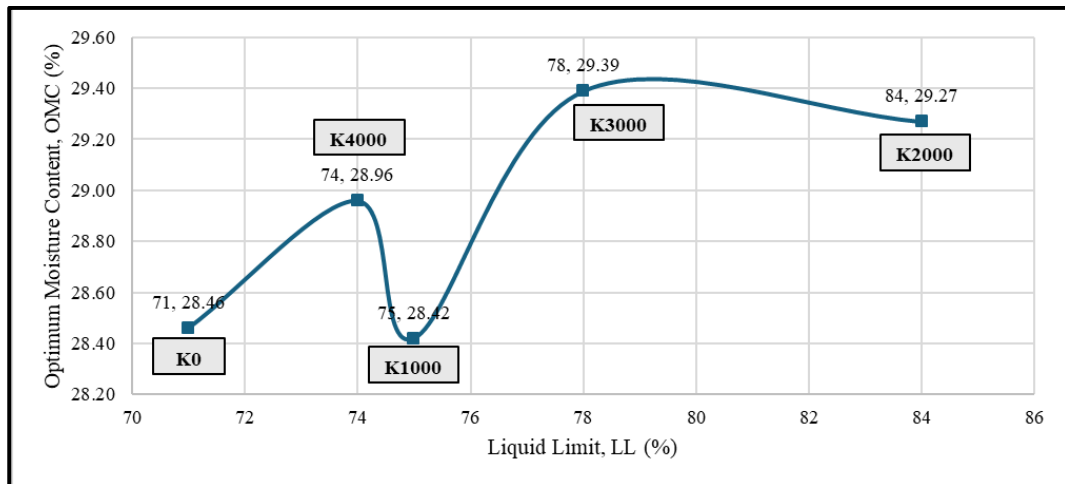


Figure 4.11 Influence of Liquid Limit on OMC

Figure 4.12 presents the relationship between LL and MDD. In contrast to the clearer OMC response, the variation in MDD with LL is relatively modest and more irregular. The uncontaminated soil, with LL of 71%, records an MDD of 1.383 Mg/m³, while K1000, with LL of 75%, shows the highest MDD of 1.398 Mg/m³. As LL

increases further to 78% for K3000 and 84% for K2000, the MDD decreases slightly to 1.387 Mg/m³ and 1.383 Mg/m³, respectively, before rising again to 1.394 Mg/m³ at K4000 where LL is 74%. This indicates that LL has a stronger association with moisture demand than with achievable dry density. In other words, an increase in LL tends to alter the amount of water needed for optimum compaction, but it does not independently guarantee a higher dry density. The relatively narrow range of MDD values confirms that dry density remains less sensitive to plasticity changes than OMC under the fixed SPC energy condition.

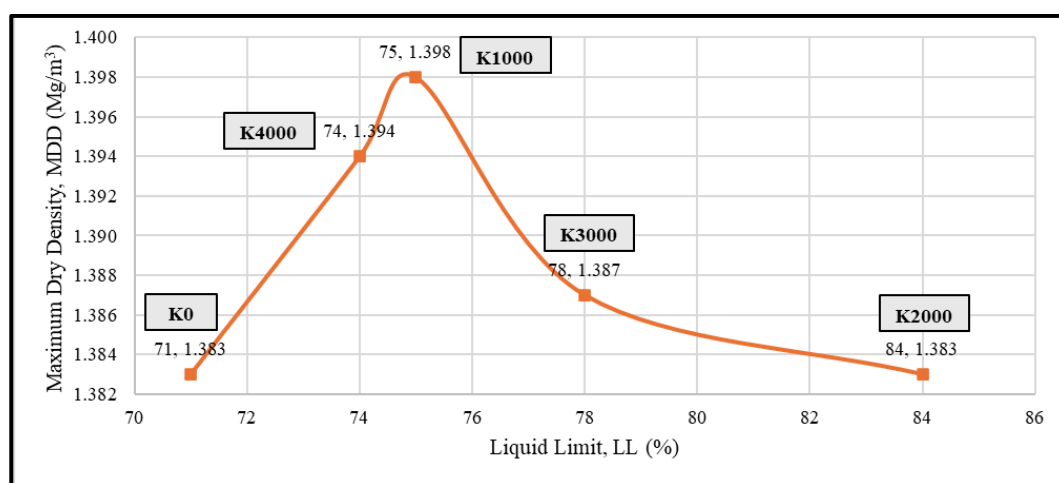


Figure 4.12 Influence of Liquid Limit on MDD

A similar pattern is observed when plasticity index is considered. As illustrated in Figure 4.13, OMC generally increases with increasing PI, especially from 33% for K0 to 39% for K3000, where the OMC reaches 29.39%. The curve shows a slight depression at K1000, where PI increases to 38% but OMC decreases marginally to 28.42%, followed by a more pronounced increase for K3000 and K2000. K2000, which records the highest PI of 42%, exhibits an OMC of 29.27%, remaining higher than the uncontaminated condition but slightly below the peak at K3000. This indicates that higher PI generally corresponds to higher optimum moisture requirement, but the relationship is again influenced by other interacting parameters. The broader interpretation is that as the clay becomes more plastic, more water is needed to overcome interparticle attraction and enable sufficient lubrication during compaction.

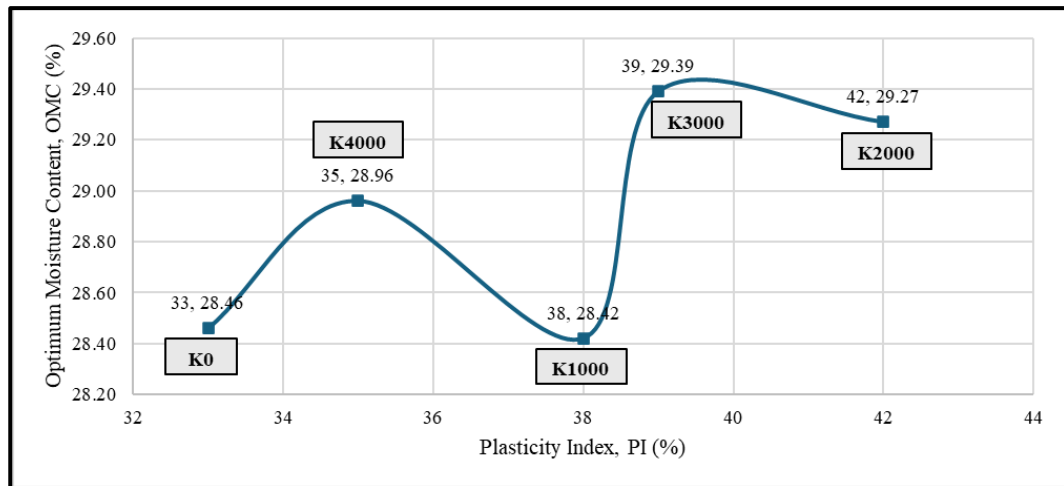


Figure 4.13 Influence of Plasticity Index on OMC

The relationship between PI and MDD shown in Figure 4.14 is again less direct. K0 with PI of 33% records an MDD of 1.383 Mg/m³, while K1000 with PI of 38% records the highest MDD of 1.398 Mg/m³. Beyond this point, increasing PI does not lead to continued density gain. Instead, MDD decreases to 1.387 Mg/m³ at PI 39% for K3000 and returns to 1.383 Mg/m³ at PI 42% for K2000. K4000, with PI of 35%, records 1.394 Mg/m³, which is higher than the uncontaminated value. These variations indicate that PI influences the compaction response primarily through its control on moisture demand rather than through direct control of dry density. Such behaviour is consistent with previous findings that soils with higher LL and PI generally require more water to reach optimum compaction, whereas the resulting dry density is also governed by particle arrangement, aggregate formation, and soil fabric development during compaction (Saikia et al., 2017; Bera & Ghosh, 2011; Tiwari et al., 2014).

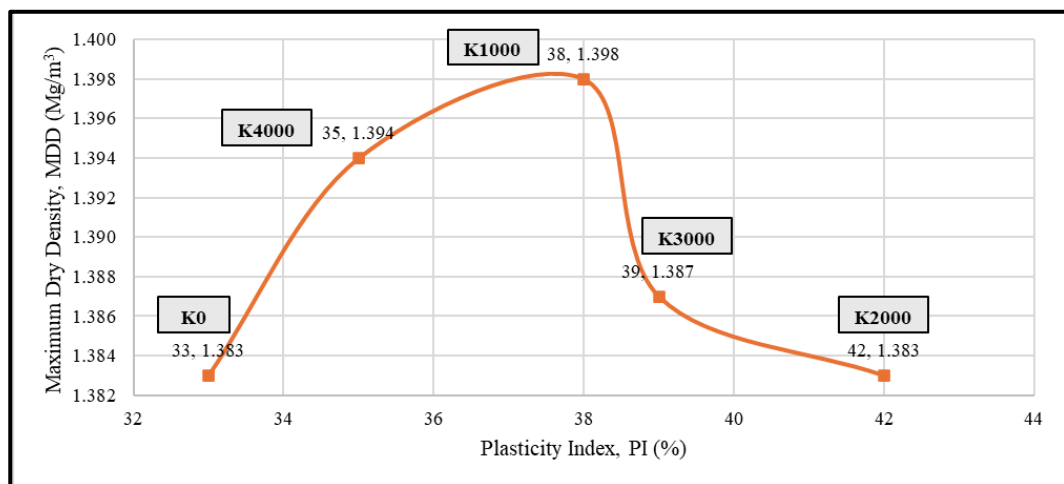


Figure 4.14 Influence of Plasticity Index on MDD

The relationships presented in Figures 4.11–4.14 demonstrate that liquid limit and plasticity index exert a stronger influence on OMC than on MDD. This behaviour indicates that increasing soil plasticity primarily modifies the amount of water required to achieve effective particle lubrication during compaction rather than substantially altering the ultimate packing efficiency of the soil. The observed relationships are consistent with the findings discussed in Chapter 2, where higher consistency limits were associated with increased moisture demand but only relatively small variations in dry density.

4.3.2 Specific Gravity, Linear Shrinkage and Density

The influence of specific gravity and linear shrinkage on the compaction response are examined. Figure 4.15 shows the relationship between MDD and G_s under SPC conditions. In general, there is a modest positive association between these two parameters, although the relationship is not strictly monotonic. The uncontaminated specimen, with $G_s = 2.50$, records an MDD of 1.383 Mg/m^3 . As G_s increases to 2.57 for K1000, the MDD also increases to 1.398 Mg/m^3 , representing the highest dry density among the SPC specimens. However, for K2000 and K3000, where G_s values are 2.56 and 2.55, the MDD values decrease slightly to 1.383 Mg/m^3 and 1.387 Mg/m^3 , respectively. K4000, with G_s of 2.51, records 1.394 Mg/m^3 , which remains above the uncontaminated value. These observations suggest that higher particle density can support higher dry density, but the relationship is moderated by accompanying changes in plasticity and soil structure. Thus, specific gravity contributes positively to MDD, but it does not act as an isolated controlling factor.

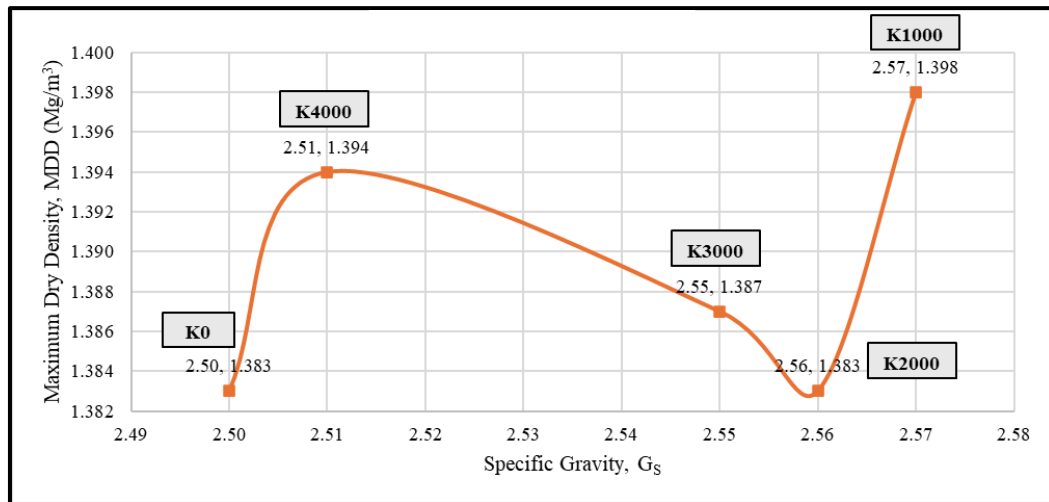


Figure 4.15 Correlation Between MDD and Specific Gravity

Figure 4.16 illustrates the relationship between OMC and LS. A generally increasing trend is evident from the uncontaminated to the intermediate contaminated states. OMC rises from 28.46% at LS = 7.69% for K0 to 29.39% at LS = 8.47% for K3000, indicating that soils with greater shrinkage potential tend to require more water for optimum compaction. K2000, which exhibits the highest LS value of 8.85%, records an OMC of 29.27%, while K1000, with LS of 8.26%, records a lower OMC of 28.42%. K4000, with LS of 7.98%, records an intermediate OMC of 28.96%. Although the trend is not perfectly linear, the graph suggests that increased shrinkage susceptibility is associated with greater moisture demand during compaction. This is reasonable because soils that undergo greater dimensional change with moisture variation are also likely to exhibit stronger water sensitivity during particle rearrangement. The subsequent reduction in OMC at the highest contamination level, despite prior increases, may indicate that excessive contamination alters the clay fabric in a manner that limits further moisture demand, possibly due to aggregation or reduced diffuse double-layer expansion.

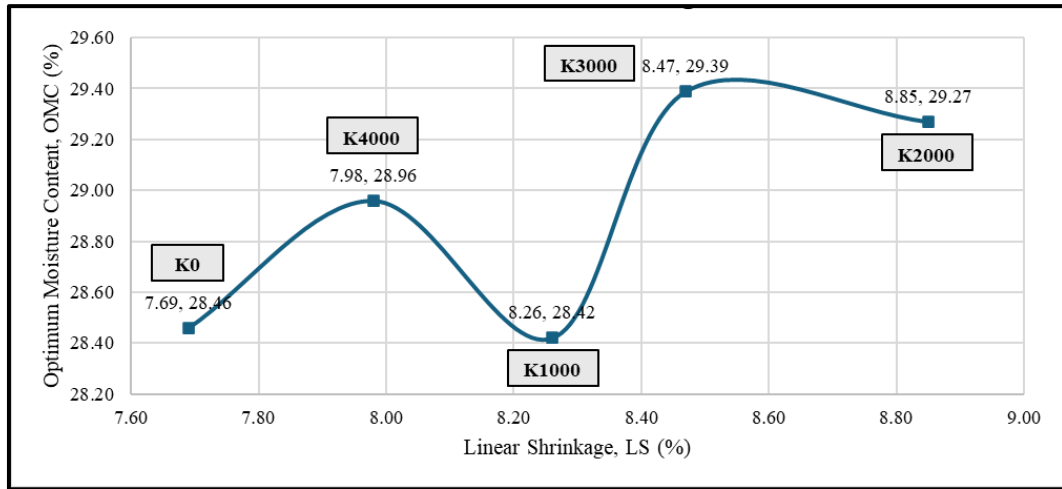


Figure 4.16 Correlation Between OMC and Linear Shrinkage

The combined relationships between specific gravity, linear shrinkage and the compaction parameters indicate that these properties assist in explaining the changes observed in moisture–density behaviour following lead contamination. While specific gravity exhibits a closer relationship with maximum dry density, linear shrinkage demonstrates a comparatively stronger association with optimum moisture content. These observations further support the interpretation that different physical properties contribute differently to the compaction response of contaminated kaolin.

4.3.3 *pH* and Compaction Behaviour

The effect of chemical environment on compaction response is evaluated through the relationship between *pH* and both OMC and MDD. The introduction of lead nitrate causes a marked decrease in *pH* from 5.43 in the uncontaminated soil to approximately 3.79–3.83 in the contaminated mixtures, indicating that contamination substantially alters the chemical condition of the clay–water system. This shift towards acidity is expected to modify surface charge interactions, cation exchange processes, and diffuse double-layer behaviour.

As shown in Figure 4.17, the lower *pH* values associated with contaminated specimens generally correspond to higher OMC values compared with the uncontaminated condition. K0, with *pH* 5.43, records an OMC of 28.46%, whereas the contaminated specimens with *pH* values between 3.79 and 3.83 record OMC values ranging from 28.42% to 29.39%. The highest OMC occurs at K3000, where *pH* is 3.81, while K4000 at *pH* 3.79 records a slightly lower OMC of 28.96%. The graph therefore

suggests that the acidic environment produced by lead contamination tends to increase the water demand for compaction, although the response is not strictly proportional to pH alone. This implies that pH acts together with changes in plasticity and shrinkage behaviour rather than as an independent predictor.

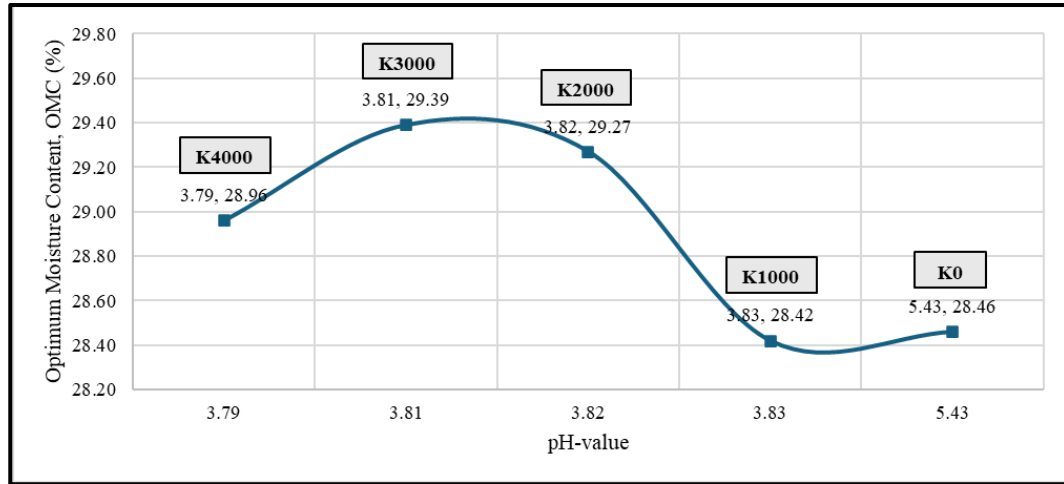


Figure 4.17 Influence of pH -value on OMC

Figure 4.18 shows that the relationship between pH and MDD is relatively small in magnitude but still meaningful. The uncontaminated soil at pH 5.43 records an MDD of 1.383 Mg/m^3 . Among the contaminated specimens, the highest MDD of 1.398 Mg/m^3 occurs at K1000 with pH 3.83, while K3000 and K2000 record lower MDD values of 1.387 Mg/m^3 and 1.383 Mg/m^3 , respectively. K4000 at pH 3.79 exhibits an MDD of 1.394 Mg/m^3 . These results indicate that acidic conditions do not necessarily reduce achievable dry density. Instead, the altered ionic environment may promote flocculation and aggregation of clay particles, and when compacted under sufficient energy, this restructured fabric may permit slightly higher dry density. This interpretation is consistent with previous studies reporting that heavy-metal contamination and acidic conditions can alter interparticle forces and soil arrangement, thereby modifying compaction behaviour (Du et al., 2015; Zha et al., 2021; Zhang et al., 2024).

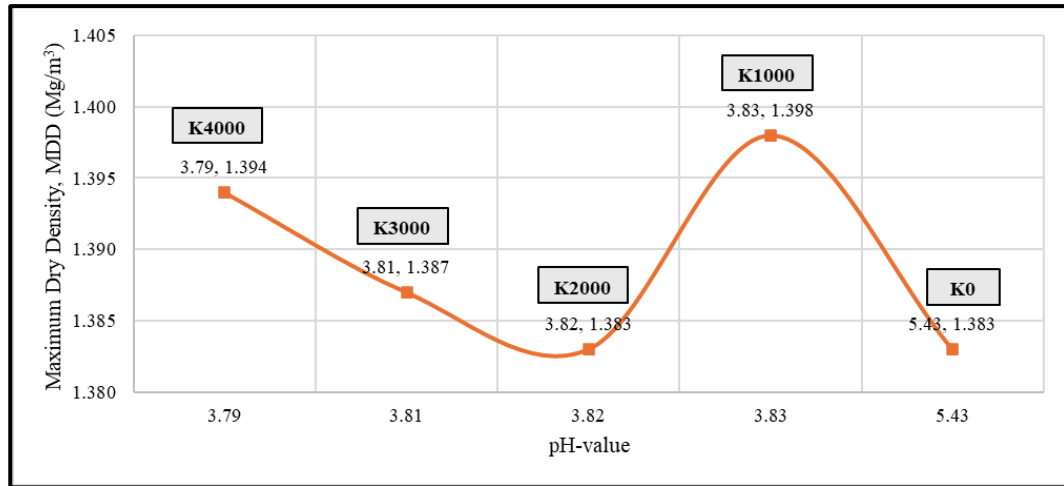


Figure 4.18 Influence of pH -value on MDD

The relationships between pH and the compaction parameters further demonstrate that the chemical environment of the soil influences the moisture–density response indirectly through its effect on clay–water interactions. The decrease in pH following lead contamination corresponds to the changes observed in plasticity and shrinkage characteristics discussed in Section 4.1, indicating that physicochemical modifications occurring within the clay matrix collectively contribute to the observed compaction behaviour rather than acting independently

4.3.4 Correlation Enhancement and Overview

To further clarify the sensitivity of compaction parameters to lead contamination, normalised OMC and MDD values under SPC conditions are presented in Table 4.7 and Table 4.8. Normalisation was carried out with respect to the uncontaminated reference state (K0), allowing the relative changes caused by contamination to be assessed independently of the absolute values.

Table 4.7
Normalised Optimum Moisture Content at SPC

Sample	OMC (%)	$\Delta\text{OMC} = \text{OMC} - 28.46$ (%)	Normalised OMC = $\Delta\text{OMC} / 28.46$
K0	28.46	0.00	0.0000
K1000	28.42	-0.04	-0.0014
K2000	29.27	+0.81	+0.0285
K3000	29.39	+0.93	+0.0327
K4000	28.96	+0.50	+0.0176

Table 4.8
Normalised Maximum Dry Density at SPC

Sample	MDD (Mg/m ³)	$\Delta\text{MDD} = \text{MDD} - 1.383 \text{ (Mg/m}^3\text{)}$	Normalised MDD = $\Delta\text{MDD} / 1.383$
K0	1.383	0.000	0.0000
K1000	1.398	+0.015	+0.0108
K2000	1.383	0.000	0.0000
K3000	1.387	+0.004	+0.0029
K4000	1.394	+0.011	+0.0080

Figure 4.19 shows the normalised OMC response. Relative to K0, the OMC of K1000 decreases slightly by 0.14%, indicating that very low contamination does not significantly increase moisture demand. However, the normalised OMC rises sharply to 2.85% at K2000 and reaches its maximum value of 3.27% at K3000, before declining to 1.76% at K4000. This pattern confirms that the influence of lead contamination on moisture demand is not linear but instead becomes most pronounced at intermediate-to-high concentrations. The peak response at K3000 suggests that this concentration range produces the strongest combined effect of plasticity increase, shrinkage tendency, and chemical alteration on optimum water requirement.

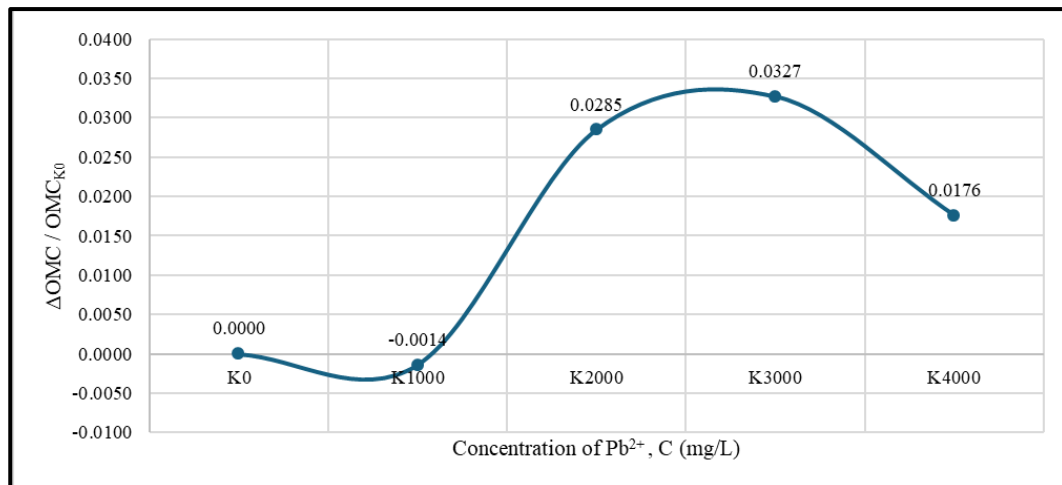


Figure 4.19 Normalised OMC vs Concentration of Pb^{2+}

The normalised MDD response shown in Figure 4.20 is much smaller in magnitude. K1000 records the highest increase, with a normalised MDD of 1.08%, while K2000 shows no net change relative to K0. K3000 and K4000 record increases of 0.29% and 0.80%, respectively. The limited variation in these values demonstrates that MDD is much less sensitive to contamination than OMC under the same compactive effort. This supports the earlier interpretation that moisture demand

responds more directly to changes in soil physicochemical properties, whereas dry density remains controlled predominantly by the imposed compactive energy and the resulting efficiency of particle packing.

