

ENGINEERING GEOLOGICAL ASSESSMENT OF
LATERITIC SOILS AS LANDFILL LINERS IN EKITI STATE,
SOUTHWESTERN NIGERIA

By

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ABSTRACT

The quantity of waste generated in Ekiti state, southwestern Nigeria, has been increasing dramatically due to a rapid urban expansion resulting from population growth and associated economic activities. However, these increasing wastes produced are disposed of into large open dumpsites located in the premises of urban and peri-urban centres, which lack engineered control systems designed to prevent environmental degradation, especially contamination of groundwater and the ecosystem. Thus, there is a need for an affordable and viable long-term solution to protect the environment, including the groundwater system. Landfilling of waste in engineered facilities has gained a wide acceptance especially in developing countries, where it is almost the only viable way of solid waste disposal. Landfills usually require the emplacement of liners, which are constructed with geosynthetic materials and or the use of compacted natural soils. Due to the low cost, good contaminant attenuation capacity and ease of use, compacted soil liners (CSLs) are more attractive options than Geosynthetic Clay Liners (GCLs). However, the unavailability of clay soils for the construction of CSLs has necessitated the search for alternative materials such as lateritic soils. Lateritic soils are the most common construction soils in tropical environments where their formation and nature are determined by different environmental factors. These soils are very diverse in their physicochemical properties and it is essential that their suitability as potential CSLs must be carefully evaluated.

The aims of this research are to evaluate the suitability of lateritic soils from Ekiti State, southwestern Nigeria for use as landfill liners, and examine the influence of various parent rocks on the geotechnical and geochemical properties of these soils. Field observations, petrographic, geochemical and mineralogical analyses of the various rock types were undertaken to ascertain the different parent rocks that are present in the study area. Geochemical and geotechnical analyses as well as batch equilibrium tests were conducted on representative soil samples derived from the different parent rock types in order to determine the clay mineralogy of the different soil types, their index and geotechnical properties, and their contaminant attenuation capacities.

Petrographic and geochemical analyses show that the dominant parent rocks present on site are porphyritic granite, charnockite, migmatite, granite-gneiss, schist and quartzite. The dominant clay minerals present in the lateritic soils are kaolinite and dickite, implying low desiccation cracking and low shrink-swell behaviour. The tested soils have cation exchange capacities that range from 10.3 to 15.9 meq/100g, indicating good contaminant attenuation potential. The batch equilibrium sorption analysis undertaken to assess the competitive sorption of trace metals, namely, Cd, Pb, Cr, Mn and Cu found commonly in landfill leachate of the study area showed that the lateritic soils derived from granite-gneiss and charnockite exhibit better sorption potential than those derived from schist and quartzite as indicated by their maximum

adsorption capacity, which is closely related to the goethite content in the soils. The sorption isotherms of these trace metals onto the lateritic soils are described by the Langmuir equation and these isotherms deviate from the corresponding desorption isotherms to different degrees which is indicative of various extents of hysteresis. The sorption hysteresis indices for these trace metals range from 0.63 to 0.99 and imply that the trace metals may be re-released and leached to the surrounding soils and groundwater.

The geotechnical index test results indicate that the lateritic soils are well graded and could be classified as inorganic clays and silts of low to high plasticity. Furthermore, the lateritic soils derived from porphyritic granite possess the lowest average Maximum Dry Density (MDD) of 1.45 mg/m^3 , while the highest MDD of 1.61 mg/m^3 was obtained for lateritic soils derived from granite-gneiss. Lateritic soils derived from charnockite, migmatite and quartzite are found to have MDD of 1.48 mg/m^3 , 1.50 mg/m^3 and 1.51 mg/m^3 , respectively. The total shear strength parameters indicate that the average values of the total cohesion of the soils derived from porphyritic granite, charnockite, migmatite, granite-gneiss and quartzite are 45.6 kPa, 44.7 kPa, 40.3 kPa, 42.7 kPa and 35.2 kPa, respectively. The average total angle of internal friction obtained for the lateritic soils derived from porphyritic granite, charnockite, migmatite, granite-gneiss and quartzite friction are 10.8° , 10.9° , 11.3° , 11.1° and 9.6° , respectively. These shear strength parameters indicate that the soils derived from the various parent rocks have adequate shear strength as they display results above the required minimum for landfill liners. The measured coefficient of permeability (K) values of the lateritic soils tested range from $1.1 \times 10^{-8} \text{ m/s}$ for soils derived from porphyritic granite to $1.3 \times 10^{-8} \text{ m/s}$ for soils derived from quartzite. Although, these K values indicate very low degree of permeability, they do not conform to the required limit ($\leq 1 \times 10^{-9} \text{ m/s}$) for landfill liners.

The most converging findings of this study are that most of the lateritic soils in Ekiti state in southwestern Nigeria meet the index and engineering quality requirements stipulated by the USEPA (2021) for soil liner materials except for the hydraulic conductivity. The coefficient of permeability observed in some lateritic soils was significantly reduced by mixing of lateritic soils of various provenances having low coefficient of permeability. Furthermore, the significant adsorption capacity of the lateritic soils for Cd and Pb indicates the remarkable efficiency of the soils to sorb these trace metals if it comes in contact with leachate. However, the sorption hysteresis indices of the soils are very high and close to unity for some soils, indicating a high reversibility of the sorption process. Hence, it is recommended that landfills that utilize these lateritic soils adopt a composite containment design by integrating liners and leachate collection systems coupled with routine monitoring.

Keywords: Batch equilibrium tests, Contaminant attenuation, Index and geotechnical properties, Landfill liners, Lateritic soils, Sorption, Southwestern Nigeria.

ABBREVIATIONS

| | |
|------------------|---|
| AAS | Atomic absorption spectroscopy |
| USEPA | United States Environmental Protection Agency |
| NPC | National Populations commission |
| NBS | National Bureau of Statistics |
| NIMET | Nigerian Meteorological Agency |
| NSWEPA | New South Wales Environmental Protection Agency |
| PI | Plasticity Index |
| LL | Liquid limit |
| UCS | Unconfined compressive strength |
| UKEPA | United Kingdom Environmental Protection Agency |
| TCEQ | Texas Commission on Environmental Quality |
| MDD | Maximum dry density |
| OMC | Optimum moisture content |
| CEC | Cation exchange capacity |
| C | Total cohesion |
| ϕ | Total angle of internal friction |
| LS | Linear shrinkage |
| XRF | X-ray fluorescence |
| USCS | Universal soil classification system |
| XRD | X-ray diffraction |
| B.S | British standard |
| HNO ₃ | Nitric acid |
| K | Hydraulic conductivity |
| SG | Specific gravity |
| C _{eq} | equilibrium concentration |
| Q _m | maximum absorption capacity |
| HI | Hysteresis Index |
| KL | Absorption – equilibrium constant |
| K _f | Freudlich constant |

DECLARATIONS

DECLARATION 1 – PLAGIARISM

I, **Sunday Olabisi Daramola** declare that

1. The research reported in this thesis is my original research, except where otherwise indicated.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
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 - b. where their exact words have been used, then their writing has been placed in italics and inside quotation marks and referenced.
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DECLARATION 2 - PUBLICATIONS

1. Daramola, S.O., Hingston, E.D.C. and Demlie, M. (2024): A Review of Lateritic Soils and their use as Landfill Liners. *Environmental Earth Sciences*, 83, 118
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Contribution: As first author, I was responsible for sample collection (guided by my supervisors), undertaken index, geotechnical, mineralogical, geochemical, physicochemical and batch equilibrium analyses and interpretation of all the data, writing and preparation of all the manuscripts and management of all submissions and revision processes of the manuscripts. The second and third authors are my supervisors, who provided guidance throughout the project as well as critically reviewing and editing the manuscript.

Signed. 

Date:19-07-2024

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CHAPTER ONE: INTRODUCTION

1.1 Background and Research Rationale

Waste generation is a natural result of human activities, and it is closely linked to the increase in global population and economic growth. The rate of increase in the world's population and economic growth has resulted in an inevitable increase in the generation of solid waste (Endene *et al.*, 2020a; Regadio *et al.*, 2020). Hence, waste management has become a pivotal focus in the millennium development goals, prompting significant attention from stakeholders in the solid waste management cycle (Ferronato and Torretta, 2019). However, unlike the disposal of liquid waste, sewage, and industrial effluents, the problem of solid waste disposal has not received much attention (Oluwaseun, 2019; Adekola *et al.*, 2021).

Sanitary landfilling, which is considered as cost-effective and environmentally responsible strategy for solid waste disposal, has gained wide acceptance, especially in developing countries where it is taken as the only viable way of waste disposal (USEPA 2010; Regadio *et al.*, 2015; Tchobanglas and Krieth, 2002; Anifowose *et al.*, 2021). Nevertheless, this method generates leachates, toxic liquids produced by the percolation of aqueous substances through the deposited waste materials, which contain pollutants that pose significant environmental risks (Rahman, 2000; Regadio *et al.*, 2015). Landfills are designed and constructed using liners that are made from either geosynthetics or natural soils to prevent contamination of the surrounding environment including water and the ecosystem. However, despite their impermeability, geosynthetic clay liners (GCLs) may not protect the environment and human health against landfill leachate pollution, as they are susceptible to failure during and after installation. Conversely, the low cost, good attenuation capacity, and ease of implementation of compacted soil liners (CSLs) make them more attractive than GCLs.

Ekiti State, which is located in southwestern Nigeria, is one of Nigeria's newest states, with a rapidly growing metropolitan population. Since its inception in 1996, the population of Ekiti State has risen dramatically from 1,629,162 in 1991 to 2,384,212 in 2006 (NPC, 2007). This has resulted in an increase in the quantity of waste generated. A negative consequence of improper waste management is its environmental nuisance and health hazard. Sporadic refuse dumps and a breakdown in the waste management arrangement are few problems associated with solid waste management in the study area (Southwestern Nigeria). In many parts of the study area, inadequate

plans for waste management persist as most wastes are dumped in poorly controlled dumpsites, stream channels and on roadsides. Thus, it is evident that there is an imminent risk of environmental pollution in the form of groundwater and soil contamination, which necessitates the identification of suitable landfill sites and associated construction materials. Liner materials constitute essential parts of landfills, and according to Met and Akgun (2015), clayey liners have a long record of performance with respect to the containment of chemical wastes, but it is always impossible to find sufficient amount of natural undisturbed clayey materials. This has resulted in the search for locally available alternative materials such as lateritic soils, soil blends and geosynthetic materials. Hence, numerous studies have been conducted (e.g., Ojuri *et al.*, 2017; Daramola and Ilesanmi, 2018; Endene *et al.*, 2020a & b; Motoshima *et al.*, 2023; Onyelowe *et al.*, 2023; Rasheed *et al.*, 2023) on the utilization of different varieties of locally available natural soils for compacted liner application. Prominent among the commonly investigated alternative materials is the utilization of lateritic soils because of their low exploitation costs and ready availability in the tropical regions (Oyelami and Van Rooy, 2016a; Mvindi *et al.*, 2017).

Lateritic soils are among the widely employed soils for various kinds of construction projects in different parts of Nigeria as it is believed to be an excellent construction material without paying close attention to the effect of the parent rock on their geotechnical properties (Oyelami, 2017; Daramola and Ilesanmi, 2018). This has led to many infrastructural failures in numerous places. The contamination and pollution related to the failure of waste disposal facilities may be very detrimental. Therefore, it is pertinent to ascertain the soils used in the construction of such facility in order to avert such harm. A review of the literature on the use of lateritic soils from Nigeria and other central/west African countries indicates that few researchers have assessed the suitability of lateritic soils for use as landfill liners (e.g., Ogunsanwo, 1996; Frempong, 1999; Frempong and Yanful, 2005; Frempong and Yanful, 2008; Ige and Ogunsanwo, 2009; Ige *et al.*, 2011; Adeoye *et al.*, 2013; Oyediran and Iroegbuchi, 2013; Ige, 2014; Daramola and Ilesanmi, 2018).

However, there is a dearth of research on the use or evaluation of lateritic soils from the study area (Ekiti State) as landfill liners. Moreover, most of the authors did not consider the influence of geology and their position in the lateritic profile while evaluating the suitability of the lateritic soils for use as landfill liners. Additionally, none have attempted to determine the attenuation capacity of the lateritic soils from the study area. Hence, this research attempts to fill these research

gaps through an integrated approach of assessment of lateritic soils for use as locally available compacted soil landfill liners in Ekiti State. The significance of this study lies in its potential to improve waste management practices in Ekiti State, Southwest Nigeria. By identifying the strengths and weaknesses of lateritic soils as landfill liners, this study provides a foundation for developing more effective and sustainable landfill solutions. Moreover, this research emphasizes the need for localized assessments and tailored engineering approaches to optimize the use of lateritic soils in landfill applications. Furthermore, the comprehensive methodology utilized in this study serves as a valuable framework for future research, contributing to the broader understanding of soil-based landfill liners.

1.2 Problem statement

The rapid growth of population and urbanization, coupled with the ever-increasing generation of solid waste, presents a pressing challenge for Ekiti State, Southwestern Nigeria (Awosusi et al., 2012; Ogunleye and Uzoma, 2018). Although sanitary landfilling is considered an effective method for solid waste disposal, the generation of leachates and the vulnerability of GCLs raise significant concerns. Moreover, the financial constraints of Ekiti State necessitate cost-effective solutions and the reliance on locally available resources offers a practical and sustainable approach. However, the scarcity of natural clay deposits for liner applications require the search for alternative materials such as lateritic soils. Therefore, to address these challenges, there is a growing interest in exploring the suitability of locally abundant lateritic soils as landfill liners in Ekiti State, southwestern Nigeria. However, the use of lateritic soils as landfill liners in Ekiti State presents significant engineering and environmental challenges. While lateritic soils are abundant and cost-effective, their geochemical capacity for attenuating and interacting with landfill leachate remains poorly understood. Specifically, current knowledge is limited regarding their sorption and desorption potentials and the effects of pH levels on their performance. Additionally, the influence of the nature of parent rock types on the geotechnical properties and sorption potentials of lateritic soils are poorly understood. Moreover, the long-term performance of lateritic soils is a key concern, especially their ability to function as a compacted clay liner (CCL) under varying temperature conditions, and their potential to prevent leachate contamination over extended periods. This uncertainty raises concerns about potential environmental risks, such as groundwater contamination and reduced landfill stability.

1.3 Research Hypothesis

The nature of the parent rocks is a prominent factor that determines the characteristics of the soils derived from them. This is essentially dictated by the nature, types, and amount of the minerals present in the rocks. Therefore, the identification and characterization of the parent rocks are essential for comprehending the formation process and mineral composition as well as the geotechnical properties of the lateritic soils. Hence, it is hypothesized that the variations in the mineralogical and geochemical characteristics of these parent rocks significantly influence the properties of lateritic soils formed.

Lateritic soils exhibit differential capacities to immobilize heavy metals, a characteristic vital for landfill liner performance. It is hypothesized that the mineralogical composition, geochemical features, and specific clay minerals in the lateritic soils will significantly influence their ability to retain and immobilize heavy metals, ultimately impacting their role in preventing environmental contamination.

1.4 Research aim and objectives

The main aim of this research is to conduct a comprehensive engineering geological assessment of lateritic soils from Ekiti State, Nigeria in order to determine their suitability for use as landfill liners.

The specific objectives of the research are:

- a) To determine the geotechnical properties of lateritic soils at different horizons across the lateritic profiles developed from different parent rock types;
- b) To evaluate the clay mineralogical composition and geochemical properties of the lateritic soils;
- c) To assess the heavy metal sorption potentials of the lateritic soils using batch equilibrium sorption laboratory test;
- d) To appraise the suitability of the soils around the study area for use as landfill liners based on the results in a,b and c above;
- e) To determine the influence of geology on the geotechnical properties of lateritic soils.

1.5 Thesis Structure

This PhD thesis is organized in nine chapters. These are:

- Chapter One introduces the study and gives a background, rationale and the aims and objectives of the research.
- Chapter Two provides a thorough literature review on the nature, distribution, physicochemical and geotechnical properties of lateritic soils and their use as landfill liners. Additionally, the review includes the types, nature and desirable engineering, geochemical and mineralogical properties of lateritic soils for landfill liner applications.
- The third chapter presents a description of the study area with respect to its location, climate, drainage, physiography, land use, vegetation, and geology.
- Chapter Four describes the details of the methodology and approach followed to achieve the aims and objectives of the research.
- The petrographic and geochemical characteristics of the parent rocks of the lateritic soils are presented in Chapter Five.
- Chapter Six focuses on the geotechnical characterization and analysis of the lateritic soils and discusses the implications of the properties on their suitability as landfill liners.
- The mineralogical, geochemical and physicochemical properties of the lateritic soils are provided in Chapter Seven, along with their suitability for landfill liner applications.
- Chapter Eight provides the attenuation capacity of the lateritic soils. Results of the batch equilibrium sorption and desorption tests are examined and interpreted to characterise the contaminant attenuation potential of these soils.
- The conclusions, which present the summary of the main findings of the research, are presented in Chapter Nine together with the recommendations.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Liners are important components of landfills, which are usually made up of compacted natural soil or synthetic materials such as geotextiles and geomembranes (Endene *et al.*, 2019; Muhsina & Chandrakaran, 2019). In developing countries, soil liners are commonly used because of the unaffordable cost of synthetic materials (Ige, 2013). Soil liners are designed to be a low permeable barrier emplaced beneath an engineered landfill site to prevent the migration of leachates into the underlying aquifers and nearby surface water resources such as rivers, streams and lakes (Mohamed & Anita, 1998; Norouzi *et al.*, 2022). Thus, they play a major role in preventing environmental contamination, especially to surface and groundwater resources. The basic requirements for soil liners in modern landfills are that they must have a maximum hydraulic conductivity of 1×10^{-9} m/s and a thickness greater than 1 m (Mohamed & Anita, 1998; USEPA, 2000; NSW EPA, 2016; USEPA, 2021). Nevertheless, some other properties such as index, chemical and mineralogical are also desirable for use as liners (Endene *et al.*, 2019). Therefore, the reliable determination of these properties is vital for the design of a sustainable landfill and other related waste containment facilities. Clay soils are commonly utilized in the construction of liners since they have a very high tendency to achieve the desired minimum hydraulic conductivity and suitable chemical and mineralogical properties (Oyediran & Iroegbuchi, 2013). However, their limited availability has resulted in the search and utilization of other locally available materials such as laterites and lateritic soils (Murray, 1998). Lateritic soils have been identified as one of the predominant soil types in the tropics, covering a third of the land area of the earth's continental land area (Tardy, 1997; Metelka, 2011). Thus, countries lying in this region often utilize it for various construction purposes with little or no concern about their properties (Mesida, 2006). It is worthy to note that the nature and definition of lateritic soils have been subjected to scientific debate for some decades as a result of the extensive pedological and geological research on these soils. Consequently, it has been classified based on its location in the terrain, morphology, chemistry, and minerals.

The utilization of lateritic soils in tropical regions is justified by their availability, abundance and low cost of exploration (Ngo'o Ze *et al.*, 2019; Basu & Sinha, 2021). As a result, numerous investigations (e.g., Millogo *et al.*, 2008; Kamtchueng *et al.*, 2015; Oyelami & Van Rooy, 2016a;

Onana *et al.*, 2017; Norat & da Costa, 2019; Sinha & Basu, 2021) on the suitability of lateritic soils for various construction purposes have been executed. However, in spite of the inexhaustible literature published on the various engineering properties of lateritic soils, considerable confusion still exists on their nature and properties in addition to the lack of uniform and widely acceptable definition. Furthermore, the properties of lateritic soils can vary over short horizontal distances and across profiles (Adeyemi & Wahab, 2008; Ngo'oZe *et al.*, 2019) rendering it to be highly unpredictable. From the foregoing, a thorough appraisal of the origin, nature, distribution and geotechnical characteristics of lateritic soils is essential since it would be of tremendous benefits to engineers and engineering geologists engaged in the identification and evaluation of these soils for engineering purposes, particularly for use as liner materials. This chapter presents an overview of lateritic soils and their applications as liners. Furthermore, an overview of liners and their applications, types and desirable properties, which make them useful as liners, are presented.

2.2 Distribution, genesis, nature and profiles of lateritic soils

Buchanan (1807) coined the term laterite to denote soft materials that readily exhibit the tendency to be cut into blocks by metallic instrument but harden rapidly when exposed to air and is practically resistant to the action of air and water (Vallerga & Rananandana, 1969; Ghosh & Guchhait, 2019). Since the definition by Buchanan (1807), the word laterite has been applied to a wide variety of tropical soils linked to the similarities in color, composition, occurrence and their behaviour. Thus, numerous definitions of laterite exist in the literature (e.g. Buchanan, 1807; Alexander & Cady, 1962; Maignien, 1966; Giorgis *et al.*, 2014; Oyelami & Van Rooy, 2016b). Several authors (e.g., Sivarajasingham *et al.*, 1962; Gidigas, 1972; Malomo, 1977; Giorgis *et al.*, 2014) presented a comprehensive review of the “old” definitions of lateritic soils, which specially focused on the basic concepts of physical and morphological features, as well as the relative geochemical composition of these soils in relation to silica.

According to Gidigas (1972), laterite refers to “all the reddish, tropically weathered residual and non-residual soils including laterite rocks”. Pendleton & Sharasuvana (1946), described "laterite" as "soils in which a laterite horizon is discovered" while "laterite soils" have a young laterite horizon that can develop into a true laterite under the proper conditions. Consequently, lateritic soils might be defined as having a young, immature laterite horizon that has the potential to develop into real laterite under the proper conditions and sufficient period of time. In an effort to

redefine laterite, Schellmann (1986) defined and classified laterites based on the chemical composition of rocks, primarily on the ratio of silica sesquioxide to the chemical composition of the underlying parent rocks of the laterite. Despite its initial acceptance, this definition received scathing criticism from several authors (Bourman and Ollier, 2002; Schellmann, 1986, 2003). For instance, Bourman & Ollier (2002, 2003) suggested the complete abandonment of the term laterite. Furthermore, it is noteworthy that lateritic soils and laterite have been synonymously applied to red tropical soils (Varghese & Byju, 1993; Fritsch *et al.*, 2002).

Disagreements regarding the various definitions of laterites persist as new definitions only add to the confusion (Giorgis *et al.*, 2014; Stoops & Marcelino, 2018). Therefore, it is extremely challenging to restrict the terminology (laterite) to a particular soil group with clearly specified characteristics. Consequently, the term lateritic soils will be adopted for this research in accordance with the description given by Oyelami & Van Rooy (2016a), which refers to a highly weathered, well-graded, tropical or sub-tropical residual soil that is typically coated with sesquioxide rich concretions and with color ranging from red to brown.

2.2.1 Worldwide distribution of lateritic soils

Lateritic soils form in humid tropics and subtropics (Figure 2.1) under specific weathering conditions including in equatorial forests, wet tropical savannah and the Sahellian steepes (Maignien, 1966; Gidigas, 2012; Ghosh & Guchhait, 2019; Basu & Sinha, 2021) from different parent rock materials (Gidigas, 2012). They generally cover the majority of regions between the Tropics of Cancer and Capricorn. However, they occur in other regions including southwestern Africa, the western edge of Southern America, arid regions of north-central Africa and the interior of Australia (Tardy, 1997). Climate is also a significant factor in the physico-chemical processes controlling the formation of lateritic soils (Loughnan, 1969; Sinha & Basu, 2021).

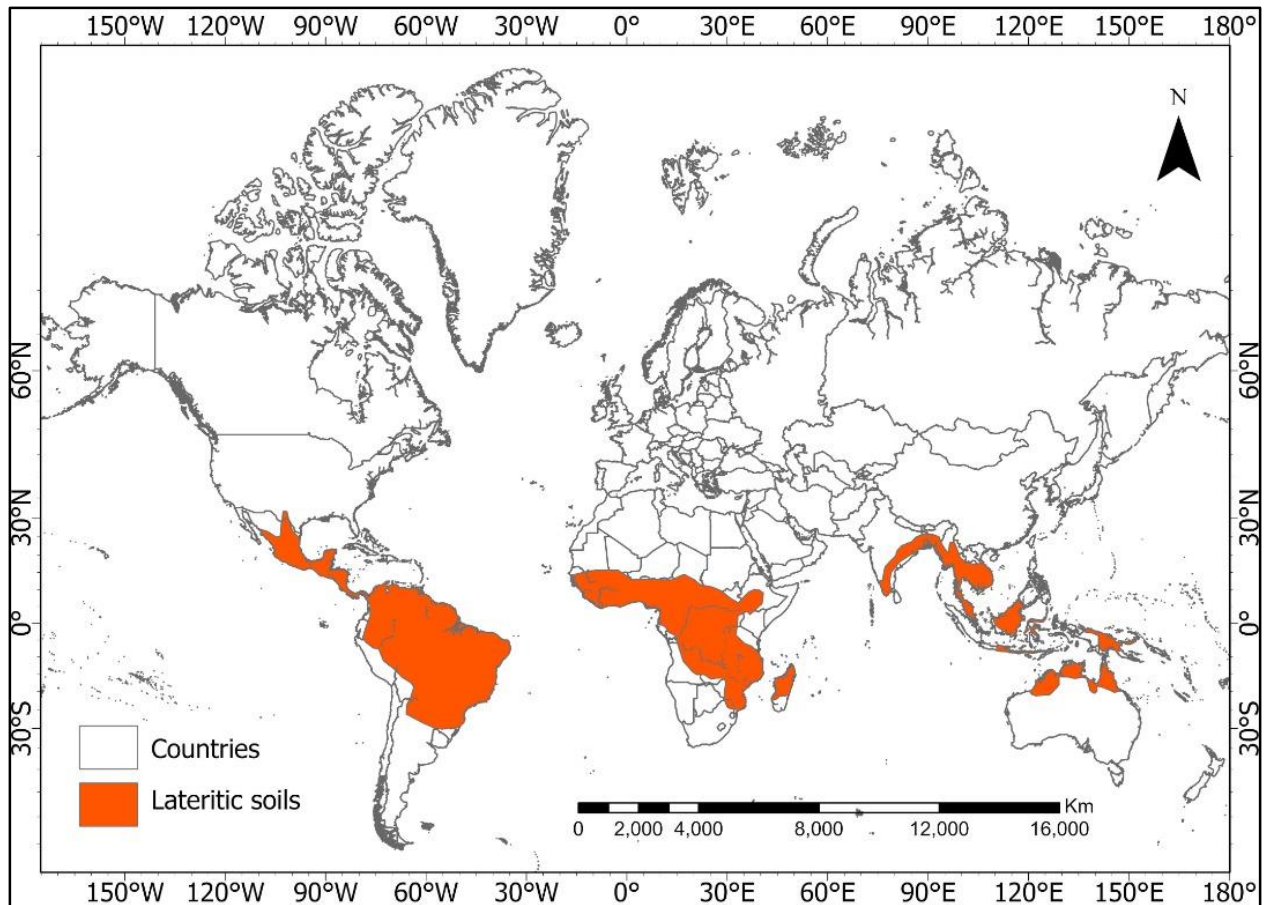


Figure 2.1. Location and distribution of Lateritic soils (modified from Netterberg, 2014).