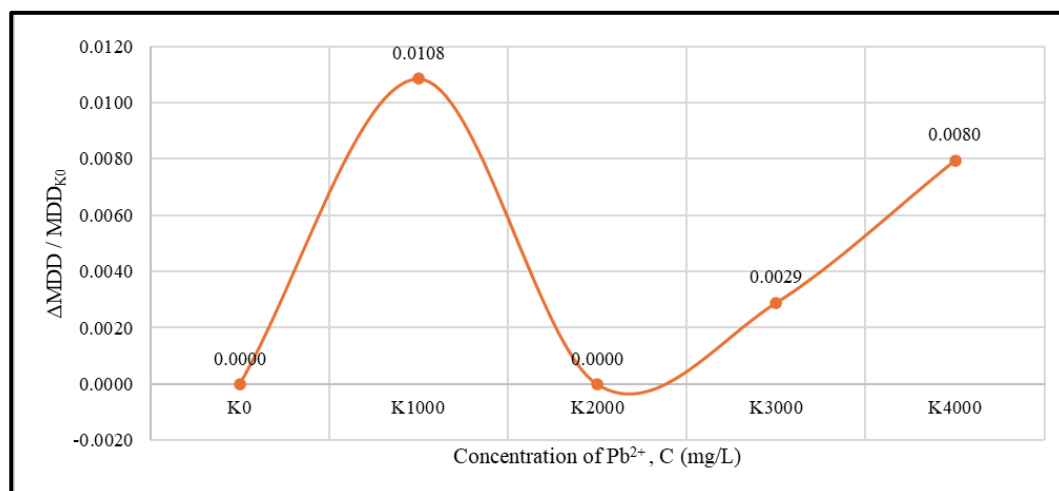


Figure 4.20 Normalised MDD vs Concentration of Pb^{2+}

The graphical relationships and normalised responses discussed in the preceding sections demonstrate that each physical property exhibits a different degree of influence on the compaction behaviour of lead-contaminated kaolin. To provide a clearer overall interpretation, the general relationships between the investigated physical properties and the compaction parameters under Standard Proctor Compaction (SPC) are summarised in Table 4.9. The table synthesises the principal observations obtained from the graphical analyses by indicating the relative strength and direction of the relationships between each physical property and both OMC and MDD. This summary facilitates comparison among the investigated parameters and provides an integrated interpretation of the mechanisms governing the observed compaction behaviour prior to the presentation of the complete experimental dataset.

Table 4.9

Summary of the Relationships Between Physical Properties and Compaction Parameters Under Standard Proctor Compaction

Physical Property	Relationship with OMC	Relationship with MDD	General Interpretation
Liquid Limit (LL)	Positive	Weak	Higher LL increases moisture demand during compaction.
Plasticity Index (PI)	Positive	Weak	Greater plasticity requires higher optimum moisture for effective particle rearrangement.
Specific Gravity (Gs)	Weak	Positive	Higher particle density contributes to slightly greater achievable dry density.
Linear Shrinkage (LS)	Positive	Weak	Greater shrinkage potential reflects increased water sensitivity during compaction.
<i>pH</i>	Negative	Weak	Lower <i>pH</i> modifies physicochemical interactions, influencing moisture demand more than dry density.

The qualitative relationships summarised in Table 4.9 are supported by the experimental results obtained throughout this study. For completeness, the measured physical properties together with the corresponding compaction parameters under the three compactive efforts are summarised in Table 4.10. The table provides an integrated overview of the complete experimental dataset discussed in Sections 4.1 to 4.3 and serves as a reference for the empirical model development presented in the following section.

Table 4.10

Index Properties of Non-contaminated and Contaminated Kaolin Clay Across Different Compactive Efforts

Behaviour	K0	K1000	K2000	K3000	K4000
Liquid Limit, LL (%)	71	75	84	78	74
Plastic Limit, PL (%)	38	37	42	39	39
Plasticity Index, PI (%)	33	38	42	39	35
Specific Gravity, G _s	2.50	2.57	2.56	2.55	2.51
Linear Shrinkage, LS (%)	7.69	8.26	8.85	8.47	7.98
pH-value	5.43	3.83	3.82	3.81	3.79

Compactive Efforts	K0	K1000	K2000	K3000	K4000
RPC - OMC (%)	29.47	29.68	30.07	30.31	29.86
- MDD (Mg/m ³)	1.352	1.367	1.351	1.356	1.363
SPC - OMC (%)	28.46	28.42	29.27	29.39	28.96
- MDD (Mg/m ³)	1.383	1.398	1.383	1.387	1.394
MPC - OMC (%)	25.93	25.82	26.43	26.68	26.28
- MDD (Mg/m ³)	1.474	1.489	1.474	1.478	1.485

Overall, the graphical analyses presented in this section demonstrate that variations in the physical properties of lead-contaminated kaolin are consistently accompanied by corresponding changes in compaction behaviour. Among the investigated properties, liquid limit, plasticity index and linear shrinkage exhibit stronger relationships with optimum moisture content, whereas specific gravity shows a comparatively closer association with maximum dry density. Furthermore, the normalised responses indicate that OMC is more sensitive to lead contamination than MDD under a constant compactive effort. These findings provide a mechanistic explanation of the observed moisture–density behaviour and establish the scientific basis for interpreting the empirical Multiple Linear Regression models developed in Objective 4.

4.4 Model Development of Compaction Behaviour

This section presents the development, statistical evaluation, and external validation of the empirical models formulated to predict optimum moisture content and maximum dry density of lead-contaminated kaolin clay subjected to different compactive efforts. The modelling framework established in Chapter 3 was implemented using a two-stage design, where data from K0, K1000, and K2000 were used for model development, while K3000 and K4000 were reserved as sensitive datasets for independent validation.

The empirical models developed in this section build upon the experimental observations and relationships established in Objectives 1 to 3. Rather than serving solely as statistical prediction tools, the models aim to quantify the combined influence of lead contamination and compactive effort on the compaction behaviour of kaolin while maintaining physical interpretability. Accordingly, model development was

performed using Multiple Linear Regression (MLR) followed by independent validation to evaluate both statistical performance and predictive capability.

4.4.1 Development Model for OMC

Regression analysis was performed using the development dataset (K0–K2000) to quantify the influence of scaled lead concentration (C_{scaled}), scaled compactive effort (E_{scaled}), and moisture state indicator ($State_code$) on OMC. After statistical screening and evaluation of multicollinearity, these three (3) variables were retained as significant predictors. The final regression equation for OMC is expressed as in (4.1).

$$MC = 29.625 + 0.3183C_{scaled} - 1.4518E_{scaled} + 3.000State_code \quad (4.1)$$

Where MC is moisture content (%), C_{scaled} is lead concentration (mg/L) divided by 1000, E_{scaled} is compactive effort (kN-m/m³) divided by 1000, and $State_code$ is indicator of moisture condition. The regression coefficients and associated statistical parameters are summarised in Table 4.11.

Table 4.11
Regression Coefficients for OMC Model (Development Dataset: K0–K2000)

Predictor	Coefficient	Std. Error	t-Value	p-Value	VIF
Constant	29.625	0.132	224.37	0.000	-
C_{scaled}	0.3183	0.0824	3.86	0.001	1.00
E_{scaled}	-1.4518	0.0640	-22.67	0.000	1.00
$State_code$	3.0000	0.0824	36.39	0.000	1.00

The positive coefficient for C_{scaled} confirms that increasing lead concentration increases moisture demand, reflecting enhanced water retention due to physicochemical modification of the clay matrix. Conversely, the negative coefficient for E_{scaled} indicates that higher compactive energy reduces the moisture required to achieve maximum density, consistent with classical compaction theory. The significant positive coefficient of $State_code$ confirms the expected increase in moisture content from dry-of-optimum to wet-of-optimum conditions.

The model achieved a coefficient of determination R^2 of 98.77%, with an adjusted R^2 of 98.61% and predicted R^2 of 98.40%. These values indicate that nearly all

observed variability in OMC within the development range is explained by the selected predictors. The consistently high values of R^2 , adjusted R^2 and predicted R^2 indicate that the model is unlikely to be overfitted, as its predictive capability remains comparable to its calibration performance. The regression standard error of 0.35% indicates low dispersion around the fitted model. Overall statistical performance indicators are summarised in Table 4.12.

Table 4.12
Statistical Performance Indicators for OMC Model (Development Stage)

Metric	Value
R^2	98.77%
Adjusted R^2	98.61%
Predicted R^2	98.40%
Standard Error (S)	0.349794
Overall p-value	0.000

Residual diagnostics were examined to verify regression assumptions. The normal probability plot shows that residuals follow an approximately linear trend, with only minor deviation at the extreme tails, indicating that the normality assumption is reasonably satisfied. The residuals versus fitted values plot demonstrates random dispersion about the zero line without curvature or funnel-shaped variance expansion, confirming adequacy of the linear formulation and homoscedastic error structure.

The residuals versus observation order plot does not display progressive drift or cyclic behaviour, suggesting independence of residuals within the experimental sequence. Additionally, residuals plotted against C_scaled and E_scaled show no systematic upward or downward trend, indicating that the linear functional form appropriately captures the influence of both predictors. Variance Inflation Factors (VIF) of 1.00 confirm absence of multicollinearity among predictors. Collectively, these diagnostic evaluations support the statistical validity and structural stability of the OMC regression model. These diagnostic evaluations are presented in Figure 4.21.

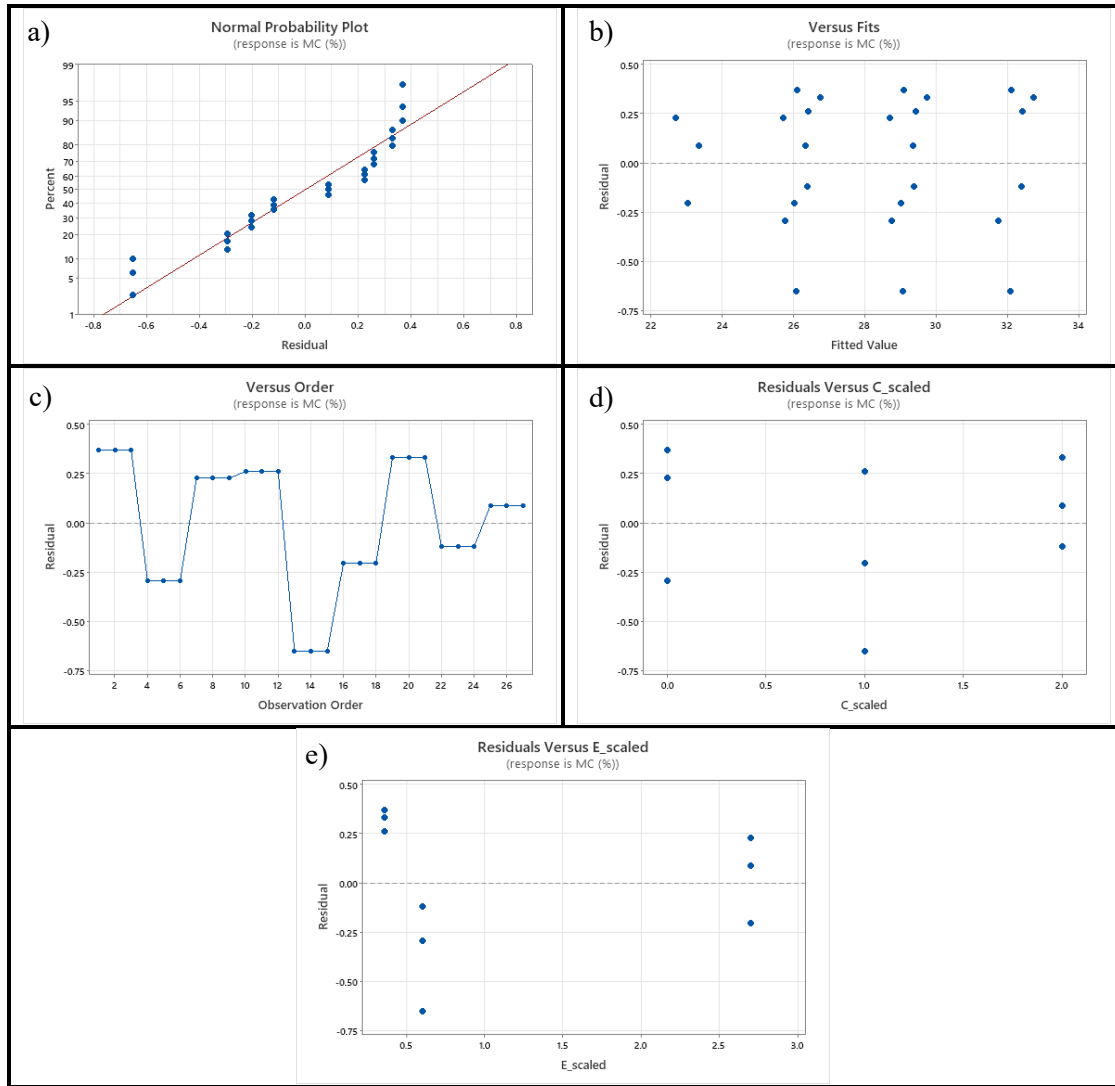


Figure 4.21 Residual Diagnostic Plots for OMC Regression Model (a) Graph of Normal Probability Plot (b) Graph of Residuals vs Fitted (c) Graph of Residuals vs Order (d) Graph of Residuals vs C_scaled Predictors (e) Graph of Residuals vs E_scaled Predictors

4.4.2 Validation of OMC Model Using K3000 and K4000

The developed OMC model was applied to predict values for K3000 and K4000 samples. Predictive accuracy was assessed using Mean Absolute Percentage Error (MAPE), Root Mean Square Error (RMSE), and paired t-test analysis. The evaluation metrics are defined as in (4.2) and (4.3).

$$MAPE = \frac{1}{n} \sum \left| \frac{MC_{actual} - MC_{pred}}{MC_{actual}} \right| \times 100 \quad (4.2)$$

$$RMSE = \sqrt{\frac{1}{n} \sum (MC_{actual} - MC_{pred})^2} \quad (4.3)$$

The validation results are summarised in Table 4.13.

Table 4.13
External Validation Performance for OMC Model (K3000 & K4000)

Metric	Value
MAPE	1.69%
Maximum Error	4.11%
RMSE	0.5857% (moisture content)
Validation R^2	97.71%
Mean Difference	-0.388
Paired t-test (p-value)	0.002

The model produced a low MAPE of 1.69% and an RMSE of 0.586 percentage points of moisture content, indicating strong predictive accuracy. Considering that the observed OMC values range approximately between 23% and 33%, the magnitude of RMSE is small relative to the overall variation, confirming that prediction errors are limited in practical terms. The validation coefficient of determination ($R^2 = 97.71\%$) further demonstrates that the model explains the majority of variability within the independent dataset.

However, the paired t-test yielded a p-value of 0.002, indicating the presence of a statistically significant but minor systematic bias at higher contamination levels. The mean difference of -0.388% suggests a slight tendency toward underprediction, although the magnitude of deviation remains small relative to the overall OMC range. This slight bias is expected because the validation dataset represents contamination levels that were not used during model calibration, thereby providing a more rigorous assessment of model generalisation capability.

The measured versus predicted relationship is illustrated in Figure 4.22. The scatterplot shows a strong linear alignment of validation points along the regression line, with distinct clustering corresponding to compactive effort levels. No visible curvature or dispersion pattern is observed, indicating stable predictive behaviour across the investigated moisture range. The close proximity of data points to the fitted

line further confirms the robustness of the empirical model under extrapolation conditions.

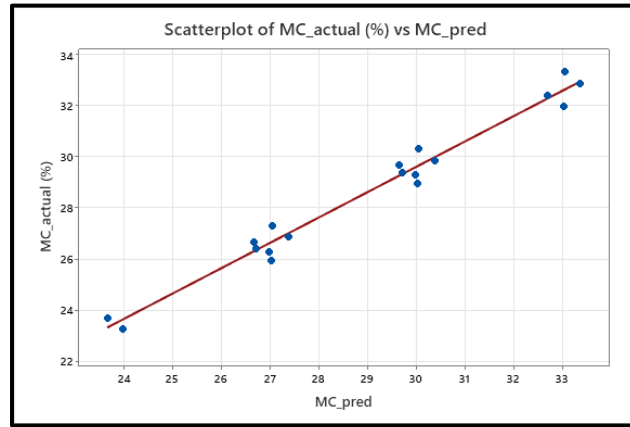


Figure 4.22 Measured vs Predicted OMC for Validation Dataset

4.4.3 Development of Model for MDD

A separate regression analysis was conducted to develop the model for maximum dry density. Unlike OMC, statistical analysis indicated that MDD is predominantly influenced by compactive effort, with comparatively limited sensitivity to contamination level within the investigated range. The final regression equation for MDD is given in (4.4).

$$DD = 1.34089 - 0.00161C_{\text{scaled}} + 0.04883E_{\text{scaled}} \quad (4.4)$$

Where DD is dry density (Mg/m^3). The regression coefficients and statistical indicators are presented in Table 4.14.

Table 4.14

Regression Coefficients for MDD Model (Development Dataset: K0–K2000)

Predictor	Coefficient	Std. Error	t-Value	p-Value	VIF
Constant	1.34089	0.00451	297.31	0.000	-
C_scaled	-0.00161	0.00282	-0.57	0.573	1.00
E_scaled	0.04883	0.00219	22.32	0.000	1.00

The coefficient for E_{scaled} was highly significant ($p < 0.001$), confirming the dominant role of compactive energy in controlling dry density. In contrast, the

coefficient for C_{scaled} was statistically insignificant ($p = 0.573$), suggesting that within the investigated contamination range, chemical effects exert limited influence on packing efficiency compared to mechanical compaction. Although the coefficient for C_{scaled} was statistically insignificant, it was retained in the regression equation to preserve the physical representation of lead concentration within the investigated system and to evaluate its influence during independent model validation.

The model achieved R^2 of 95.41%, with adjusted and predicted R^2 values exceeding 94%, indicating strong explanatory power. This implies that more than 95% of the observed variability in maximum dry density within the development dataset is explained by the selected predictors. The regression standard error of approximately 0.012 Mg/m³ indicates low dispersion around the fitted model, reflecting high precision of density prediction. Considering that the observed MDD values range approximately between 1.33 and 1.49 Mg/m³, this magnitude of error represents less than 1% of the total variation, further confirming predictive precision. Overall performance indicators are summarised in Table 4.15, while diagnostic plots are presented in Figure 4.23.

Table 4.15
Statistical Performance Indicators for MDD Model (Development Stage)

Metric	Value
R^2	95.41%
Adjusted R^2	95.03%
Predicted R^2	94.36%
Standard Error (S)	0.0119478
Overall p-value	0.000

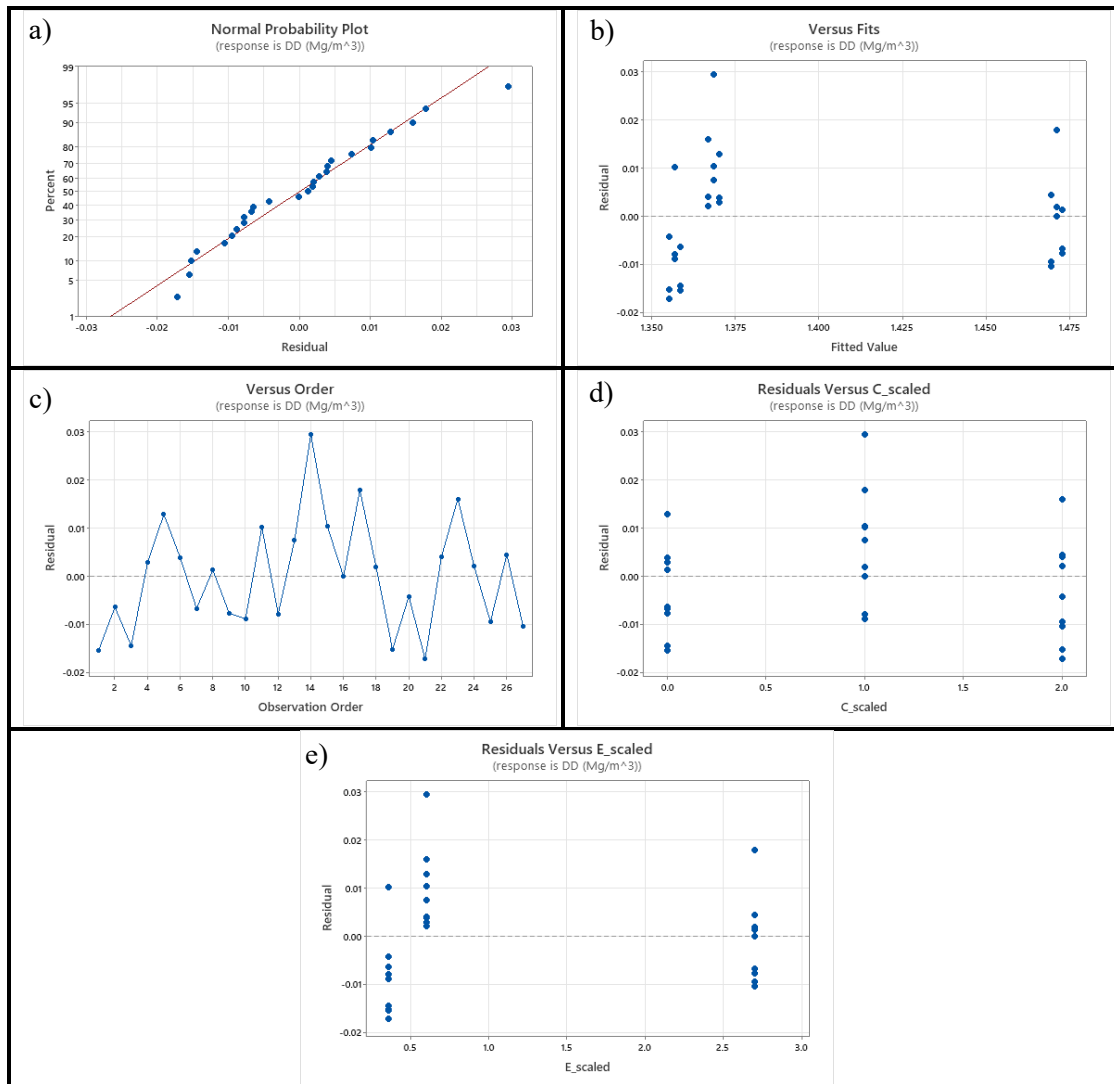


Figure 4.23 Residual Diagnostic Plots for MDD Regression Model (a) Graph of Normal Probability Plot (b) Graph of Residuals vs Fitted (c) Graph of Residuals vs Order (d) Graph of Residuals vs C_scaled Predictors (e) Graph of Residuals vs E_scaled Predictors

Residual diagnostic evaluation was conducted to verify regression assumptions. The normal probability plot shows that residuals closely follow the reference line, with only minor deviation at the extreme tail, indicating that the assumption of normality is satisfactorily met. The residuals versus fitted values plot demonstrates random dispersion about zero without curvature or variance expansion, confirming homoscedasticity and adequacy of the linear model structure.

The residuals versus observation order plot does not exhibit progressive drift or cyclical patterns, suggesting independence of residuals across the experimental sequence. Additionally, residuals plotted against both C_scaled and E_scaled show no systematic upward or downward trend, indicating that the functional form appropriately captures the influence of contamination level and compactive effort. Collectively, these

diagnostic results confirm the statistical validity and structural stability of the MDD regression model.

4.4.4 Validation of MDD Model Using K3000 and K4000

The MDD model was validated using the reserved sensitive dataset comprising K3000 and K4000 samples. The external validation performance indicators are summarised in Table 4.16.

Table 4.16
External Validation Performance for MDD Model (K3000 & K4000)

Metric	Value
MAPE	0.784%
Maximum Error	2.17%
RMSE	0.01366 Mg/m ³ (DD units)
Validation R^2	93.84%
Mean Difference	0.00334
Paired t-test (p-value)	0.313

The validation R^2 of 93.84% indicates that the model explains the majority of variability in maximum dry density within the independent dataset, demonstrating strong generalisation capability beyond the calibration range. The RMSE of 0.01366 Mg/m³ is small relative to the observed density range (approximately 1.33–1.49 Mg/m³), confirming that prediction deviations are minor in practical terms.

The mean difference of 0.00334 Mg/m³ is negligible and, together with the non-significant paired t-test result ($p = 0.313$), confirms the absence of systematic prediction bias. The MAPE of 0.784% further indicates high predictive precision, with the maximum observed deviation limited to 2.17%, which remains within acceptable engineering tolerance for compaction control.

The measured versus predicted relationship is illustrated in Figure 4.24. The scatterplot shows close clustering of validation points around the fitted line, with no observable curvature or divergence at higher density levels. The data form distinct energy-dependent clusters while maintaining tight alignment with the regression trend, further supporting the stability and robustness of the empirical formulation.

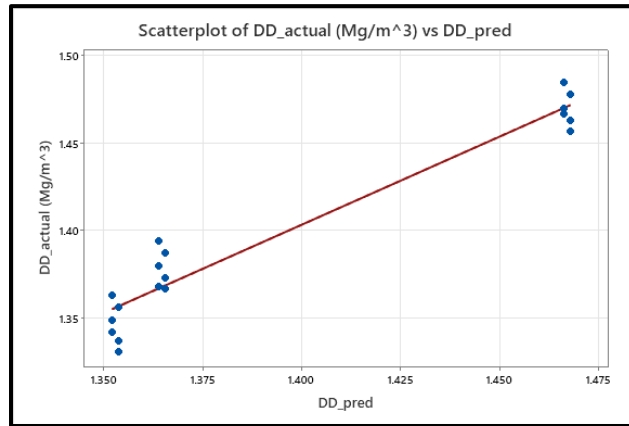


Figure 4.24 Measured vs Predicted MDD for Validation Dataset

4.4.5 Final Model Equations and Comparative Evaluation

For practical implementation, the final predictive equations derived from the regression analysis are expressed as in (4.5) and (4.6).

$$MC = 29.625 + 0.3183C_{\text{scaled}} - 1.4518E_{\text{scaled}} + 3.000\text{State_code} \quad (4.5)$$

$$DD = 1.34089 - 0.00161C_{\text{scaled}} + 0.04883E_{\text{scaled}} \quad (4.6)$$

A comparative summary of both empirical models is provided in Table 4.17.

Table 4.17

Comparative Performance of MC and DD Empirical Models

Indicator	MC Model	DD Model
Training R^2	98.77%	95.41%
Validation R^2	97.71%	93.84%
Validation MAPE	1.69%	0.784%
Validation RMSE	0.5857% (moisture content)	0.01366 Mg/m ³
System Bias (Paired t-test)	Significant but minor ($p = 0.002$)	Not significant ($p = 0.313$)
Dominant Predictor	C_{scaled}	E_{scaled}

The comparative evaluation demonstrates that the two empirical models capture different aspects of the compaction behaviour of lead-contaminated kaolin. While the OMC model reflects the influence of physicochemical interactions governing the moisture required for optimum particle rearrangement, the MDD model confirms that

compactive effort remains the dominant factor controlling the achievable dry density. Together, the models provide statistically validated and physically interpretable predictive equations that can represent the experimental behaviour within the investigated range of lead contamination and compactive effort.

4.5 Summary of the Chapter

This chapter presented and discussed the experimental findings in accordance with the four research objectives. The physical properties of uncontaminated and lead-contaminated kaolin demonstrated that lead contamination altered the consistency and physicochemical characteristics of the soil, particularly the liquid limit, plasticity index, linear shrinkage and pH, with the greatest changes generally observed at intermediate contamination levels. These findings indicate that lead contamination modifies the soil–water interaction and contributes to changes in the moisture demand during compaction.

The compaction results further demonstrated that increasing the compactive effort from Reduced Proctor Compaction (RPC) to Standard Proctor Compaction (SPC) and Modified Proctor Compaction (MPC) consistently decreased the optimum moisture content (OMC) while increasing the maximum dry density (MDD), confirming that compactive effort is the dominant factor governing the compaction behaviour of lead-contaminated kaolin. Correlation analysis also showed that variations in the measured physical properties were accompanied by corresponding changes in OMC and MDD, providing a mechanistic explanation of the observed moisture–density behaviour.

Finally, empirical Multiple Linear Regression (MLR) models were successfully developed to predict OMC and MDD using the principal experimental variables. The developed models demonstrated high coefficients of determination together with satisfactory validation performance, indicating that they are capable of representing the compaction behaviour of lead-contaminated kaolin within the investigated range of contamination levels and compactive efforts. The findings presented in this chapter provide the basis for the conclusions, engineering implications and recommendations for future research discussed in Chapter 5.

CHAPTER 5

CONCLUSION

5.0 Introduction

This chapter presents the overall conclusions drawn from the findings discussed in Chapter 4 in relation to the research objectives established in Chapter 1. The conclusions summarise the influence of lead contamination on the physical properties and compaction behaviour of kaolin clay, the relationships between the measured physical properties and compaction parameters, and the development of empirical Multiple Linear Regression (MLR) models for predicting optimum moisture content (OMC) and maximum dry density (MDD). Finally, recommendations are provided to facilitate the practical application of the research findings and to identify potential directions for future investigations.

5.1 Physical Properties of Uncontaminated and Lead-Contaminated Kaolin

The first objective of this research was to determine how lead contamination influences the fundamental physical properties of kaolin clay, including liquid limit (LL), plastic limit (PL), plasticity index (PI), specific gravity (G_s), linear shrinkage (LS), and pH .

The results show that uncontaminated kaolin exhibits LL and PL values of 71% and 38%, respectively, resulting in a PI of 33% and confirming its classification as a highly plastic fine-grained soil. Upon the introduction of $Pb(NO_3)_2$ at concentrations of 1000–2000 mg/L, both LL and PI increased, reaching maximum values of 84% and 42% at 2000 mg/L. At higher concentrations of 3000–4000 mg/L, LL and PI decreased slightly but remained higher than those of the uncontaminated soil.

Specific gravity increased from 2.50 for the uncontaminated kaolin to approximately 2.56–2.57 at 1000–2000 mg/L, before decreasing to 2.51 at 4000 mg/L. Linear shrinkage followed a similar trend, increasing from 7.69% to a maximum of 8.85% at 2000 mg/L and then decreasing towards 8% at 4000 mg/L.

Soil pH decreased markedly from 5.43 in the uncontaminated state to approximately 3.8–3.9 for all contaminated mixtures, confirming that lead nitrate

introduces a strongly acidic environment. Overall, Objective 1 is fulfilled, as the results clearly demonstrate that lead contamination modifies the physicochemical state of kaolin in a systematic manner, with particularly pronounced effects occurring at intermediate concentrations around 2000 mg/L.

5.2 Compaction Behaviour Under Different Compactive Efforts

The second objective of this study was to evaluate the compaction behaviour of uncontaminated and lead-contaminated kaolin clay under Reduced Proctor Compaction (RPC, 360 kN·m/m³), Standard Proctor Compaction (SPC, 600 kN·m/m³), and Modified Proctor Compaction (MPC, 2700 kN·m/m³), with emphasis on OMC and MDD at moisture states of OMC–3%, OMC, and OMC+3%.

Across all contamination levels, increasing compactive effort consistently resulted in a reduction in OMC and an increase in MDD. At the optimum condition, OMC decreased by approximately 3–4 percentage points when moving from RPC to MPC, while MDD increased by about 0.12 Mg/m³. For example, in the uncontaminated condition, OMC decreased from 29.47% under RPC to 25.93% under MPC, while MDD increased from 1.352 Mg/m³ to 1.474 Mg/m³. Similar systematic trends were observed for all contaminated mixtures, confirming that compactive effort remains the dominant factor governing moisture demand and achievable dry density. At each compactive effort and contamination level, the maximum dry density occurred at the central OMC, with slightly lower values recorded at OMC–3% and OMC+3%.

Lead contamination introduced secondary, yet consistent, modifications to compaction behaviour. At optimum conditions, OMC increased modestly with contamination level, particularly up to 2000–3000 mg/L, mirroring the observed increase in LL and PI. MDD also exhibited a slight increase with contamination, especially under higher compactive energies. Objective 2 is therefore achieved, as the study provides a clear and internally consistent understanding of how lead contamination and compactive effort jointly influence kaolin compaction behaviour.

5.3 Relationships Between Physical Properties and Compaction Parameters

The third objective focused on analysing the relationships between index properties (LL, PI, G_s, LS, and *pH*), lead concentration, and the compaction parameters

OMC and MDD using Excel-based graphical and correlation methods.

The analysis indicates that OMC generally increases with LL and PI, reflecting the direct link between soil plasticity and water demand during compaction. Kaolin samples exhibiting higher LL and PI at intermediate contamination levels required slightly more moisture to achieve optimum density, regardless of compactive effort. In contrast, MDD was found to be more strongly influenced by specific gravity and compactive energy, confirming that denser mineral solids and higher applied energy promote greater dry density.

The relationship between MDD and PI was comparatively weak and occasionally non-monotonic, suggesting that higher plasticity may both facilitate densification through improved lubrication and hinder it through increased resistance to particle rearrangement. Linear shrinkage showed a moderate association with plasticity and OMC, supporting its interpretation as an indicator of volumetric sensitivity linked to moisture demand. Soil *pH* primarily served to distinguish uncontaminated from contaminated states; within the contaminated range, *pH* variation was limited, and its direct influence on OMC and MDD was therefore secondary.

Overall, Objective 3 is achieved, as the study successfully explains the relationships between the measured physical properties and the observed compaction behaviour. These relationships provide a mechanistic interpretation of the experimental findings and support the development and interpretation of the empirical Multiple Linear Regression (MLR) models presented under Objective 4.

5.4 Development of Compaction Behaviour Model for Kaolin Clay

The fourth objective was to develop validated compaction behaviour model capable of predicting Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of lead-contaminated kaolin clay under varying compactive efforts. The modelling framework adopted a two-stage design in which K0, K1000, and K2000 datasets were used for calibration, while K3000 and K4000 were reserved for independent validation.

The model developed for OMC as in (5.1) demonstrated strong explanatory capacity, achieving a coefficient of determination exceeding 98% within the development dataset. The regression structure confirmed that both contamination level and compactive effort exert statistically significant influence on moisture demand. The

positive coefficient associated with scaled lead concentration indicates that increasing *Pb* content increases the optimum moisture required for effective compaction. Conversely, the negative coefficient associated with compactive effort confirms that increased mechanical energy reduces the moisture necessary to achieve maximum density, consistent with classical compaction principles.

$$MC = 29.625 + 0.3183C_{\text{scaled}} - 1.4518E_{\text{scaled}} + 3.000\text{State_code} \quad (5.1)$$

External validation using K3000 and K4000 demonstrated low mean absolute percentage error and acceptable root mean square error, indicating strong predictive capability. Although the paired t-test revealed a minor systematic bias at higher contamination levels, the magnitude of deviation remained small and within engineering tolerance.

In contrast, the model developed for MDD as in (5.2) revealed a distinct behavioural pattern. The model achieved an explanatory power exceeding 95% during calibration and maintained a validation R^2 of approximately 94% under independent testing. The dominant predictor was compactive effort, which exhibited strong statistical significance. Lead concentration, while retained for conceptual completeness, did not demonstrate significant influence within the development range. This indicates that density development under compaction is governed primarily by mechanical energy rather than chemical modification, at least within the investigated contamination levels.

$$DD = 1.34089 - 0.00161C_{\text{scaled}} + 0.04883E_{\text{scaled}} \quad (5.2)$$

Validation of the MDD model yielded very low average percentage error and no statistically significant difference between measured and predicted values. The absence of systematic bias strengthens confidence in the robustness of the density prediction model. Collectively, the modelling outcomes reveal a mechanistic differentiation: contamination substantially affects moisture demand but exerts comparatively limited influence on dry density under compactive loading.

The successful formulation and validation of these models confirm that compaction behaviour of lead-contaminated kaolin clay can be predicted with high

reliability using statistically robust yet physically interpretable regression relationships. Objective 4 is therefore considered fully achieved.

5.5 Recommendations

This section presents recommendations for engineering practice and future research based on the findings obtained in this study. The recommendations are intended to facilitate the practical application of the proposed compaction behaviour models for lead-contaminated kaolin clay while identifying potential areas for further investigation to improve their applicability and robustness.

Recommendations for engineering practice:

- a) Consider contamination level and compactive effort during compaction design. Lead contamination increases the optimum moisture content, whereas maximum dry density is primarily governed by compactive effort. Therefore, both factors should be considered when establishing field compaction specifications for contaminated fine-grained soils.
- b) Adopt the developed empirical models for preliminary compaction assessment. The proposed MLR models can be used to estimate OMC and MDD within the investigated contamination range, thereby assisting preliminary design and reducing the need for extensive trial compaction tests.

Recommendations for future research:

- a) Extend the study to different soil types and contaminant systems. Future investigations should evaluate soils with different mineralogical compositions and other heavy metal contaminants to assess the wider applicability of the proposed models.
- b) Investigate advanced modelling techniques and long-term behaviour. Future studies should compare the developed MLR models with advanced predictive techniques and evaluate the long-term performance of compacted contaminated soils under different environmental conditions.

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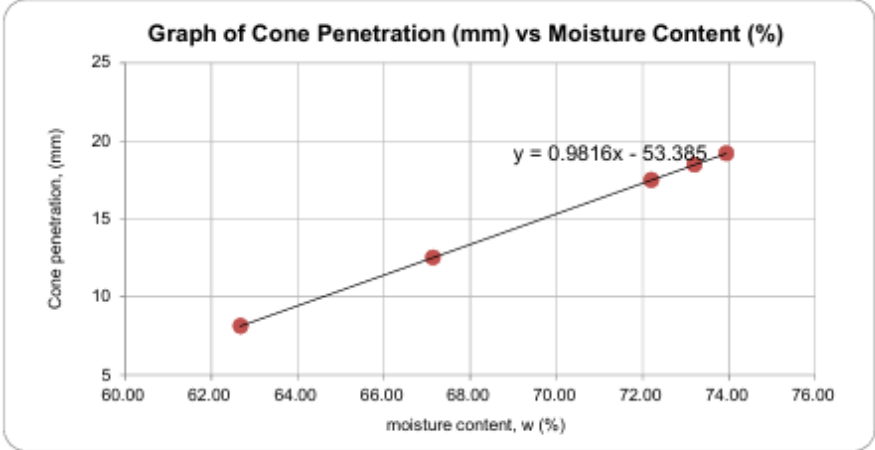
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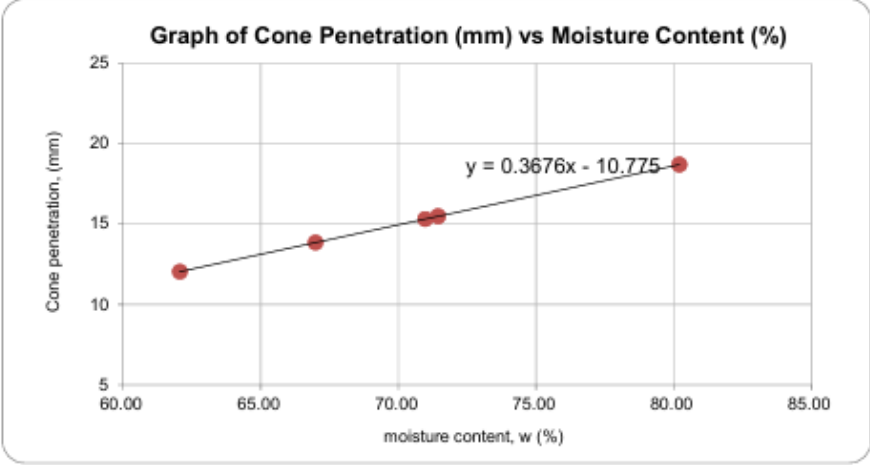
APPENDICES

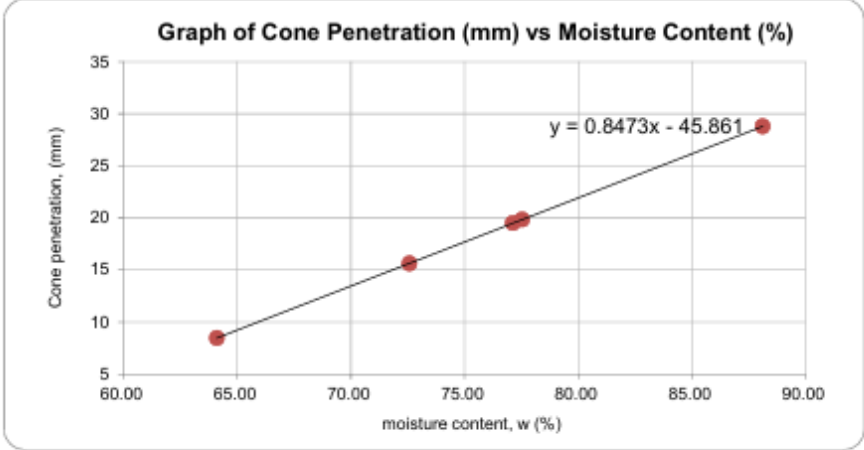
APPENDIX 1

Result of Atterberg Limits for Non-contaminated and Contaminated Kaolin Clay

		PLASTIC LIMIT AND LIQUID LIMIT TESTS (Using Cone penetrometer for liquid limit determination)				AL1	
Job no.	1	Site	Kaolin Clay (FM-C)		BH/Pit no.		
Project	Model of Compaction Behaviour for Various Concentration Lead-Contaminated Kaolin Clay under Different Compactive Efforts				Sample no.	K0	
Client					Depth (m)		
Soil descrip.	Non-contaminated Kaolin Clay			Particle Density, (Mg/m ³)	2.50		
Proportion of soil retained on 425 mm sieve (%)					Soil equilibrated with water for (hours)		
PLASTIC LIMIT DETERMINATION	Container no	1	2	3			
	Mass of container (g)	8.20	8.37	8.20			
	Mass of container + wet soil (g)	11.25	10.42	9.87			
	Mass of container + dry soil (g)	10.35	9.89	9.41			
	Mass of water (g)	0.90	0.53	0.46			
	Mass of dry soil (g)	2.15	1.52	1.21			
	MOISTURE CONTENT (%)	41.86	34.87	38.02			
LIQUID LIMIT DETERMINATION	Container no.	1	2	3	4	5	
	Cone penetration (mm)	9.00	10.20	16.50	17.30	20.50	
	Mass of container (g)	8.19	8.33	8.05	8.09	8.21	
	Mass of container + wet soil (g)	20.43	19.83	19.15	22.38	19.79	
	Mass of container + dry soil (g)	15.91	15.40	14.65	16.56	15.01	
	Mass of water (g)	4.52	4.43	4.50	5.82	4.78	
	Mass of dry soil (g)	7.72	7.07	6.60	8.47	6.80	
	MOISTURE CONTENT (%)	58.55	62.66	68.18	68.71	70.29	
PENETRATION CURVE	Graph of Cone Penetration (mm) vs Moisture Content (%)						
	Cone penetration, (mm) moisture content, w (%) $y = 0.9656x - 48.717$						
Plastic limit (%)		38	Liquid limit (%)		71	Plasticity index (%)	33
Soil classification		SILT of very high plasticity, MV					
Tested by	Aliaa Awatif Omar		Checked by	N/A		Date	26 March 2025
Soil Mechanics Laboratory, Universiti Teknologi MARA						© BBB2005	

 PLASTIC LIMIT AND LIQUID LIMIT TESTS (Using Cone penetrometer for liquid limit determination)		AL1				
Job no.	2	Site	Kaolin Clay (FM-C)			
Project	Model of Compaction Behaviour for Various Concentration Lead-Contaminated Kaolin Clay under Different Compactive Efforts		BH/Pit no.			
Client		Sample no.	K1000			
Soil descrip.	Contaminated Kaolin with 1000 mg/L Pb(NO ₃) ₂ Solution	Depth (m)				
	Particle Density, (Mg/m ³)	2.57				
Proportion of soil retained on 425 mm sieve (%)		Soil equilibrated with water for (hours)				
PLASTIC LIMIT DETERMINATION	Container no	1	2	3		
	Mass of container (g)	8.28	8.08	8.26		
	Mass of container + wet soil (g)	12.54	11.15	10.30		
	Mass of container + dry soil (g)	11.40	10.31	9.75		
	Mass of water (g)	1.14	0.84	0.55		
	Mass of dry soil (g)	3.12	2.23	1.49		
	MOISTURE CONTENT (%)	36.54	37.67	36.91		
LIQUID LIMIT DETERMINATION	Container no.	1	2	3	4	5
	Cone penetration (mm)	9.20	11.30	14.80	19.80	20.70
	Mass of container (g)	8.22	8.14	8.22	8.23	8.15
	Mass of container + wet soil (g)	17.33	21.16	17.76	17.86	20.03
	Mass of container + dry soil (g)	13.82	15.93	13.76	13.79	14.98
	Mass of water (g)	3.51	5.23	4.00	4.07	5.05
	Mass of dry soil (g)	5.60	7.79	5.54	5.56	6.83
	MOISTURE CONTENT (%)	62.68	67.14	72.20	73.20	73.94
PENETRATION CURVE						
Plastic limit (%)	37	Liquid limit (%)	75	Plasticity index (%)	38	
Soil classification	SILT of very high plasticity, MV					
Tested by	Aliaa Awatif Omar	Checked by	N/A	Date	26 March 2025	
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 PLASTIC LIMIT AND LIQUID LIMIT TESTS (Using Cone penetrometer for liquid limit determination)		AL1				
Job no.	3	Site	Kaolin Clay (FM-C)			
Project	Model of Compaction Behaviour for Various Concentration Lead-Contaminated Kaolin Clay under Different Compactive Efforts		BH/Pit no.			
Client		Sample no.	K2000			
Soil descrip.	Contaminated Kaolin with 2000 mg/L Pb(NO ₃) ₂ Solution	Depth (m)				
	Particle Density, (Mg/m ³)	2.56				
Proportion of soil retained on 425 mm sieve (%)		Soil equilibrated with water for (hours)				
PLASTIC LIMIT DETERMINATION	Container no	1	2	3		
	Mass of container (g)	8.18	8.33	8.15		
	Mass of container + wet soil (g)	10.93	11.62	10.28		
	Mass of container + dry soil (g)	10.12	10.64	9.66		
	Mass of water (g)	0.81	0.98	0.62		
	Mass of dry soil (g)	1.94	2.31	1.51		
	MOISTURE CONTENT (%)	41.75	42.42	41.06		
LIQUID LIMIT DETERMINATION	Container no.	1	2	3	4	5
	Cone penetration (mm)	10.50	14.20	16.50	16.90	17.30
	Mass of container (g)	8.05	8.37	8.13	8.25	8.24
	Mass of container + wet soil (g)	17.32	20.36	22.27	21.40	20.53
	Mass of container + dry soil (g)	13.77	15.55	16.40	15.92	15.06
	Mass of water (g)	3.55	4.81	5.87	5.48	5.47
	Mass of dry soil (g)	5.72	7.18	8.27	7.67	6.82
	MOISTURE CONTENT (%)	62.06	66.99	70.98	71.45	80.21
PENETRATION CURVE						
Plastic limit (%)	42	Liquid limit (%)	84	Plasticity index (%)	42	
Soil classification	SILT of very high plasticity, MV					
Tested by	Aliaa Awatif Omar	Checked by	N/A	Date	26 March 2025	
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 PLASTIC LIMIT AND LIQUID LIMIT TESTS (Using Cone penetrometer for liquid limit determination)		AL1	
Job no.	4	Site	Kaolin Clay (FM-C)
Project	Model of Compaction Behaviour for Various Concentration Lead-Contaminated Kaolin Clay under Different Compactive Efforts		BH/Pit no.
Client		Sample no.	K3000
Soil descrip.	Contaminated Kaolin with 3000 mg/L Pb(NO ₃) ₂ Solution		Depth (m)
	Particle Density, (Mg/m ³)		2.55
Proportion of soil retained on 425 mm sieve (%)		Soil equilibrated with water for (hours)	
PLASTIC LIMIT DETERMINATION	Container no	1	2
	Mass of container (g)	8.20	8.22
	Mass of container + wet soil (g)	10.60	10.42
	Mass of container + dry soil (g)	9.93	9.80
	Mass of water (g)	0.67	0.62
	Mass of dry soil (g)	1.73	1.58
	MOISTURE CONTENT (%)	38.73	39.24
LIQUID LIMIT DETERMINATION	Container no.	1	2
	Cone penetration (mm)	9.40	14.60
	Mass of container (g)	8.24	8.15
	Mass of container + wet soil (g)	19.76	22.06
	Mass of container + dry soil (g)	15.26	16.21
	Mass of water (g)	4.50	5.85
	Mass of dry soil (g)	7.02	8.06
	MOISTURE CONTENT (%)	64.10	72.58
PENETRATION CURVE			
	Plastic limit (%) 39 Liquid limit (%) 78 Plasticity index (%) 39 Soil classification: SILT of very high plasticity, MV Tested by: Aliaa Awatif Omar Checked by: N/A Date: 26 March 2025		
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APPENDIX 2