2.2.2 Genesis of lateritic soils

Laterization, which is the pedogenic process that convert rocks to lateritic soils, is initiated by the development of fractures in the rocks. The parent material, climate, terrain, vegetation, and time are the five main determinants of the rate of laterization (Pinard *et al.*, 2014; Oyelami & Van Rooy, 2018; Ghosh & Guchhait 2019; Sinha & Basu, 2021). The genesis and hence the formation of lateritic soils is attributed to the three main processes of decomposition of minerals, leaching and desiccation (Zelalem, 2005). Primary weathering often referred to as decomposition, is the full or partial physical (disintegration) and chemical (decomposition) breakdown of primary minerals, followed by the discharge of sesquioxide gels and minor primary elements (Gidigas, 1972). Tropical decomposition tends to favour the formation of kaolinite, which is recognized as the most prevalent type of clay mineral in residual soils formed around the tropics. Thus, the amount of kaolinite present signifies the degree of laterization (Gidigas, 2012). The decomposition of

primary minerals is followed by leaching of silica and bases followed by the relative enrichment of oxides and hydroxides of alumina and iron, which are the least susceptible component to leaching. Leaching occurs during the wet season as a result of infiltrating water, the extent of which is influenced by drainage conditions and the pH of the infiltrating water (Lecomte-nana *et al.*, 2009). The final stage, which is desiccation, is the process of dehydrating secondary minerals and sesquioxide-rich solids (Lundgren, 1969; Oyelami, 2017).

2.2.3 Nature of lateritic soils

Iron oxides occur in various states of hydration that gives lateritic soils various colour shades including pink, red, liver red, brown and ochre (Bell, 2007; Gidigasu, 2012). The variation in the colour of lateritic soils is generally influenced by the degree of weathering and hydration. Malomo (1977) reported that colour could be an indicator in the determination of the degree of evolution of these soils. The presence of manganese gives a purple colour or shades of it to the soils. On the other hand, the various forms of occurrence of sesquioxides of iron and alumina gives lateritic soils a distinctive structure that differ from those found in soils of the temperate zone (Malomo, 1977). Maignien (1966) recognized three dominant structural patterns in lateritic soils based on the actual physical occurrence, namely, either the indurated elements are nodules in an earth matrix, free concretions or form a continuous coherent skeleton. Different macro-structural types have been identified based on morphological studies including the vesicular, vermicular, oolitic, cellular and pisolitic (Pullan, 1967). However, these distinct macrostructures are not always indicative of variations in the microstructure. For example, despite variations in macro-morphology, Alexander and Cady (1962) reported some similarities in the microstructure of indurated lateritic soils from West Africa. Microscopic observations made on lateritic soils from Brazil and Nigeria revealed cemented surfaces coated by iron oxides, which were originally semi-gelatinous (Malomo, 1989). This coating could either become thicker as a result of the loss of moisture or gradually crystallize into crystalline forms such as haematite or goethite. Consequently, two major microstructural arrangements were identified namely, the matrix and the skeletal. A recent study on the microstructure of compacted lateritic soils by Otálvaro *et al.* (2015) revealed a bimodal distribution of the pore sizes and a change in the shape of the pore distribution curve during compaction. Furthermore, Kasthurba *et al.* (2008) and Otálvaro *et al.* (2015) reported a strong correlation between microstructures and the mechanical behavior of lateritic soils.

2.2.4 The lateritic soil profiles

Walther (1915) publicized the concept of a laterite profile, which is known as the "Walther profile". Laterite profile refers to a succession of horizons or zones commonly associated with lateritic soils. In the process of lateritic soil formation, the upper parts of the protolith elements are often more susceptible to degradation, while the impact of weathering reduces with depth, creating a vertical zone of weathering (Widdowson, 2007). However, lateritic soil profiles are difficult to compare because many of them are products of the truncation and deposition during consecutive pedimentation cycles (Stoops & Marcelino, 2018; Fedoroff *et al.*, 2018).

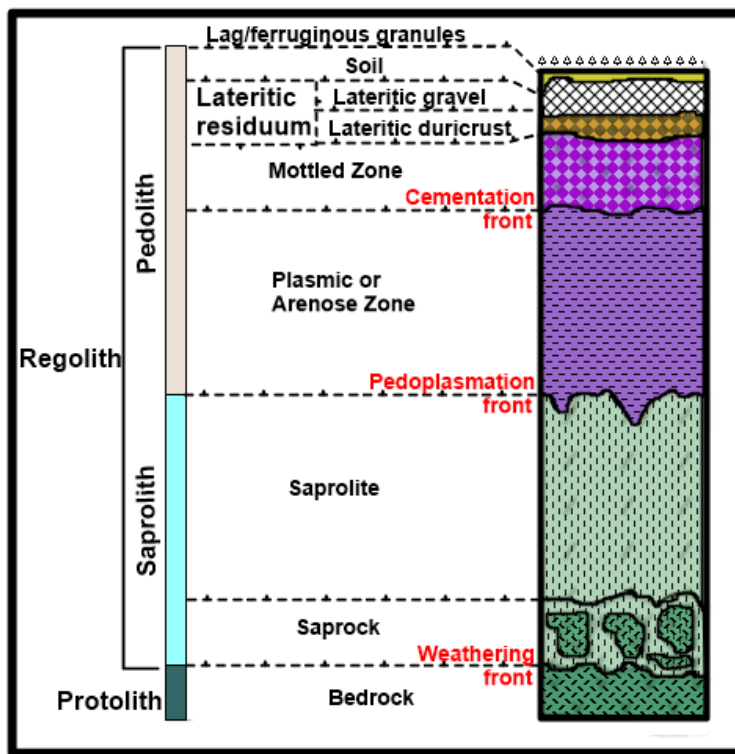


Figure 2.2. Complete idealized lateritic regolith profile with lateritic residuum (adapted from Eggleton, 2001).

According to Eggleton (2001) and Gidigas (2012), a typical lateritic profile includes multiple regolith facies as shown in Figure 2.2. The intensity of weathering processes is reflected in the facies, although not every facies must always be present due to mechanical erosion or variations in the constituents of the parent rock components and topographic locations (Eggleton, 2001). All zones could be present during a vertical transportation of iron, which leads to a relative accumulation of iron oxide. Conversely, absolute accumulation occurs when iron is horizontally

transported from higher elevations, and some of the different horizons may not be missing in the profile (Mahalinga-Iyer & Williams 1991). A section of the profile where the fabric of the parent rock is preserved is termed saprolith, while the zone where the fabric has been completely destroyed and replaced by new fabrics or soil developed is called pedolith (Widdowson, 2007). The weathering front separates the saprolith and the fresh rock (Philips *et al.*, 2019). The bottommost saprock layer located in the saprolith is the least chemically altered zone and typically show signs of the most recent weathering (McQueen & Scott, 2008). Widdowson (2007) described the plasmic zone as the mesoscopic portion containing a significant amount of clay, without a lithic fabric of the saprolite or any significant development of secondary materials such as pisoliths and nodules. The cementation front is the transformation front that results in cementation by various oxides and hydroxide constituents (e.g., oxides and oxyhydroxides of iron, manganese and aluminium, silica and carbonates). The part of a lateritic profile showing mottles is known as the mottled zone, which typically occurs above the plasmic zone and lies beneath the lateritic residuum. The surface lag consists of physically and chemically resistant granule to cobble sized materials of diverse origins derived from the removal of finer particles by aeolian and pluvial processes, or by matrix removal during differential weathering (Widdowson, 2007; Eggleton, 2001; Eggleton *et al.*, 2008; Stoops & Marcelino, 2018).

Arhin *et al.* (2015) noted that lateritic residuum, which comprises the lateritic gravel and/or lateritic duricrusts, constitutes the upper portion of a complete lateritic profile. According to Anand (2001), partial collapse of ferruginous or mottled regolith, characterized by localized lateral and vertical motions after chemical wasting advances their formation while the duricrust is derived from the ferruginization and residual accumulation of iron oxides and silica in the upper section of the residual regolith. Anand (2001) and Arhin *et al.* (2015) further described these ferruginous lag as the remnants of a variety of iron-rich regolith materials whose character reflects the type of the upper regolith and varies depending on the amount of erosion and geographic location. Gidigas & Kuma (1987) noted that materials in the horizons vary vertically and horizontally in terms of mineralogy, chemistry and morphology.

2.3 Geochemical and mineralogical characteristics of lateritic soils

The chemical characteristics of lateritic soils was first described in Oldham (1893) and later by Bauer (1898) who reported that their chemical composition is dominated by aluminium hydroxide

with minor quantities of iron and combined silica. Bauer (1898) stated that the composition of these lateritic soils is comparable to that of German bauxites. Furthermore, Warth & Warth (1903) analyzed lateritic soil samples from India and found out that some contained small amounts of alumina but were rich in iron oxides, while others contained large amounts of alumina and were poor in iron oxides. These observations demonstrate that lateritic soils have a chemical composition that varies from almost pure iron oxide to almost pure alumina. Based on this, Gidigas (2012) identified two groups of lateritic soils, namely, ferrogenous lateritic soils, in which iron oxide predominates, and the aluminous lateritic soils with dominant alumina.

Table 2.1 shows mean concentration of major elements in some lateritic soils derived from different rocks and locations around the world. A notable characteristic feature of the lateritic soils is the dominantly higher proportions of sesquioxides of aluminium and iron in comparison to other chemical constituents and negligible composition of the bases (Table 2.1). The influence of parent materials on the chemical composition is also shown. According to Table 2.1, the lowest amount of silica is found in lateritic soils derived from basic rocks, whilst the lateritic soils derived from felsic rocks have higher amount of silica, commensurate with parent material composition. Gidigas (2012) reported oxides of manganese, titanium, chromium and vanadium as some other common chemical constituents of lateritic soils.

The chemical composition of lateritic soils has been employed in their classification (Fermor, 1911; Gidigas, 2012; Giorgis *et al.*, 2014). Fermor (1911) comprehensively classified lateritic soils based on the so-called lateritic content (i.e., iron, Titanium, aluminium and Manganese), while Lacroix (1913) presented a comparable classification based on the overall amount of hydrous oxides. A classification based on the silica/alumina ratio was presented by Martin & Doyne (1930) where ratios below 1.33 are thought to be suggestive of true laterites while those between 1.33 and 2 are thought to be lateritic soils, and non-laterites have ratios greater than 2. This grouping was criticized by various authors for ignoring the importance of iron oxide contents in the soils and their engineering behaviour (Winterkorn & Chandrasekharan, 1951; Schellman, 1986; Oyelami and van Rooy, 2016a; Oyelami, 2017). The preceding argument led to the proposition of the molecular silica-sesquioxides ratio by Joachin and Kandiah (1941). Schellman (1986) attempted a redefinition of lateritic soils basically on the silica/alumina ratio compared with the chemical composition of the parent rock.

Table 2.1. Mean concentration (%) of major elements in lateritic soils derived from different rocks and locations around the world.

| Location | Parent Rock | Fe ₂ O ₃ | SiO ₂ | Al ₂ O ₃ | MgO | K ₂ O | CaO | TiO ₂ | Na ₂ O | MnO | P ₂ O ₅ | References |
|--------------|-----------------|--------------------------------|------------------|--------------------------------|------|------------------|------|------------------|-------------------|------|-------------------------------|-------------------------------|
| Argentina | Basalt | 6.67 | 42.42 | 9.95 | | 0.08 | 0.01 | | 0.04 | | | Gustavo <i>et al.</i> (2017) |
| | | 12.13 | 32.7 | 12.6 | | 0.12 | 0.01 | | 0.01 | | | |
| | | 30.85 | 15.96 | 10.84 | | 0.79 | 0.01 | | 0.05 | | | |
| | | 9.74 | 36.68 | 9.97 | | 0.25 | 0.12 | | 0.7 | | | |
| | | 9.97 | 28.15 | 11.14 | | 0.15 | 0.3 | | 0.6 | | | |
| Australia | Sandstone | 6.22 | 62.56 | 14.95 | | | | | | | | Eggleton <i>et al.</i> (2008) |
| | | 6.07 | 60.21 | 16.76 | | | | | | | | |
| | | 8.24 | 64.56 | 12.86 | | | | | | | | |
| | | 10.55 | 59.07 | 14.85 | | | | | | | | |
| Burkina-Faso | Granodiorite | 54.9 | 19.05 | 16.25 | 0.02 | 0.02 | 0.11 | 0.51 | 0.08 | 0.02 | 0.21 | Giorgis <i>et al.</i> (2014) |
| | | 31.39 | 36.12 | 18.67 | 0.02 | 0.03 | 0.01 | 0.67 | 0.11 | 0.03 | 0.08 | |
| | | 13.8 | 47.05 | 24.4 | 0.05 | 0.01 | 0.01 | 0.67 | 0.08 | 0.01 | 0.06 | |
| | | 10.7 | 60.34 | 19.85 | 0.06 | 0.02 | 0.01 | 0.67 | 0.14 | 0.02 | 0.04 | |
| | | 9.51 | 56.11 | 23.6 | 0.06 | 0.01 | 0.01 | 0.79 | 0.14 | 0.01 | 0.06 | |
| | | 6.08 | 65.88 | 12.9 | 1.7 | 0.03 | 0.98 | 0.62 | 0.98 | 0.03 | 0.04 | |
| Cameroon | chlorite schist | 9.16 | 52.6 | 17.9 | 2.68 | 0.88 | 3.22 | 1.18 | 5.89 | 0.24 | 0.12 | Onana <i>et al.</i> (2020) |
| | | 13.54 | 52.72 | 18.19 | 1.47 | 1.67 | 0.96 | 1.43 | 0.46 | 0.32 | 0.06 | |
| | | 10 | 49.96 | 17.08 | 2.41 | 0.61 | 2.77 | 1.18 | 7.03 | 0.21 | 0.27 | |
| | | 9.57 | 51.36 | 17.26 | 1.69 | 0.57 | 2.72 | 1.6 | 5.78 | 0.66 | 0.19 | |
| India | Basalt | 8.46 | 7.7 | 42.35 | 0.01 | 0.21 | 4.47 | 1.87 | 0.35 | 0.01 | 1.87 | Narayanaswamy (1992) |
| | | 21.55 | 8.8 | 40.53 | 0.03 | 0.11 | 1.29 | 4.04 | 0.26 | 0.01 | 4.04 | |

| | | | | | | | | | | | | |
|-------|-------------|-------|-------|-------|-------|-------|------|------|------|------|------|--|
| | | 4.83 | 4.43 | 58.71 | 0.09 | 0.04 | 1.15 | 5.34 | 0.47 | 0.02 | 5.34 | |
| | | 22.09 | 10.48 | 38.05 | 0.47 | 0.05 | 0.11 | 6.09 | 0.99 | 0.02 | 6.09 | |
| | | 30.09 | 12.91 | 26.18 | 0.07 | 0.33 | 1.17 | 4.39 | 0.51 | 0.01 | 4.39 | |
| | | 8.39 | 19.38 | 43.94 | 0.01 | 0.58 | 1.92 | 1.07 | 0.12 | 0.01 | 1.07 | |
| | | 39.62 | 9.98 | 21.83 | 0.03 | 0.39 | 1.42 | 3.12 | 0.34 | 0.01 | 3.12 | |
| India | Charnockite | 14.43 | 45.88 | 14.78 | 5.32 | 0.7 | 9.87 | 2.14 | 3.6 | | 0.3 | |
| | | 9.98 | 41.56 | 23.98 | 1.45 | 0.96 | 2.24 | 0.9 | 1.42 | | 0.32 | |
| | | 12.91 | 35.67 | 28.05 | 1.13 | 0.07 | 1.57 | 0.64 | 0.08 | | 0.36 | |
| | | 21.77 | 31.82 | 27.03 | 0.65 | 0.12 | 0.9 | 0.84 | 0.88 | | 0.42 | |
| | Gneiss | 2.09 | 75.3 | 14.96 | 0.01 | 0.12 | 0.26 | 0.32 | 5.18 | | | |
| | | 4.05 | 57.34 | 19.88 | 1.64 | 2.94 | 2.47 | 0.29 | 3.37 | | | |
| | | 10.56 | 36.6 | 31.1 | 0.48 | 0.32 | 0.9 | 0.68 | 0.78 | | | |
| | Quartzite | 0.72 | 66.94 | 16.82 | 1.12 | 0.35 | 0.29 | 0.24 | 0.32 | | | |
| | | 18.2 | 61.18 | 10.71 | 0.4 | 0.39 | 0.14 | 0.84 | 0.3 | | | |
| | | 46.23 | 22.64 | 16.78 | 0.35 | 0.28 | 0.13 | 1.22 | 0.26 | | | |
| | Ultramafite | 7.99 | 53.6 | 5.73 | 25.03 | 0.3 | 2.06 | 0.06 | 1.4 | | | |
| | | 8.38 | 32.5 | 18.35 | 20.6 | 0.22 | 2.02 | 0.1 | 1.1 | | | |
| | | 28.11 | 30.05 | 22.36 | 0.32 | 0.15 | 0.45 | 0.53 | 0.94 | | | |
| | Schist | 7.29 | 54.28 | 17.35 | 3.74 | 0.23 | 1.12 | 0.65 | 1.11 | | 0.22 | |
| | | 13.75 | 49.36 | 7.14 | 16.28 | 0.01 | 2.02 | 0.73 | 0.98 | | 0.33 | |
| | | 19.18 | 34.43 | 26.04 | 0.48 | 0.36 | 1.12 | 0.81 | 0.95 | | 0.3 | |
| | Syenite | 2.45 | 59.21 | 13.97 | 1.13 | 13.89 | 3.39 | 0.3 | 3.28 | | | |
| | | 0.46 | 57.33 | 23.46 | 0.48 | 6.56 | 2.02 | 0.16 | 4.83 | | 0.08 | |
| | | 2.27 | 45.05 | 28.04 | 0.48 | 6.6 | 1.12 | 0.19 | 1.69 | | 0.04 | |

| | | | | | | | | | | | | |
|-----------|-----------------------|-------|-------|-------|-------|------|------|------|------|------|------|-------------------------------|
| | | 6.44 | 44.14 | 28.04 | 0.48 | 3.47 | 0.9 | 0.41 | 1.12 | | 0.08 | |
| | | 31.28 | 33.16 | 17.85 | 0.8 | 3.2 | 1.12 | 0.38 | 1.04 | | 0.5 | |
| Indonesia | Serpentinite | 63.45 | 3.71 | 11.6 | 0.55 | 0.02 | 0.24 | 0.38 | 0.03 | 0.28 | 0.02 | Fu <i>et al.</i> (2014) |
| | | 63.22 | 3.21 | 11.96 | 0.44 | 0.03 | 0.45 | 0.41 | 0.03 | 0.36 | 0.02 | |
| | | 22.65 | 35.89 | 2.61 | 21.81 | 0.01 | 0.12 | 0.05 | 0.41 | 0.28 | | |
| | Basalt | 31.46 | 9.7 | 28.5 | 0.14 | 0.01 | 0.17 | 4.77 | 0.01 | 0.29 | 0.11 | |
| | | 26.42 | 36.71 | 26.1 | 0.28 | 0.02 | 0.07 | 2.81 | 0.01 | 0.33 | 0.11 | |
| | Peridotite | 41.25 | 17.48 | 14.03 | 1.31 | 0.22 | 0.62 | 0.26 | 2.01 | 0.1 | 0.03 | |
| | | 47.08 | 22.85 | 5.99 | 3.55 | 0.28 | 0.66 | 0.21 | 0.11 | 1.03 | 0.03 | |
| | Gabbro | 62.5 | 14.67 | 11.97 | 0.51 | 0.01 | 0.21 | 0.21 | 0.15 | 0.41 | 0.02 | |
| | | 16.82 | 27.06 | 24.49 | 3.8 | 0.84 | 1.3 | 0.57 | 0.14 | 0.18 | 0.01 | |
| Iran | Dolomitised limestone | 21.81 | 30.12 | 29.74 | 0.63 | 0.44 | 0.01 | 3.76 | 0.03 | 0.36 | 0.65 | Abedini <i>et al.</i> (2008) |
| | | 24.35 | 26.49 | 28.2 | 0.29 | 0.56 | 0.02 | 4.19 | 0.07 | 0.3 | 0.21 | |
| | | 15.71 | 51.63 | 10.96 | 0.59 | 0.19 | 0.01 | 1.78 | 0.11 | 0.26 | 0.25 | |
| | | 13.71 | 54.66 | 11.54 | 0.77 | 0.21 | 0.02 | 1.75 | 0.11 | 0.3 | 0.28 | |
| Iran | Sandstone | 43.77 | 19.37 | 16.9 | 0.43 | 0.06 | 0.08 | 3.35 | 0.25 | 0.08 | 0.27 | Banakeng <i>et al.</i> (2016) |
| | | 35.78 | 25.32 | 20.2 | 0.58 | 0.15 | 0.14 | 3 | 0.34 | 0.06 | 0.09 | |
| | | 24.07 | 27.3 | 23.86 | 0.65 | 0.06 | 0.08 | 3.55 | 0.86 | 0.1 | 1.33 | |
| Nigeria | Pegmatite | 12.61 | 51.4 | 24.24 | 0.13 | 0.26 | 0.03 | 1.03 | 0.02 | 0.03 | 0.04 | Adeola and Dada (2016) |
| | Granite-gneiss | 11.87 | 59.75 | 17.06 | 0.42 | 0.21 | 0.69 | 1.35 | 0.47 | 0.15 | 0.09 | |
| | Granite | 14.1 | 64.45 | 12.99 | 0.16 | 0.13 | 0.21 | 0.88 | 0.1 | 0.08 | 0.06 | Adebisi <i>et al.</i> (2013) |
| | Sandstone | 7.21 | 32.1 | 33.6 | 0.38 | 0.9 | 0.41 | 4.33 | 0.06 | 0.06 | 0.36 | |

However, several authors (Bourman & Ollier, 2003; Schellmann, 2003; Giorgis *et al.*, 2014; Oyelami, 2017) strongly criticized it despite the wide acceptance. The nature of the elemental constituents of lateritic soils commonly varies as their chemical composition. The elements primarily occur as hydroxides, oxides and silicates (Maignien, 1966). Hematite, goethite, and lepidocrocite are all mineral forms of iron. Additionally, it can be found as amorphous hydroxides with an indeterminate physical composition. Gibbsite, boehmite, diaspore, as well as amorphous alumina and clays, are all possible forms of aluminum. Furthermore, quartz, amorphous silica, and clay minerals like kaolinite, illite and montmorillonite, can all be forms of silica. However, the clay mineral content of lateritic soils is a function of the prevailing weathering conditions (Gidigas, 2012; Alhassan *et al.*, 2012). These conditions include the type of parent rock, ratio of water to rock, presence of organisms/organic materials and time. Consideration of the clay minerals present in the characterization of lateritic soils has been useful for engineering studies (Gidigas, 1971). This includes the characterization of their engineering properties, the formulation of local engineering soil classifications and its interpretation.

2.4 Engineering properties of lateritic Soils and their application as compacted soil liners

2.4.1 Types and use of compacted soil liners

Natural liners are very low hydraulic conductivity, clay rich soils that are naturally occurring and are commonly used as a back-up to engineered liners. These liners are applied as hydraulic barriers in various civil engineering projects such as in earth dams, canal lining, landfills and surface impoundments, sewerage lagoon and heap leaching pads. However, utmost attention has been given to their applications in sanitary landfills (Rahman, 2000; Endene *et al.*, 2019). Daniel (1993) classified three categories of soil liners including the compacted, natural and geosynthetic soil liners (Figure 2.3).

Natural soil liners may sometimes be the sole liner deployed at a waste disposal facility. Compacted soil liners are typically made of natural soils, but they can also contain synthetic materials like polymers and treated materials like bentonite. They are usually positioned at the side, base and top of sanitary landfills as indicated in Figure 2.3 (Christensen *et al.*, 1994; Corsu & Steggmann, 2019). Geosynthetic soil liners consist of a lamina of clayey soil attached to a geomembrane or wedged between geotextiles (Rahman, 2000).

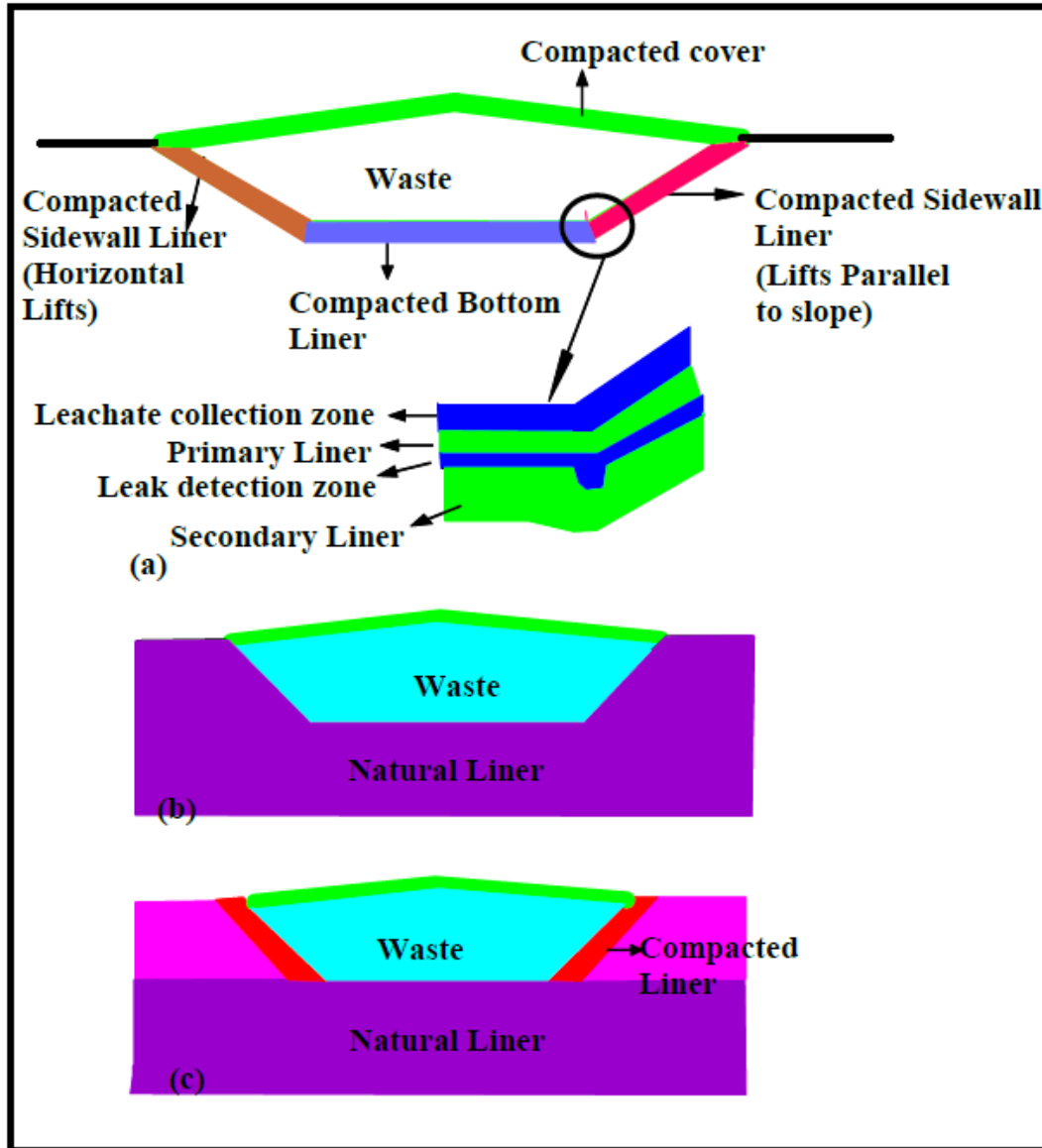


Figure 2.3. Types of Landfill Liners: (a) compacted; (b) and (c) natural (modified after Daniel, 1993).

2.4.2 Desirable properties and standard requirements of compacted soil liner (CSL)

CSLs are primarily constructed to effectively impede the spread of contaminants over their design lifespan. Several researchers (e.g., Ige, 2013; Endene *et al.*, 2019; Norouzi *et al.*, 2022) have investigated the desirable characteristics of CSLs. The most important desirable properties include low diffusivity and hydraulic conductivity, sufficient strength, high attenuation potential, and ductility. Others are long-term stability, constructability, long-term stability, low freeze/thaw effects and shrink/swell potential. The minimum requirements specified by various environmental

authorities and literature are presented in Table 2.2. Additionally, Endene *et al.* (2019) emphasized the need to certify the pH, electrical conductivity, cation exchange capacity, specific surface area and mineralogy of prospective soil liners. The desirable properties of landfill liners are those that overcome the notable potential problems such as cracking, erosion, chemical/biological degradation and hydraulic conductivity changes. In essence, the desirable properties of soil liners are these properties that are either construction related, inactivity related and operational related that will make the lining system to function properly (Mohamed & Anita, 1998; Regadio, *et al.*, 2020). Specifically, the problems relating to desiccation cracking, freeze-thaw cracking, deformation cracking, thermal stress, erosion, slope instability, animal attack, ultraviolet degradation, chemical and biological degradation, penetration from equipment and loading, material uniformity, material availability and hydraulic conductivity changes must be overcome (Mohamed & Anita, 1998; Rowe *et al.*, 2004; Endene *et al.*, 2019).

According to the USEPA (2004), liners must adhere to the following essential criteria:

- they should be made of significantly strong materials with the right chemical qualities, and adequate thickness to avert failure related to pressure gradients, direct interaction with the leachates to which they are subjected, installation or operational stress and climatic conditions;
- liners must be placed on a foundation that can sustain it and resist pressure gradients above and below, which will help to avoid the liner from failing resulting from uplift settlement or compression;
- liners should be constructed to protect the entire area of nearby soil from exposure to waste or leachates; and
- liner systems must be meticulously examined for consistency, flaws and damages during construction.

Table 2.2. Standard specifications for compacted soil liners.

| Parameters | Recommendations | Reference(s) |
|-----------------------------|--|---|
| Activity | ≥ 0.3 < 1.25 | Mohamedzein <i>et al.</i> (2005); Ige (2013) Oeltzschner (1992) |
| Atterberg limits | $PI \geq 15\%$, $LL \geq 30\%$ $PI \geq 7\%$, $LL \geq 20\%$ $PI \geq 10\%$, $LL \geq 30\%$ $10\% \leq PI \leq 65\%$, $LL \leq 90\%$ $10\% \leq PI \leq 30\%$ $LL \geq 30\%$ | Oeltzschner (1992) Qian <i>et al.</i> (2002) Rowe <i>et al.</i> (1995); Mohamedzein <i>et al.</i> , (2005) UKEPA (2009); USEPA (2000) TCEQ (2017) |
| Coefficient of permeability | $\leq 1 \times 10^{-8}$ m/s $\leq 1 \times 10^{-9}$ m/s $\leq 1 \times 10^{-10}$ m/s | Rowe <i>et al.</i> , (1995); Wagner (2013) Wagner (2013); NSW EPA (2016); USEPA (2021), Oeltzschner, (1992); Farquhar (1994); Ige (2013) |
| Particle Sizes | Clay fraction $> 20\%$ $LGS \leq 63$ mm Silt fraction $\geq 15\%$ $LGS \leq 50$ mm $LGS \leq 25$ mm $\% \text{ gravel} \leq 30 \%$ Clay fraction $\geq 10\%$ Fines content ≥ 30 Fines content $\geq 20\%$ Clay fraction $\geq 30\%$ Fines content $\geq 15\%$ | Oeltzschner (1992); NSW EPA (2016) Ige (2013) Ige (2013) Daniel (1993) Mohamedzein <i>et al.</i> (2005); Ige (2013) Daniel (1993); U.K EPA (2014) Wagner (2013) Mohamedzein <i>et al.</i> (2005) UK EPA (2009); Favaretti & Cossu (2018) Rowe <i>et al.</i> (2004) Ige (2013) |
| Maximum dry density (MDD) | $MDD \geq 1.70$ g/cm ³ | Taha & Kabir (2005); Ige (2013) |
| Optimum moisture content | Optimum Moisture Content +(2-4%) | Afolagboye <i>et al.</i> (2017) |
| Specific gravity | ≥ 2.2 ≥ 2.5 | ÖNORMS 2074 (1990) USEPA (1982) |

| | | |
|---------------------------------|----------------------|--|
| Unconfined compressive strength | ≥ 200 kPa | Daniel & Wu (1993) |
| Cohesion | ≥ 35 kPa | Majer <i>et al.</i> , (2007) |
| Cation exchange capacity | ≥ 10 meq/100 g. | Rowe <i>et al.</i> , (1995); Endene <i>et al.</i> , (2019) |
| Chemical flux point | $\leq 10^{-8}$ cm/s | Rowe <i>et al.</i> , (1995); Endene <i>et al.</i> , (2019) |

2.4.3 Index and Engineering characteristics of lateritic soils

The engineering behavior and application of soils are generally determined by identifying the properties that are significantly relevant to a particular type of engineering structure. This crucial stage is the cornerstone of all sound geotechnical design. In light of this, datasets on the index and geotechnical properties of lateritic soils were collated from available literature from two hundred and seventy-eight (278) locations from different countries. A summary of the engineering properties based on the standard requirements for landfill liners is presented in appendix 1.

2.4.3.1 Grain size distribution

The texture of lateritic soils is very variable and unpredictable (Gidigas, 2012; Abdela, 2017). A typical variation of the particle size characteristics of lateritic soils formed from a variety of parent rocks is shown in Figure 2.4. It contains all size fractions ranging from boulders to clay, as well as massive concretionary rocks generally referred to as curiase. Bell (2007) and Oyelami & van Rooy (2016b) referred to them as c- ϕ soils as it is made up of both cohesive and cohesionless soils. Several researchers (e.g., Okagbue & Yakubu, 1999; Bell, 2007; Oyelami & Alimi, 2016; Adebisi & Olufemi, 2017) stated that lateritic soils are coarse grained soils with granular or friable structure resulting from the enormous amount of sesquioxides that occupy the void spaces, cover the pore walls and cause the soil particles to clump together thereby forming modules of different sizes or spongy aggregates.

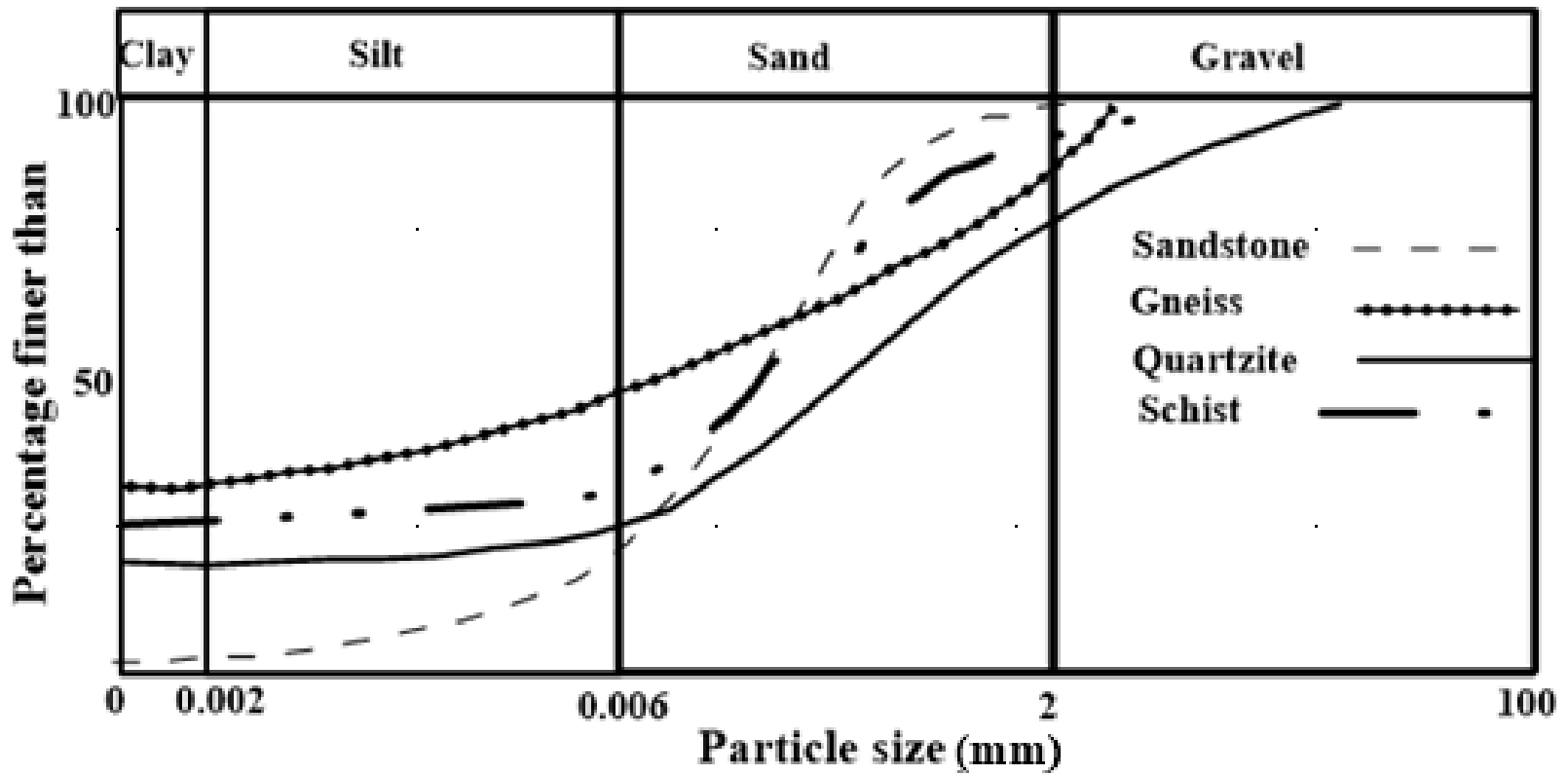


Figure 2.4. Grain size distribution curves of lateritic soils with respect to parent rocks (after Kahl, 1976).

A close observation of the compiled lateritic soil samples data shows that the particle size distribution varies with the parent rock. For example, the amount of fines in some of the lateritic soils are essentially high and this could be traced to the mafic and ultramafic nature of their parent materials which are basalt and serpentinite, respectively (Gidigas, 2012). Furthermore, an abundance of clays and silt were observed in soils derived from andesite and basalt. Similarly, some lateritic soils reflect these variations with lithology as the soils derived from charnockite have higher fines contents while the migmatites and gneisses with granitic compositions are essentially sandy with some amount of fines. However, some soils derived from granites have also recorded high clay contents, which may be due to the high feldspar content as observed by Afolagboye *et al.* (2016) and Owoyemi & Adeyemi (2018).

2.4.3.2 Atterberg limits

The liquid limit data compiled for the soils under consideration vary from 17 to 135% while the plasticity index varies from 2 and 73%. All but three of the lateritic soils possess liquid limit less than 90% as specified by UKEPA (2014). A liquid limit greater than 30% was specified by Rowe *et al.* (1995) and TCEQ (2017) for soils to be utilized as liners. Only 9.5% of the samples failed to meet this requirement. On the other hand, Quian *et al.* (2002) specified a minimum liquid limit of 20%, which all but one sample fulfilled. USEPA (2000) and UKEPA (2014) suggested a 10% to 30% limit for the plasticity index of soils designated for utilization as liner. This is based on the notion that, soils with essentially high plasticity index are commonly sticky when wet. Moreover, since it is anticipated that soils with high plasticity index and liquid limit will exhibit minimal hydraulic conductivity, the soils are considered acceptable for utilization as landfill liners. However, the shrink-swell potential of such soils should be adequately evaluated before use as soils with essentially high plasticity index and high liquid limit may likely contain abundant swelling clays such as montmorillonite or illite. The plasticity index of few of the lateritic soils is higher than 30%, hence, adequate precaution should be taken when using them for lining purposes. Moreover, Endene *et al.* (2019) indicated that a plasticity index of at least 10% is essential to achieve a very low desirable hydraulic conductivity for landfill liners. Similar recommendations were given by various authors including Benson *et al.* (1994); Rowe *et al.* (1995); USEPA (2000) and UKEPA (2014). Similarly, the compiled data indicates that the vast majority of the considered lateritic soils fulfill the $\geq 15\%$ benchmark recommended by Oeltzschner (1992) for soil liners used in landfills. Figure 2.5 shows the position plots of the soils on a Cassagrande plasticity chart used

in the classification of fine soils. The soils fall within the category of low, intermediate and high plasticity. Thus, these soils have the tendency to exhibit low, medium and high swelling potential and compressibility. The position plot of Figure 2.5 also indicates the presence of different amount and types of clay minerals (Nweke *et al.*, 2015; Afolagboye *et al.*, 2021). Since they plot above and below the arbitrary A-line, they could be classified as inorganic clays and silts, indicating CL, CI, CH, ML and MH groups in the USCS classification system (Figure 2.5). The variation in the position reflects the variation in the essential properties of the soils (e.g., swelling, permeability, strength) which are important in the selection for landfill liners. Additionally, the positions of the soils on the chart are not controlled by their location but by the prevailing soil forming factors. Variation of consistency limits with parent materials is noticed similar to the particle size variation. The soils derived from basalt and schist recorded the highest plasticity index and liquid limit, respectively, while the serpentinite-derived soils have the lowest plasticity index. This could be attributed to the different kinds of clay minerals present in the soil (Datta and Adhikari, 1972; Loi *et al.*, 1982; Velde and Meunier, 2008).

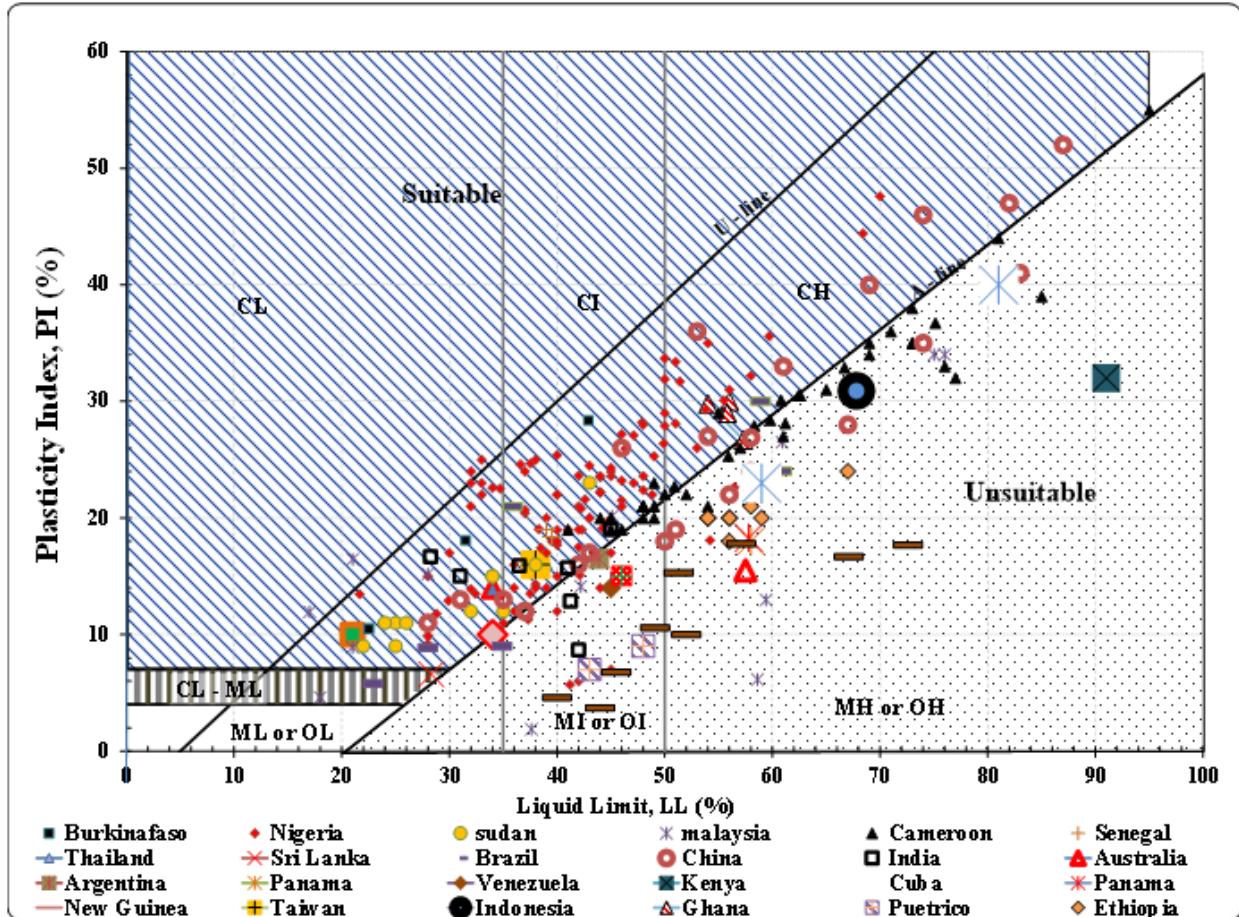


Figure 2.5. Landfill liner suitability classes of the lateritic soils based on their position on the Cassagrande Plasticity Chart (after, Jones *et al.*, 1993).

2.4.3.3 Specific gravity

The Specific gravity is a very useful index property in the identification of lateritic soils since it gives an indication of the degree of laterization and mechanical strength of soils (Adeyemi & Wahab, 2008; Kamthchueng *et al.*, 2015; Oyediran & Durojaiye, 2011; Endene *et al.*, 2019). Gidigasu (2012) and Goswami (2005) reported that the specific gravity of lateritic soils depends mainly on the iron content and to a limited extent on the accumulation of titaniferous materials whose concentration may be correlated with the degree of laterization and desiccation. The lateritic soils have a specific gravity ranging from 2.36-3.49 with a mean value of 2.72. Soils derived from basalt and serpentinite recorded the highest specific gravity values, which again indicates an influence of parent materials on the specific gravity. The values reported in the 270 samples compiled from worldwide sources fulfill the specification proposed by Ige (2013) while one of the lateritic soils fell short of 2.5 specified by USEPA (1982) for landfill liner applications.

2.4.3.4 Compaction characteristics

The MDD and OMC of lateritic soil depends on factors such as grading, degree of weathering, strength of coarse materials, dominant clay minerals, and placement condition (Gidigas, 2012; Villamizar *et al.*, 2012). The presence of mica influences the compaction characteristics of lateritic soils (Onana *et al.*, 2017; Daramola *et al.*, 2018). Compaction is a fundamental property in the selection of soil liners as the coefficient of permeability depends on the energy of compaction and molding water content (UKEPA, 2014; Endene *et al.*, 2019). The compiled data indicates that the MDD values range between 1.170 and 2.780 Mg/m³ with a mean of 1.80 Mg/m³ with the optimum moisture contents ranging from 6.6 - 39% with a mean of 15%. The data on MDD values indicate an extensive range of values, which may be linked to variations in their origin (i.e. type of parent rock) of the lateritic soils and the different energy levels of compaction (Mesida, 1989; Owoseni & Aro, 2018). Lateritic soils with the least MDD values are sourced from mica rich soils derived from mica schist, biotite granite and charnockite. Furthermore, soils derived from mafic rocks such as serpentinite and basalt recorded high OMC and very low MDD values. This is expected of such soils as they possess high amount of fines resulting in greater affinity for water (Afolgboye *et al.*, 2017; Olofinyo *et al.*, 2019). Although the average value of the MDD of the soils data collated is within the specified values for landfill liners, about 26.3% of the soils did not meet the minimum requirement of 1.700 Mg/m³ as specified by Ige (2013).

2.4.3.5 Strength characteristics of lateritic soils

It is well established that the friction and cohesion of soil particles influence the shear strength characteristics of lateritic soils (Ojo, 2013; Otoko, 2014). The structural integrity and competence of liners are ascertained by ensuring that they have adequate shear strength. Bello & Osinubi (2009) reported that liner materials must possess adequate shear strength and ample durability to resist the pressures of repeated freeze-thaw and wet-dry cycles. These authors recommended an unconfined compressive strength of 200 kPa, which represent the lower limit for very stiff soils according to consistency classification. The values of unconfined compressive strength of the lateritic soils collated from worldwide sources range from 4.23 to 1260 kPa with an average of 135.3 kPa. The majority of the soils fail to meet the standard value of ≥ 200 kPa. The value of the cohesion ranged from 5.5-153 kPa with angle of internal friction ranging from 3.2° to 49°. The average value of the cohesion is generally greater than the benchmark of 35 kPa stipulated for the compacted soil liners.

2.4.3.6 Permeability

Permeability has been described as the key parameter in the evaluation of soils as landfill liners. The variations in the permeability of compacted soils tremendously depend on the composition of the soil as well as the conditions of compaction (Met *et al.*, 2005; Rosli, 2019; Yamusa *et al.*, 2022). The permeability values of various lateritic soil sample data collated across the world vary from 2.95×10^{-12} to 1.22×10^{-3} m/s with a mean of 7.17×10^{-5} m/s. According to different regulatory bodies, the benchmark stipulated for coefficient of permeability of landfill liners are 1×10^{-10} m/s, 1×10^{-9} m/s and 1×10^{-8} m/s (Endene *et al.*, 2019). The mean coefficient of permeability recorded by the lateritic soils collated exceeds all the benchmarks reported for liner applications. However, individually, a larger proportion of the lateritic soils (76%) meet the 1×10^{-8} m/s minimum requirement specified by UKEPA (2014) and Endene *et al.* (2019). However, only 61% of the lateritic soils satisfy the maximum limit of 1×10^{-9} m/s while 51% satisfy the 1×10^{-10} m/s limits set by Oeltzschner (1992); Farquhar (1994); Ige (2013); Wagner (2013); NSW EPA (2016); Favaretti & Cossu (2018) and USEPA (2021).