Result of Specific Gravity for Non-contaminated and Contaminated Kaolin Clay

	SPECIFIC GRAVITY TESTS (Using Small Pycnometer of 50 mL)				
Job no.	1	Site	Kaolin Clay (FM-C)		BH/Pit no.
Project	Model of Compaction Behaviour for Various Concentration Lead-Contaminated Kaolin Clay under Different Compactive Efforts			Sample no.	K0
Client				Depth (m)	
Soil descrip.	Non-contaminated Kaolin Clay			Particle Density, (Mg/m ³)	2.50
Density bottle no.	#	1	2	3	
Mass of density bottle + stopper (g)	m ₁	29.678	27.747	30.072	
Mass of density bottle + stopper + dry soil (g)	m ₂	35.870	34.493	37.199	
Mass of density bottle + stopper + dry soil + water (g)	m ₃	83.773	82.437	84.080	
Mass of density bottle + stopper + water (g)	m ₄	80.108	78.370	79.772	
Mass of dry soil used (g)	m ₂ - m ₁	6.192	6.746	7.127	
Mass of water used (g)	m ₃ - m ₂	47.903	47.944	46.881	
Mass of water to fill density bottle (g)	m ₄ - m ₁	50.430	50.623	49.700	
Specific Gravity of soil	G _s	2.450	2.518	2.528	
Formula: $\text{Specific Gravity, } G_s = (m_2 - m_1) / [(m_4 - m_1) - (m_3 - m_2)]$ $\text{Particle Density, } \rho_s = G_s \rho_w \quad \text{where } \rho_w = 1.00 \text{ Mg/m}^3$ $\rho_s = G_s (\text{Mg/m}^3)$					
AVERAGE SPECIFIC GRAVITY OF SOIL		G _s	2.499		
AVERAGE PARTICLE DENSITY OF SOIL (Mg/m ³)		ρ _s	2.499		
Tested by	Aliaa Awatif Omar	Checked by	N/A	Date	26 March 2025
Soil Mechanics Laboratory, Universiti Teknologi MARA					

		SPECIFIC GRAVITY TESTS (Using Small Pycnometer of 50 mL)			
Job no.	2	Site	Kaolin Clay (FM-C)		BH/Pit no.
Project	Model of Compaction Behaviour for Various Concentration Lead-Contaminated Kaolin Clay under Different Compactive Efforts			Sample no.	K1000
Client				Depth (m)	
Soil descrip.	Contaminated Kaolin with 1000 mg/L Pb(NO ₃) ₂ Solution			Particle Density, (Mg/m ³)	2.57
Density bottle no.	#	1	2	3	
Mass of density bottle + stopper (g)	m ₁	32.239	28.608	28.507	
Mass of density bottle + stopper + dry soil (g)	m ₂	38.102	35.603	36.314	
Mass of density bottle + stopper + dry soil + water (g)	m ₃	85.213	83.878	83.618	
Mass of density bottle + stopper + water (g)	m ₄	81.589	79.649	78.871	
Mass of dry soil used (g)	m ₂ - m ₁	5.863	6.995	7.807	
Mass of water used (g)	m ₃ - m ₂	47.111	48.275	47.304	
Mass of water to fill density bottle (g)	m ₄ - m ₁	49.350	51.041	50.364	
Specific Gravity of soil	G _s	2.619	2.529	2.551	
Formula: $\text{Specific Gravity, } G_s = (m_2 - m_1) / [(m_4 - m_1) - (m_3 - m_2)]$ $\text{Particle Density, } \rho_s = G_s \rho_w \quad \text{where } \rho_w = 1.00 \text{ Mg/m}^3$ $\rho_s = G_s (\text{Mg/m}^3)$					
AVERAGE SPECIFIC GRAVITY OF SOIL		G _s	2.566		
AVERAGE PARTICLE DENSITY OF SOIL (Mg/m ³)		ρ _s	2.566		
Tested by	Aliaa Awatif Omar	Checked by	N/A	Date	26 March 2025
Soil Mechanics Laboratory, Universiti Teknologi MARA					

		SPECIFIC GRAVITY TESTS (Using Small Pycnometer of 50 mL)			
Job no.	3	Site	Kaolin Clay (FM-C)		BH/Pit no.
Project	Model of Compaction Behaviour for Various Concentration Lead-Contaminated Kaolin Clay under Different Compactive Efforts			Sample no.	K2000
Client				Depth (m)	
Soil descrip.	Contaminated Kaolin with 2000 mg/L Pb(NO ₃) ₂ Solution			Particle Density, (Mg/m ³)	2.56
Density bottle no.	#	1	2	3	
Mass of density bottle + stopper (g)	m ₁	30.612	30.312	30.172	
Mass of density bottle + stopper + dry soil (g)	m ₂	38.060	37.296	38.060	
Mass of density bottle + stopper + dry soil + water (g)	m ₃	84.929	84.936	85.494	
Mass of density bottle + stopper + water (g)	m ₄	81.312	80.706	80.670	
Mass of dry soil used (g)	m ₂ - m ₁	7.448	6.984	7.888	
Mass of water used (g)	m ₃ - m ₂	46.869	47.640	47.434	
Mass of water to fill density bottle (g)	m ₄ - m ₁	50.700	50.394	50.498	
Specific Gravity of soil	G _s	1.944	2.536	2.574	
Formula: $\text{Specific Gravity, } G_s = (m_2 - m_1) / [(m_4 - m_1) - (m_3 - m_2)]$ $\text{Particle Density, } \rho_s = G_s \rho_w \quad \text{where } \rho_w = 1.00 \text{ Mg/m}^3$ $\rho_s = G_s (\text{Mg/m}^3)$					
AVERAGE SPECIFIC GRAVITY OF SOIL		G _s	2.555		
AVERAGE PARTICLE DENSITY OF SOIL (Mg/m ³)		ρ _s	2.555		
Tested by	Aliaa Awatif Omar	Checked by	N/A	Date	26 March 2025
Soil Mechanics Laboratory, Universiti Teknologi MARA					

		SPECIFIC GRAVITY TESTS (Using Small Pycnometer of 50 mL)			
Job no.	4	Site	Kaolin Clay (FM-C)		BH/Pit no.
Project	Model of Compaction Behaviour for Various Concentration Lead-Contaminated Kaolin Clay under Different Compactive Efforts				Sample no. K3000
Client					Depth (m)
Soil descrip.	Contaminated Kaolin with 3000 mg/L Pb(NO ₃) ₂ Solution			Particle Density, (Mg/m ³)	2.55
Density bottle no.	#	1	2	3	
Mass of density bottle + stopper (g)	m ₁	28.757	34.255	29.952	
Mass of density bottle + stopper + dry soil (g)	m ₂	34.786	41.240	37.896	
Mass of density bottle + stopper + dry soil + water (g)	m ₃	83.198	89.118	85.467	
Mass of density bottle + stopper + water (g)	m ₄	79.492	84.848	80.729	
Mass of dry soil used (g)	m ₂ - m ₁	6.029	6.985	7.944	
Mass of water used (g)	m ₃ - m ₂	48.412	47.878	47.571	
Mass of water to fill density bottle (g)	m ₄ - m ₁	50.735	50.593	50.777	
Specific Gravity of soil	G _s	2.595	2.573	2.478	
Formula: $\text{Specific Gravity, } G_s = (m_2 - m_1) / [(m_4 - m_1) - (m_3 - m_2)]$ $\text{Particle Density, } \rho_s = G_s \rho_w \quad \text{where } \rho_w = 1.00 \text{ Mg/m}^3$ $\rho_s = G_s (\text{Mg/m}^3)$					
AVERAGE SPECIFIC GRAVITY OF SOIL		G _s	2.549		
AVERAGE PARTICLE DENSITY OF SOIL (Mg/m ³)		ρ _s	2.549		
Tested by	Aliaa Awatif Omar	Checked by	N/A	Date	26 March 2025
Soil Mechanics Laboratory, Universiti Teknologi MARA					

		SPECIFIC GRAVITY TESTS (Using Small Pycnometer of 50 mL)		
Job no.	5	Site	Kaolin Clay (FM-C)	
Project	Model of Compaction Behaviour for Various Concentration Lead-Contaminated Kaolin Clay under Different Compactive Efforts			Sample no.
Client				Depth (m)
Soil descrip.	Contaminated Kaolin with 4000 mg/L Pb(NO ₃) ₂ Solution			Particle Density, (Mg/m ³)
Density bottle no.	#	1	2	3
Mass of density bottle + stopper (g)	m ₁	30.433	32.019	33.024
Mass of density bottle + stopper + dry soil (g)	m ₂	38.337	38.602	39.026
Mass of density bottle + stopper + dry soil + water (g)	m ₃	85.633	87.563	86.719
Mass of density bottle + stopper + water (g)	m ₄	81.000	83.569	83.051
Mass of dry soil used (g)	m ₂ - m ₁	7.904	6.583	6.002
Mass of water used (g)	m ₃ - m ₂	47.296	48.961	47.693
Mass of water to fill density bottle (g)	m ₄ - m ₁	50.567	51.550	50.027
Specific Gravity of soil	G _s	2.416	2.543	2.572
Formula: $\text{Specific Gravity, } G_s = (m_2 - m_1) / [(m_4 - m_1) - (m_3 - m_2)]$ $\text{Particle Density, } \rho_s = G_s \rho_w \quad \text{where } \rho_w = 1.00 \text{ Mg/m}^3$ $\rho_s = G_s (\text{Mg/m}^3)$				
AVERAGE SPECIFIC GRAVITY OF SOIL		G _s	2.510	
AVERAGE PARTICLE DENSITY OF SOIL (Mg/m ³)		ρ _s	2.510	
Tested by	Aliaa Awatif Omar	Checked by	N/A	Date
26 March 2025				
Soil Mechanics Laboratory, Universiti Teknologi MARA				

APPENDIX 3

Result of Linear Shrinkage for Non-contaminated and Contaminated Kaolin Clay

		SHRINKAGE LIMIT TESTS (Using Linear Shrinkage Mould)				
Job no.	1	Site	Kaolin Clay (FM-C)		BH/Pit no.	
Project	Model of Compaction Behaviour for Various Concentration Lead-Contaminated Kaolin Clay under Different Compactive Efforts			Sample no.	K0 - K4000	
Client				Depth (m)		
Soil descrip.	Non-contaminated and Contaminated Kaolin Clay					
Sample	#	Initial length, L_0 (mm)	Dried length, L_D (mm)	Linear Shrinkage (%)	Avg LS, (%)	
K0	A	139.04	128.06	7.90	7.69	
K0	B	139.09	128.66	7.50		
K0	C	139.01	128.36	7.66		
K1000	A	139.04	127.87	8.03	8.26	
K1000	B	139.09	127.31	8.47		
K1000	C	139.01	127.50	8.28		
K2000	A	139.05	127.29	8.46	8.85	
K2000	B	139.18	126.42	9.17		
K2000	C	139.54	127.09	8.92		
K3000	A	139.63	128.23	8.16	8.47	
K3000	B	139.17	126.64	9.00		
K3000	C	139.23	127.75	8.25		
K4000	A	139.17	128.32	7.80	7.98	
K4000	B	138.94	127.26	8.41		
K4000	C	139.13	128.37	7.73		
Formula: $\text{Linear Shrinkage, LS (\%)} = [(L_0 - L_D) / L_0] \times 100$						
Tested by	Aliaa Awatif Omar	Checked by	N/A	Date	06 March 2025	
Soil Mechanics Laboratory, Universiti Teknologi MARA						

APPENDIX 4

Result of pH-Value for Non-contaminated and Contaminated Kaolin Clay

	pH TESTS (Using pH Meter)					
Job no.	1	Site	Kaolin Clay (FM-C)		BH/Pit no.	
Project	Model of Compaction Behaviour for Various Concentration Lead-Contaminated Kaolin Clay under Different Compactive Efforts				Sample no.	K0 - K4000
Client					Depth (m)	
Soil descrip.	Non-contaminated and Contaminated Kaolin Clay					
Sample	#	pH-value 1	pH-value 2	pH-value 3	Avg pH-value	
K0		5.49	5.36	5.44	5.43	
K1000		3.82	3.85	3.83	3.83	
K2000		3.84	3.81	3.80	3.82	
K3000		3.82	3.80	3.81	3.81	
K4000		3.78	3.79	3.81	3.79	
Tested by	Aliaa Awatif Omar	Checked by	N/A	Date	06 March 2025	
Soil Mechanics Laboratory, Universiti Teknologi MARA						

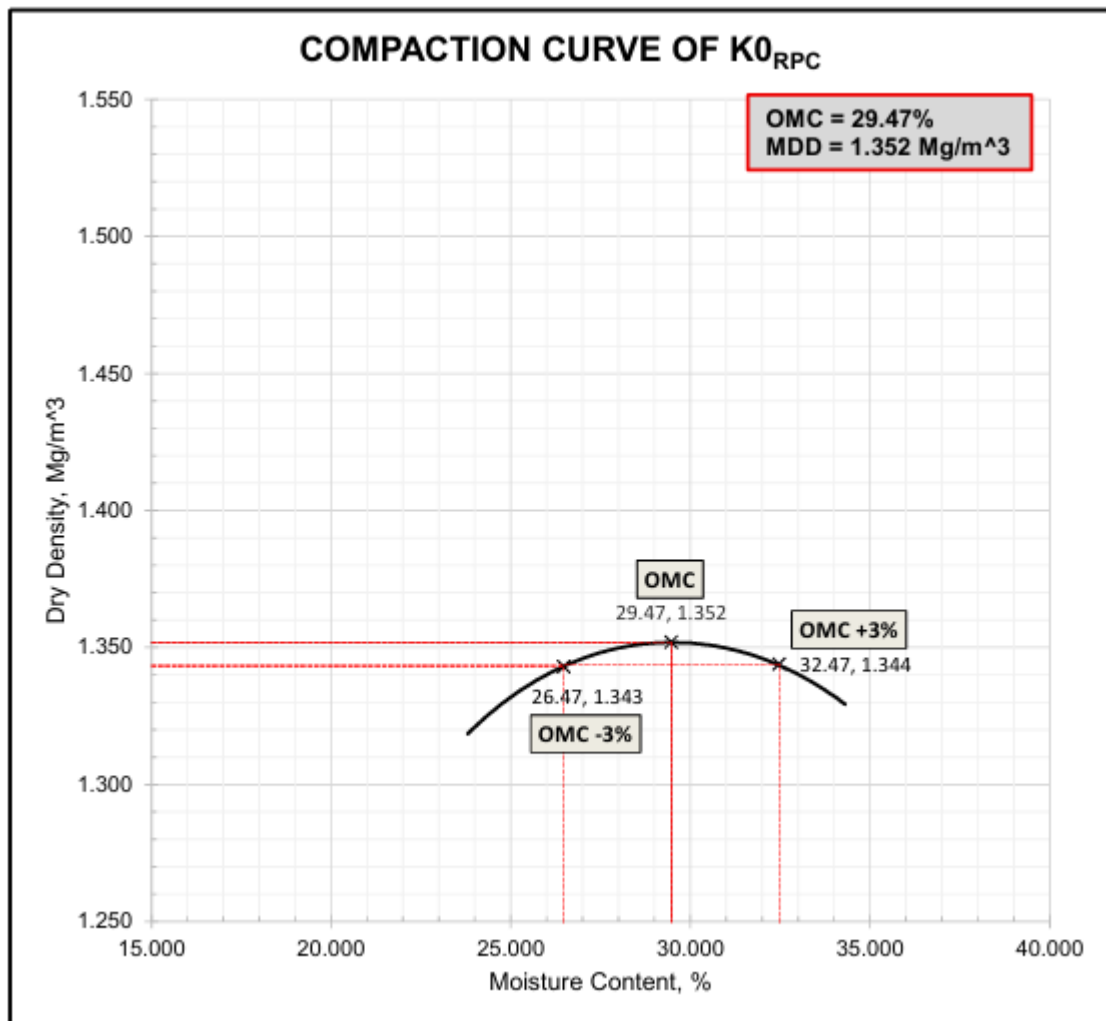
APPENDIX 5

Result of Reduced Proctor Compaction (RPC) for Non-contaminated and Contaminated Kaolin Clay

COMPACTION TEST RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT

Project	COMPACTION BEHAVIOUR	Test Method	Reduced Proctor Compaction (RPC)
Site	UNCONTAMINATED KAOLIN CLAY	Mass of Rammer	2.5 kg
No. of Sample	K0 (RPC)	Diameter of Mould	10.5 cm
Depth of Sample		Height of Mould	11.5 cm
Date		Volume of mould	995.9158 cm ³
Conducted by	Aliaa Awatif Binti Omar	Specific Gravity of Soil, G _s	2.50 Mg/m ³
		Remarks	

COMPACTION DATA	2			3			4			5			6		
Test no.	2			3			4			5			6		
Mass of mould + base (g)	4955			4955			4955			4955			4955		
Mass of mould + base + soil (g)	6597			6644			6697			6727			6733		
Mass of soil (g)	1642			1689			1742			1772			1778		
BULK DENSITY (Mg/m ³)	1.649			1.696			1.749			1.779			1.785		
MOISTURE CONTENT DETERMINATION															
Container no.	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	F3
Mass of container (g)	8.1700	8.2400	8.1900	8.2200	8.2800	8.3600	8.2200	8.1400	16.4000	16.8600	16.8800	16.8600	16.7000	13.5800	16.5100
Mass of container + wet soil (g)	25.3300	24.3000	24.6100	24.0900	22.9400	23.4000	24.9400	28.1200	34.6100	35.4000	34.5000	34.2200	42.4600	49.2500	46.3700
Mass of container + dry soil (g)	21.9800	21.1600	21.3700	20.7800	19.8900	20.2600	21.1400	23.5900	30.4700	30.8800	30.1800	29.9700	35.8700	40.1500	38.7100
Mass of water (%)	0.243	0.243	0.246	0.264	0.263	0.264	0.294	0.293	0.294	0.322	0.325	0.324	0.344	0.342	0.345
Average moisture content	0.244			0.263			0.294			0.324			0.344		
AVERAGE MOISTURE CONTENT (%)	24.381			26.337			29.385			32.380			34.377		
DRY DENSITY (Mg/m ³)	1.326			1.342			1.352			1.344			1.329		
DRY UNIT WEIGHT (kN/m ³)	13.004			13.169			13.262			13.185			13.033		



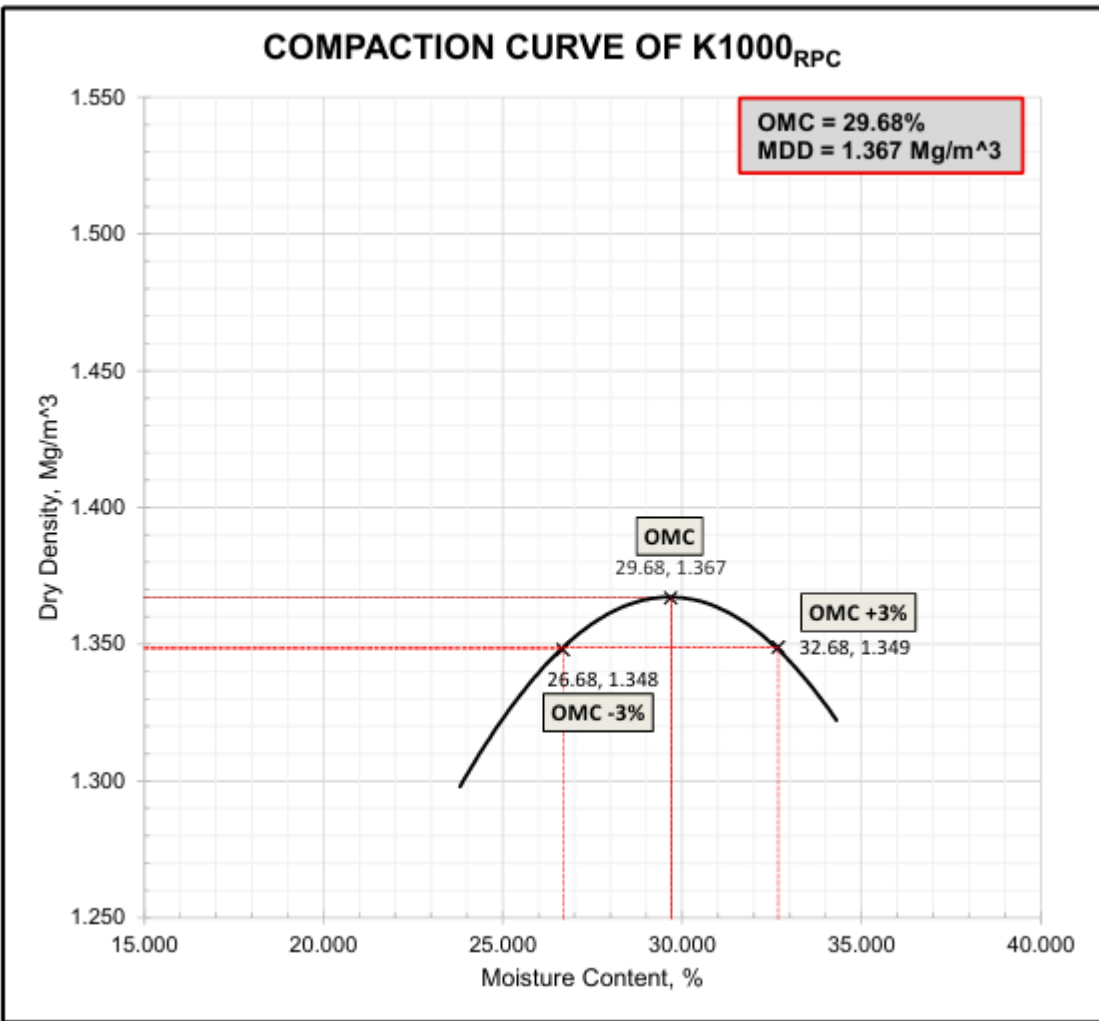
COMPACTION TEST
RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT

Project	COMPACTION BEHAVIOUR
Site	CONTAMINATED KAOLIN CLAY
No. of Sample	K1000 (RPC)
Depth of Sample	
Date	
Conducted by	Aliaa Awatif Binti Omar

Test Method
Mass of Rammer
Diameter of Mould
Height of Mould
Volume of mould
Specific Gravity of Soil, G_s
Remarks

Reduced Proctor Compaction (RPC)	
2.5	kg
10.5	cm
11.5	cm
995.9158	cm ³
2.57	Mg/m ³

COMPACTION DATA																		
Test no.	2			3			4			5			6					
Mass of mould + base (g)	4955			4955			4955			4955			4955					
Mass of mould + base + soil (g)	6577			6647			6716			6737			6723					
Mass of soil (g)	1622			1692			1761			1782			1768					
BULK DENSITY (Mg/m^3)	1.629			1.699			1.768			1.789			1.775					
MOISTURE CONTENT DETERMINATION																		
Container no.	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	F3			
Mass of container (g)	8.2500	8.1800	8.2200	8.3100	8.2700	8.2900	8.2400	8.2000	8.2600	8.3300	8.2800	8.3000	16.8800	16.4300	8.3300			
Mass of container + wet soil (g)	26.8100	26.8700	27.2600	27.6700	28.6100	25.9400	24.5300	24.0400	32.0700	29.4900	25.5300	24.6900	34.6600	36.6000	28.3100			
Mass of container + dry soil (g)	23.1900	23.2100	23.5200	23.6400	24.3600	22.2600	20.8300	20.4700	26.6400	24.3300	21.3000	20.6900	30.1200	31.4500	23.1900			
Mass of water (%)	0.242	0.244	0.244	0.263	0.264	0.263	0.294	0.291	0.295	0.323	0.325	0.323	0.343	0.343	0.345			
Average moisture content	0.243			0.263			0.293			0.323			0.343					
AVERAGE MOISTURE CONTENT (%)	24.342			26.348			29.342			32.341			34.344					
DRY DENSITY (Mg/m^3)	1.310			1.345			1.367			1.352			1.321					
DRY UNIT WEIGHT (kN/m^3)	12.849			13.191			13.411			13.264			12.963					