2.4.4 Effect of the geochemical and mineralogical composition of lateritic soils on their engineering properties

The importance of the mineralogical characteristics of soils used as landfill liners has been underscored by various authors (e.g., Allen, 2001; Yong & Mulligan, 2005; Frempong & Yanful, 2008; Guney *et al.*, 2014). It has been observed that liner systems typically contain some layers of bentonite clays that belong to the expansive smectite group. Significant variations in the coefficient of permeability of soils have been linked to variations in their mineralogical composition (Benson *et al.*, 1994; Met *et al.*, 2005). It has been reported that bentonite mineral layers are highly prone to severe desiccation cracking as a result of inaccessibility of moisture at high temperature (Allen, 2007). Fernandez & Quigley (1985), Gates *et al.* (2004) and Hu Yang *et al.*, (2019) stated that chemical interactions between bentonites and organic compounds increases permeability. Additionally, Wagner (1994) and Ugwu & Igbokwe (2018) noted that such interactions lead to heavy metal ion sorption in the intermediate layer of smectite, which could trigger the decline of swelling potential, plasticity and significant changes in the volume of smectite.

Lateritic soils commonly contain the common clay minerals such as montmorillonite, kaolinite and illite, in some rare instances they are dominated by a single clay mineral type, whilst in others some interesting mixtures are present in different proportions (Malomo, 1977; Gidigas, 2012). Ogunsanwo (1996) noted that some lateritic soils derived from charnockite contains kaolinite, halloysite, illite, chlorite and montmorillonite. On the other hand, Mesida (1987) reported the occurrence of kaolinite, illite, chlorite and montmorillonite in some lateritic soils derived from mica schists. This interesting combination of clay minerals could help achieve the desired coefficient of permeability with shrinkage and desiccation that is acceptable for compacted soil liners. Compacted liners predominated by non-swelling clay minerals are not significantly damaged by interaction with leachate generated within the municipal solid waste landfill as far as the smectites are kept minimal (Allen, 2007; Widomski *et al.*, 2018). Frempong & Yanful (2008) have investigated the interaction between landfill leachates and Ghanaian lateritic soils and reported some mineralogical transformation after the permeation of leachates through lateritic soils. The new minerals that were formed were non-clay minerals such as ferrihydrite, hydroxypyromorphite, hydroxyapatite, pyromorphite and strengite. Furthermore, the specific surface of the soil was found to be decreased due to soil transformation with corresponding increase in cation exchange capacity. The mineralogical transformation did not negatively impact the coefficient of permeability of compacted soil liner. Sunil *et al.* (2009) and Norouzi *et al.* (2022) observed some effects of leachates on the shear strength, atterberg limits, and the chemical composition of lateritic soils. Lateritic soils were found to have increased liquid limit, electrical conductivity, calcium, sulphate, and iron concentration. The increase in liquid limit was attributed to the altered characteristics of the pore fluid.

2.4.5 Attenuation capacity of lateritic soils

Apart from offering a competent impermeable barrier within the landfill facility and the surrounding ground, liner materials are expected to provide a means of attenuation of the contaminants that pass through the barriers designed to control leachate. After a thorough examination of the flaws in the containment strategies, Allen (2001, 2007) advocated for attenuation landfill, which could take advantage of attenuation properties of soils utilized for liner purposes. Several studies (e.g., Wagner, 1994; Allen, 2001; Yong & Mulligan, 2005, 2019; Regadio *et al.*, 2020) have indicated that the attenuation property could be achieved naturally *in*

situ (i.e. natural attenuation) or in engineered landfill (i.e. engineered natural attenuation). Attenuation properties of lateritic soils help in mitigating the migration of contaminants through engineered natural attenuation processes. It employs the processes of sorption, filtration and ion exchange (Yong & Mulligan, 2019). Attenuation potential is controlled by the types and proportion of clay mineral as well as the manganese oxide content. Different clay mineral groups possess variably different sorption and ion exchange capacity. According to Van Olphen (1977), the sorption including cation exchange capacity of clay minerals have the following order: kandite < illite < sepiolite < palygorskites < vermiculite < smectite. The ability of smectite clays both to sorb ions between their lattice sheet and onto their external surfaces enhances their sorptive and cation exchange capacities.

Various investigations (e.g. Frempong & Yanful, 2008; Chatermyanont *et al.*, 2009; Ko, 2014) on the contaminant attenuation properties of lateritic soil have revealed that they possess suitable sorption, diffusion and cation exchange properties. Chalermyanont *et al.* (2009) reported that trace metal contaminant sorption capacity of lateritic soils from Thailand followed the order: Cr>Pb>Ni>Zn>>Cd, whilst for Ghanaian lateritic soils, Frempong & Yanful (2008) observed the following order of sorption selectivity: K>Br>NA>Cl. Similarly, Partey *et al.* (2008) reported that iron concretion in lateritic soils could sorb common aqueous species of arsenic and stated that the link between temperature and positive sorption of lateritic iron concretions will improve sorption in tropical environments, particularly where groundwater sources are connected to geothermal systems.

2.4.6 Improvement of lateritic soils through stabilization for use as liners

Efforts have been made by several authors (e.g. Ojuri & Oluwatuyi, 2018; Adedokun & Oluremi, 2019; Chen *et al.*, 2019) to enhance the properties of lateritic soils for utilization as liner material including landfill liners. Consequently, various materials including bentonite, sawdust, flyash and mine tailings were mixed at various proportions to determine the best mix with resultant positive influence on their engineering properties. Positive improvement in the engineering properties notably a reduction in hydraulic conductivity, optimum moisture contents and Atterberg limits with an attendant increase in strength and sorption capacity was achieved. However, attempts of mixing with some materials including sawdust ash-lime did not yield the desired improvement. Ojuri & Oluwatuyi (2018) concluded that lateritic soil samples from southwest Nigeria that were

stabilized with compressed sawdust, ash, and lime might not be appropriate for use as liners in landfill. However, they could be easily deployed as subsoil at waste disposal sites because the stabilized lateritic soils yielded coefficient of permeability that exceed the specified limit of 1×10^{-9} m/s while their maximum dry density decreased and the optimum moisture content increased. Attempts to enhance the contaminant attenuation characteristics of lateritic soils by treating them with appropriate blends of various materials including Bagasse ash, fly ash, bentonites and quarry dust have been largely successful (Amadi & Odedede, 2009; Muhsina and Chandrakaran, 2019; Chen *et al.*, 2019).

2.5 Comparative analysis of lateritic soils with some common soils used for compacted soil liners

Various researchers (eg. Mohamedzein *et al.*, 2005; Afolagboye *et al.*, 2016; Thankam *et al.* 2017; Endene *et al.*, 2020a & b; Redhwa and Al-Amen, 2020) have explored the possibility of utilizing different soil types for landfill liner applications as a result of their proximity to these soil types. Among the various soil types, lateritic soils, crushed shales, bentonite, red mud and marine clays are frequently considered. Each has distinct geohydraulic properties that influence their performance as landfill liners. According to Endene *et al.* (2019), lateritic soils exhibit low to high plasticity and variable shrink-swell behavior. While they provide good compaction and strength, their permeability can be higher than required without proper treatment. Furthermore, Afolagboye *et al.* (2016) noted that crushed shales offer a balance between permeability and compaction characteristics. These materials exhibit moderate coefficient of permeability, which can be reduced further when compacted, while their high shear strength makes them suitable for structural stability. However, they may require amendments to achieve the low permeability desirable for effective landfill liners, as their natural hydraulic properties might not be sufficient. Bentonite is renowned for its exceptional swelling property and extremely low permeability (Moradini and Leitie, 2010; Amadi & Eberemu, 2013). Due to its potential to expand significantly, it creates an impermeable barrier that is highly effective at containing contaminants (Nath *et al.*, 2023). Its high adsorption capacity and low coefficient of permeability make it one of the most preferred materials for compacted soil liners, despite the potential for desiccation cracking under dry conditions. Marine clays are typically soft and exhibit high plasticity while they have low coefficient of

permeability, making them effective barriers for landfill liners (Endene *et al.*, 2019, 2020a). However, their high compressibility and potential for significant settlement under load can pose challenges. Chalermyanont *et al.* (2009) noted that the diffusion coefficient of marine clays commonly range from 3×10^{-11} to $9.14 \times 10^{-9} \text{ m}^2/\text{s}$ while their coefficient of permeability usually falls below 10^{-9} m/s when it is permeated with heavy metals. However, Thankam *et al.* (2017) observed that an increase in concentration of heavy metals in the pore spaces of marine clays resulted in the shrinkage of the double layer leading to the enlargement of pore space causing an increase in the coefficient of permeability.

Among these materials mentioned, bentonite stands out for its superior geohydraulic performance, offering minimal permeability and excellent contaminant containment. Marine clays also provide low permeability but may require stabilization to address structural issues. Lateritic soils and crushed shales, while offering good strength, typically need amendments to achieve the desired low permeability.

2.6 Summary

A review of lateritic soils and their use as liners has been undertaken. The review included the genesis, geochemical, mineralogical and engineering characteristics of lateritic soils towards utilizing them as liner material. The review indicates that lateritic soils are ubiquitous natural resources in the tropical regions and observed to have formed in hot humid tropical environments. These soils dominantly consist of significant amount of sesquioxides of aluminum and iron with respect to other constituents. The performance of soil-based liners is usually measured by its coefficient of permeability, flexibility and strength, which depends on the structure of the soil. The initial soil structure is gauged based on compositional factors (mineralogy, particle size, composition and molding water content). Review of available data on the engineering characteristics of lateritic soils across the world show that a vast majority of them possess suitable engineering properties for liner applications including for landfills. Additionally, lateritic soils possess important properties including interesting clay mineralogical combinations, which could help achieve the desired coefficient of permeability with shrinkage and desiccation that is acceptable for soil liners. They also possess leachate attenuation properties such as sorption, diffusion and cation exchange. Analyses of lateritic soil data collated from around the world show that only 60% of the lateritic soils meet the $<10^{-9} \text{ m/s}$ coefficient of permeability specification

required for use as barrier soils. Therefore, efforts should be made to evaluate the appropriate compaction condition, which could yield the minimum required coefficient of permeability. However, it is important to build laboratory scale models to evaluate the long-term performance, efficiency, durability and compatibility of each region's lateritic soils with leachates while considering local climatic variations. The review further indicates that the suitability of the lateritic soils for landfill liner and other applications is not strictly constrained by parent rock types or geographical locations as some soils developed over same rock types conform to the set standards while in other cases they do not. These observations necessitate for a detailed evaluation of the lateritic soils locally in order to capture variations in the relevant geotechnical properties that are needed for liner applications.

Furthermore, although most lateritic soils possess suitable engineering properties for landfill liner applications, their relevant geotechnical characteristics can be suitably amended by blending with various materials including bentonites, flyash and sawdust. These amendments were found to improve the contaminant attenuation capacities of lateritic soils substantially.

It is important to note that some notable research gaps were identified during the course of conducting this literature review. Firstly, there exists noticeable deficiency in studies delving into influence of geology on essential properties required for landfill liner applications. This is the case in the study area where sufficient exploration of the attenuation capacity, specifically focusing on the desorption potential of lateritic soils is lacking. Secondly, the stabilization of lateritic soils for liner applications, incorporating those derived from different parent rocks and provinces are not undertaken. Addressing these research gaps is paramount for advancing the understanding of lateritic soils for use as landfill liner materials and enhancing their efficacy when uses in waste containment systems.

CHAPTER THREE: DESCRIPTION OF THE STUDY AREA

3.1 Location and climate

The formation of lateritic soils is largely influenced by a host of physical and environmental factors prevalent in the area of formation (Schellmann, 1986; Gidigas, 2012). Thus, a comprehensive study of the physical, geographical and geological setting of the study area is essential for understanding the nature and characteristics of lateritic soils. This chapter provides a description of the study area in relation to the aforementioned factors.

The study area (Figure 3.1) is located in southwestern Nigeria ($5^{\circ}1'33''\text{E}$ to $5^{\circ}25' 33''\text{E}$ and $7^{\circ}26'27''\text{N}$ to $7^{\circ}48'3''\text{N}$) covering an approximate area of 875 km² with a total population of 3,270,789 in 2016 (NBS, 2016). A vast majority of the populace occupies the urban areas because of rural-urban migration. The area experiences a humid tropical climate and has two seasons of the year; warm and overcast rainy season (from April to October) and a hot and partly cloudy dry season (from November to March). The wet seasons are caused by the moist maritime southwestern monsoon trade winds blowing from the Atlantic Ocean while the dry spell arise from the dust laden dry wind blowing from the sahara desert (Oyelami, 2017). Variations in the durations of the two seasons have been noticed in recent times due to global climate changes. Thus, on some occasions, the dry season may extend till May while in some instances it may extend for a very short period from December to January. The rainy season may sometimes extend up to December. The average monthly meteorological data for the area is presented in Figure 3.2. The annual rainfall fluctuates between 1499 and 2500 mm while the average relative humidity is about 73.1% and mean annual temperature is about 28°C (Oyelami, 2017). The annual temperature ranges from 21.89°C to 32.85°C. These combinations of the rainfall and temperature condition coupled with the seasonal fluctuations prevalent in the study area presents a typical condition that favours the formation of lateritic soils.

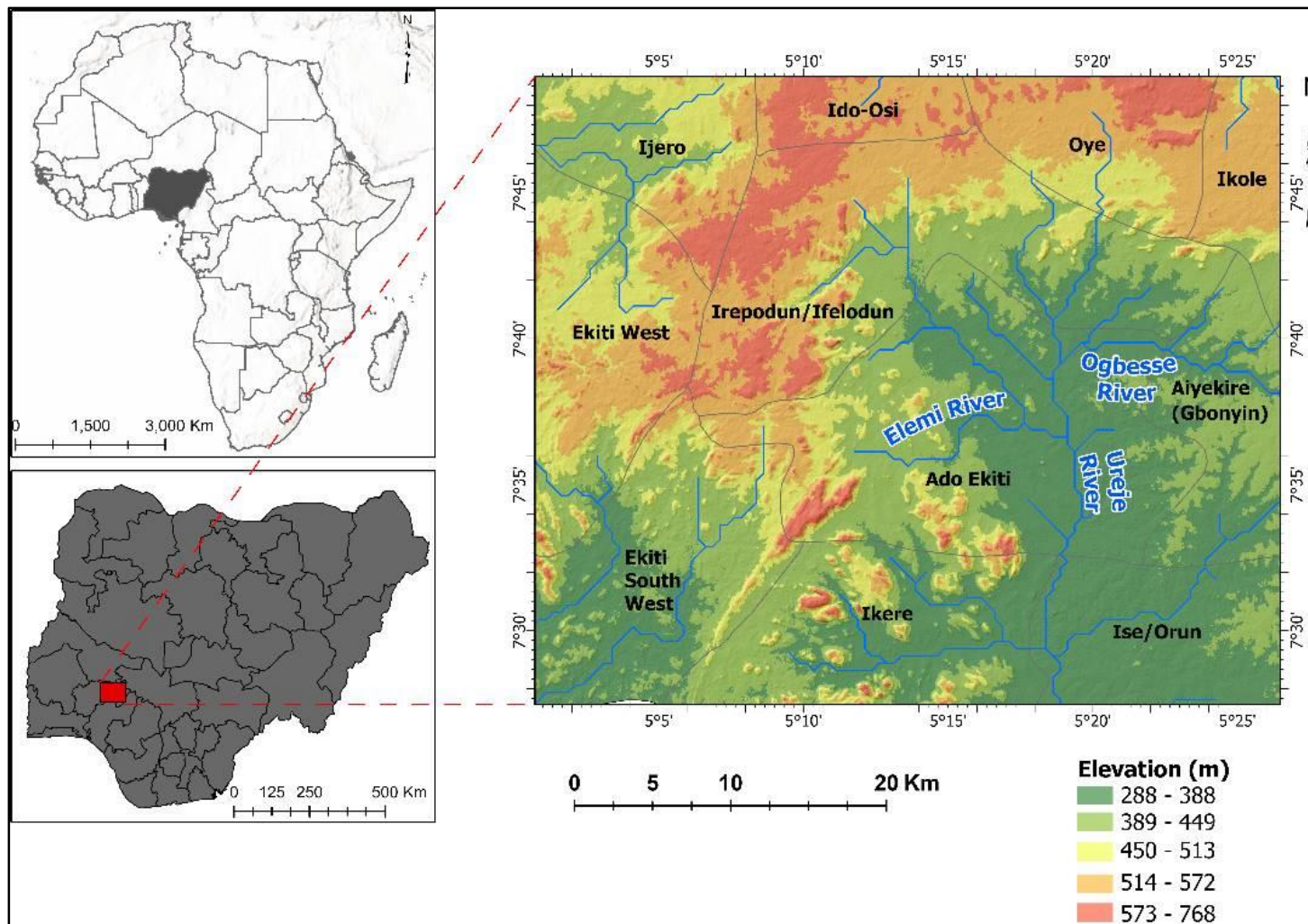


Figure 3.1. Location map of the study area in southwestern Nigeria.

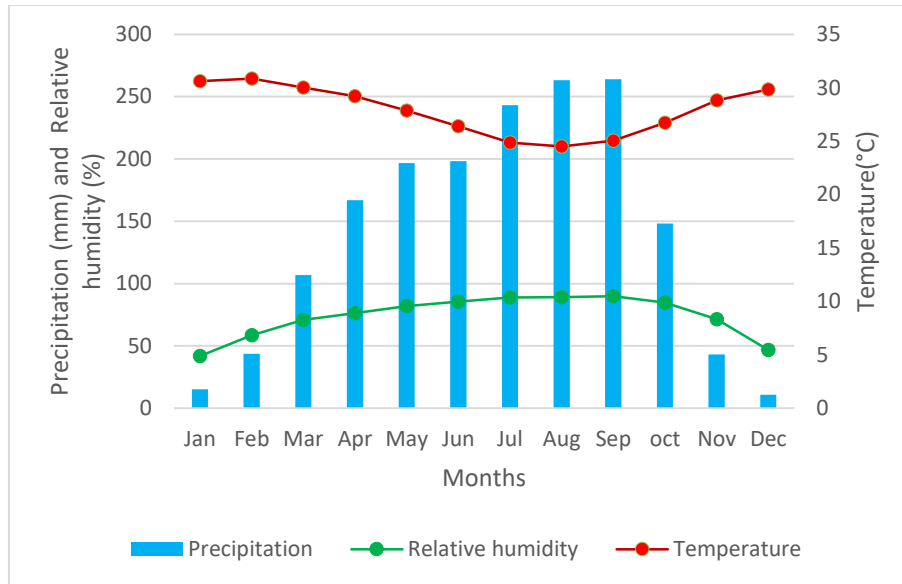


Figure 3.2. Average monthly rainfall, temperature and relative humidity for the study area for the period 2006 to 2021 (data obtained from Nigerian Meteorological Agency, 2022).

3.2 Topography and drainage

The study area is principally an upland region rising over 400 m above sea level with an undulating terrain and a typical landscape that comprises old plain separated by steep sided outcrops occurring singularly or in groups or ridges (Talabi, 2013). Hence, the state is spotted with rugged hills. The flow of large rivers and streams is controlled by underlying rocks. The dendritic drainage pattern dominates the area (Figure 3.3), implying that the underlying rocks are to a large extent uniformly resistant to weathering. The research area is well drained, although many of the streams are affected by seasonal changes and the main rivers that drain the area flow southwards. The main rivers draining the area are the Eleme, the Ogbese, the Ose and the Ureje and their system of tributaries and streams (Ayodele, 2022).

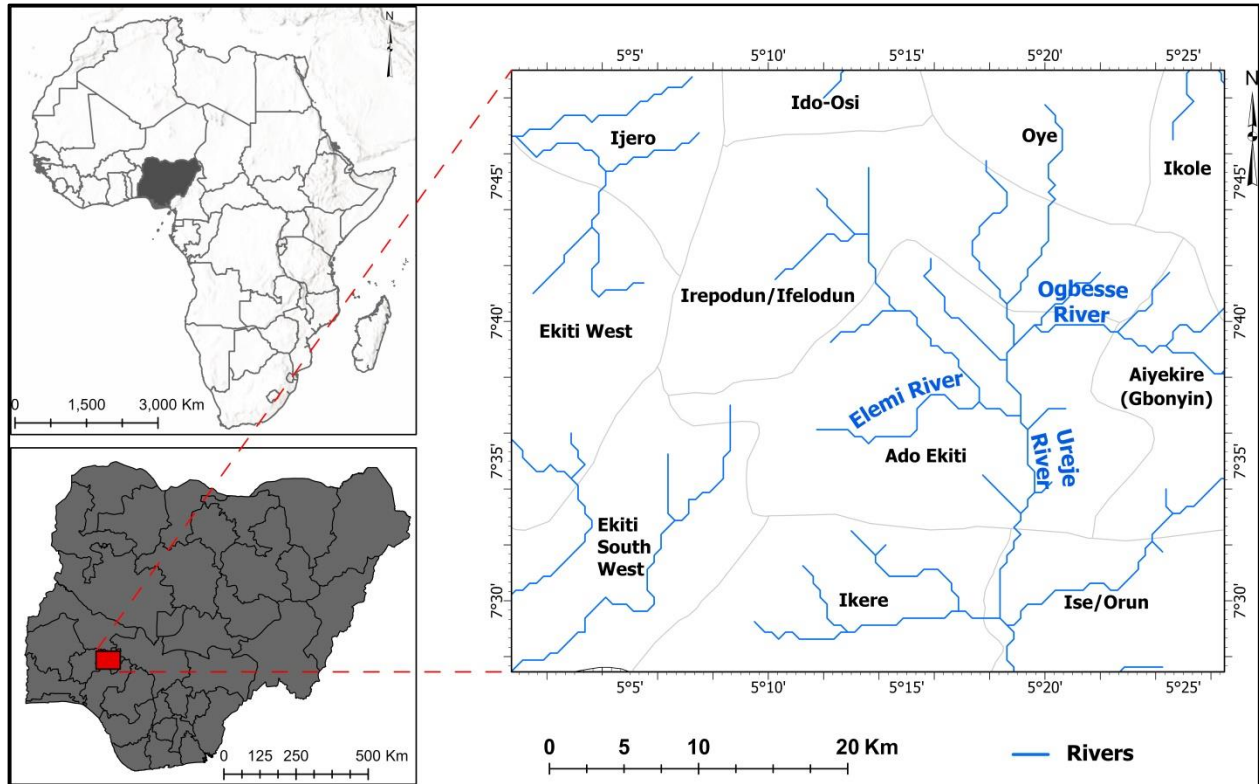


Figure 3.3. Drainage map of the study area.

3.3 Geological Setting

Ekiti State is located within a major part of the Precambrian basement complex of Nigeria (Figure 3.4), that forms part of the Pan-African belt and is flanked by the Congo and West African Cratons (Talabi *et al.*, 2018). Oyinloye (1998) noted that the rocks of the basement complex were formed as a consequence of four orogenic events namely, the Liberian (2700 Ma) the Eburnean (2 000 Ma), the Kibaran (1100 Ma) and the Pan-African cycle (600 Ma). The Liberian, Eburnean and Kibaran events were typified by strong deformations with associated regional metamorphism that was later followed by migmatization. The Pan-African cycle (600 Ma) was accompanied by regional metamorphism, migmatization, extensive granitization and gneissification. This resulted in the formation of homogeneous gneisses and syntectonic granites (Rahaman and Ocan, 1978). Late tectonic emplacement of granodiorites, granites and contact metamorphism complemented the final phases of this latter deformation. Olayinka (1992) noted that fracturing and faulting marked the end of the Pan-African orogeny. Ekiti state is predominantly underlain by Precambrian crystalline rocks of igneous and metamorphic origin (Rahaman and Ocan, 1978; Talabi and Tijani,

2013; Oyelami and Van Rooy, 2018). The notable rock types in the study area are charnockite, Pan African granite, schists with pegmatite, quartzites and migmatite (Figure 3.5).

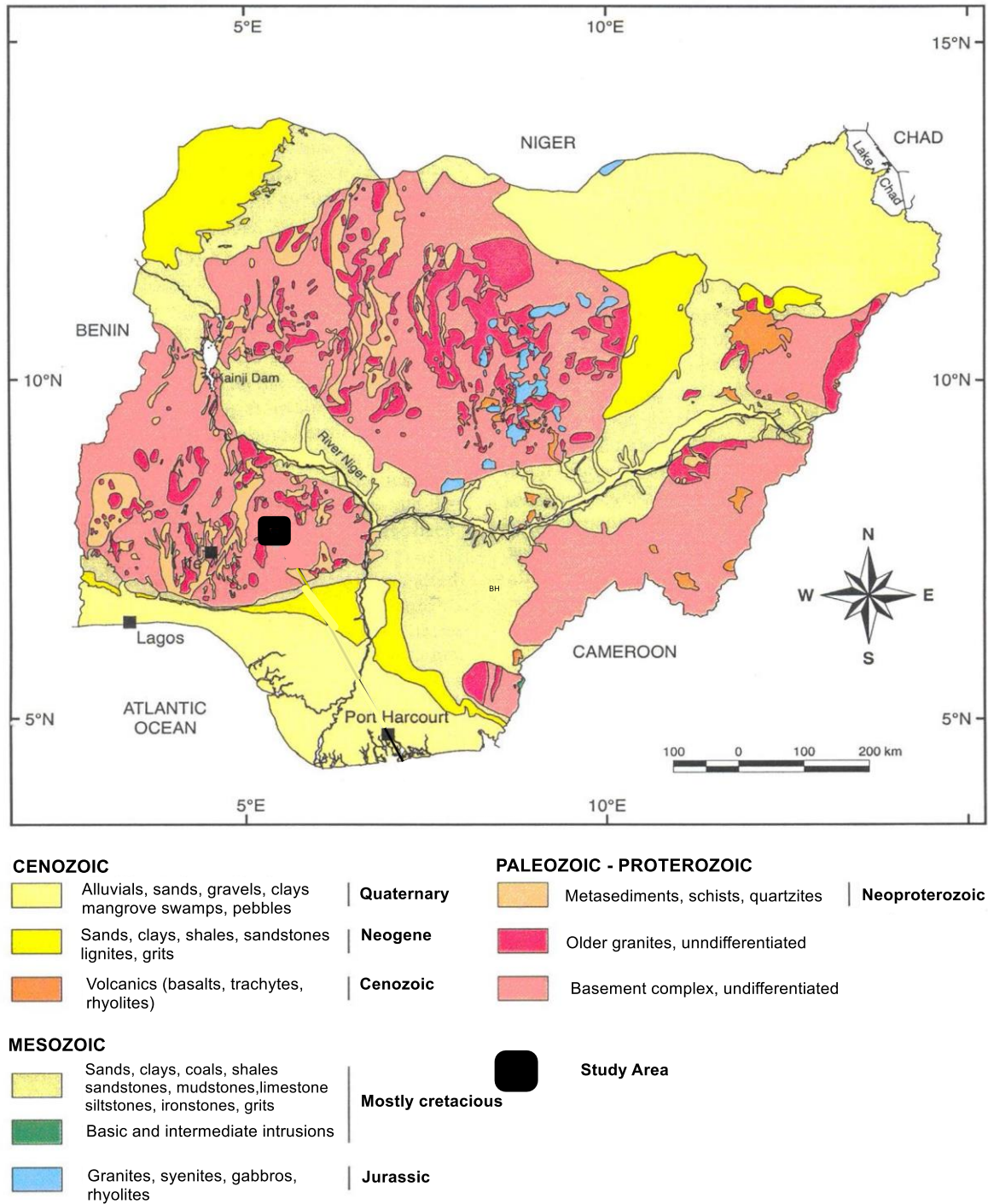


Figure 3.4. Geological map of Nigeria (modified from Akinsunmade *et al.*, 2020).