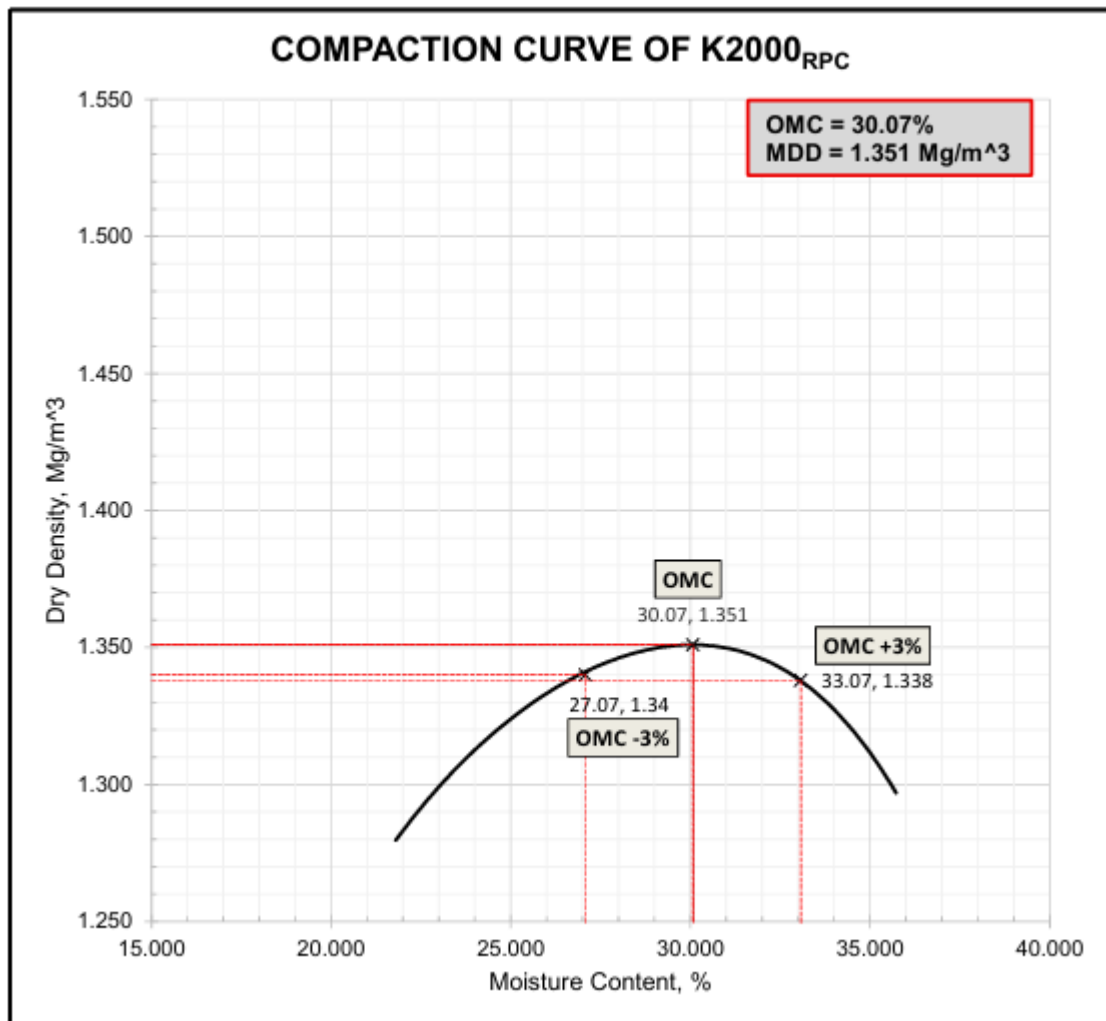


COMPACTION TEST
RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT

Project	COMPACTION BEHAVIOUR
Site	CONTAMINATED KAOLIN CLAY
No. of Sample	K2000 (RPC)
Depth of Sample	
Date	
Conducted by	Aliaa Awatif Binti Omar

Test Method	Reduced Proctor Compaction (RPC)
Mass of Rammer	2.5 kg
Diameter of Mould	10.5 cm
Height of Mould	11.5 cm
Volume of mould	995.9158 cm ³
Specific Gravity of Soil, G _s	2.56 Mg/m ³
Remarks	

COMPACTION DATA																		
Test no.	2			3			5			6			7					
Mass of mould + base (g)	4955			4955			4955			4955			4955					
Mass of mould + base + soil (g)	6515			6631			6708			6728			6705					
Mass of soil (g)	1560			1676			1753			1773			1750					
BULK DENSITY (Mg/m^3)	1.566			1.683			1.760			1.780			1.757					
MOISTURE CONTENT DETERMINATION																		
Container no.	B1	B2	B3	C1	C2	C3	E1	E2	E3	F1	F2	F3	G1	G2	G3			
Mass of container (g)	8.1300	8.2900	8.2300	8.2500	8.2100	8.4100	8.3100	8.2000	8.4000	8.2400	8.1800	8.4200	8.2200	8.3300	8.1300			
Mass of container + wet soil (g)	22.6500	26.6300	22.6000	26.6500	25.2400	23.8700	29.8900	27.5100	25.2400	26.5100	24.2600	26.3700	29.7600	26.5400	23.7300			
Mass of container + dry soil (g)	20.0300	23.3400	19.9900	22.8300	21.7300	20.6600	24.8700	23.0400	21.3100	21.9200	20.2500	21.8700	24.0700	21.7300	19.6100			
Mass of water (%)	0.220	0.219	0.222	0.262	0.260	0.262	0.303	0.301	0.304	0.336	0.332	0.335	0.359	0.359	0.359			
Average moisture content	0.220			0.261			0.303			0.334			0.359					
AVERAGE MOISTURE CONTENT (%)	22.024			26.122			30.292			33.411			35.894					
DRY DENSITY (Mg/m^3)	1.284			1.334			1.351			1.334			1.293					
DRY UNIT WEIGHT (kN/m^3)	12.593			13.090			13.253			13.091			12.685					



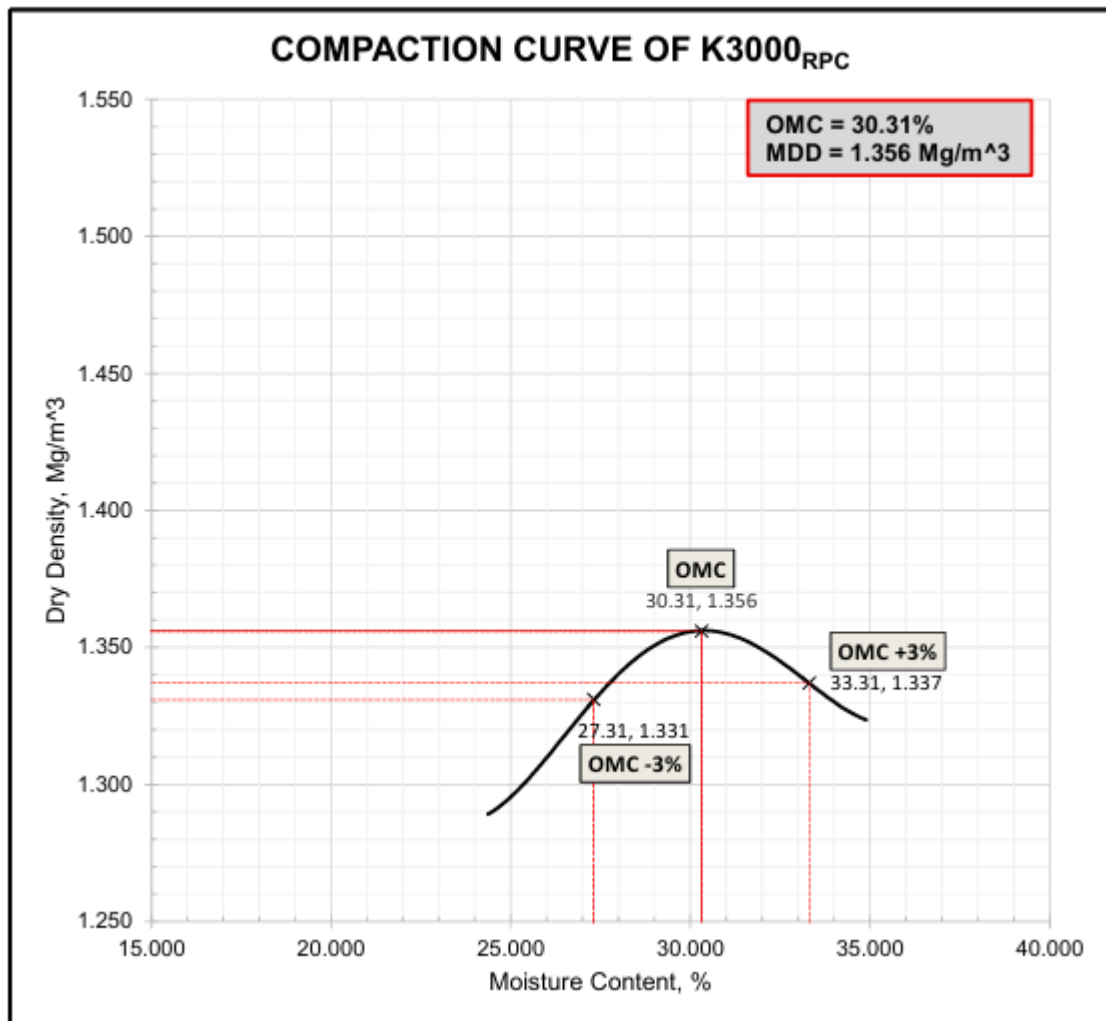
COMPACTION TEST
RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT

Project	COMPACTION BEHAVIOUR
Site	CONTAMINATED KAOLIN CLAY
No. of Sample	K3000 (RPC)
Depth of Sample	
Date	
Conducted by	Aliaa Awatif Binti Omar

Test Method
Mass of Rammer
Diameter of Mould
Height of Mould
Volume of mould
Specific Gravity of Soil, G_s
Remarks

Reduced Proctor Compaction (RPC)	
2.5	kg
10.5	cm
11.5	cm
995.9158	cm ³
2.55	Mg/m ³

COMPACTION DATA															
Test no.	2			3			4			5			6		
Mass of mould + base (g)	4955			4955			4955			4955			4955		
Mass of mould + base + soil (g)	6540			6628			6715			6730			6732		
Mass of soil (g)	1585			1673			1760			1775			1777		
BULK DENSITY (Mg/m^3)	1.591			1.680			1.767			1.782			1.784		
MOISTURE CONTENT DETERMINATION															
Container no.	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	F3
Mass of container (g)	8.2600	8.2400	8.2200	8.2500	8.1800	8.1000	8.2900	8.2500	8.1600	8.1300	8.3200	8.2400	8.3200	8.2700	8.3500
Mass of container + wet soil (g)	19.5100	18.7800	19.8500	20.9500	20.4000	21.1800	23.9000	23.3800	24.3300	27.0300	26.7300	27.5800	29.1800	28.4900	29.6300
Mass of container + dry soil (g)	17.4600	16.8400	17.7200	18.2600	17.8200	18.4000	20.2900	19.8500	20.5600	22.3300	22.1200	22.7400	23.8200	23.2700	24.1500
Mass of water (%)	0.223	0.226	0.224	0.269	0.268	0.270	0.301	0.304	0.304	0.331	0.334	0.334	0.346	0.348	0.347
Average moisture content	0.224			0.269			0.303			0.333			0.347		
AVERAGE MOISTURE CONTENT (%)	22.421			26.876			30.306			33.295			34.688		
DRY DENSITY (Mg/m^3)	1.300			1.324			1.356			1.337			1.325		
DRY UNIT WEIGHT (kN/m^3)	12.753			12.989			13.304			13.117			12.996		

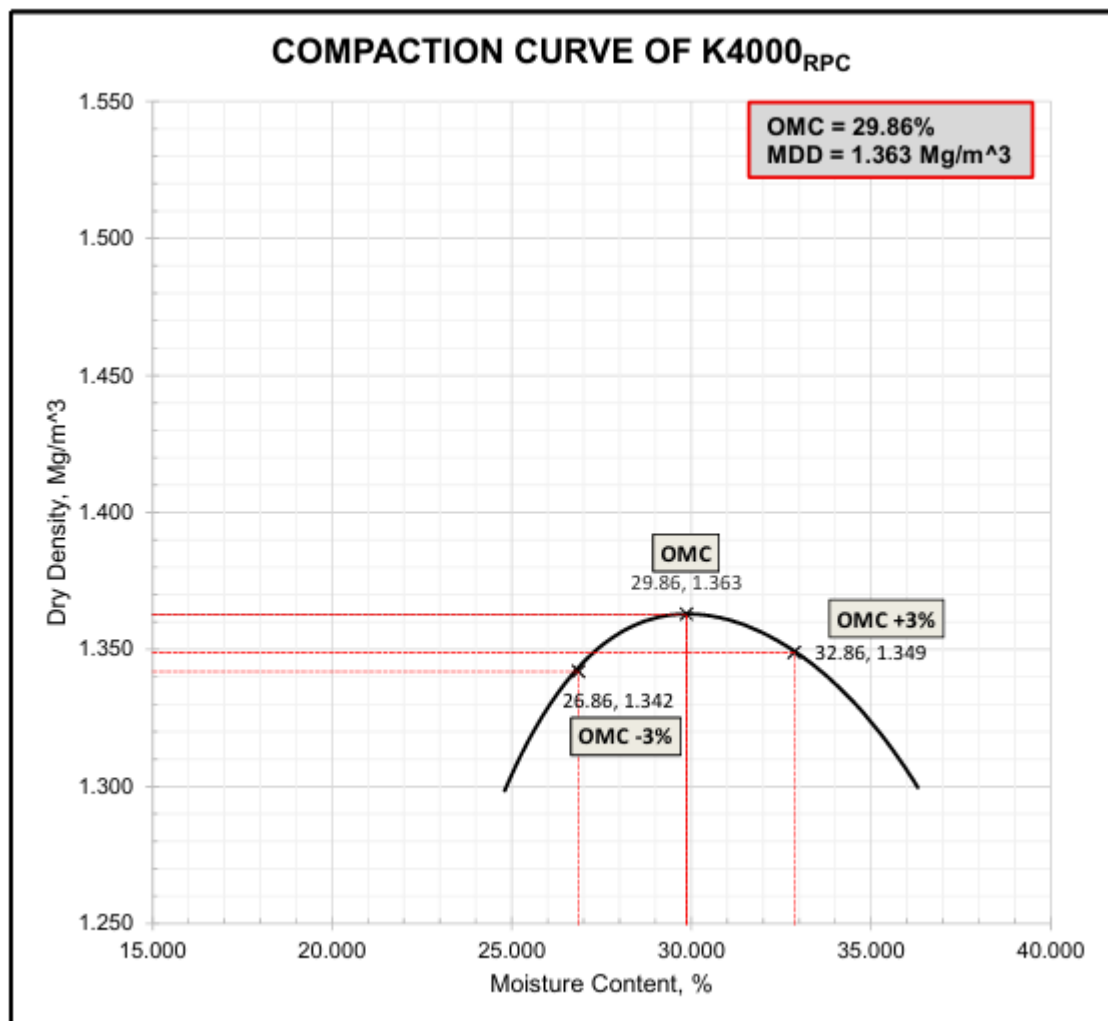


COMPACTION TEST
RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT

Project	COMPACTION BEHAVIOUR
Site	CONTAMINATED KAOLIN CLAY
No. of Sample	K4000 (RPC)
Depth of Sample	
Date	
Conducted by	Aliaa Awatif Binti Omar

Test Method	Reduced Proctor Compaction (RPC)
Mass of Rammer	2.5 kg
Diameter of Mould	10.5 cm
Height of Mould	11.5 cm
Volume of mould	995.9158 cm ³
Specific Gravity of Soil, G _s	2.51
Remarks	

COMPACTION DATA																
Test no.	2			3			4			5			6			
Mass of mould + base (g)	4950			4950			4950			4950			4950			
Mass of mould + base + soil (g)	6575			6626			6713			6736			6725			
Mass of soil (g)	1625			1676			1763			1786			1775			
BULK DENSITY (Mg/m^3)	1.631			1.682			1.771			1.793			1.782			
MOISTURE CONTENT DETERMINATION																
Container no.	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	F3	
Mass of container (g)	8.2400	8.2400	8.3000	8.1600	8.2900	8.1900	8.1700	8.1600	8.2100	8.0900	8.1500	8.2200	8.1200	8.1900	8.2500	
Mass of container + wet soil (g)	25.3700	24.5800	26.9500	26.3900	27.2300	25.8100	29.6500	29.0000	31.1300	32.8000	31.7700	33.1900	33.9800	33.7500	34.4800	
Mass of container + dry soil (g)	21.9400	21.3100	23.2200	22.6000	23.3000	22.1500	24.7000	24.2000	25.8600	26.6800	25.9200	27.0100	27.2000	27.0600	27.6000	
Mass of water (%)	0.250	0.250	0.250	0.262	0.262	0.262	0.299	0.299	0.299	0.329	0.329	0.329	0.355	0.355	0.356	
Average moisture content	0.250			0.262			0.299			0.329			0.355			
AVERAGE MOISTURE CONTENT (%)	25.019			26.216			29.910			32.910			35.514			
DRY DENSITY (Mg/m^3)	1.305			1.333			1.363			1.349			1.315			
DRY UNIT WEIGHT (kN/m^3)	12.802			13.077			13.371			13.234			12.900			



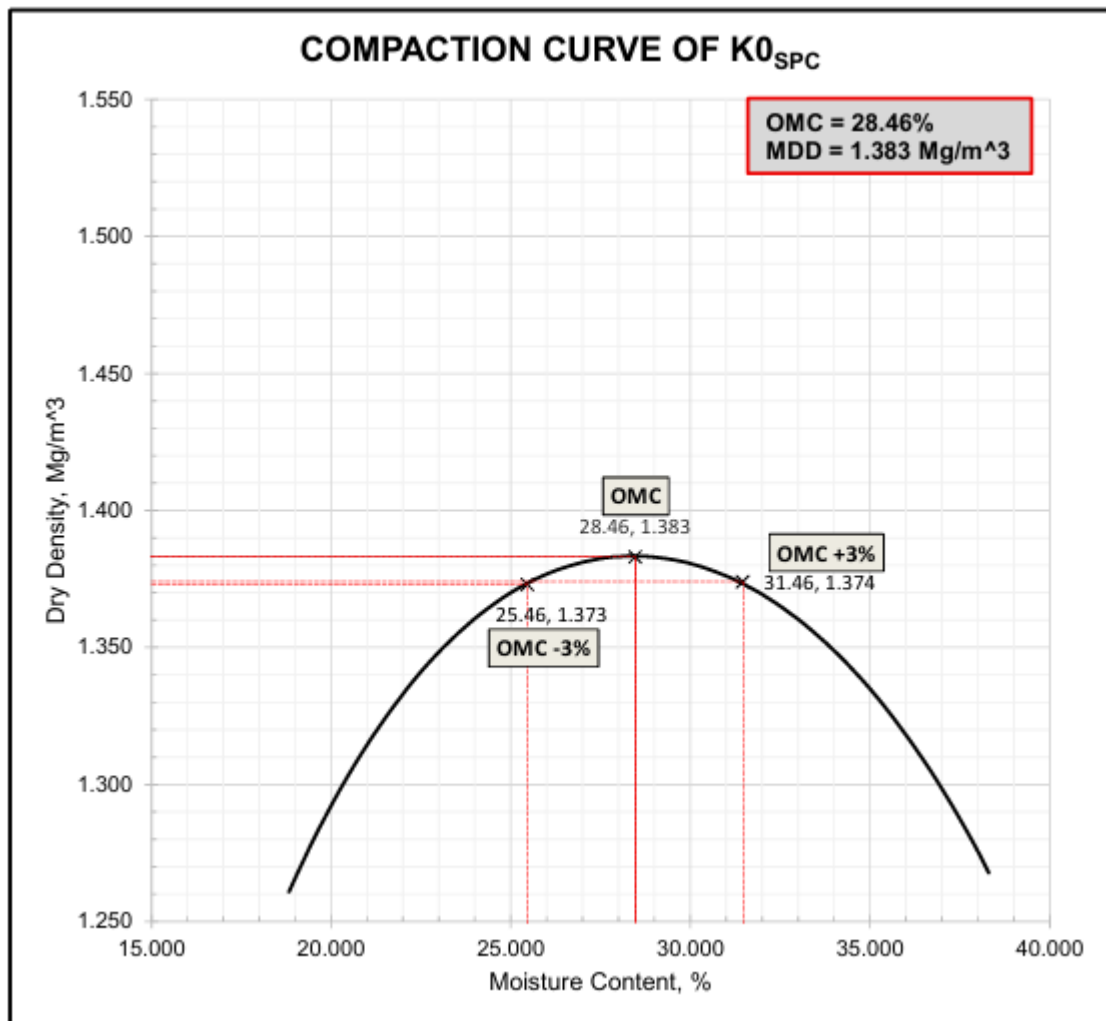
APPENDIX 6

Result of Standard Proctor Compaction (SPC) for Non-contaminated and Contaminated Kaolin Clay

COMPACTION TEST RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT

Project	COMPACTION BEHAVIOUR	Test Method	Standard Proctor Compaction (SPC)
Site	UNCONTAMINATED KAOLIN CLAY	Mass of Rammer	2.5 kg
No. of Sample	K0 (SPC)	Diameter of Mould	10.5 cm
Depth of Sample		Height of Mould	11.5 cm
Date		Volume of mould	995.9158 cm ³
Conducted by	Aliaa Awatif Binti Omar	Specific Gravity of Soil, G _s	2.50 Mg/m ³
		Remarks	

COMPACTION DATA	2			3			4			5			6		
Test no.															
Mass of mould + base (g)	4955			4955			4955			4955			4955		
Mass of mould + base + soil (g)	6420			6570			6680			6755			6705		
Mass of soil (g)	1465			1615			1725			1800			1750		
BULK DENSITY (Mg/m ³)	1.471			1.622			1.732			1.807			1.757		
MOISTURE CONTENT DETERMINATION															
Container no.	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	F3
Mass of container (g)	8.1700	8.2400	8.1900	8.2200	8.2800	8.3600	8.2200	8.1400	16.4000	16.8600	16.8800	16.8600	16.7000	13.5800	16.5100
Mass of container + wet soil (g)	24.1100	22.2400	22.0100	23.8800	19.4100	20.6200	23.5900	19.4200	33.1300	39.7200	34.6700	34.6400	46.7200	51.6100	42.5000
Mass of container + dry soil (g)	21.6300	20.0700	19.9000	21.0500	17.4200	18.4300	20.4300	17.1100	29.6800	34.1800	30.3800	30.3200	38.4500	41.0800	35.3300
Mass of water (%)	0.184	0.183	0.180	0.221	0.218	0.217	0.259	0.258	0.260	0.320	0.318	0.321	0.380	0.383	0.381
Average moisture content	0.183			0.219			0.259			0.320			0.381		
AVERAGE MOISTURE CONTENT (%)	18.262			21.859			25.871			31.953			38.137		
DRY DENSITY (Mg/m ³)	1.244			1.331			1.376			1.370			1.272		
DRY UNIT WEIGHT (kN/m ³)	12.202			13.055			13.499			13.437			12.479		