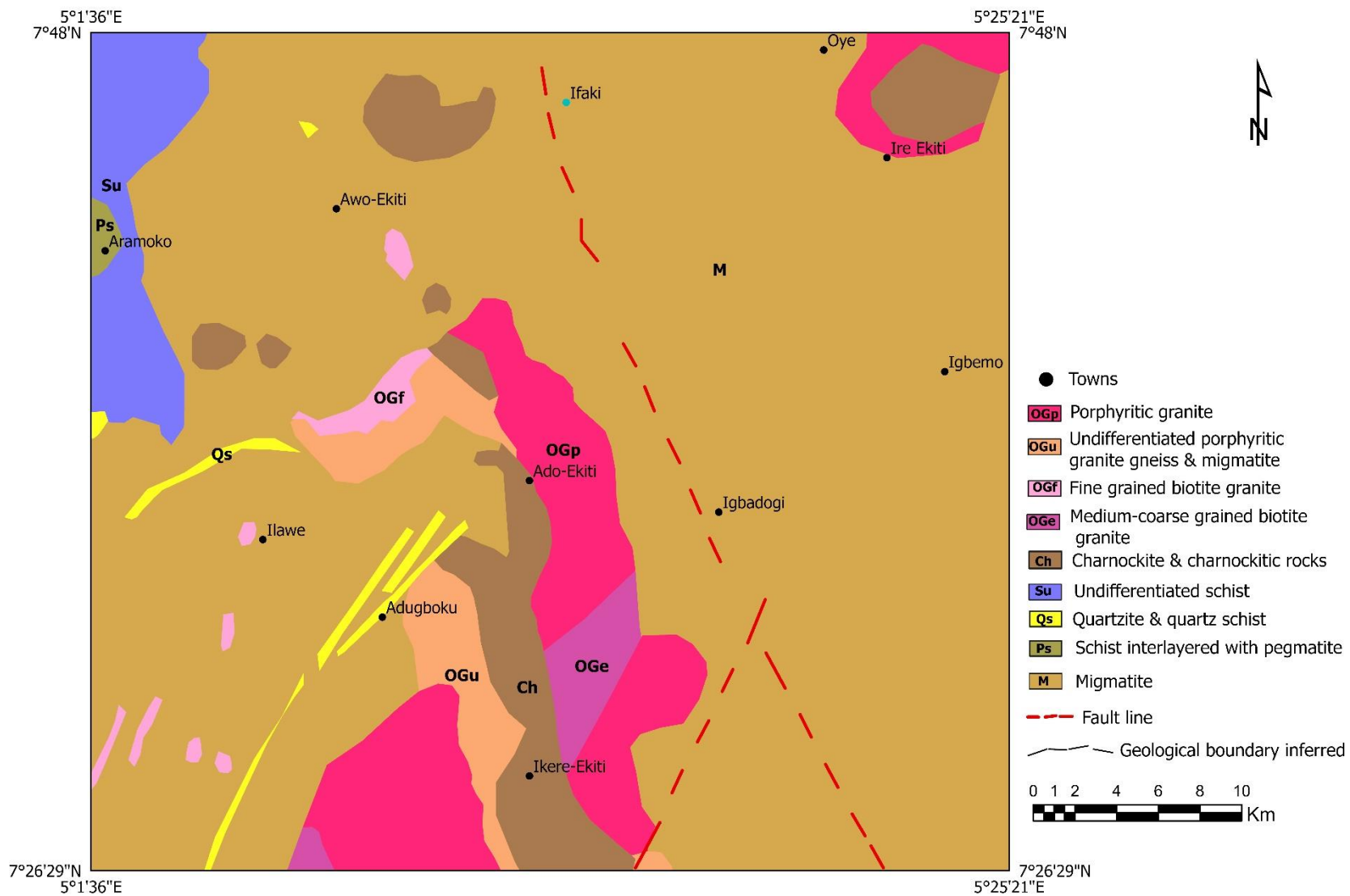


Figure 3.5. Geological map of the study area (modified from NGSa, 2006).

3.3.1 Migmatite

Migmatite forms a prominent member of the migmatite-gneiss-quartzite Complex, which is generally regarded as the basement complex in the study area (Rahaman, 1988; Obaje, 2009). Field observation by Talabi (2013) revealed a very close structural relationship between the granites, charnockites and quartzites. It is seen as depleted hills and covers about half of Ekiti State (Figure 3.5), existing in different varieties as reflected by the compositional varieties within the frame of leucocratic minerals such as feldspar and quartz, and melanocratic minerals which are dominantly biotite and hornblende (Oyelami, 2017). The banded gneisses are very common in the study area particularly at Ado, Iworoko, Iyin Ikere, Ise, Ikole and Emure. Quartz veins commonly occur in varying dimensions in the migmatites and may cut across the whole width/length of the host rocks.

3.3.2 Quartz-schist/quartzite

Quartzite and quartz schist occur as ridges of steeply dipping, massively bedded fine grained bodies rising to 100 m in parts of the region. This is partly due to their high resistance to weathering while some varieties including white, pink, and grey types were reported by Ayodele (2015). The colour of the quartzite/quartz-schist in the study area varies from white to gray due to the variation in the iron oxide content in the rock. Some massive quartzite outcrops rising up to hundred metres above the adjoining terrain occur around Ado-Ekiti, while the quartzite outcrops around Ikogosi are schistose with flakes of muscovite littering its environment (Talabi, 2013; Ayodele, 2015). However, they commonly exist as rubbles in the southwestern region of the study area. The nearly pure silica content of the rock results in the formation of little soil. Thus, the ridges of quartzite are frequently bare or covered with a thin soil layer and little vegetation.

3.3.3 Pan African granites

The terminology older granites was introduced by Falconer (1911) and is now preferably referred to as Pan-African granites because it covers some significant petrologic groups formed at the same time and its merit on age (Dada, 2006). The Pan-African granites (ca. 600 Ma) occur as intrusions within the migmatite-gneiss-quartzite complex (Oyinloye, 2011; Okonkwo & Folorunso, 2013). Dome-shaped hills of Pan African granites are abundant in the area with varieties ranging from fine-medium grained to porphyritic types. This includes the porphyritic biotite and biotite-

hornblende-granite and undifferentiated older granites, which includes granite, gneiss, pegmatites, aplite and quartz veins commonly occurs as intrusions into the granitic rocks. The granites are unique because of their conspicuously observable minerals, fine-medium grained texture, lack of foliation and compact interlocking crystals that developed during the crystallisation of magma. However, prominent occurrences of porphyritic granite exist around Ikere, Ado-Ekiti, and Ikole-Ekiti. The contact relationships of the PanAfrican granites with the surrounding country rock are mostly gradational over very short distances while they are abrupt in very few cases.

3.3.4 Charnockites and charnockitic rocks

Afolagboye *et al.* (2016) stated that the charnockites occur along the margins of older granite boundary in the study area and they outcrop as pavement and semi-circular hills with many boulders in some places. They are generally massive, dark grey to greenish in colour while their texture commonly varies from medium to coarse grained. The fresh outcrops have a lot of quartz, aplite and pegmatite intrusions occurring in it. The intrusions and joints that occur on the charnockitic rocks dominantly trend N-S (Talabi, 2013). Furthermore, Talabi *et al.* (2018) revealed two modes of occurrence of the charnockitic rocks through field investigation. These include the charnockites that occur along the margins of older porphyritic granite bodies as typified by the charnockitic outcrops in Ikere and Ado areas. The second mode of occurrence includes the charnockitic rocks that align in a NW-SE direction as characterized by the charnockitic rock occurrences around Ijelu and Oye Ekiti areas. The authors further emphasized that contact relationship of the charnockites to the surrounding rocks is variable. The rocks commonly contain alkali feldspar, quartz, orthopyroxene, plagioclase, clinopyroxene, hornblende, biotite and fayalite as essential minerals, while zircon, apatite and iron ores are the common accessory minerals (Olawajaju, 2006).

3.3.5 Undifferentiated schist

The undifferentiated schist is part of the schist belts of Nigeria, which contain low-grade metasedimentary rocks occupying synformal troughs with a north-south trend. Elueze (2000) noted that the schist belts are generally folded into the migmatite-gneiss-quartzite complex. The undifferentiated schist within the study area consists of pelitic schist, quartz schist and sometimes includes phyllite and amphibolitic layers. The pelitic schist generally outcrops poorly and is mostly low lying because of their low resistance to weathering.

The prominent structural features in Ekiti State include faults, folds, joints and fractures. A notable fault traverses the study area trending northwest-southwest as indicated by the NGS (2006). The presence of distinct folds known as Okemesi fold, which is a prominent geological feature in the study area, reflects the intense tectonic forces that have shaped the area (Ayodele, 2010). The occurrence of other structural features such as joints and fractures has also been reported by previous researchers (Talabi, 2013; Talabi *et al.*, 2018). These geological structures not only add intricacy to the overall structural framework of Ekiti State but also have implications for resource exploration and subsurface geological conditions.

3.4 Soils distribution in the study area

The study area is characterized by five major soil associations, which are closely related to the nature of the underlying geology (Smith & Montgomery, 1962). These include the Itagunmodi, Iwo, Jago, Okemesi and Ondo soil associations (Figure 3.6). The Iwo soil association is found in areas underlain by coarse-grained granite and gneiss, covering approximately 1,124 km². The soils are coarse-textured and exhibit shades of grayish brown to brown. Due to their sandy nature, these soils are highly susceptible to erosion (Ojo *et al.*, 2015). The Ondo association, covering about 512.4 km², typically occurs in regions underlain by medium-grained granite and gneiss. The soils display shades ranging from orange-brown to brownish-red, and contain significant amount of clay, often overlying mottled clay in shades of orange-brown to red. This soil type is found in the central, southwestern and southeastern parts of the study area. The Itagunmodi association, which is underlain by amphibolite and related basic rocks, spans an area of 27.5 km². The soils are characterized by fine textures and shades of brownish-red or chocolate brown, and are very clayey. The Okemesi association occurs in areas underlain by quartzite in the southwestern part of the study area and consists of coarse-textured, gravelly soils that are pale grayish-brown to brown, usually sandy, and often associated with steep-sided, elongated ridges. The Jago association typically occupies lower slopes near streams, where the soils are influenced by fluctuations in the regional groundwater table. These soils are derived largely from alluvium with some local colluvium and have extremely variable textures, often containing exceptionally high proportion of silt. Figure 3.7 presents some exposures of lateritic soil profiles in the study area, highlighting the variations across the profiles.

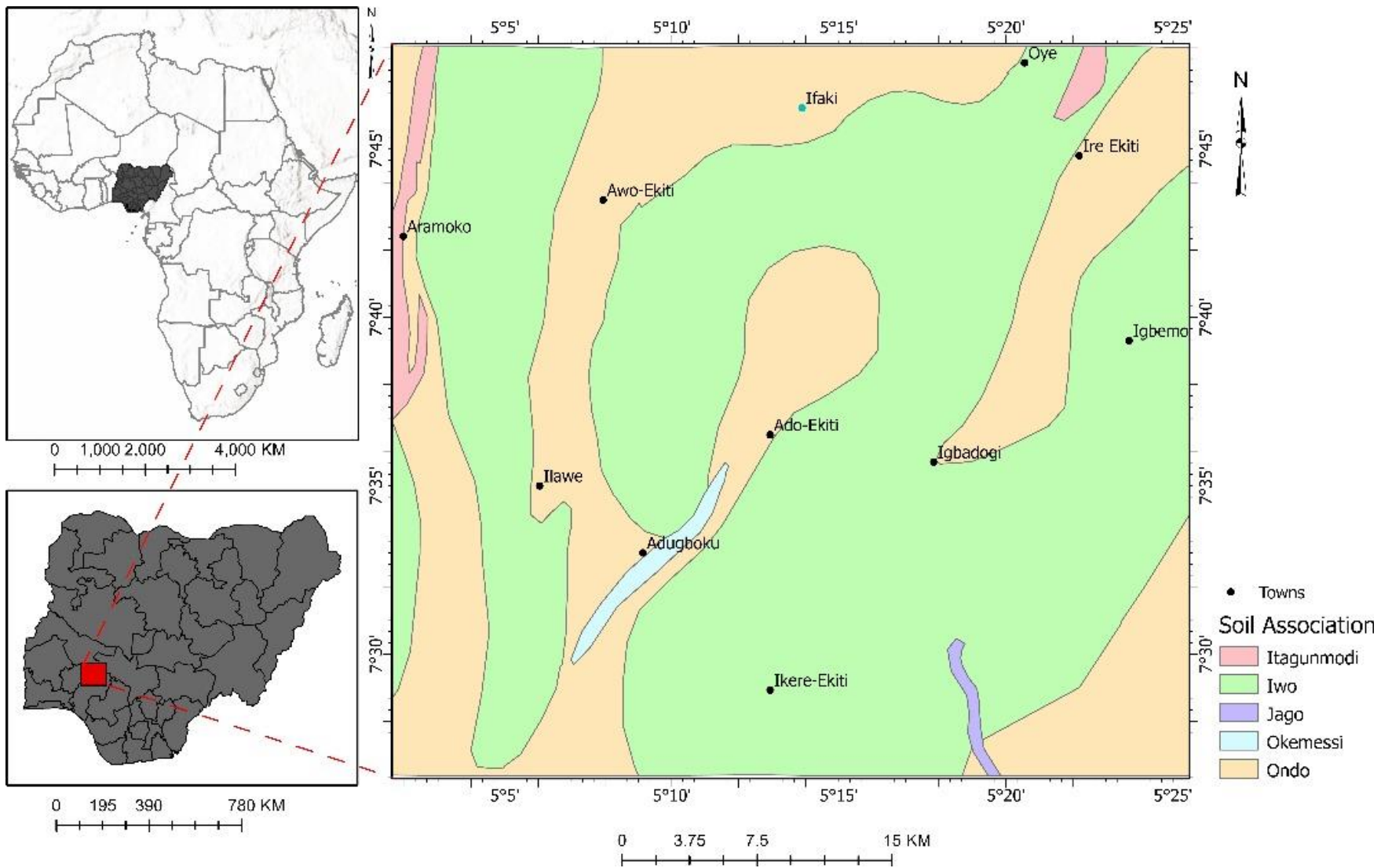


Figure 3.6. Soil map of the study area (modified from Smith & Montgomery, 1962).

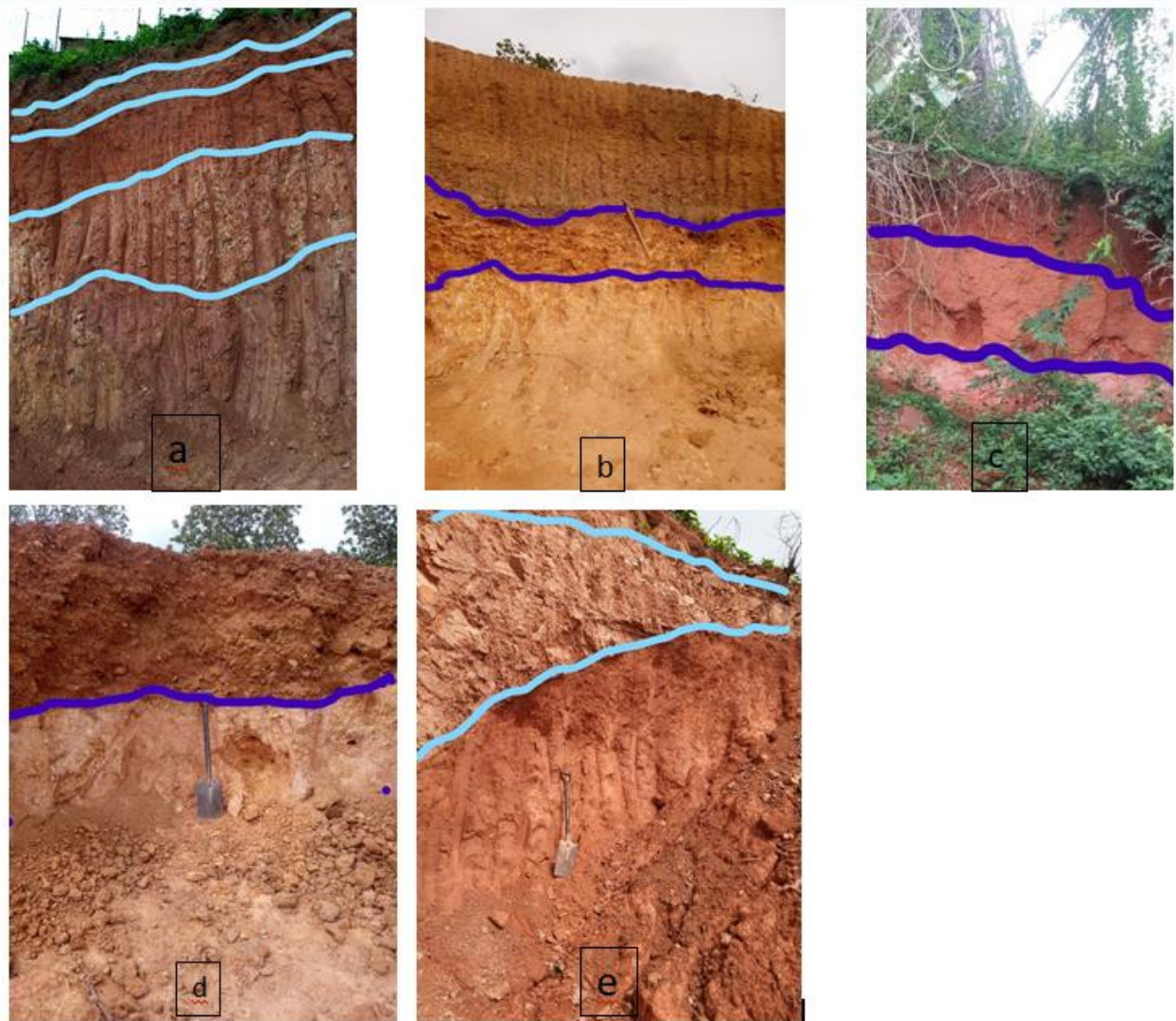


Figure 3.7. Some of the exposures showing the variations across the profiles: (a) a lateritic profile developed over porphyritic granite consisting of the topmost organic topsoil, gravelly layer, reddish brown fine-medium grained laterite layer; (b) a lateritic profile exposing an indurated upperpart underlain by a fine to medium yellowish lateritic layer; (c) a profile showing the variation in color and fineness downwards; (d) a profile of a gravelly uppermost zone underlain by a fine to medium reddish-brown layer with a finer pinkish lateritic lowermost part; (e) a residual resistant quartzo-feldspathic layer overlying a brownish lateritic layer.

CHAPTER FOUR: RESEARCH METHODOLOGY AND APPROACH

The following methodologies involving detailed literature review, fieldwork and laboratory analyses were undertaken to collect data and information. These data and information are collated, analysed and interpreted following standard methodologies in order to achieve the aims and objectives of the PhD research project.

4.1 Literature Review

Detailed review of existing scientific articles, reports, maps and memoirs were undertaken in order to understand the state of science of the area of research, to be acquainted with various methods of lateritic soil analysis and identify research gaps. The review included an examination of both historical and contemporary literature to gain insight into the evolution of scientific understanding of lateritic soils over time thereby ensuring a comprehensive perspective on the subject.

4.2 Field Investigation

4.2.1 Field reconnaissance Survey

A reconnaissance investigation was conducted in order to be familiar with the study area and confirm the relevant information gathered during the desk study/literature review. Potential sampling points were also located with reference to the geology of the study area.

4.2.2 Sampling

Field observations of fresh rock samples were made on the texture and mineralogical characteristics while fresh rock samples were collected for detailed petrographic analysis. Lateritic soil samples were obtained from sites identified at the reconnaissance phase of the fieldwork. The soil samples were taken from borrow-pits and road-cuts where the lateritic profiles were well exposed. Attempts were made to visually categorize the various layers of the lateritic profiles based on the relative proportion of the grain size and colour. In doing this, note of the texture, colour and moisture condition of the soil samples were taken at the various horizons identified based on the properties stated above. A summary of the exact location of each sampling points is presented in Figure 4.1 while the details of the exact location of each sampling points, its underlying lithology, color and textural characteristics is presented in Appendix 2. Forty soil samples (50 kg each) were taken from various lateritic profiles in different localities within the study area. The soil samples were bagged and labelled appropriately before taking them to the laboratory for analysis.

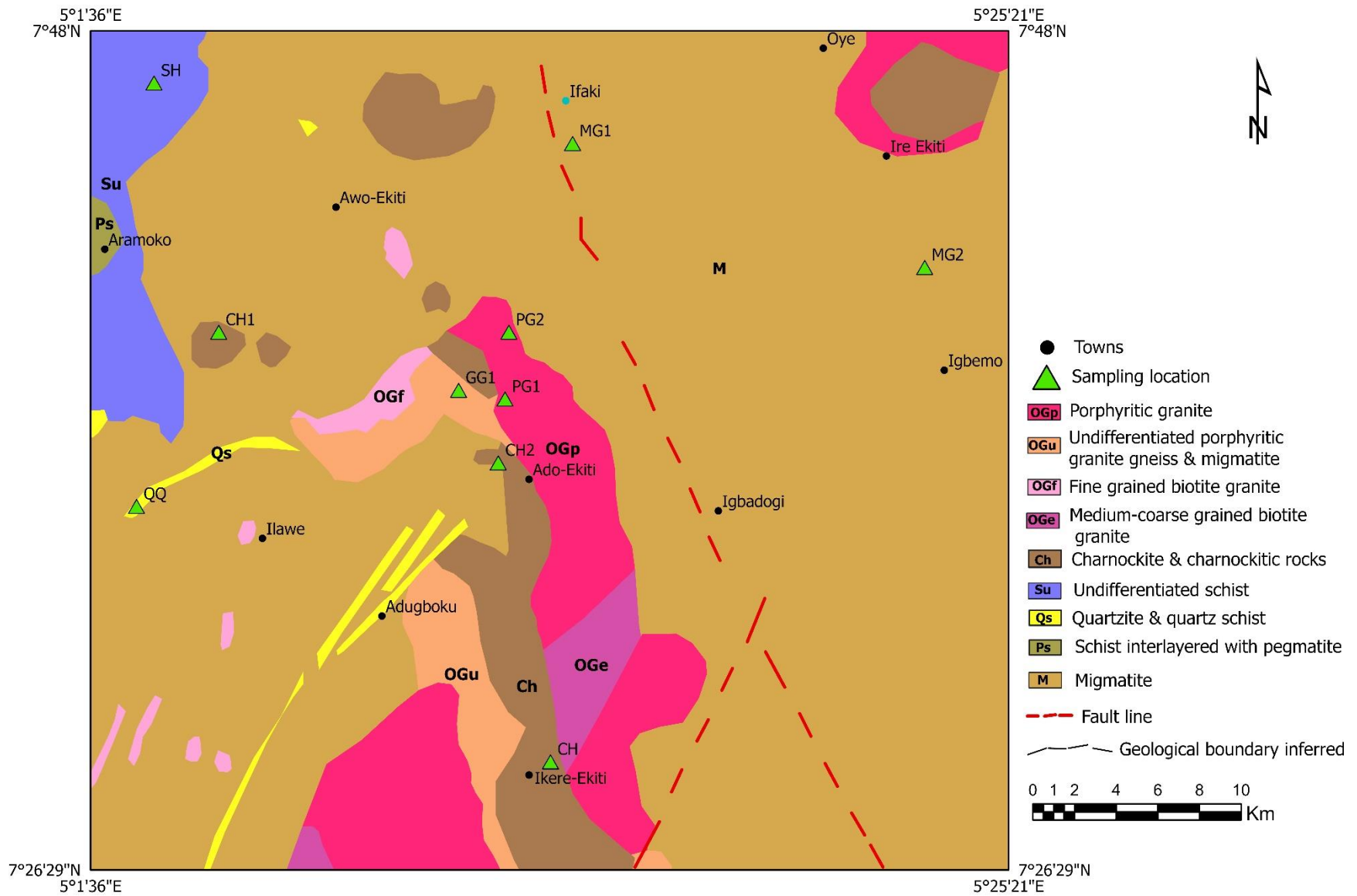


Figure 4.1. Location of the sampling points within the study area.

4.3 Laboratory analyses

4.3.1 Petrographic and geochemical analysis of rocks

Thin sections of selected fresh rock samples were prepared at the petrology laboratory of the Federal University, Akure, Nigeria. The preparation of the thin sections were done in accordance with the specification of the British Standard Institution (BSI) (2007). Subsequently, textural and mineralogical characteristics of the fresh rock samples were examined by studying prepared thin sections under a polarizing microscope and analyzing the slides while the modal composition was determined using the point counting method. Additionally, geochemical evaluation of the rock samples was carried out using X-Ray fluorescence analysis to determine the major oxide contents at the Nigerian institute of raw materials research laboratory using the Genius IF Xenometrix XRF.

4.4 Soil Sample Preparation

The determination of the natural moisture content of the lateritic soil samples collected was done immediately it was taken to the engineering geology laboratory of the Federal University, Akure, Nigeria. Thereafter, the samples were air-dried for seven days with a view to obtaining a fairly constant water content. The lateritic soil specimens were later loosened cautiously using rubber mallet. Lastly, the soil samples were then sieved in accordance with the type of laboratory test that would be performed on each sample. The appropriateness of the lateritic soil samples for the proposed purpose was then evaluated using applicable geotechnical, mineralogical, geochemical, and physicochemical tests.

4.5 Laboratory Testing and Procedure

The laboratory experiments performed for adequate validation of the favorable behaviour of the lateritic soils for utilization as landfill liners include: Atterberg consistency limit test following the specification of BSI (1990), Part 2:4 to 2:6; particle/grain size distribution in accordance with the BSI (1990), Part 2:9; specific gravity test as specified by BSI (1990), Part 2:8; quick undrained shear strength test: BSI (1990), Part 8; moisture content test according to BSI (1990), Part 2:3; permeability test in accordance with the BSI (1990), Part 5:5 and compaction test in accordance with the BSI (1990), Part 4:4. The pH of the lateritic soils was measured following the specification of the USEPA (1986). Furthermore, the experiment of the cation exchange capacity (CEC) of the

samples of the lateritic soil followed Method 9081 as specified by USEPA (1986). The batch equilibrium test was conducted following the USEPA (1992) method.

4.5.1 Compaction

Representative lateritic soil samples were compacted using the Standard Proctor and West African compaction apparatus at varying molding water contents. The tests were conducted in accordance to the BSI (1990) and the Nigerian standard specification (FMWH, 1997). De-aired distilled water was used to bring the crushed soils to varied water contents. To achieve equal moisture throughout the soil samples, the dampened soils were packed in plastic bags and left for a minimum of twenty-four hours prior to compaction. Following hydration, the soil specimens were compacted with the compaction hammer depending on the energy levels. The water content and bulk density of the compacted soil specimens were evaluated so as to calculate the equivalent dry unit weights. The procedure of compaction was replicated with varied water contents. Thereafter, the compaction properties of the lateritic soils were then presented as plots of dry density against water content. It is important to note that the proctor compaction test is the most widely used in earthwork. Although higher energy of compactations has been employed, but compaction achieved is between these two levels. UKEPA (2014) also stated that conducting a few tests are not necessary but may provide useful insight that can enhance the comprehension of the behaviour of soils. Considering some peculiarities of lateritic soils, Adeyemi (2003) and Gidigas (2012), advocated for the compaction of lateritic soils at the West African energy level in order to avoid over-compaction, although there is still no recommendation of hydraulic conductivity or compaction parameter for this energy level for liner applications. The lateritic soils were therefore compacted at the West African energy level in order to acquire more knowledge about the behavior of the researched soils. The West African standard compaction procedure utilized intermediate compaction compactive effort for the densification of the lateritic soils. The compaction energy lies between the standard proctor and the modified proctor. The soils are compacted into five layers with ten blows each with a 4.5 kg rammer dropping from a height of 0.4575 m. Figure 4.3 shows a typical compaction mould, rammer and a soil sample for the compaction test.



Figure 4.2. A compaction mould and the rammer with the lateritic soil to be compacted

4.5.2 Permeability

The compacted soil specimens (at both proctor and the west African energy levels) were carefully positioned in a rigid-wall permeameter for the determination of the hydraulic conductivity. The falling head permeameter test setup included a de-airing tank, a compaction permeameter, burettes, a vacuum pump and a distilled water tank. The samples were deaired using a vacuum pump, and the burette was linked to the compaction permeameter by valves and water hoses. The experiment utilized distilled and de-aired water, and the permeant was applied to thoroughly saturated soil samples. Water discharge through the outputs of the compaction permeameters indicated full saturation. A typical set-up of the falling head permeameter is shown in Figure 4.3. Equation 4.1 was used to compute the hydraulic conductivity (k) values in accordance with Budhu (2011).

$$k = \frac{aL}{A(t_2 - t_1)} \ln \frac{h_1}{h_2} \quad (4.1)$$

where h_1 represents the total head at time t_1 , h_2 represents the total head at time t_2 , L is the length of the specimen, A is the cross-sectional area of the compacted soil specimen, and a represents the interior cross-sectional area of the burette. A typical set-up of the permeameter is shown in Figure 4.4.



Figure 4.3. Typical setup of the falling head permeameter.

4.5.3 Shear strength

Shear strength is the property which provides the supporting ability or bearing capacity of soil (Gidigas, 2012). Determination of the shear strength enters into virtually every soil-engineering problem. Shear strength tests generally try to ascertain the shear strength parameters, namely angle of internal friction and cohesion, in terms of total, effective, or residual stress under established test conditions. The quick undrained triaxial test is employed here to evaluate the total shear strength parameters of the lateritic soil samples. The quick undrained triaxial test and UCS test were determined using the conventional triaxial apparatus having prepared the compacted samples at the optimum moisture content corresponding to the proctor energy level. The UCS and quick undrained triaxial tests were conducted in accordance with the BSI (1990), Parts 7 and 8 respectively.

4.5.4 pH and Cation Exchange Capacity

The pH of the lateritic soils was measured by the electrometric procedure where the lateritic soils sample was mixed with reagent water while the pH of the resultant aqueous solution is determined as described in the method 9045d specified by USEPA (1986). Furthermore, the cation exchange capacity of the lateritic soils was also determined following the method 9081 of USEPA (1986). The method involves weighing 4 g of the soil and transferring it to a 50 cm³-capacity polypropylene centrifuge tube with a tight stopper. After that, a mechanical shaker was utilized to shake the soil suspension with 33 ml of sodium acetate for 5 minutes. Thereafter, the liquid phase was decanted after the liquid and solid phases had been separated by centrifugation at 3000 g for 10 min. This was followed by the addition of 10 ml of 99% isopropyl alcohol and the suspension was shaken for five minutes in a mechanical shaker and later centrifuged at 3000 g for 10 minutes. The same technique was repeated twice. The soil was then treated with 33 ml of 1 mol dm⁻³ ammonium acetate solution, which was agitated in a mechanical shaker for 5 minutes before being centrifuged at 3000 g for 10 minutes. The supernatant was decanted into a 100 cm³ volumetric flask. This technique was performed twice more, and the pooled supernatants were diluted with ammonium acetate solution to 100 cm³. Flame emission spectroscopy (FES) was used to determine the sodium concentration in the extract. The CEC was estimated as the difference between the initial sodium concentration in the extraction solution and the amount retained in the extract.

4.5.5 X-ray diffraction analysis

The D8 advance diffractometer (Figure 4.5) with a flipstick automated multi-position sample stage was used to collect XRD data from lateritic soil samples at the radiation laboratory, nuclear energy commission, South Africa. The analyses was conducted by using the standard open polystyrene sample holder in θ - θ configuration with a Goebel mirror, exit slit and anti-divergent slit with Ni filtered Cu radiation ($\lambda = 1.5406 \text{ \AA}$) while the phases identification and quantification were conducted by means of ICDD PDF-4⁺ Software.

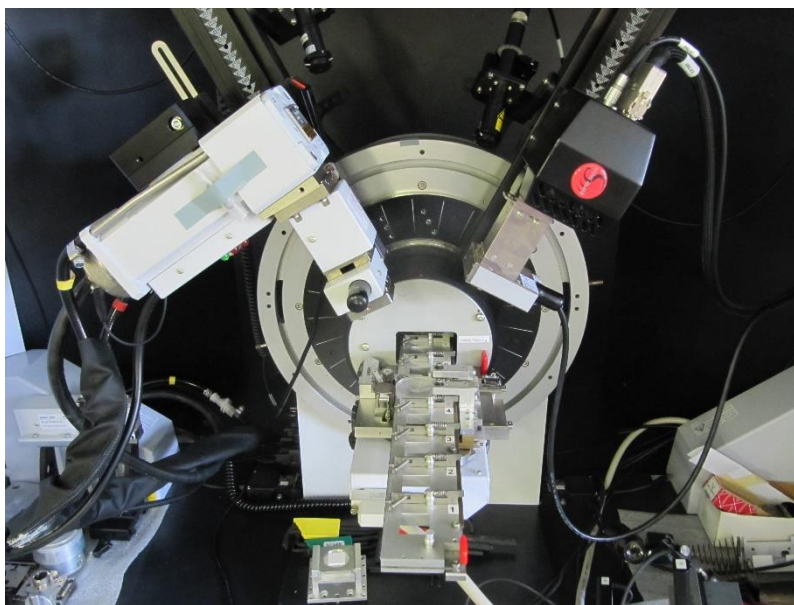


Figure 4.4. Photograph of the D8 Advance diffractometer indicating the flipstick sample stage (front centre of photograph) used for the analysis.

4.5.6 X-ray Fluorescence

The major oxide composition was determined using The Genius IF Xenometrix XRF. A tungsten Carbide milling pot was utilized to mill the samples in order to achieve particle sizes of <150microns. Thereafter, each specimen was carefully mixed with lithiumteraborate flux and fused at 1050⁰C to generate a stable fused glass bead. Subsequently, the Thermo Fisher ARL Perform 'X Sequential XRF with OXSAS software was used for the analysis. The software analyses for all elements in the periodic table between Na and U, but only elements found above the detection limits are reported.

4.5.7 Batch sorption equilibrium test

Simultaneous competitive batch equilibrium sorption investigations were conducted on the lateritic soils following the USEPA (1992) method. Heavy trace metals including cadmium, chromium, copper, manganese and lead were selected based on the chemical composition of leachates (Table 4.1) reported around the study area (Ogunmodede *et al.*, 2014). Stock solutions containing 50, 100, 150, and 200 mg/l of Cd, Cr, Cu, Mn, and Pb nitrate were prepared from standard stock solutions and the pH of the solutions was determined while HNO₃ was added to adjust the solution to a pH between 2.5 and 3.0 (the stock solutions contain identical concentrations of each metals). About 4 g of homogenized pooled subsamples of air-dried lateritic soil was taken from the samples collected and poured into 50-ml Nalgene tubes and 40 ml of the stock solution was added to the tubes. Subsequently, the centrifuge tubes were shaken at 3000 revolutions per minute (rpm) for 24 hours to reach equilibrium and were centrifuged.

Table 4.1. Mean composition of heavy metal in the leachates from the study area (Ogunmodede *et al.*, 2014)

| Heavy metal | Concentration (mg/l) in leachate |
|-------------|----------------------------------|
| Cadium | 0.01±0.03 |
| Chromium | 0.01±0.02 |
| Nickel | 0.17±0.01 |
| Iron | 8.80±0.31 |
| Manganese | 1.56±0.16 |
| Copper | 0.61±0.01 |
| Lead | 0.04±0.09 |

This was followed by the collection of the supernatants for heavy metal analysis using Atomic Absorption Spectrography with Bulk scientific model 211VGP. The summary of the procedure is presented in Figure 4.5.

The efficiency of adsorption (% adsorbed) and the amount of heavy metal adsorbed (q_{eq}) were computed using Equations (4.2) and (4.3), respectively:

$$\% \text{ adsorbed} = \frac{C_i - C_{eq}}{C_i} \times 100 \quad (4.2)$$

$$q_{eq} = \frac{C_i - C_{eq}}{m} \times V \quad (4.3)$$

where, C_i represents the initial concentration (mg/l), C_{eq} denotes equilibrium concentration (mg/l), m is the adsorbent mass (g) while V denotes the volume of the solution (L). The batch equilibrium experiments produced data which were modeled by fitting them to Freundlich and Langmuir sorption isotherm equations. The Langmuir isotherm is described using Equation 4.4 (Hamzaoui *et al.*, 2018; Lu *et al.*, 2021):

$$\frac{1}{q_e} = \frac{1}{bq_m} \times \frac{1}{C_e} + \frac{1}{q_m} \quad (4.4)$$

Where, q_m represents the maximum adsorption capacity (mg/g) while C_e (mg/L) and q_e (mg/g) denote the concentration liquid-phase and solid phase of the adsorbate at equilibrium, respectively, and K_L (L m/g) represents the adsorption equilibrium constant.

The Freundlich sorption isotherm is expressed using Equation 4.5 (Lu *et al.*, 2021):

$$\ln q_e = \ln K_f + \frac{1}{n} \times \ln C_e \quad (4.5)$$

n represents the heterogeneity factor while K_f (mg/g) implies the Freundlich constant linked to the capacity of adsorption

The soil residue (after the supernatant solution is removed) from the adsorption experiment was digested and analysed for the trace metals concentration. The quantity of heavy metal retained on the soil residue was estimated based on this initial concentration of heavy metals in the initial respective stock solutions and the soils. The proportion of metal desorbed by the lateritic soils at equilibrium, q_{de} (mg/kg), was computed using Equation 4.6 (Lu *et al.*, 2021):

$$q_{de} = \frac{C_f \times V}{m} \quad (4.6)$$

Where m represents the soil mass and V the volume of the solution, C_f denotes the difference between C_{eq} (the equilibrium concentration) and the final concentration of the trace metals in the residue. The extent of hysteresis of sorption-desorption was measured by an index of hysteresis (HI) using equation 4.7

$$HI = \frac{n_{desorb}}{n_{sorb}} \quad (4.7)$$

where n_{desorb} and n_{sorb} are the exponents of Freundlich desorption and sorption equations respectively. A lower value of hysteresis index indicates an increased difficulty to desorb the sorbed metal from the soil and vice versa (Hamidpour *et al.* 2010)

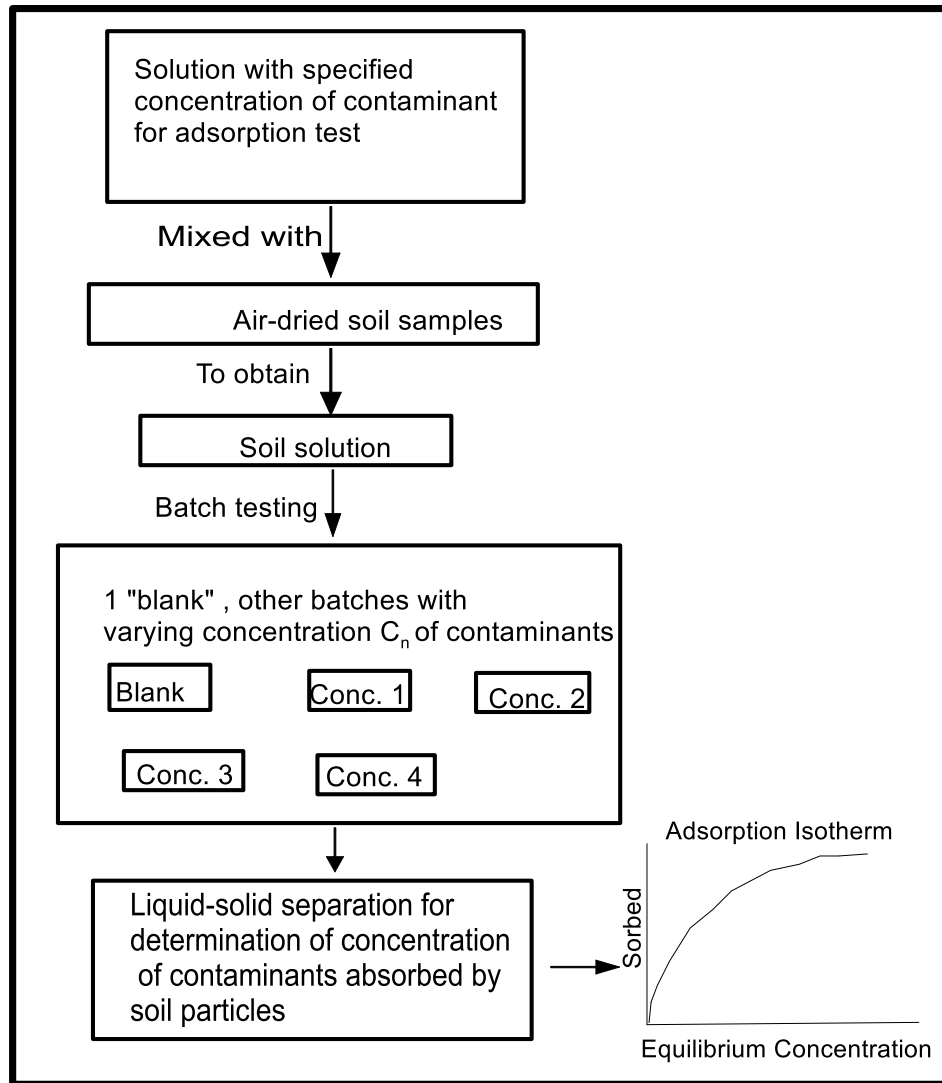


Figure 4.5. Summary of the procedure of batch equilibrium adsorption test (Yong and Mulligan, 2019).

4.5.8 Data Analysis and Interpretation

The data generated during the field was plotted on maps using ArcGis Pro 2.0. The index, geotechnical, mineralogical and sorption data were processed, analysed and presented in the form of tables and graphs using Microsoft Excel, grapher and surfer. Additionally, Microsoft Excel was utilized for the descriptive statistics as well as the regression plots. A flow chart of the research methodology is shown in Figure 4.6.

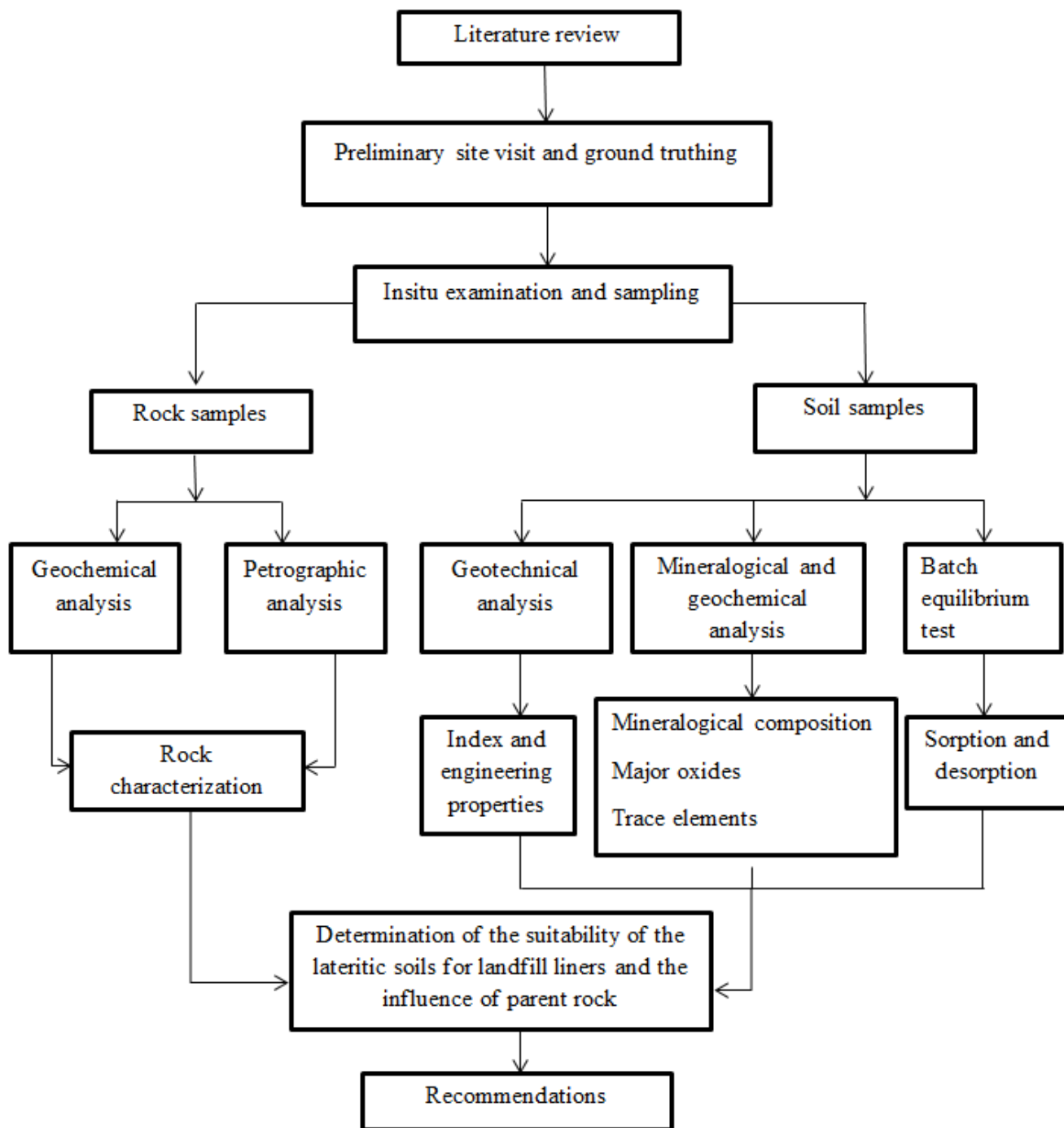


Figure 4.6. Flow chat of the research methodology followed.

CHAPTER FIVE

MINERALOGICAL AND GEOCHEMICAL CHARACTERISTICS OF THE PARENT ROCKS OF THE LATERITIC SOILS IN THE STUDY AREA

5.1 Petrography of the parent rocks

The photomicrographs of the thin sections of the main rock types are shown in Figure 5.1- 5.6. The modal mineralogical compositions obtained from point counting are presented in Table 5.1

5.1.1 Granite-gneiss

The granite-gneiss is light grey, weakly foliated as indicated by alternating bands of dark and light-coloured minerals. The light-coloured bands are rich in feldspar and quartz and are the realigned phenocrysts of the protolith while the dark-coloured bands are rich in biotite, mostly derived from the matrix of the protolith. In thin section (Figure 5.1) the rock consists of large euhedral crystals of quartz and microcline that form a weak preferred orientation. In addition to quartz and microcline, the matrix also contains biotite and specks of opaque minerals.

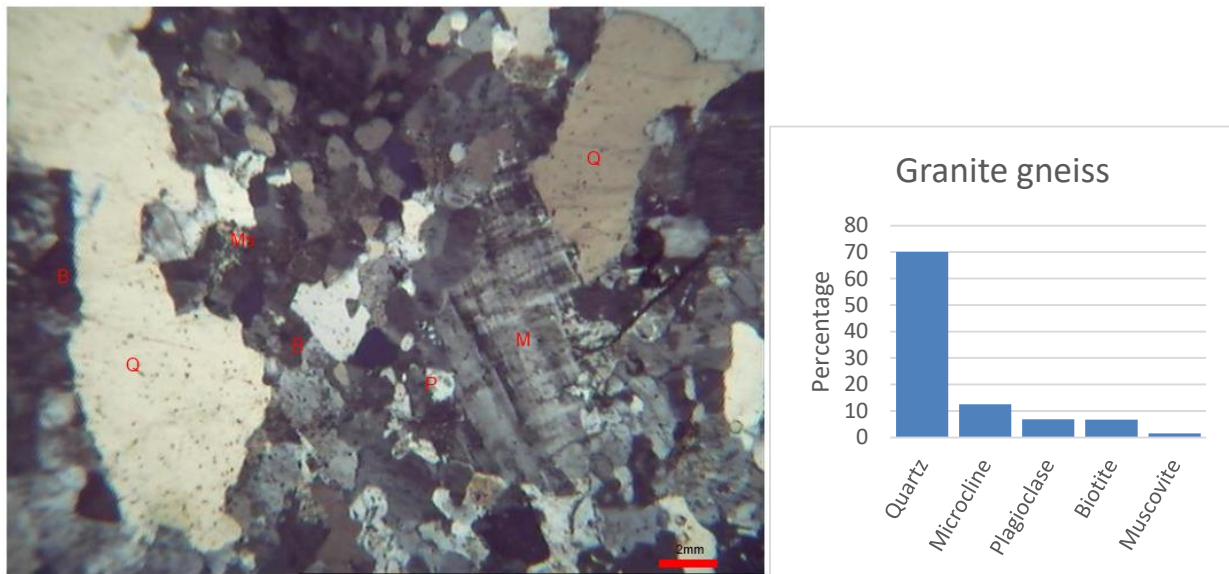


Figure 5.1. Photomicrographs of representative sample of granite-gneiss in the study area under cross-polarized light and a bar chart showing the distribution of minerals (Q- quartz; B-Biotite; P- Plagioclase; M-Microcline; Ms-muscovite).

5.1.2 Charnockite

The charnockites are the massive, non-foliated variety; they are dark-greenish to greyish-green in colour and having medium to coarse-grained texture. The essential minerals are quartz, feldspar,

biotite and hypersthene. Thin sections of the charnockite revealed weakly aligned grains of quartz and feldspars as the dominant minerals as shown in Figure 5.2. The quartz crystals have high relief with interlocking grains and are pleochroic in shades of dark grey and light grey. The main feldspars present are plagioclase of albite composition, microcline and orthoclase. The plagioclase exhibits typical albite twinning and occurs as poikilitic fragments surrounded by orthoclase and microcline crystals. Hornblende, biotite and pyroxene constitute the mafic minerals, which are disseminated between the crevices of large crystals of quartz and feldspars, while subhedral crystals of opaque minerals are sparse between the crevices of the mafic minerals.