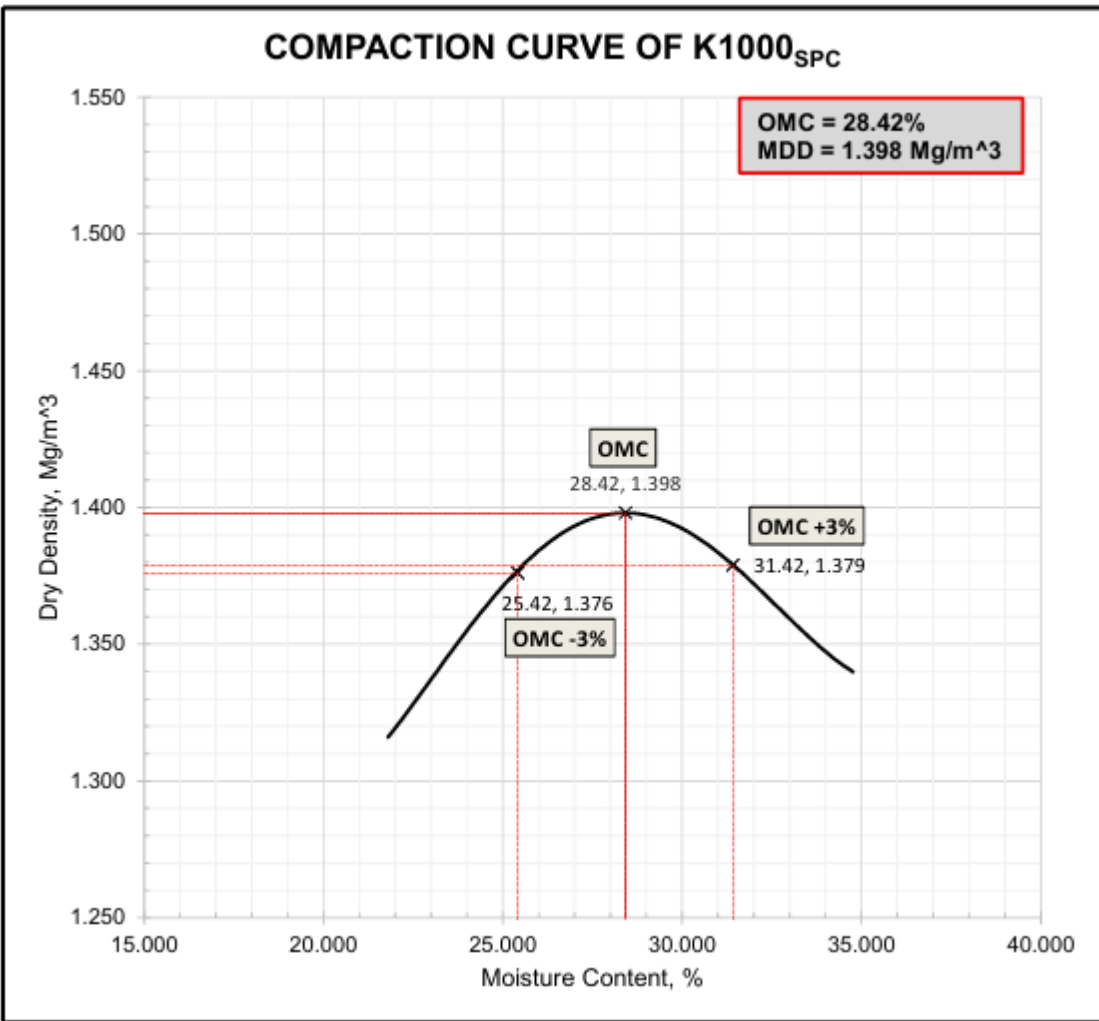


COMPACTION TEST
RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT

Project	COMPACTION BEHAVIOUR
Site	CONTAMINATED KAOLIN CLAY
No. of Sample	K1000 (SPC)
Depth of Sample	
Date	
Conducted by	Aliaa Awatif Binti Omar

Test Method	Standard Proctor Compaction (SPC)
Mass of Rammer	2.5 kg
Diameter of Mould	10.5 cm
Height of Mould	11.5 cm
Volume of mould	995.9158 cm ³
Specific Gravity of Soil, G _s	2.57 Mg/m ³
Remarks	

COMPACTION DATA																		
Test no.	2			3			4			5			6					
Mass of mould + base (g)	4955			4955			4955			4955			4955					
Mass of mould + base + soil (g)	6550			6655			6735			6760			6755					
Mass of soil (g)	1595			1700			1780			1805			1800					
BULK DENSITY (Mg/m^3)	1.602			1.707			1.787			1.812			1.807					
MOISTURE CONTENT DETERMINATION																		
Container no.	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	F3			
Mass of container (g)	8.2500	8.2400	8.2100	8.2300	8.2100	8.2000	8.2300	8.3100	8.1300	8.2600	8.1400	8.1600	8.1800	8.2200	8.1600			
Mass of container + wet soil (g)	30.1400	25.1800	27.2400	27.7000	22.7900	24.2400	35.4500	30.7000	27.6700	27.2300	30.9000	31.5300	34.2600	34.7000	28.0400			
Mass of container + dry soil (g)	26.2500	22.1900	23.7800	23.8300	19.9100	21.0400	29.6000	25.8100	23.3500	22.6800	25.5200	25.9600	27.4700	27.7900	22.8900			
Mass of water (%)	0.216	0.214	0.222	0.248	0.246	0.249	0.274	0.279	0.284	0.316	0.310	0.313	0.352	0.353	0.350			
Average moisture content	0.218			0.248			0.279			0.313			0.352					
AVERAGE MOISTURE CONTENT (%)	21.756			24.782			27.900			31.267			35.157					
DRY DENSITY (Mg/m^3)	1.315			1.368			1.397			1.381			1.337					
DRY UNIT WEIGHT (kN/m^3)	12.904			13.420			13.709			13.545			13.118					

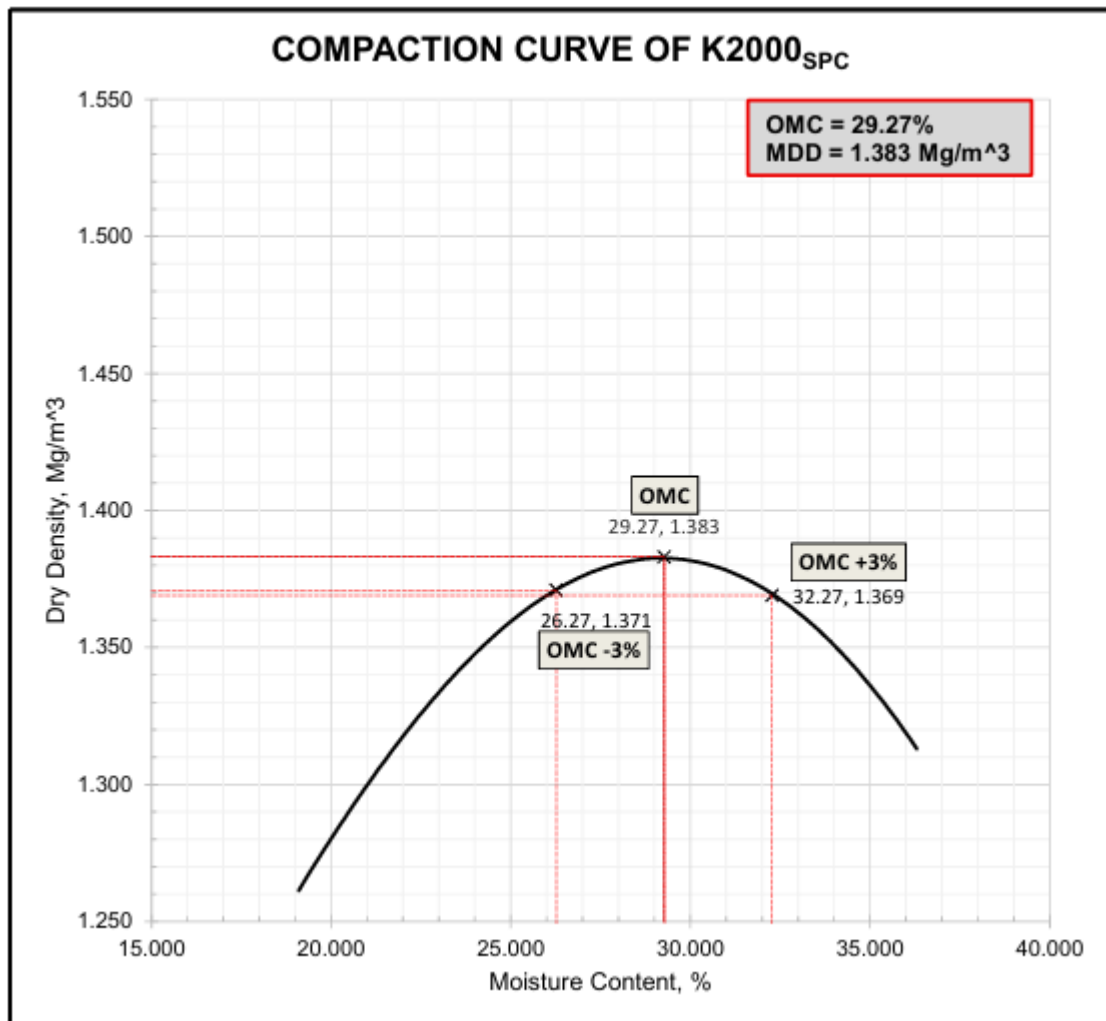


COMPACTION TEST
RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT

Project	COMPACTION BEHAVIOUR
Site	CONTAMINATED KAOLIN CLAY
No. of Sample	K2000 (SPC)
Depth of Sample	
Date	
Conducted by	Aliaa Awatif Binti Omar

Test Method	Standard Proctor Compaction (SPC)
Mass of Rammer	2.5 kg
Diameter of Mould	10.5 cm
Height of Mould	11.5 cm
Volume of mould	995.9158 cm ³
Specific Gravity of Soil, G _s	2.56 Mg/m ³
Remarks	

COMPACTION DATA																		
Test no.	2			3			5			6			7					
Mass of mould + base (g)	4955			4955			4955			4955			4955					
Mass of mould + base + soil (g)	6395			6550			6730			6760			6740					
Mass of soil (g)	1440			1595			1775			1805			1785					
BULK DENSITY (Mg/m^3)	1.446			1.602			1.782			1.812			1.792					
MOISTURE CONTENT DETERMINATION																		
Container no.	B1	B2	B3	C1	C2	C3	E1	E2	E3	F1	F2	F3	G1	G2	G3			
Mass of container (g)	8.1900	8.2700	8.1700	8.3900	8.2100	8.2500	8.3100	8.3200	8.2500	8.2200	8.3600	8.2600	16.8800	16.4300	8.3300			
Mass of container + wet soil (g)	17.0800	17.5300	16.2900	20.9900	15.4000	17.1100	26.3100	22.6600	21.6600	18.9400	23.9600	17.5900	36.9500	36.2200	22.7400			
Mass of container + dry soil (g)	15.7400	16.1400	15.0800	18.7400	14.1100	15.5200	22.2400	19.4400	18.6800	16.2900	20.1200	15.2900	31.6200	30.9600	18.9300			
Mass of water (%)	0.177	0.177	0.175	0.217	0.219	0.219	0.292	0.290	0.286	0.328	0.327	0.327	0.362	0.362	0.359			
Average moisture content	0.176			0.218			0.289			0.327			0.361					
AVERAGE MOISTURE CONTENT (%)	17.640			21.825			28.915			32.736			36.101					
DRY DENSITY (Mg/m^3)	1.229			1.315			1.383			1.365			1.317					
DRY UNIT WEIGHT (kN/m^3)	12.057			12.896			13.563			13.395			12.919					

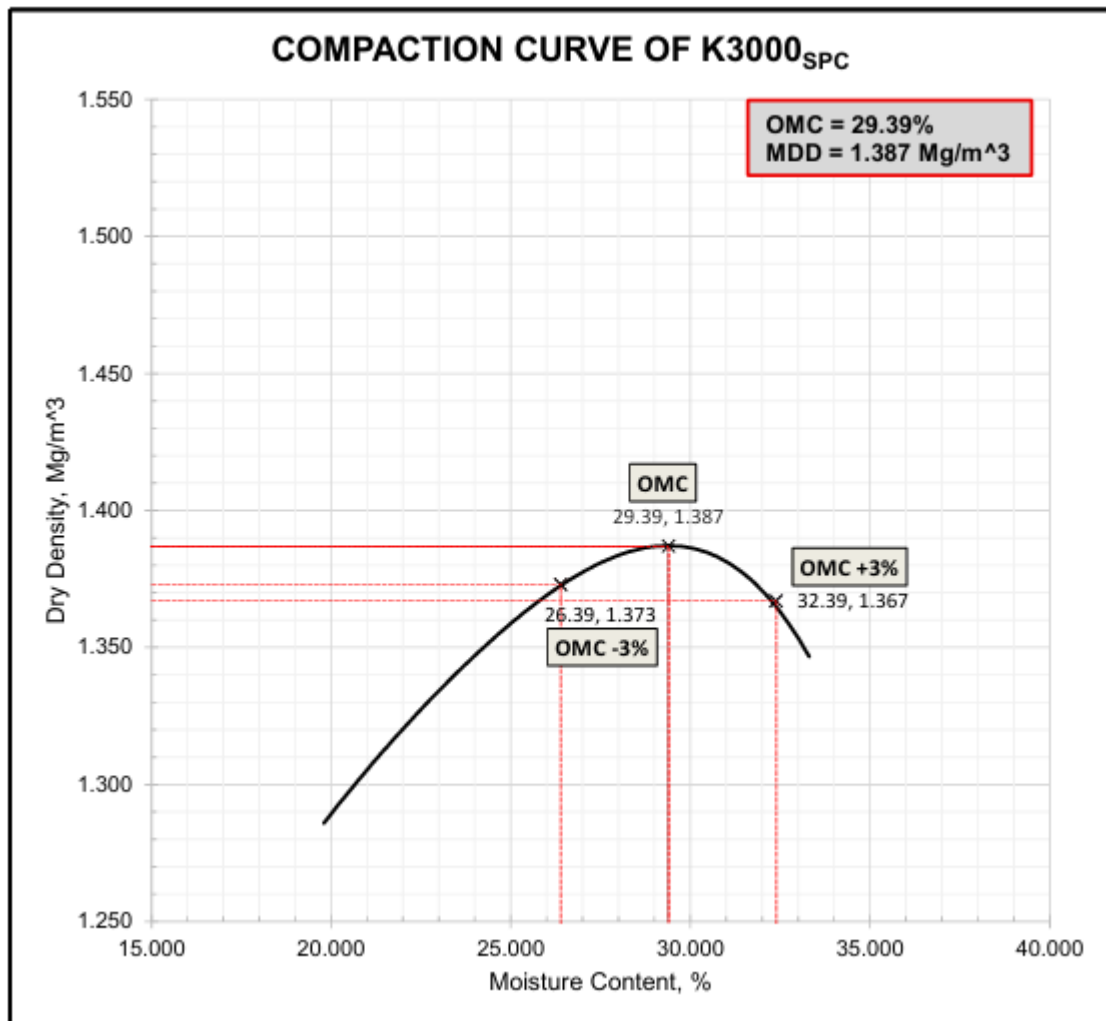


**COMPACTION TEST
RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT**

Project	COMPACTION BEHAVIOUR
Site	CONTAMINATED KAOLIN CLAY
No. of Sample	K3000 (SPC)
Depth of Sample	
Date	
Conducted by	Aliaa Awatif Binti Omar

Test Method	Standard Proctor Compaction (SPC)
Mass of Rammer	2.5 kg
Diameter of Mould	10.5 cm
Height of Mould	11.5 cm
Volume of mould	995.9158 cm ³
Specific Gravity of Soil, G _s	2.55 Mg/m ³
Remarks	

COMPACTION DATA																		
Test no.	2			3			4			5			6					
Mass of mould + base (g)	4955			4955			4955			4955			4955					
Mass of mould + base + soil (g)	6480			6600			6680			6750			6740					
Mass of soil (g)	1525			1645			1725			1795			1785					
BULK DENSITY (Mg/m^3)	1.531			1.652			1.732			1.802			1.792					
MOISTURE CONTENT DETERMINATION																		
Container no.	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	F3			
Mass of container (g)	8.2600	8.2400	8.2200	8.2500	8.1800	8.1000	8.2900	8.2500	8.1600	8.1300	8.3200	8.2400	8.3200	8.2700	8.3500			
Mass of container + wet soil (g)	14.4800	17.9700	16.4100	16.4100	15.0100	15.7200	22.0100	19.6100	20.0700	22.4300	22.1600	26.0800	25.4300	23.0600	23.5200			
Mass of container + dry soil (g)	13.4600	16.3900	15.0700	14.8700	13.7100	14.2800	19.1400	17.2600	17.5900	21.4200	18.9600	21.9700	21.1300	19.3500	19.7300			
Mass of water (%)	0.196	0.194	0.196	0.233	0.235	0.233	0.265	0.261	0.263	0.076	0.301	0.299	0.336	0.335	0.333			
Average moisture content	0.195			0.234			0.263			0.300			0.335					
AVERAGE MOISTURE CONTENT (%)	19.521			23.357			26.278			30.005			33.452					
DRY DENSITY (Mg/m^3)	1.281			1.339			1.372			1.386			1.343					
DRY UNIT WEIGHT (kN/m^3)	12.568			13.136			13.456			13.600			13.175					

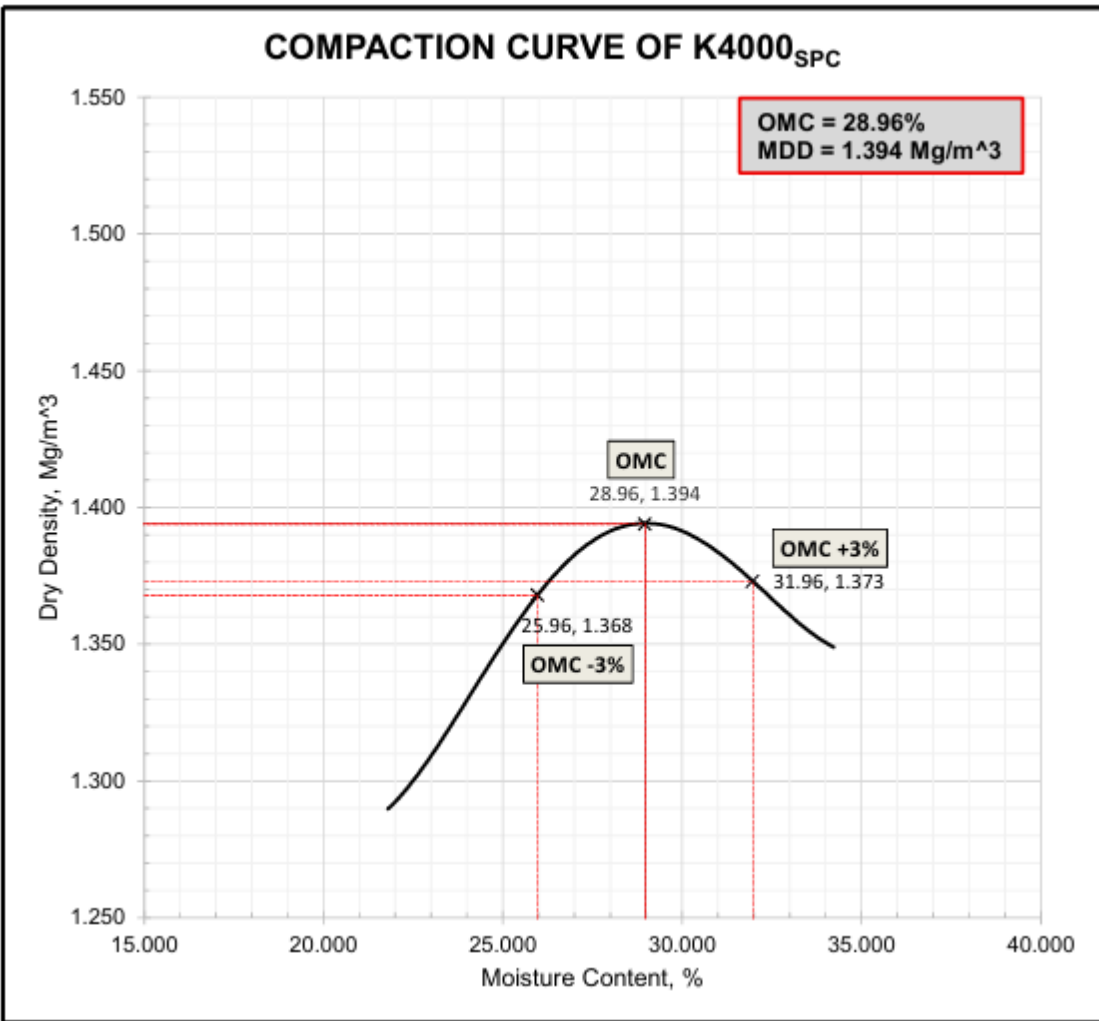


**COMPACTION TEST
RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT**

Project	COMPACTION BEHAVIOUR
Site	CONTAMINATED KAOLIN CLAY
No. of Sample	K4000 (SPC)
Depth of Sample	
Date	
Conducted by	Aliaa Awatif Binti Omar

Test Method	Standard Proctor Compaction (SPC)
Mass of Rammer	2.5 kg
Diameter of Mould	10.5 cm
Height of Mould	11.5 cm
Volume of mould	995.9158 cm ³
Specific Gravity of Soil, G _s	2.51
Remarks	

COMPACTION DATA																
Test no.	2			3			4			5			6			
Mass of mould + base (g)	4950			4950			4950			4950			4950			
Mass of mould + base + soil (g)	6515			6635			6725			6755			6760			
Mass of soil (g)	1565			1685			1775			1805			1810			
DRY DENSITY (Mg/m^3)	1.571			1.692			1.782			1.812			1.817			
MOISTURE CONTENT DETERMINATION																
Container no.	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	F3	
Mass of container (g)	8.2000	8.2100	8.2300	8.2400	8.2200	8.2100	8.2500	8.2000	8.2200	8.2500	8.2100	8.1900	8.1400	8.1900	8.2500	
Mass of container + wet soil (g)	18.5700	19.2500	20.3200	19.7100	20.3100	20.0300	19.0200	19.0200	21.1900	21.1800	23.8600	21.5700	24.7500	25.9000	27.7800	
Mass of container + dry soil (g)	16.7200	17.2700	18.1500	17.4200	17.8900	17.6400	16.6600	16.6400	18.3600	18.0800	20.0800	18.3400	20.4100	21.3200	22.7400	
Mass of water (%)	0.217	0.219	0.219	0.249	0.250	0.253	0.281	0.282	0.279	0.315	0.318	0.318	0.354	0.349	0.348	
Average moisture content	0.218			0.251			0.281			0.317			0.350			
AVERAGE MOISTURE CONTENT (%)	21.814			25.105			28.057			31.735			35.012			
DRY DENSITY (Mg/m^3)	1.290			1.352			1.392			1.376			1.346			
DRY UNIT WEIGHT (kN/m^3)	12.655			13.267			13.653			13.497			13.205			



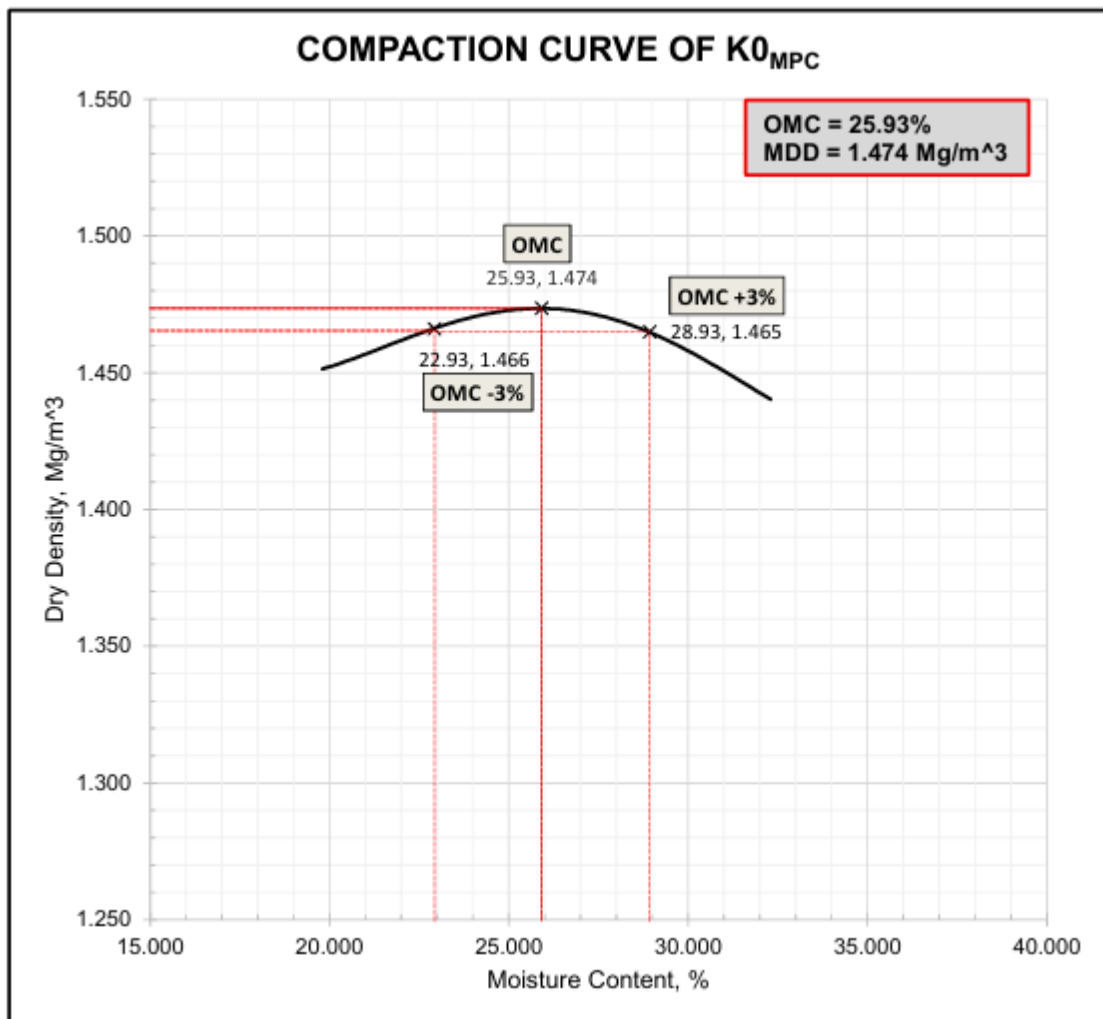
APPENDIX 7

Result of Modified Proctor Compaction (MPC) for Non-contaminated and Contaminated Kaolin Clay