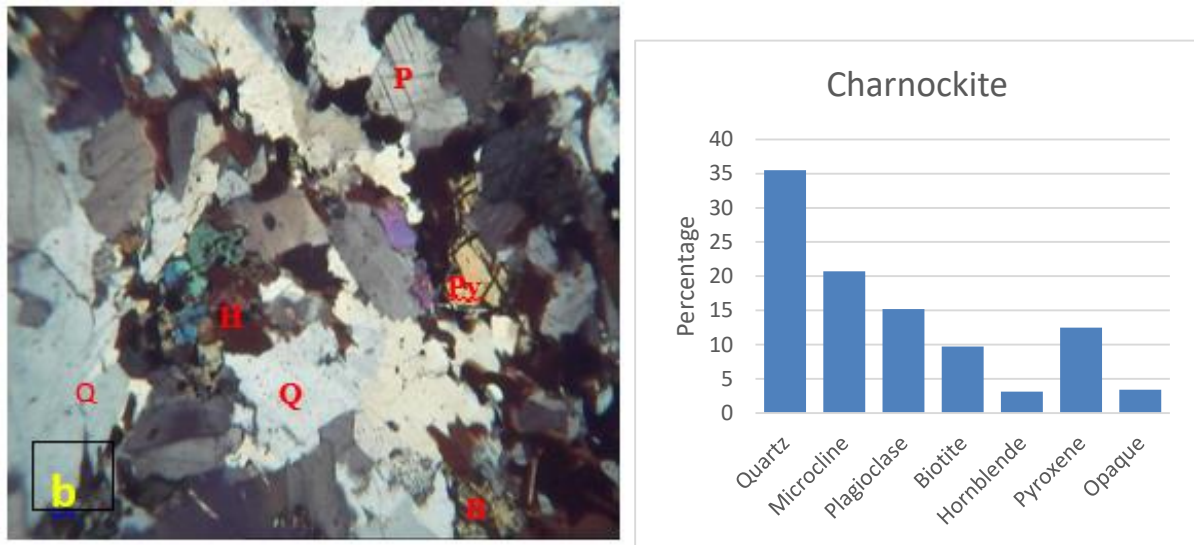


Figure 5.2. Photomicrographs of representative sample of charnockite in the study area under cross-polarized light and a bar chart showing the mineral composition and a bar chart showing the distribution of minerals (Q- quartz; B-Biotite; P-Plagioclase; M-Microcline; H-hornblende; Py-pyroxene).

5.1.3 Migmatite

The migmatites are variably banded greyish rocks with distorted and varying band thicknesses of paleosomes and neosomes. The latter are predominantly made of quartzofeldspathic minerals while the former consist of biotite and opaque minerals. Photomicrograph of the migmatite (Figure 5.3) shows abundance of quartz, microcline, biotite, plagioclase and a minor occurrence of opaque mineral. The quartz crystals consist of large euhedral crystals with relatively high fracture density. Microcline occurs as medium sized subhedral crystals exhibiting cross-hatched twinning, whilst biotite occurs as disoriented masses with poorly developed mineral alignments. Opaque minerals are trapped between large crystals of quartz and feldspar.

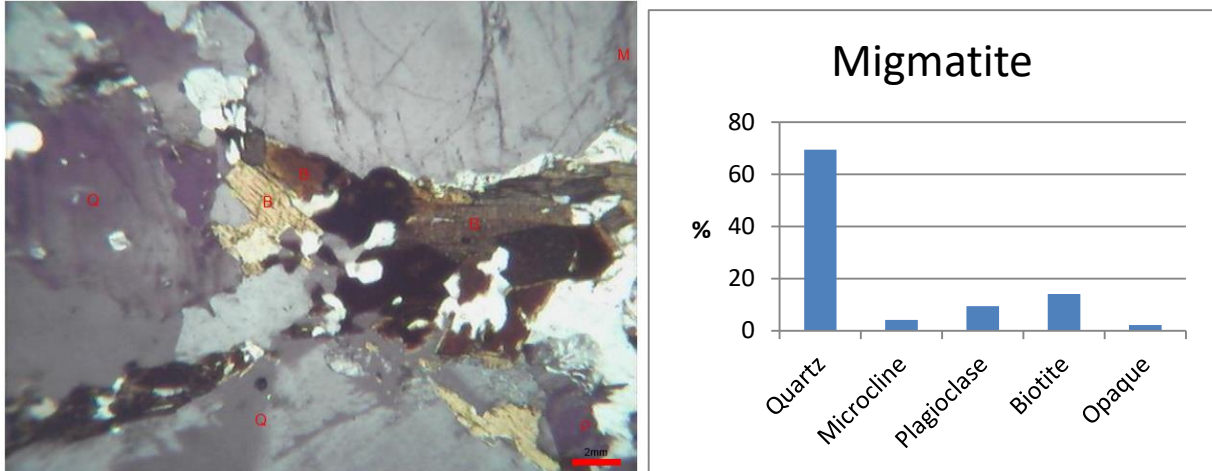


Figure 5.3. Photomicrographs of representative sample of migmatite in the study area under cross-polarized light and a bar chart showing the distribution of minerals (Q- quartz; B-Biotite; P- Plagioclase; M-Microcline).

5.1.4 Porphyritic granite

The porphyritic granites contain large crystals (phenocrysts) of feldspar set in medium-grained groundmass of quartz, biotite and muscovite. Photomicrograph shows phenocrysts of large subhedral quartz crystals in a matrix of randomly oriented crystals of microcline, biotite and muscovite (Figure 5.4). The quartz phenocrysts show hairline fractures in places, while biotite and muscovite occur as tiny fragments surrounding the phenocrysts.

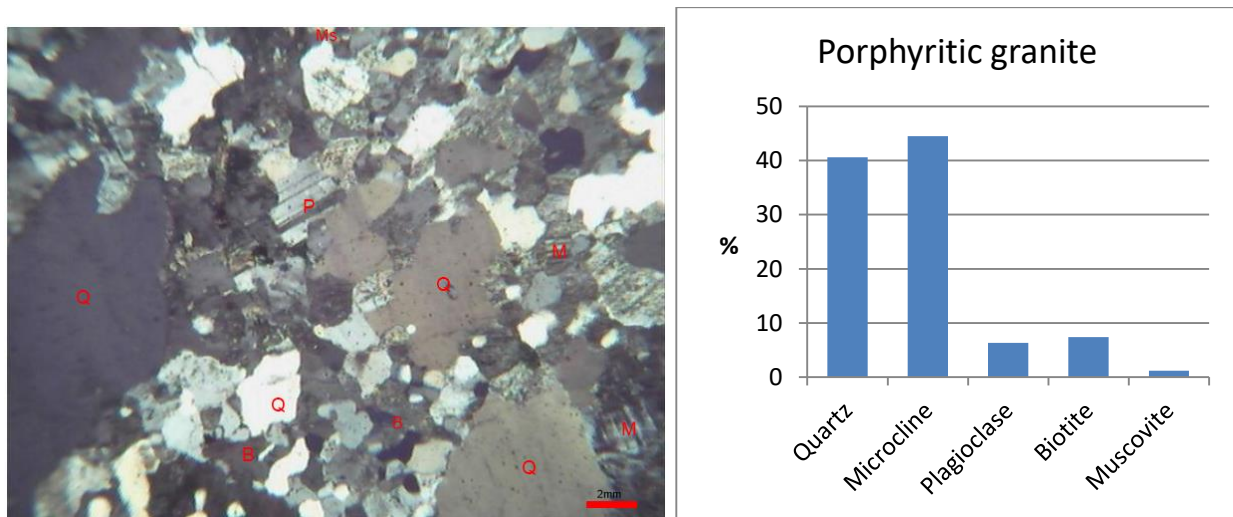


Figure 5.4. Photomicrographs of representative samples of porphyritic granite in the study area under cross-polarized light and a bar chart showing the distribution of minerals (Q- quartz; B- Biotite; P-Plagioclase; M-Microcline; Ms-muscovite).

5.1.5 Quartzite

The quartzites are massive, fine to medium grained and predominantly composed of quartz with minor occurrence of mica. In thin section, the quartzite (Figure 5.5) is generally fine to medium grained and very rich in quartz and lesser amount of biotite with texture varying from inequigranular, granuloblastic to epidoblastic in most places. Quartz occurs as granoblastic and euhedral crystals with well-defined idioblastic outlines, and it exhibits high relief with a cloudy appearance. Biotite crystals form the supporting minerals and occupy intergranular spaces of interlocking quartz crystals.

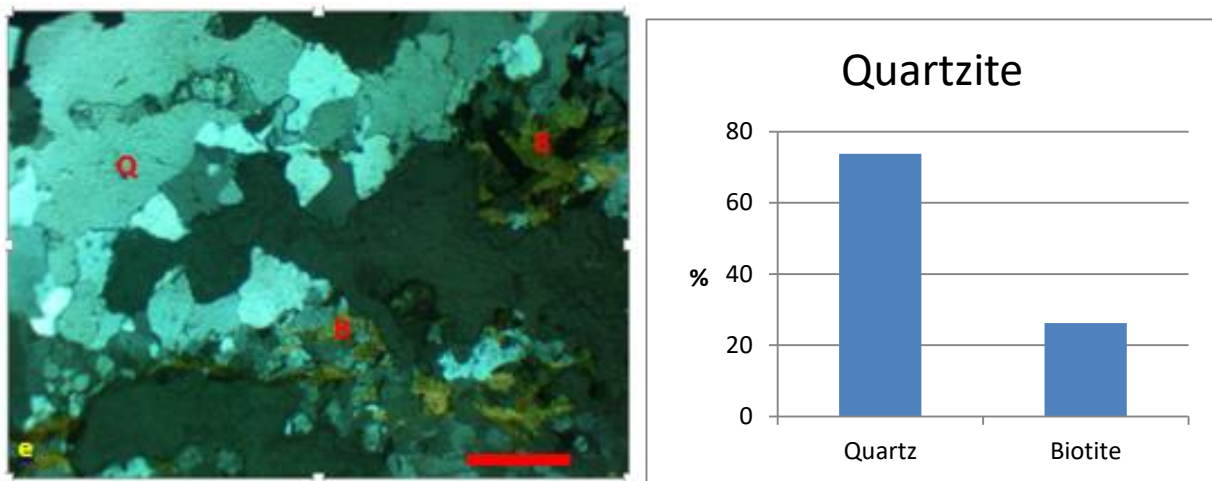


Figure 5.5. Photomicrographs of representative sample of quartzite in the study area under cross-polarized light and a bar chart showing the distribution of minerals (Q- quartz; B-Biotite).

5.1.6 Schist

The schist is dark grey and strongly foliated as reflected by prominent schistose fabric defined by the parallel allignment of platy minerals (essentially biotite), interbanded with quartz and feldspar. The photomicrograph of schist (Figure 5.6) shows biotite crystals arranged in parallel to sub-parallel planar pattern that defines the foliation. It is brown with one directional cleavage. Biotite crystals in the mica-rich layers show extreme preferred orientation and individual laths with distinct uni-directional cleavage, which are aligned and parallel to one another. Quartz occurs as an integral part of the groundmass with plagioclase whilst the boundaries of crystal grains are sutured and mutually interlocking.

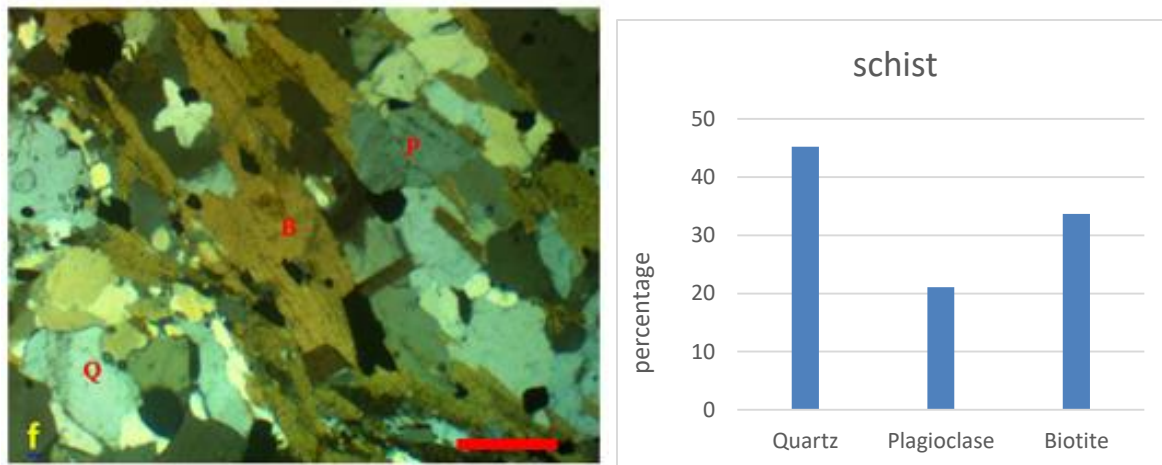


Figure 5.6. Photomicrographs of representative sample of schist under cross-polarized light and a bar chart showing the distribution of minerals (Q- quartz; B-Biotite; P-Plagioclase).

Table 5.1. Modal composition of the main rock units in the study area.

| | Quartz (%) | Microcline (%) | Plagioclase (%) | Biotite (%) | Hornblende (%) | Muscovite (%) | Pyroxene (%) | Opaque (%) |
|---------------------|------------|----------------|-----------------|-------------|----------------|---------------|--------------|------------|
| Charnockite | 35.5 | 20.7 | 15.2 | 9.7 | 3.1 | - | 12.5 | 3.4 |
| Migmatite | 69.4 | 4.1 | 9.4 | 14.1 | - | 0.9 | - | 2.1 |
| Porphyritic-granite | 40.6 | 44.5 | 6.3 | 7.4 | - | 1.2 | - | - |
| Quartzite | 73.8 | | | 26.2 | - | | - | - |
| Granite-Gneiss | 72.5 | 12.5 | 6.8 | 6.7 | - | 1.5 | - | - |
| Schist | 45 | | 21.1 | 33.7 | | | | |

5.2 Geochemical composition of the parent rocks

The major oxides and selected trace element composition for the analyzed samples of the various rocks are presented in wt% and ppm respectively in Table 5.2. Additionally, a comparison of the average major oxides (wt%) composition of the parent rocks sampled in the study area and other locations is presented in Table 5.3.

The granite-gneiss from the study area has an average SiO₂ value of 63.5 wt%, which compares favourably with those from Vandeikya (63.46 wt%) but is slightly less than those from Arigidi (70.92 wt%) and Ushongo (70.36 wt%). The average Al₂O₃ content is similar among the granite-gneiss from the study area (14.3 wt%) and Arigidi (13.09 wt%). Low Fe₂O₃ content is recorded for the granite-gneiss from the study area (1.7 wt%) as well as those from Ushongo (1.5 wt%) and Vandeikya (1.97 wt%). Na₂O is slightly lower in the granite-gneiss of the study area (2.8 wt%) than others, except for those from Arigidi (1.81 wt%). The CaO content is similar across the board except for the granite-gneiss of Ushongo, which has a value of 5.05 wt%. Charnockites from the study area compare favourably with those from Okpella, except the K₂O content, where the charnockites from the study area have an average value (5.1 wt%) more than twice that of the Okpella charnockite (2.03 wt%). When compared with migmatites from Idanre and Itaogbolu areas, the migmatites from the study area have nearly the same elemental compositions. The quartzites from the study area were compared with those from the Singhbhum region. Minor contents (0.05 wt% to 0.35 wt%) of TiO₂, MgO, and CaO were recorded for all the rocks. However, the quartzites from the study area had a much higher Al₂O₃ content (9.45 wt%) compared to the low value of 1.67 wt% recorded for the quartzites from the Singhbhum region. The porphyritic granites of the study area are lower in SiO₂ content (66.9 wt%) and Na₂O (2.75 wt%) compared to those of the Kaiama area, which have average values of 72.52 wt% and 3.69 wt%, respectively. However, the porphyritic granites from the study area are richer in other compared elements, although both areas recorded very small amounts of average MgO and TiO₂ contents. The average values of the major oxides in the schist from the study area are consistent with those from Okpella and Igarra. Generally, the major oxide composition of the sampled rocks is rich in silica, aluminum, and iron oxides due to their mineral composition, dominated by quartz, feldspar, and mica. According to Frost and Frost (2008), geochemical differentiation and tectonic settings favor felsic minerals in continental crust, resulting in higher SiO₂ and Al₂O₃. Additionally, metamorphic processes also enhance these oxides. The lower K₂O, CaO, and Na₂O levels reflect the lack of abundant calcium- and potassium-bearing minerals, despite the presence of plagioclase and microcline.

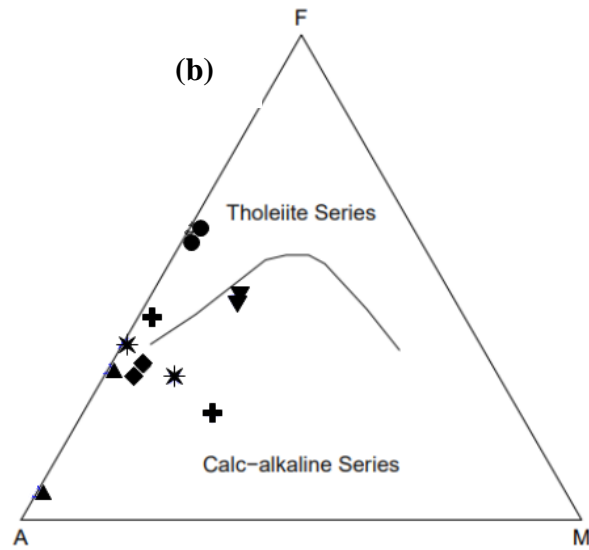
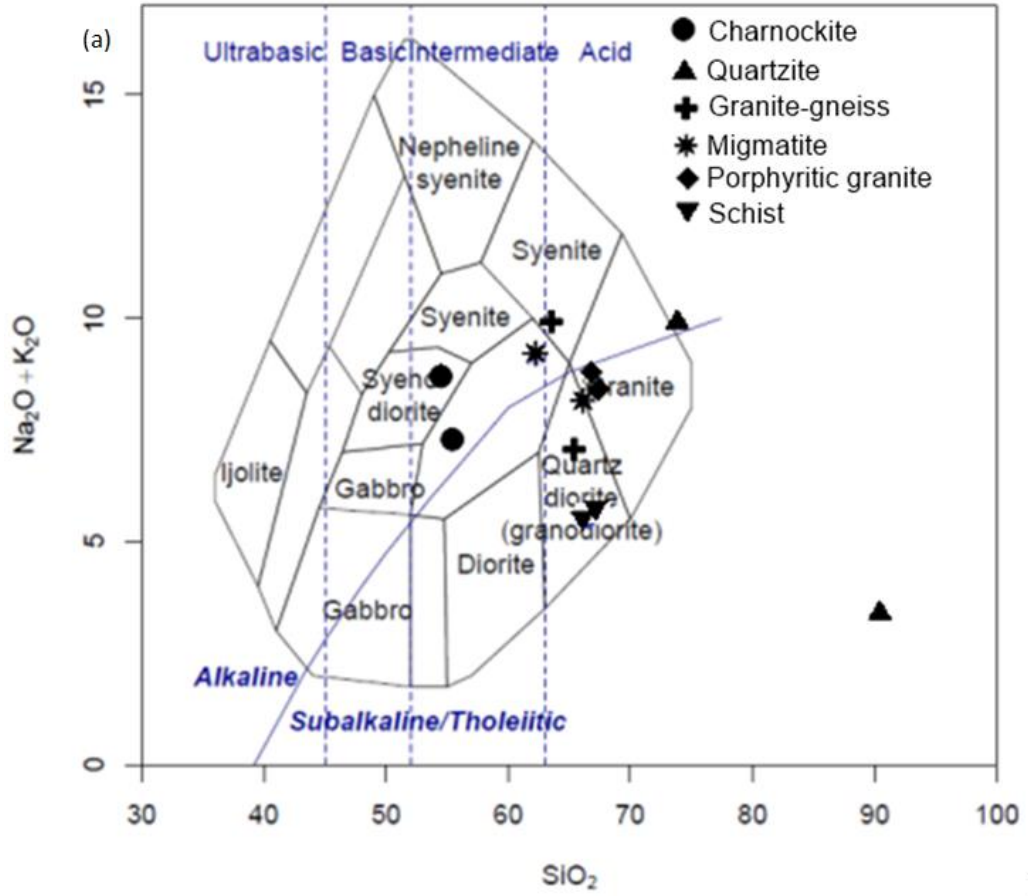
Table 5.2. Major oxides (wt%) and trace element (ppm) composition of the parent rocks sampled in the study area.

| Rock type | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | MgO | K ₂ O | Na ₂ O | TiO ₂ | P ₂ O ₅ | Cd | Cr | Cu | Mn | Pb |
|----------------------|------------------|--------------------------------|--------------------------------|------|------|------------------|-------------------|------------------|-------------------------------|-------|-------|-------|-------|-------|
| Charnockite1 | 54.5 | 12.2 | 14.7 | 7.3 | 0.0 | 6.2 | 2.5 | 1.8 | 0.4 | 0.009 | 0.207 | 0.218 | 3.191 | 0.102 |
| Charnockite 2 | 55.4 | 15.1 | 12.1 | 6.5 | 0.0 | 4.0 | 3.3 | 1.8 | 1.62 | 0.007 | 0.206 | 0.214 | 3.188 | 0.105 |
| Quartzite | 90.4 | 4.3 | 1.7 | 0.1 | 0.0 | 1.3 | 2.1 | 0.1 | 0.0 | 0.008 | 0.229 | 0.096 | 0.476 | 0.160 |
| Quartzite 2 | 73.8 | 14.6 | 0.64 | 0.6 | 0.02 | 6.1 | 3.8 | 0.01 | 0.03 | 0.005 | 0.224 | 0.092 | 0.473 | 0.160 |
| Granite-gneiss1 | 63.5 | 11.5 | 8.3 | 4.8 | 0.4 | 7.6 | 2.3 | 1.2 | 0.3 | 0.016 | 0.529 | 0.757 | 4.582 | 0.125 |
| Granite-gneiss2 | 65.3 | 17.1 | 3.1 | 3.1 | 3.0 | 3.8 | 3.3 | 0.5 | 0.3 | 0.018 | 0.534 | 0.762 | 4.580 | 0.129 |
| Migmatite1 | 62.1 | 14.3 | 5.8 | 8.0 | 0.0 | 7.0 | 2.1 | 0.6 | 0.1 | 0.011 | 0.606 | 0.013 | 2.064 | 0.083 |
| Migmatite2 | 66.2 | 15.5 | 4.6 | 2.12 | 1.8 | 5.0 | 3.2 | 0.5 | 0.7 | 0.010 | 0.610 | 0.017 | 2.072 | 0.080 |
| Porphyriticgranite1 | 66.8 | 14.4 | 4.4 | 2.7 | 0.7 | 5.8 | 2.8 | 0.6 | 0.4 | 0.001 | 0.012 | 0.120 | 0.916 | 0.148 |
| Porphyritic granite2 | 67.0 | 14.0 | 4.76 | 2.88 | 0.8 | 5.7 | 2.7 | 0.45 | 0.84 | 0.001 | 0.015 | 0.130 | 0.910 | 0.153 |
| Schist1 | 67.0 | 12.4 | 7.3 | 1.15 | 2.33 | 4.03 | 1.56 | 0.03 | 0.92 | 0.180 | 0.534 | 0.762 | 4.580 | 0.129 |
| Schist2 | 66.4 | 12.6 | 7.1 | 1.21 | 2.21 | 4.1 | 1.4 | 0.02 | 0.81 | 0.170 | 0.540 | 0.740 | 4.600 | 0.130 |

Table 5.3 Average Major oxides (wt%) composition of the parent rocks sampled in the study area and other locations.

| Location | Rocktypes | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | Na ₂ O | K ₂ O | CaO | MgO | TiO ₂ | References |
|-------------|---------------------|------------------|--------------------------------|--------------------------------|-------------------|------------------|-------|------|------------------|-----------------------------|
| Ekiti | Granite gneiss | 63.5 | 14.3 | 1.7 | 2.8 | 5.7 | 3.95 | 1.7 | 0.85 | This present study |
| Arigidi | | 70.92 | 13.09 | | 1.81 | 1.45 | 3.2 | 1.11 | 0.45 | Ademeso and Adeyeye (2011) |
| Vandeikya | | 63.46 | 17.94 | 1.97 | 4.07 | 1.07 | 3.01 | | 1.75 | Ejimofor et al. (1996) |
| Ushongo | | 70.36 | 19.87 | 1.5 | 3.48 | 5.37 | 5.05 | | 0.64 | Ejimofor et al., (1996) |
| Ekiti | Charnockite | 54.95 | 13.65 | 13.4 | 2.9 | 5.1 | 6.9 | 0 | 1.8 | This present study |
| Okpella | | 67.15 | 14.46 | 6.49 | 1.9 | 2.03 | 3.72 | 1.66 | 0.68 | Ogunyele <i>et al.</i> 2020 |
| Bauchi | | 35.06 | 13.94 | 22.86 | 0.007 | 9.81 | 0.013 | 8.86 | 5.1 | Dada, 2012 |
| Jos | | 34.75 | 13.74 | 26.15 | 0.079 | 9.41 | 0.031 | 5.88 | 4.67 | Dada, 2012 |
| Ekiti | Migmatite | 64.15 | 14.9 | 5.2 | 2.65 | 6 | 5.06 | 0.9 | 0.55 | This present study |
| Idanre | | 65 | 15.17 | 6.76 | 3.09 | 3.4 | 4.01 | 1.84 | 0.89 | Akinola and Obasi (2020) |
| Itaogbolu | | 62.53 | 14.96 | 7.65 | 3.49 | 5.03 | 3.35 | 1.55 | 1.31 | Akinola Obasi (2020) |
| Ekiti | Quartzite | 81.7 | 9.45 | 1.17 | 2.95 | 3.7 | 0.35 | 0.01 | 0.05 | This present study |
| Singhbhum | | 94.99 | 1.67 | 0.76 | 0.05 | 0.45 | 0.01 | 0.15 | 0.19 | Chaudhary and Alvi (2021) |
| Idoani | | 79.1 | 7.06 | 4.01 | 1.2 | 2.49 | 1.56 | 1.31 | 0.32 | Adegbuyi <i>et al.</i> 2017 |
| Ekiti | Porphyritic granite | 66.9 | 14.2 | 4.58 | 2.75 | 5.75 | 2.79 | 0.75 | 0.525 | This present study |
| Kaiama area | | 72.52 | 13.59 | 2.03 | 3.69 | 4.47 | 1.14 | 0.26 | 0.2 | Umaru et al. (2023) |
| Idoani | | 68.01 | 14.32 | 2.84 | 2.54 | 3.21 | 1.76 | 2.31 | 0.42 | Adegbuyi et al. (2017) |
| Akure | | 71.12 | 15.29 | 1.45 | 3.57 | 6.53 | 1.11 | 0.1 | 0.13 | Igonor et al. (2023) |
| Ekiti | Schist | 66.7 | 12.5 | 7.2 | 1.48 | 4.07 | 1.18 | 2.27 | 0.025 | This present study |
| Okpella | | 67.4 | 15 | 6.23 | 2.37 | 3.71 | 2.34 | 0.65 | 1.3 | Ogunyele et al. (2020) |
| Igarra | | 68.89 | 13.1 | 7.65 | 1.19 | 2.26 | 1.01 | 0.67 | 0.23 | Adegbuyi et al. (2017) |
| Igarra | | 69.7 | 14.84 | 7.51 | 1.18 | 3.8 | 1 | 0.67 | 0 | Okeke and Meju (1985) |

Furthermore, the major oxide content of rocks is very important for their classification and nomenclature. Based on the silica content, the rocks in the study area are classified as felsic (granite, granite-gneiss and banded gneiss) and intermediate (charnockites). In the total alkalis–silica diagram of chemical classification of Cox *et al.* (1979), the rocks plot in the granite to granodiorite and syenodiorite to syenite fields (Figure 5.2a). The AFM diagram (Irvine and Baragar, 1971) indicates a calcalkaline signature for the analyzed rock samples (Figure 5.7b). This signifies the significant availability of quartz in the rock units while the quartzite fell into alkaline series indicating higher concentration of alkalis that cannot be accommodated in feldspars alone (Fitton and Upton, 1987; Talabi *et al.*, 2018). Additionally, a few of the rocks (including the charnockites, granite-gneiss and migmatite) classify as the tholeiite series, which indicate that they are oversaturated with silica, however, in contrast to the calcalkaline suite; they are enriched in iron (Figure 5.7c). The plotting of the rocks in the calc-alkaline and tholeiitic fields indicates a mixed source of magma, thus suggesting that the rocks may have originated not only from the calc-alkaline environments of the oceanic crust but also from subduction tectonic environment (Obasi and Madukwe, 2016). In addition, the classification of the rocks into the calc-alkaline series indicates that the rocks have high ratios of large ion lithophile elements (Sheth *et al.*, 2002). Also, the alkali character of the rocks were ascertained by following the classification of Frost and Frost (2008) which employs the plot of Modified-Alkali-Lime-Index ($\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$) versus SiO_2 . In the light of this, the rock samples are calcic-alkali, alkali-calcic and metaluminous to peraluminous, with alumina saturation indices ranging from 0.5 to 1.9 (Figure 5.7c).