COMPACTION TEST RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT

Project	COMPACTION BEHAVIOUR	Test Method	Modified Proctor Compaction (MPC)
Site	UNCONTAMINATED KAOLIN CLAY	Mass of Rammer	4.5 kg
No. of Sample	K0 (MPC)	Diameter of Mould	10.5 cm
Depth of Sample		Height of Mould	11.5 cm
Date		Volume of mould	995.9158 cm ³
Conducted by	Aliaa Awatif Binti Omar	Specific Gravity of Soil, G _s	2.50
		Remarks	

COMPACTION DATA															
Test no.	2			3			4			5			6		
Mass of mould + base (g)	4955			4955			4955			4955			4955		
Mass of mould + base + soil (g)	6690			6749			6790			6840			6852		
Mass of soil (g)	1735			1794			1835			1885			1897		
BULK DENSITY (Mg/m^3)	1.742			1.801			1.843			1.893			1.905		
MOISTURE CONTENT DETERMINATION															
Container no.	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	F3
Mass of container (g)	8.2500	8.1500	8.1700	8.1600	8.2700	8.2000	8.1900	8.1700	8.2300	8.2200	8.1300	8.0900	8.1800	8.3200	8.0600
Mass of container + wet soil (g)	24.8300	24.3000	25.9400	29.2200	26.9500	27.6400	30.6500	29.1100	31.3100	30.0500	29.4400	31.7100	32.8100	30.4900	31.1200
Mass of container + dry soil (g)	22.0700	21.6200	22.9800	25.3100	23.4700	24.0200	26.1400	24.9100	26.6800	25.0700	24.5800	26.3200	26.8100	25.0900	25.5000
Mass of water (%)	0.200	0.199	0.200	0.228	0.229	0.229	0.251	0.251	0.251	0.296	0.295	0.296	0.322	0.322	0.322
Average moisture content	0.200			0.229			0.251			0.296			0.322		
AVERAGE MOISTURE CONTENT (%)	19.951			22.859			25.103			29.555			32.210		
DRY DENSITY (Mg/m^3)	1.452			1.466			1.473			1.461			1.441		
DRY UNIT WEIGHT (kN/m^3)	14.244			14.381			14.450			14.332			14.136		



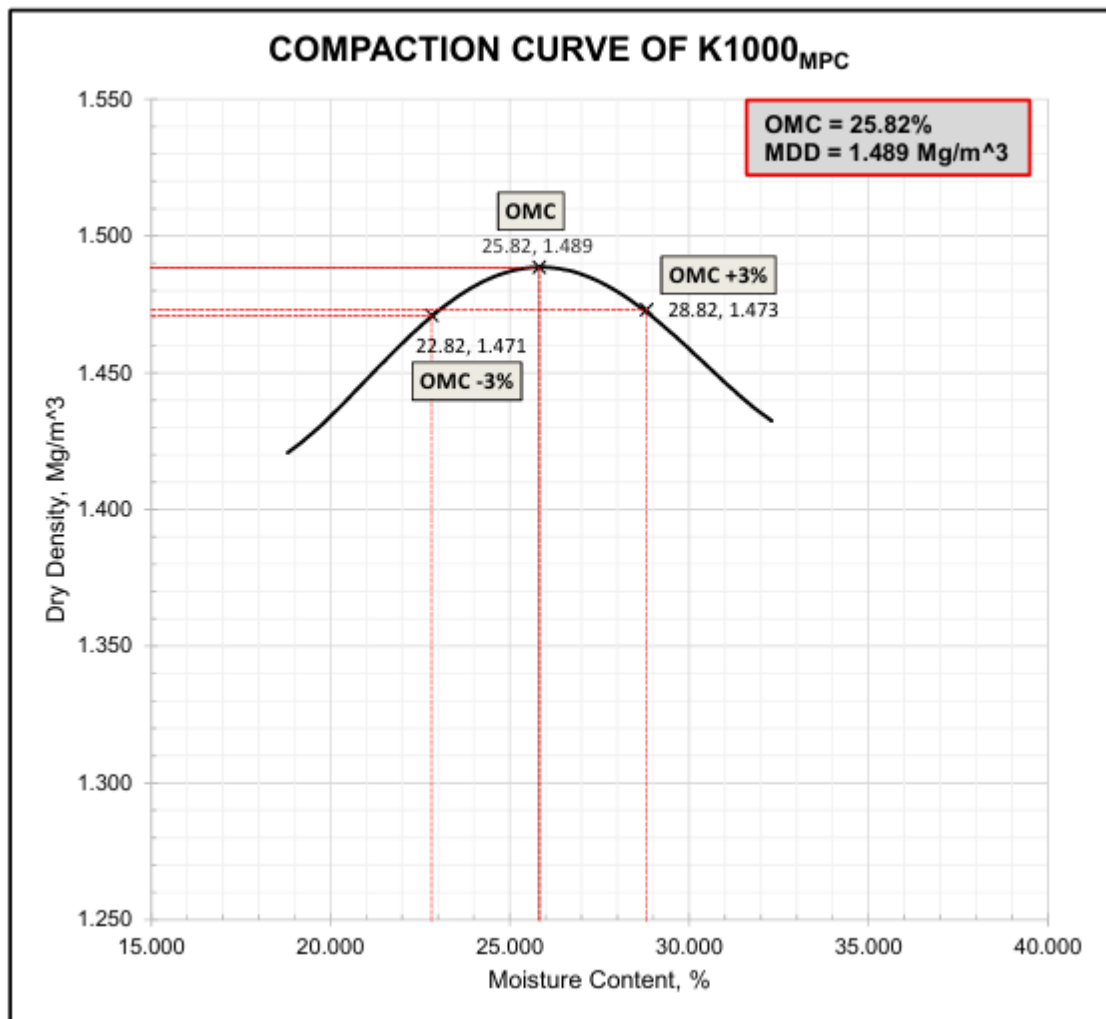
COMPACTION TEST
RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT

Project	COMPACTION BEHAVIOUR
Site	CONTAMINATED KAOLIN CLAY
No. of Sample	K1000 (MPC)
Depth of Sample	
Date	
Conducted by	Aliaa Awatif Binti Omar

Test Method
Mass of Rammer
Diameter of Mould
Height of Mould
Volume of mould
Specific Gravity of Soil, G_s
Remarks

Modified Proctor Compaction (MPC)	
4.5	kg
10.5	cm
11.5	cm
995.9158	cm ³
2.57	

COMPACTION DATA																		
Test no.	2			3			4			5			6					
Mass of mould + base (g)	4955			4955			4955			4955			4955					
Mass of mould + base + soil (g)	6654			6730			6806			6844			6842					
Mass of soil (g)	1699			1775			1851			1889			1887					
BULK DENSITY (Mg/m^3)	1.706			1.783			1.858			1.896			1.895					
MOISTURE CONTENT DETERMINATION																		
Container no.	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	F3			
Mass of container (g)	8.0500	8.4600	8.1700	8.2200	8.1300	8.3100	8.1700	8.0900	8.2500	8.1300	8.1100	8.2400	8.1700	8.2800	8.3000			
Mass of container + wet soil (g)	26.1500	25.9400	26.7700	30.1800	29.8300	31.6100	31.0200	29.1500	30.4000	29.6600	32.7500	31.6900	32.8100	30.4900	31.1200			
Mass of container + dry soil (g)	23.2000	23.0900	23.7300	26.2200	25.9000	27.4200	26.4600	24.9400	25.9700	24.8500	27.2400	26.4300	26.8300	25.0900	25.6000			
Mass of water (%)	0.195	0.195	0.195	0.220	0.221	0.219	0.249	0.250	0.250	0.288	0.288	0.289	0.320	0.321	0.319			
Average moisture content	0.195			0.220			0.250			0.288			0.320					
AVERAGE MOISTURE CONTENT (%)	19.497			22.014			24.972			28.829			32.026					
DRY DENSITY (Mg/m^3)	1.428			1.461			1.487			1.472			1.435					
DRY UNIT WEIGHT (kN/m^3)	14.009			14.332			14.587			14.440			14.077					



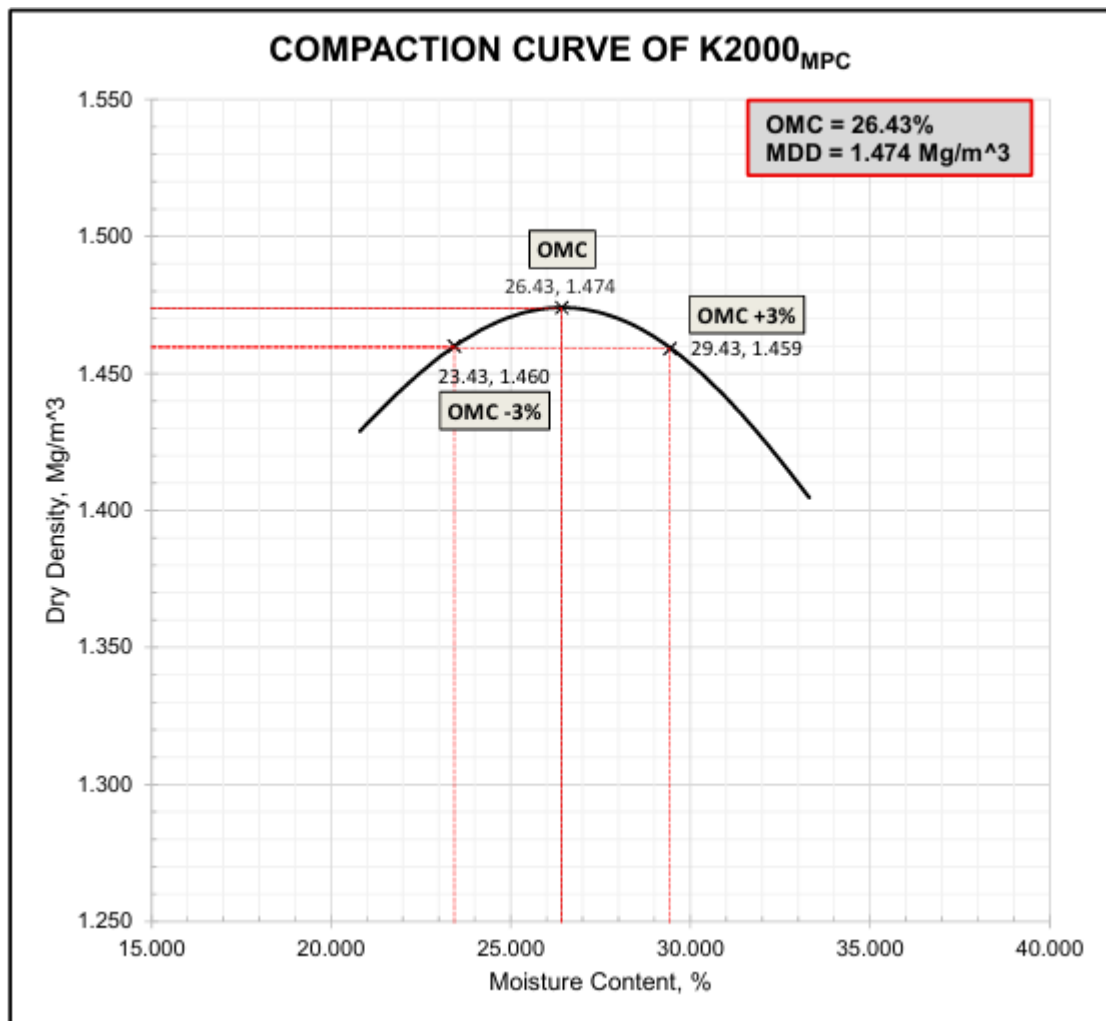
COMPACTION TEST
RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT

Project	COMPACTION BEHAVIOUR
Site	CONTAMINATED KAOLIN CLAY
No. of Sample	K2000 (MPC)
Depth of Sample	
Date	
Conducted by	Aliaa Awatif Binti Omar

Test Method
Mass of Rammer
Diameter of Mould
Height of Mould
Volume of mould
Specific Gravity of Soil, G_s
Remarks

Modified Proctor Compaction (MPC)	
4.5	kg
10.5	cm
11.5	cm
995.9158	cm ³
2.56	

COMPACTION DATA																
Test no.	2				3			4			5			6		
Mass of mould + base (g)	4955				4955			4955			4955			4955		
Mass of mould + base + soil (g)	6665				6750			6814			6837			6823		
Mass of soil (g)	1710				1795			1859			1882			1868		
BULK DENSITY (Mg/m^3)	1.717				1.802			1.866			1.889			1.875		
MOISTURE CONTENT DETERMINATION																
Container no.	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	F3	
Mass of container (g)	8.3300	8.6100	8.0200	8.1400	8.0600	8.3700	8.1500	8.1700	8.2400	8.1600	8.3200	8.2900	8.1300	8.2200	8.1800	
Mass of container + wet soil (g)	25.4400	26.1500	25.5900	29.4600	28.9100	30.7700	29.7300	31.8100	32.0600	30.1600	33.0100	32.1700	31.6700	32.9300	31.8800	
Mass of container + dry soil (g)	22.5100	23.1700	22.6100	25.4100	24.9500	26.5200	25.1900	26.8300	27.0700	25.1200	27.3500	26.7200	25.8200	26.8000	26.0100	
Mass of water (%)	0.207	0.205	0.204	0.235	0.234	0.234	0.266	0.267	0.265	0.297	0.297	0.296	0.331	0.330	0.329	
Average moisture content	0.205			0.234			0.266			0.297			0.330			
AVERAGE MOISTURE CONTENT (%)	20.518			23.438			26.611			29.677			32.995			
DRY DENSITY (Mg/m^3)	1.425			1.460			1.474			1.457			1.410			
DRY UNIT WEIGHT (kN/m^3)	13.979			14.323			14.460			14.293			13.832			



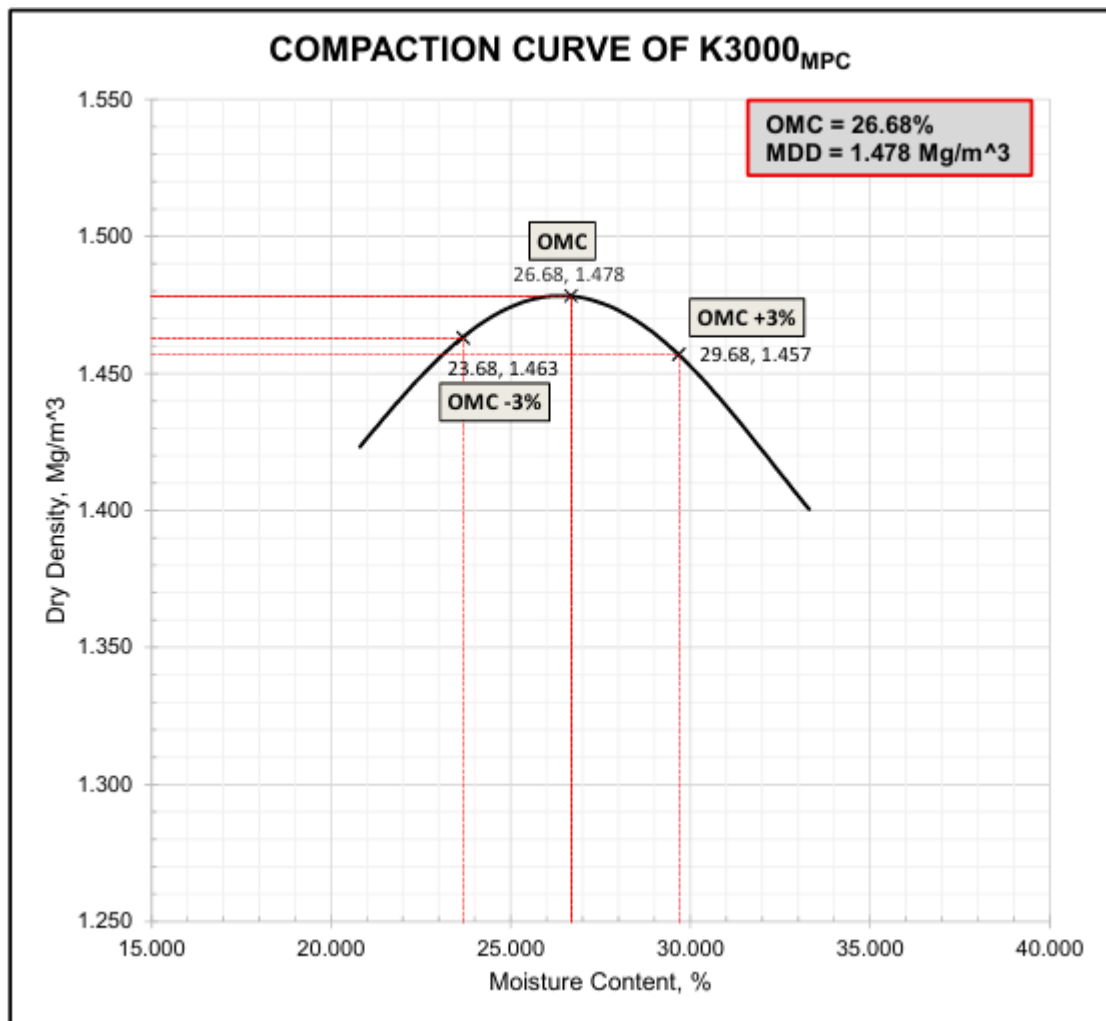
COMPACTION TEST
RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT

Project	COMPACTION BEHAVIOUR
Site	CONTAMINATED KAOLIN CLAY
No. of Sample	K3000 (MPC)
Depth of Sample	
Date	
Conducted by	Aliaa Awatif Binti Omar

Test Method
 Mass of Rammer
 Diameter of Mould
 Height of Mould
 Volume of mould
 Specific Gravity of Soil, G_s
 Remarks

Modified Proctor Compaction (MPC)	
4.5	kg
10.5	cm
11.5	cm
995.9158	cm ³
2.55	

COMPACTION DATA																
Test no.	2			3			4			5			6			
Mass of mould + base (g)	4955			4955			4955			4955			4955			
Mass of mould + base + soil (g)	6660			6764			6826			6836			6816			
Mass of soil (g)	1705			1809			1871			1881			1861			
BULK DENSITY (Mg/m^3)	1.712			1.817			1.879			1.889			1.869			
MOISTURE CONTENT DETERMINATION																
Container no.	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	F3	
Mass of container (g)	8.1700	2.1800	8.1100	8.0500	8.5300	8.2700	8.2200	8.2900	8.1400	8.1500	8.2700	8.1300	8.3900	8.2700	8.0900	
Mass of container + wet soil (g)	26.8800	25.7100	27.1200	26.9100	28.3300	27.7600	33.0400	29.2200	31.9000	30.3100	32.4700	31.1600	33.1700	31.6600	30.9800	
Mass of container + dry soil (g)	23.6800	21.6900	23.8800	23.2900	24.5000	23.9800	27.7200	24.7600	26.8100	25.2400	26.9000	25.8600	27.0100	25.8800	25.2800	
Mass of water (%)	0.206	0.206	0.205	0.238	0.240	0.241	0.273	0.271	0.273	0.297	0.299	0.299	0.331	0.328	0.332	
Average moisture content	0.206			0.239			0.272			0.298			0.330			
AVERAGE MOISTURE CONTENT (%)	20.594			23.932			27.208			29.819			33.021			
DRY DENSITY (Mg/m^3)	1.420			1.466			1.477			1.455			1.405			
DRY UNIT WEIGHT (kN/m^3)	13.930			14.381			14.489			14.274			13.783			

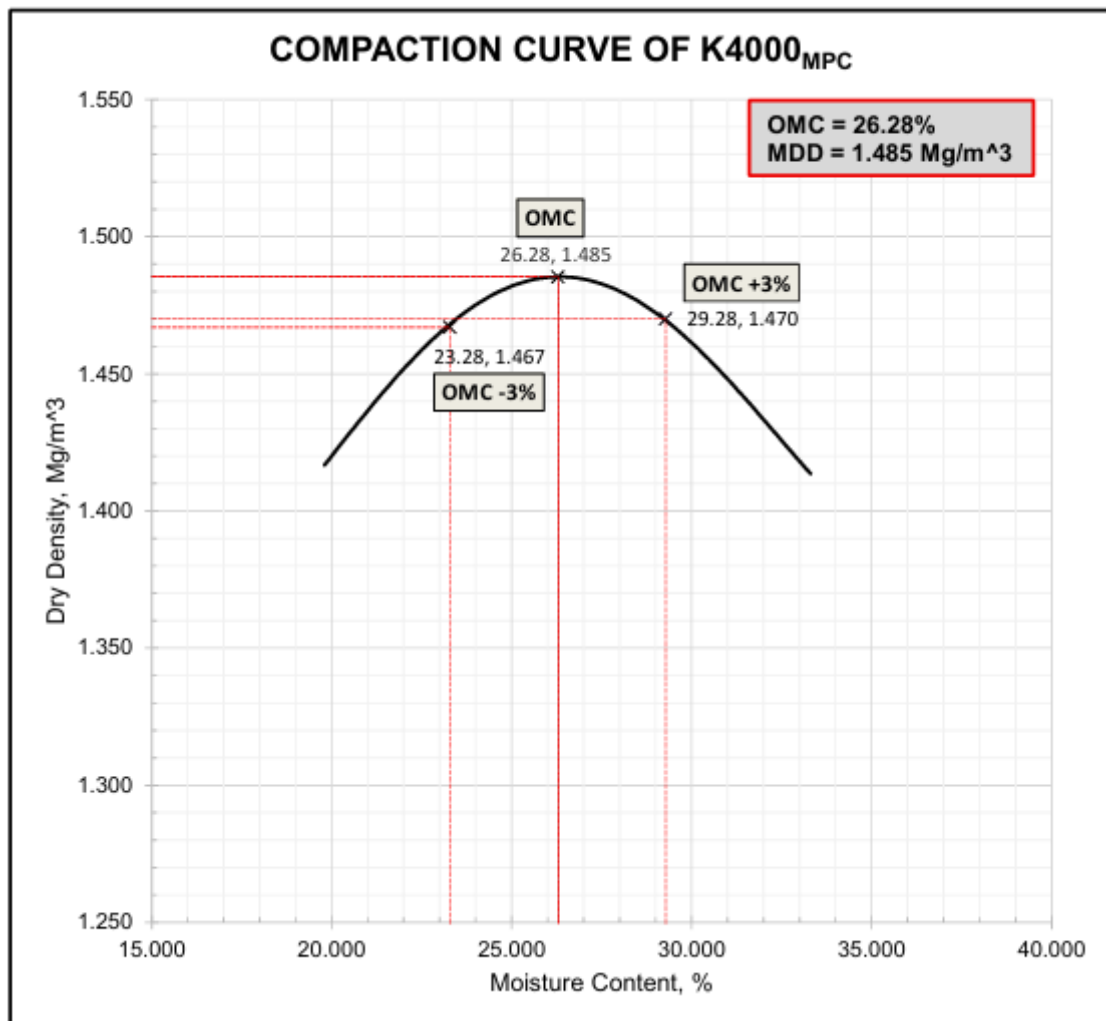


COMPACTION TEST
RELATIONSHIP OF DRY DENSITY AND MOISTURE CONTENT

Project	COMPACTION BEHAVIOUR
Site	CONTAMINATED KAOLIN CLAY
No. of Sample	K4000 (MPC)
Depth of Sample	
Date	
Conducted by	Aliaa Awatif Binti Omar

Test Method	Modified Proctor Compaction (MPC)
Mass of Rammer	4.5 kg
Diameter of Mould	10.5 cm
Height of Mould	11.5 cm
Volume of mould	995.9158 cm ³
Specific Gravity of Soil, G _s	2.51
Remarks	

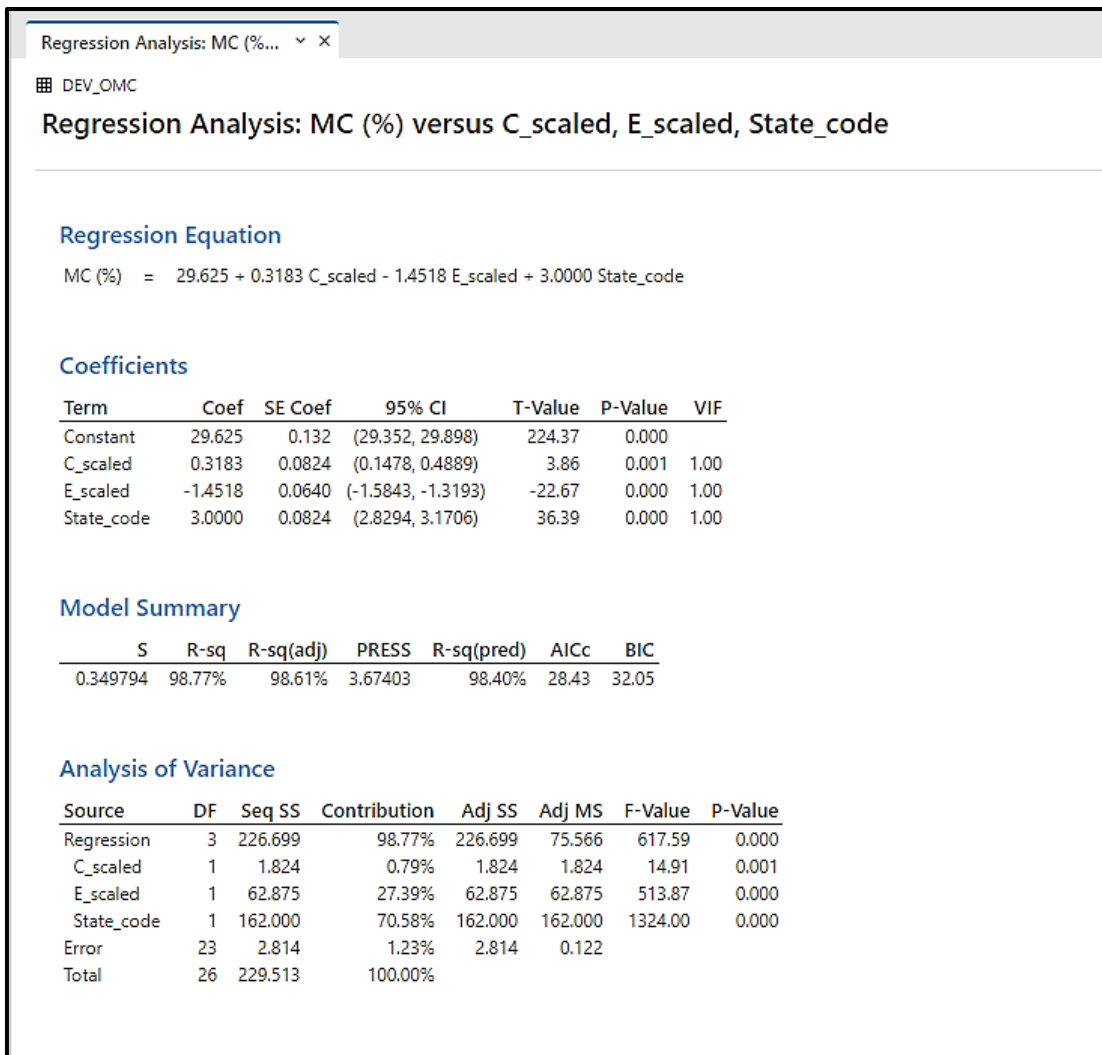
COMPACTION DATA																
Test no.	2				3			4			5			6		
Mass of mould + base (g)	4950				4950			4950			4950			4950		
Mass of mould + base + soil (g)	6653				6733			6812			6842			6826		
Mass of soil (g)	1703				1783			1862			1892			1876		
BULK DENSITY (Mg/m^3)	1.710				1.790			1.869			1.900			1.884		
MOISTURE CONTENT DETERMINATION																
Container no.	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	F3	
Mass of container (g)	8.2500	8.1600	8.1900	8.2200	8.1800	8.1500	8.2700	8.1700	8.1300	8.0600	8.3200	8.2300	8.2000	8.1700	8.0900	
Mass of container + wet soil (g)	24.9300	24.0300	24.5500	27.9500	27.3200	29.1700	29.6700	28.9400	30.7400	28.8600	32.2700	30.3800	31.2100	30.0400	30.1600	
Mass of container + dry soil (g)	22.1200	21.3800	21.8000	24.3300	23.7800	25.2900	25.2700	24.6900	26.0700	24.1500	26.8400	25.3500	25.4600	24.5600	24.6500	
Mass of water (%)	0.203	0.200	0.202	0.225	0.227	0.226	0.259	0.257	0.260	0.293	0.293	0.294	0.333	0.334	0.333	
Average moisture content	0.202			0.226			0.259			0.293			0.333			
AVERAGE MOISTURE CONTENT (%)	20.170			22.600			25.880			29.324			33.341			
DRY DENSITY (Mg/m^3)	1.423			1.460			1.485			1.469			1.413			
DRY UNIT WEIGHT (kN/m^3)	13.960			14.323			14.568			14.411			13.862			



APPENDIX 8

Development Model for Optimum Moisture Content using Minitab Software

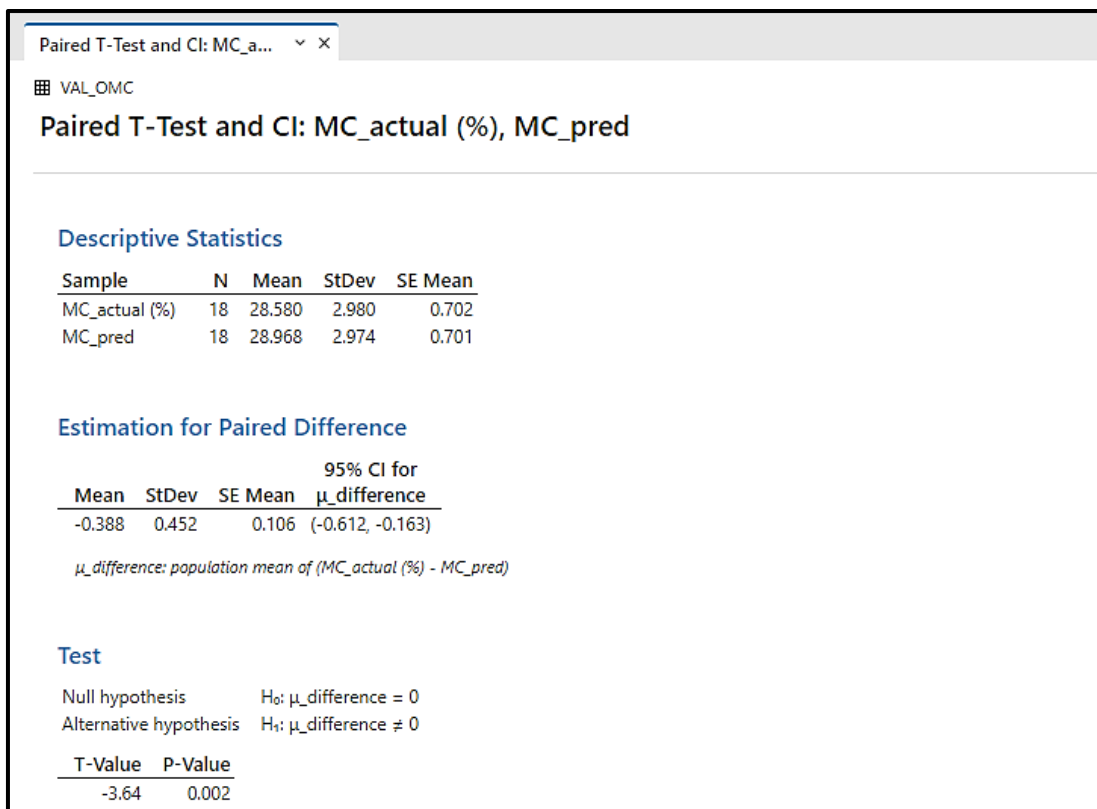
↓	C1-T	C2	C3 ☒	C4	C5	C6	C7	C8
	K-group	Energy, E (kN-m/m ³)	MC (%)	Concentration, C (mg/L)	C_scaled	E_scaled	C2_scaled	State_code
1	K0	360	26.47	0	0	0.36	0	-1
2	K0	360	29.47	0	0	0.36	0	0
3	K0	360	32.47	0	0	0.36	0	1
4	K0	600	25.46	0	0	0.60	0	-1
5	K0	600	28.46	0	0	0.60	0	0
6	K0	600	31.46	0	0	0.60	0	1
7	K0	2700	22.93	0	0	2.70	0	-1
8	K0	2700	25.93	0	0	2.70	0	0
9	K0	2700	28.93	0	0	2.70	0	1
10	K1000	360	26.68	1000	1	0.36	1	-1
11	K1000	360	29.68	1000	1	0.36	1	0
12	K100	360	32.68	1000	1	0.36	1	1
13	K100	600	25.42	1000	1	0.60	1	-1
14	K1000	600	28.42	1000	1	0.60	1	0
15	K1000	600	31.42	1000	1	0.60	1	1
16	K1000	2700	22.82	1000	1	2.70	1	-1
17	K1000	2700	25.82	1000	1	2.70	1	0
18	K1000	2700	28.82	1000	1	2.70	1	1
19	K2000	360	27.07	2000	2	0.36	4	-1
20	K2000	360	30.07	2000	2	0.36	4	0
21	K2000	360	33.07	2000	2	0.36	4	1
22	K2000	600	26.27	2000	2	0.60	4	-1
23	K2000	600	29.27	2000	2	0.60	4	0
24	K2000	600	32.27	2000	2	0.60	4	1
25	K2000	2700	23.43	2000	2	2.70	4	-1
26	K2000	2700	26.43	2000	2	2.70	4	0
27	K2000	2700	29.43	2000	2	2.70	4	1



APPENDIX 9

Validation of Optimum Moisture Content Model using Minitab Software

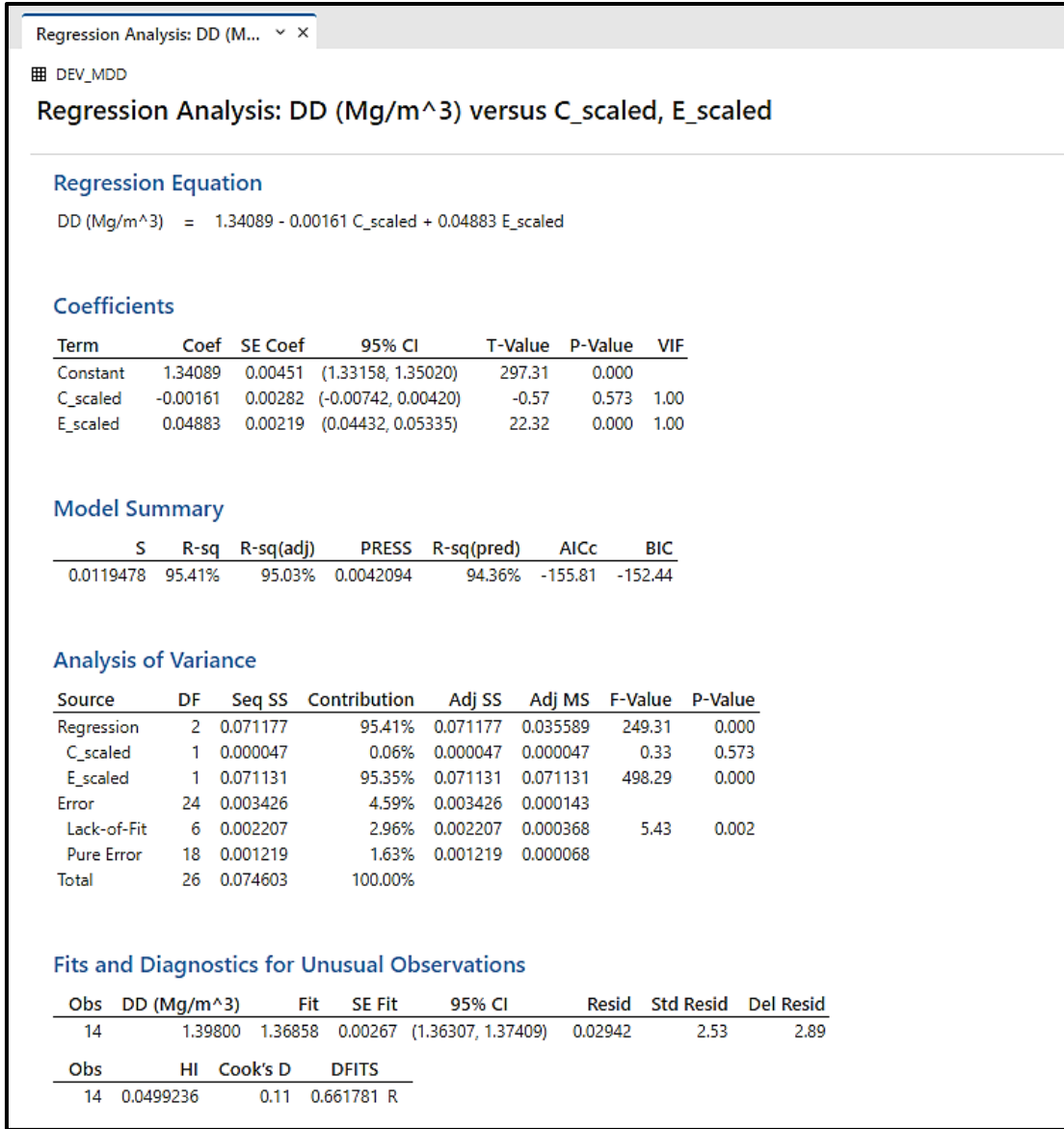
↓	C1-T	C2	C3 	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
	K-group	Energy, E (kN-m/m ³)	MC_actual (%)	Concentration, C (mg/L)	C_scaled	E_scaled	State_code	MC_pred	Error	Absolute Error	Percentage Error	Mean % Error	Squared_Error	RMSE
1	K3000	360	27.31	3000	3	0.36	-1	27.0573	0.25275	0.25275	0.92548	1.68961	0.06388	0.585683
2	K3000	360	30.31	3000	3	0.36	0	30.0573	0.25275	0.25275	0.83388		0.06388	
3	K3000	360	33.31	3000	3	0.36	1	33.0573	0.25275	0.25275	0.75878		0.06388	
4	K3000	600	26.39	3000	3	0.60	-1	26.7088	-0.31882	0.31882	1.20811		0.10165	
5	K3000	600	29.39	3000	3	0.60	0	29.7088	-0.31882	0.31882	1.08479		0.10165	
6	K3000	600	32.39	3000	3	0.60	1	32.7088	-0.31882	0.31882	0.98432		0.10165	
7	K3000	2700	23.68	3000	3	2.70	-1	23.6600	0.01996	0.01996	0.08429		0.00040	
8	K3000	2700	26.68	3000	3	2.70	0	26.6600	0.01996	0.01996	0.07481		0.00040	
9	K3000	2700	29.68	3000	3	2.70	1	29.6600	0.01996	0.01996	0.06725		0.00040	
10	K4000	360	26.86	4000	4	0.36	-1	27.3756	-0.51555	0.51555	1.91940		0.26579	
11	K4000	360	29.86	4000	4	0.36	0	30.3756	-0.51555	0.51555	1.72656		0.26579	
12	K4000	360	32.86	4000	4	0.36	1	33.3756	-0.51555	0.51555	1.56893		0.26579	
13	K4000	600	25.96	4000	4	0.60	-1	27.0271	-1.06712	1.06712	4.11063		1.13875	
14	K4000	600	28.96	4000	4	0.60	0	30.0271	-1.06712	1.06712	3.68481		1.13875	
15	K4000	600	31.96	4000	4	0.60	1	33.0271	-1.06712	1.06712	3.33892		1.13875	
16	K4000	2700	23.28	4000	4	2.70	-1	23.9783	-0.69834	0.69834	2.99974		0.48768	
17	K4000	2700	26.28	4000	4	2.70	0	26.9783	-0.69834	0.69834	2.65731		0.48768	
18	K4000	2700	29.28	4000	4	2.70	1	29.9783	-0.69834	0.69834	2.38504		0.48768	



APPENDIX 10

Development Model for Maximum Dry Density using Minitab Software

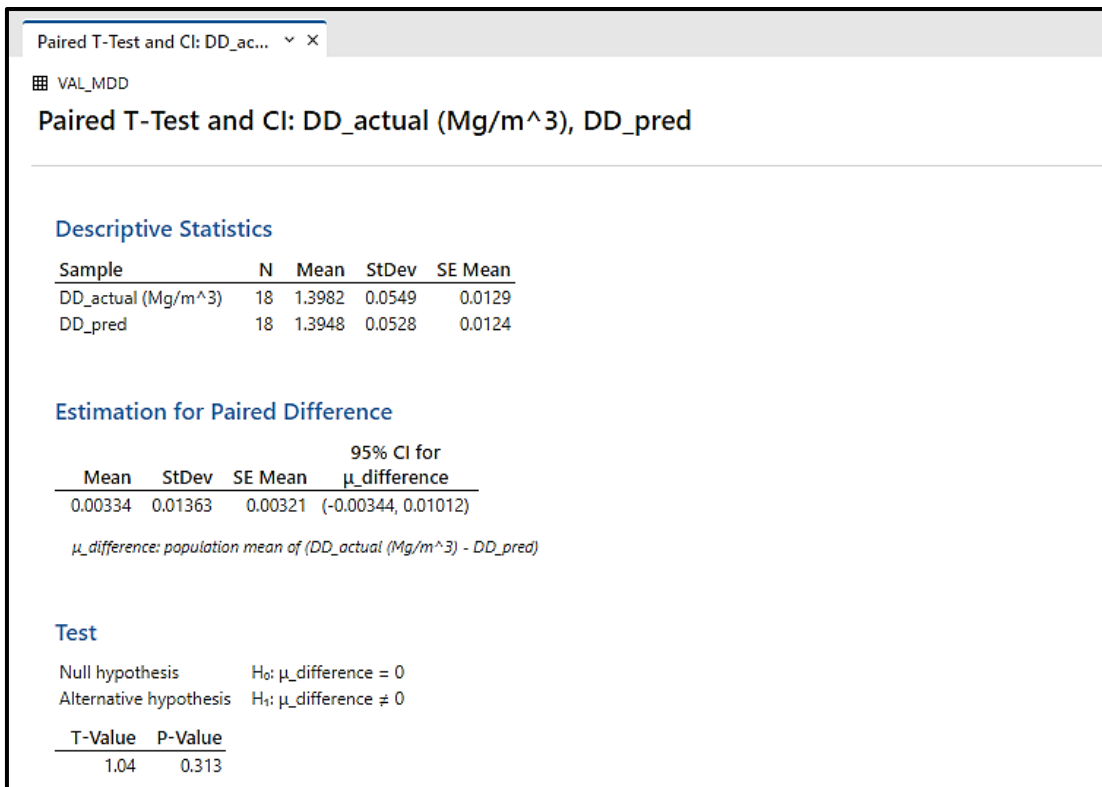
↓	C1-T	C2	C3 ☒	C4	C5	C6	C7	C8
	K-group	Energy, E (kN-m/m ³)	DD (Mg/m ³)	Concentration, C (mg/L)	C_scaled	E_scaled	C2_scaled	State_code
1	K0	360	1.343	0	0	0.36	0	-1
2	K0	360	1.352	0	0	0.36	0	0
3	K0	360	1.344	0	0	0.36	0	1
4	K0	600	1.373	0	0	0.60	0	-1
5	K0	600	1.383	0	0	0.60	0	0
6	K0	600	1.374	0	0	0.60	0	1
7	K0	2700	1.466	0	0	2.70	0	-1
8	K0	2700	1.474	0	0	2.70	0	0
9	K0	2700	1.465	0	0	2.70	0	1
10	K1000	360	1.348	1000	1	0.36	1	-1
11	K1000	360	1.367	1000	1	0.36	1	0
12	K100	360	1.349	1000	1	0.36	1	1
13	K100	600	1.376	1000	1	0.60	1	-1
14	K1000	600	1.398	1000	1	0.60	1	0
15	K1000	600	1.379	1000	1	0.60	1	1
16	K1000	2700	1.471	1000	1	2.70	1	-1
17	K1000	2700	1.489	1000	1	2.70	1	0
18	K1000	2700	1.473	1000	1	2.70	1	1
19	K2000	360	1.340	2000	2	0.36	4	-1
20	K2000	360	1.351	2000	2	0.36	4	0
21	K2000	360	1.338	2000	2	0.36	4	1
22	K2000	600	1.371	2000	2	0.60	4	-1
23	K2000	600	1.383	2000	2	0.60	4	0
24	K2000	600	1.369	2000	2	0.60	4	1
25	K2000	2700	1.460	2000	2	2.70	4	-1
26	K2000	2700	1.474	2000	2	2.70	4	0
27	K2000	2700	1.459	2000	2	2.70	4	1



APPENDIX 11

Validation of Maximum Dry Density Model using Minitab Software

↓	C1-T	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
	K-group	Energy, E (kN-m/m ³)	DD_actual (Mg/m ³)	Concentration, C (mg/L)	C_scaled	E_scaled	State_code	DD_pred	Error	Absolute Error	Percentage Error	Mean % Error
1	K3000	360	1.331	3000	3	0.36	-1	1.35364	-0.0226388	0.0226388	1.70089	0.784386
2	K3000	360	1.356	3000	3	0.36	0	1.35364	0.0023612	0.0023612	0.17413	
3	K3000	360	1.337	3000	3	0.36	1	1.35364	-0.0166388	0.0166388	1.24449	
4	K3000	600	1.373	3000	3	0.60	-1	1.36536	0.0076420	0.0076420	0.55659	
5	K3000	600	1.387	3000	3	0.60	0	1.36536	0.0216420	0.0216420	1.56035	
6	K3000	600	1.367	3000	3	0.60	1	1.36536	0.0016420	0.0016420	0.12012	
7	K3000	2700	1.463	3000	3	2.70	-1	1.46790	-0.0049010	0.0049010	0.33500	
8	K3000	2700	1.478	3000	3	2.70	0	1.46790	0.0100990	0.0100990	0.68329	
9	K3000	2700	1.457	3000	3	2.70	1	1.46790	-0.0109010	0.0109010	0.74818	
10	K4000	360	1.342	4000	4	0.36	-1	1.35203	-0.0100288	0.0100288	0.74730	
11	K4000	360	1.363	4000	4	0.36	0	1.35203	0.0109712	0.0109712	0.80493	
12	K4000	360	1.349	4000	4	0.36	1	1.35203	-0.0030288	0.0030288	0.22452	
13	K4000	600	1.368	4000	4	0.60	-1	1.36375	0.0042520	0.0042520	0.31082	
14	K4000	600	1.394	4000	4	0.60	0	1.36375	0.0302520	0.0302520	2.17016	
15	K4000	600	1.380	4000	4	0.60	1	1.36375	0.0162520	0.0162520	1.17768	
16	K4000	2700	1.467	4000	4	2.70	-1	1.46629	0.0007090	0.0007090	0.04833	
17	K4000	2700	1.485	4000	4	2.70	0	1.46629	0.0187090	0.0187090	1.25987	
18	K4000	2700	1.470	4000	4	2.70	1	1.46629	0.0037090	0.0037090	0.25231	



AUTHOR'S PROFILE



Aliaa Awatif Omar obtained her Bachelor of Engineering (Hons) Civil in 2024 and Diploma of Civil Engineering in 2021 from Universiti Teknologi MARA (UiTM), Malaysia. Her MSc thesis, Model of Compaction Behaviour for Various Concentration Lead-Contaminated Kaolin Clay under Different Compactive Efforts involves several methods including geotechnical laboratory analysis and empirical analysis in developing empirical models through regression modelling. Currently, her research interest focuses on Geoenvironmental field including soil improvement, soil remediation, and advanced analysis techniques such as digital image processing and predictive modelling.

LIST OF PUBLICATION

Mukri, M., Anuar, H. A. K., Khalid, N., & Omar, A. A. (2026). Assessment of properties and the influence on compaction characteristics, settlement behaviour, and hydraulic conductivity at Tanjung Dua Belas and Air Hitam landfills. *International Journal of Latest Technology in Engineering Management & Applied Science*, 15(2), 1179–1196. <https://doi.org/10.51583/ijltemas.2026.15020000103>