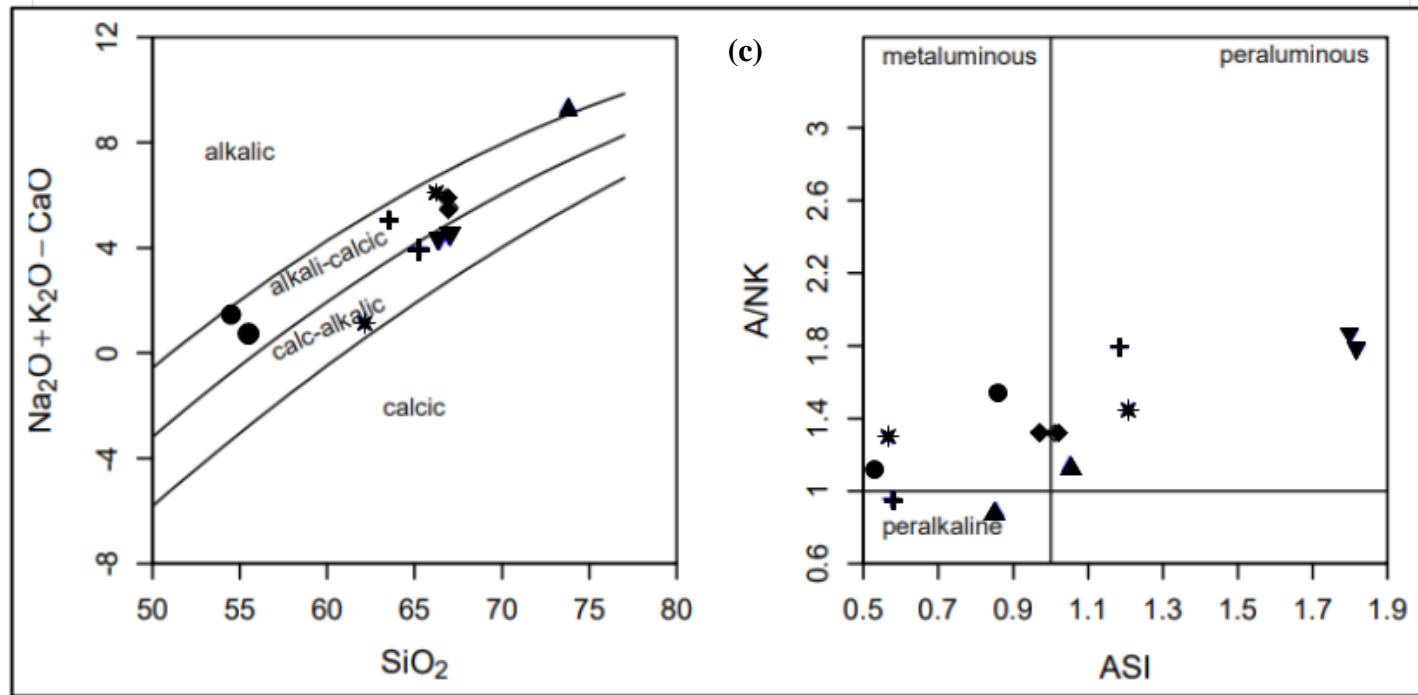


Figure 5.7. Rock sample plots on (a) the total alkalis versus silica geochemical classification diagram (Cox *et al.*, 1979), (b) the AFM classification diagram (Irvine and Baragar, 1971) and (c) the classification chart of Frost and Frost (2008).

5.3 Summary

Petrographic studies of the various parent rock samples taken from the study area show that there is no significant difference in the mineralogical composition of these parent rocks in the study area, but minor variations in the proportion of minerals. The rocks are dominantly quartzofeldspathic with minor amount of mafic minerals such as biotite, hornblende and pyroxene. However, the occurrence of iron rich mineral in the charnockite may play a significant role in its weathering process (Eze, 1997; Afolagboye *et al.*, 2016). The major element composition confirms the acidic nature of the rocks except for the charnockite, which could be classified as intermediate. Furthermore, the variation in the amount of these minerals as well as the degree of weathering/weathering conditions is expected to dictate the differences in the properties of the resulting soils. The significant occurrence of quartz is likely to result in coarse-grained materials while feldspar and the other minerals are likely to weather into fine- to medium-grained constituents.

CHAPTER SIX

INDEX AND ENGINEERING PROPERTIES OF LATERITIC SOILS FROM SOUTHWESTERN NIGERIA

6.1 Introduction

This chapter presents and discusses the results of the various index (consistency limits, specific gravity, grain size distribution) and engineering (compaction, permeability, unconfined compressive, triaxial shear strength) tests conducted on the various lateritic soil samples taken from the study area based on parent rocks described in the previous chapter. This is done with a view to ascertaining the suitability of the lateritic soils for the construction of landfill liners while noting the influence of geology on the various properties and their suitability for landfill liners. The raw laboratory data and graphs from which these summaries are derived are included in Appendices 3-8.

6.2 Particle size distribution

Figures 6.1-6.4 show the particle size distribution graphs of the sampled soils from the different parent rock types, while Figure 6.5 shows the position plot of the lateritic soils on the full soil classification chart. The lateritic soils derived from the various parent rock materials are well graded with varying amount of clay, silt, sand and gravel (Table 6.1). The well graded nature exhibited by the soils are characteristic of lateritic soils derived from felsic rocks, which is in line with the findings of previous researchers (e.g. Adeyemi and Wahab, 2008; Oyelami and Van Rooy, 2018; Yamusa *et al.*, 2022). Thus, they could be well compacted resulting in low porosity and permeability and exhibit enhanced ease of workability. Furthermore, most of the lateritic soils classify as sandy fines according to the full classification chart (Figure 6.5). The classification chart indicates that the soils contain significant amount of fines (clays and silt-sized particles), which are essential for soils designated for landfill liners as they contribute to the reduction of hydraulic conductivity thereby enhancing the effectiveness of liners in preventing the migration of leachates. Although there exists a consensus on the recommended limit for the gravel and silt content intended for liner applications, there are variations in the recommended desired largest grain size, clay and fines content (Endene *et al.*, 2019). However, all the examined lateritic soils fulfill the various guidelines for the different proportion of grain sizes as pointed out by Endene *et*

al. (2019) as indicated in Table 2.2. Regardless of the parent rocks, the average values of the clay, silt, sand and gravel fractions in the lateritic soils fulfill the requirements for landfill liners. Also, an observation of the distribution of the grain sizes of the lateritic soils in relation to the requirements for landfill liners indicate that majority of the soils are either very useful or useful without improvement as shown in Figure 6.6. Additionally, none of the soils contain more than fifty percent clay sized particles as this could attain a low hydraulic conductivity in the laboratory but will be practically impossible to lay as a compacted soil liner in the field (Watkins, 1997). Futhermore, all the soils contain significant quantity of sand size particles, which protects against volumetric shrinkage, while the presence of a substantial amount of fines implies a higher surface area and reduces the migration of leachates.

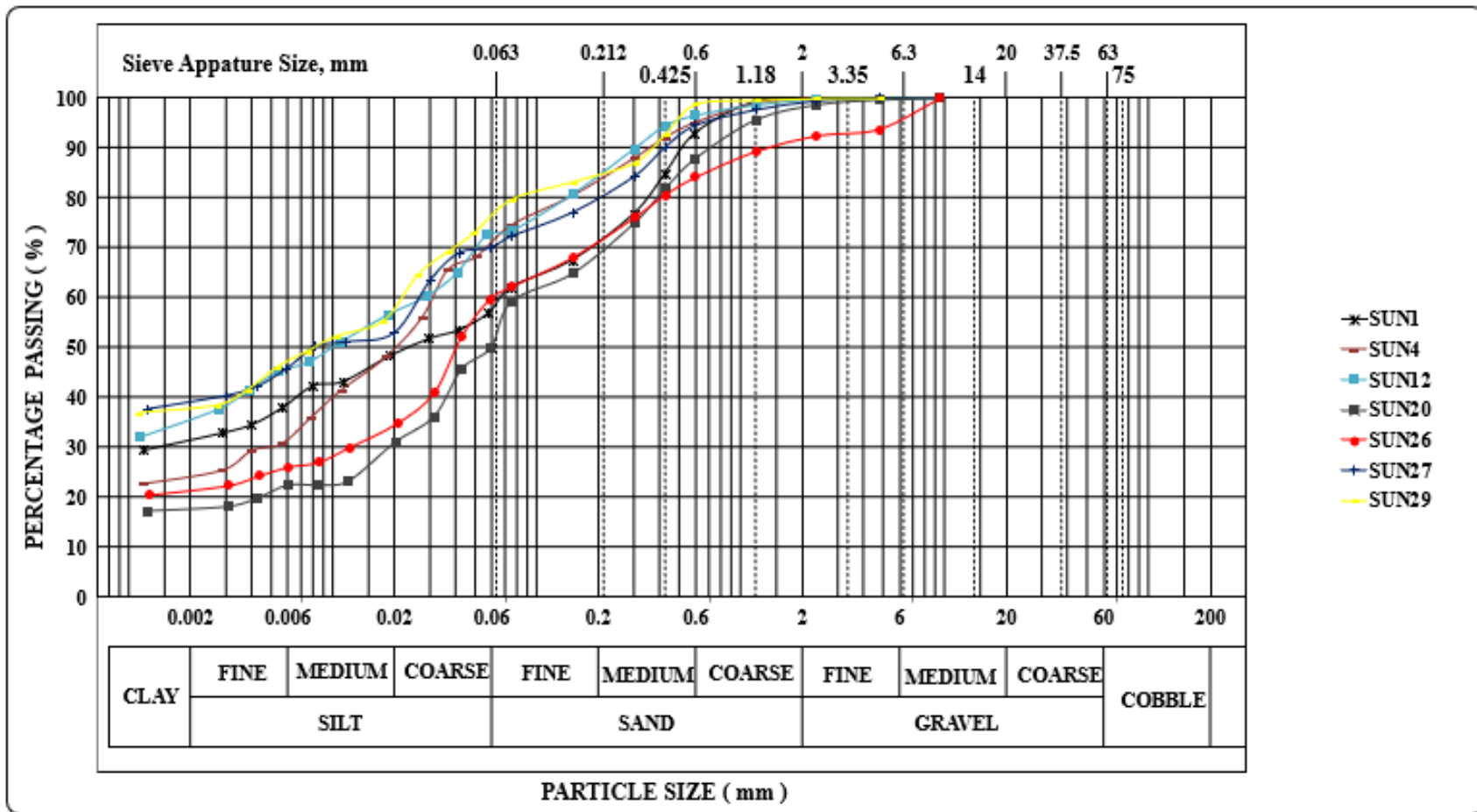


Figure 6.1. Particle size distribution curves of the lateritic soils derived from porphyritic granite.

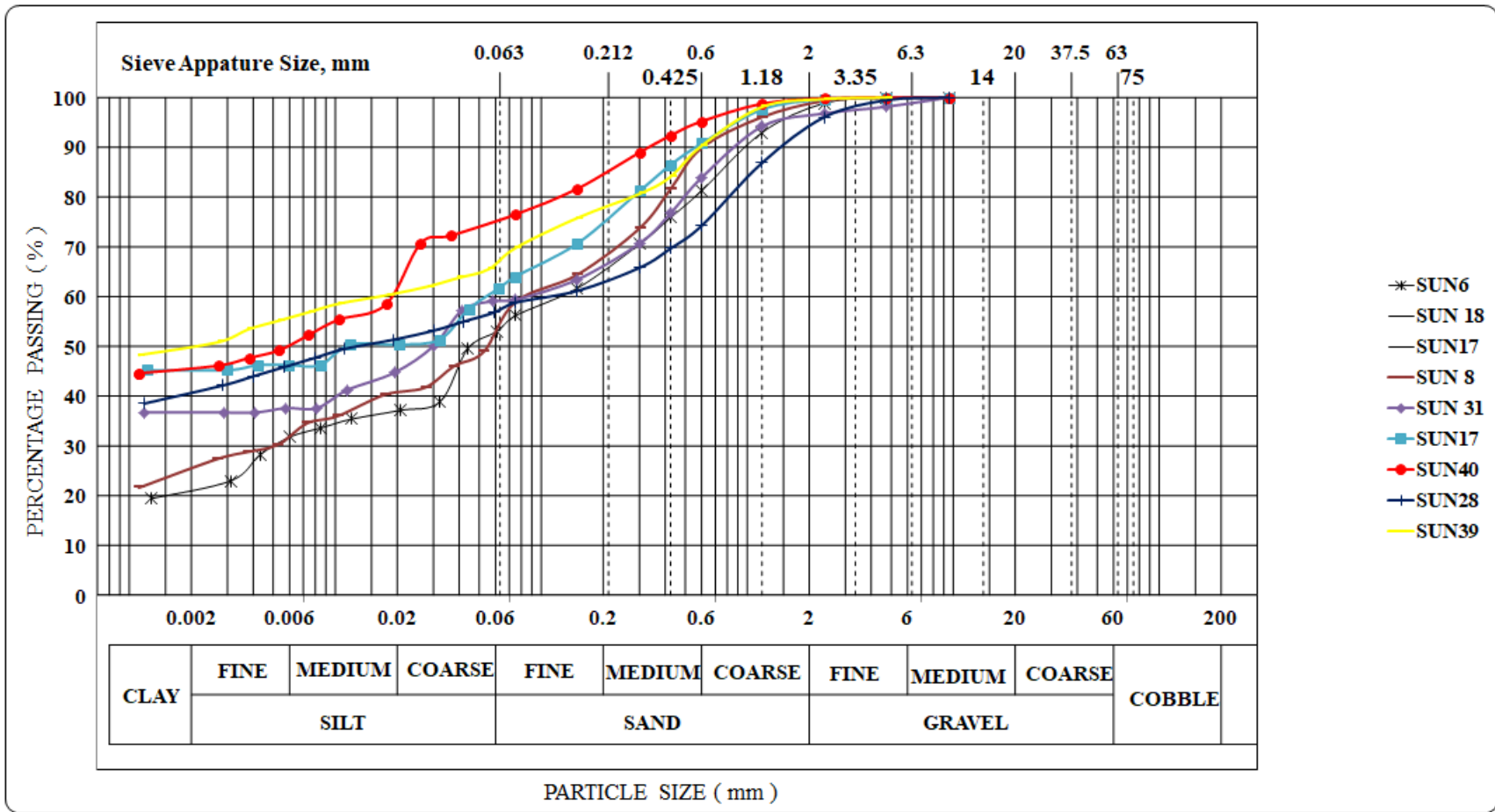


Figure 6.2. Particle size distribution curves of the lateritic soils derived from charnockite.

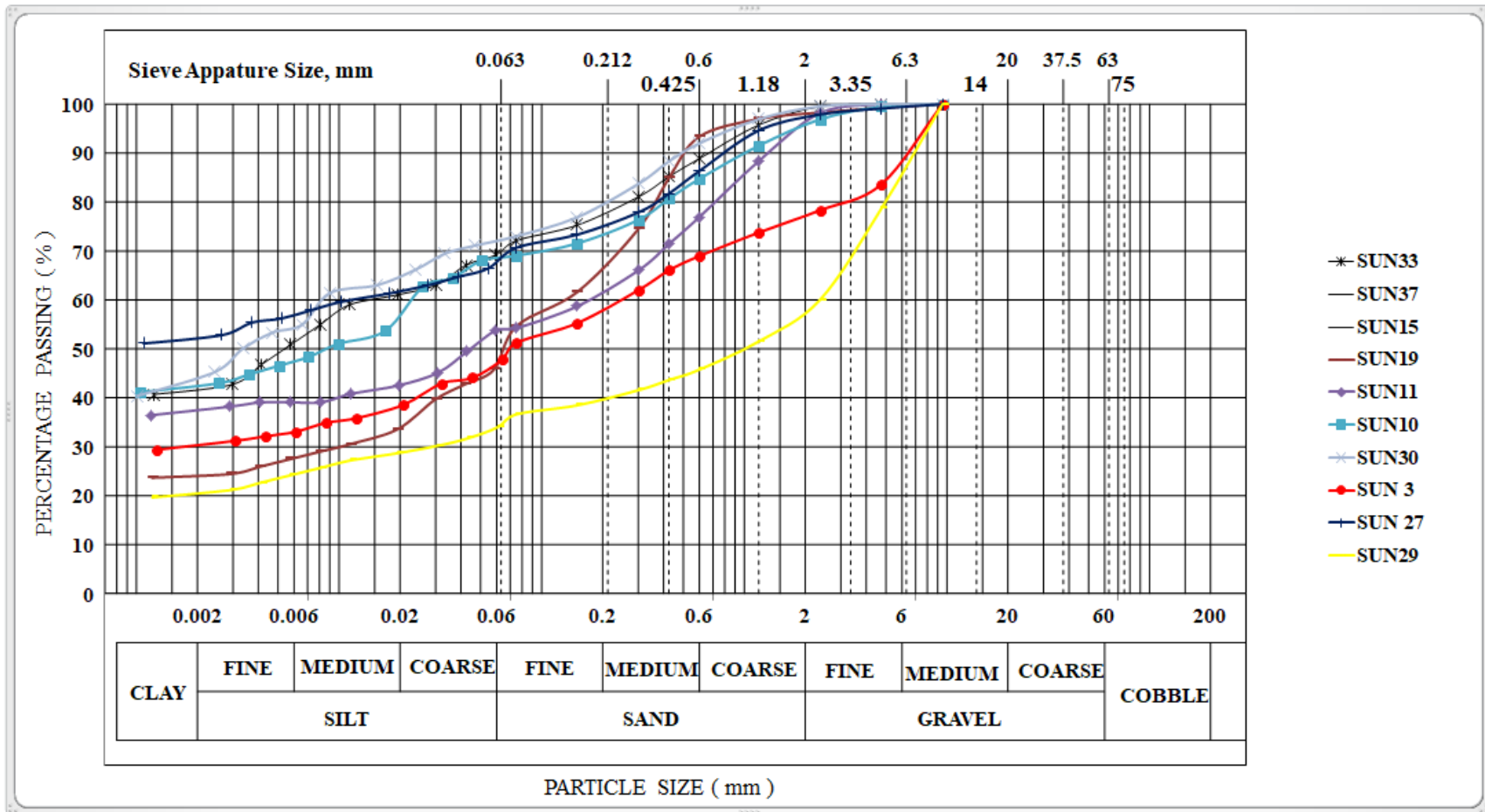


Figure 6.3. Particle size distribution curves of the lateritic soils derived from migmatite.

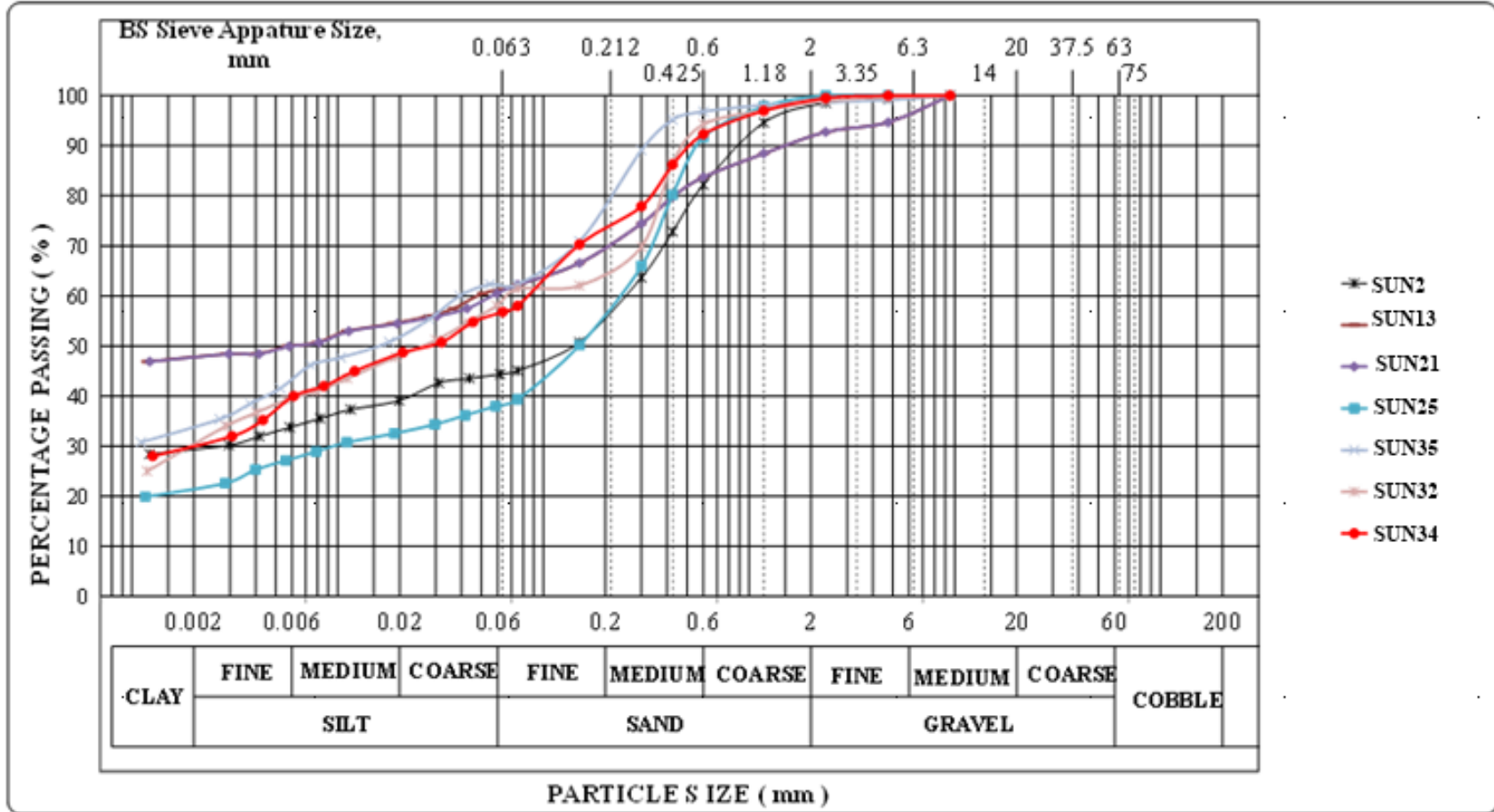


Figure 6.4. Particle size distribution curves of the lateritic soils derived from schist (SUN35), quartzite (SUN32, SUN34) and granite-gneiss (SUN2, SUN13, SUN21, SUN25).

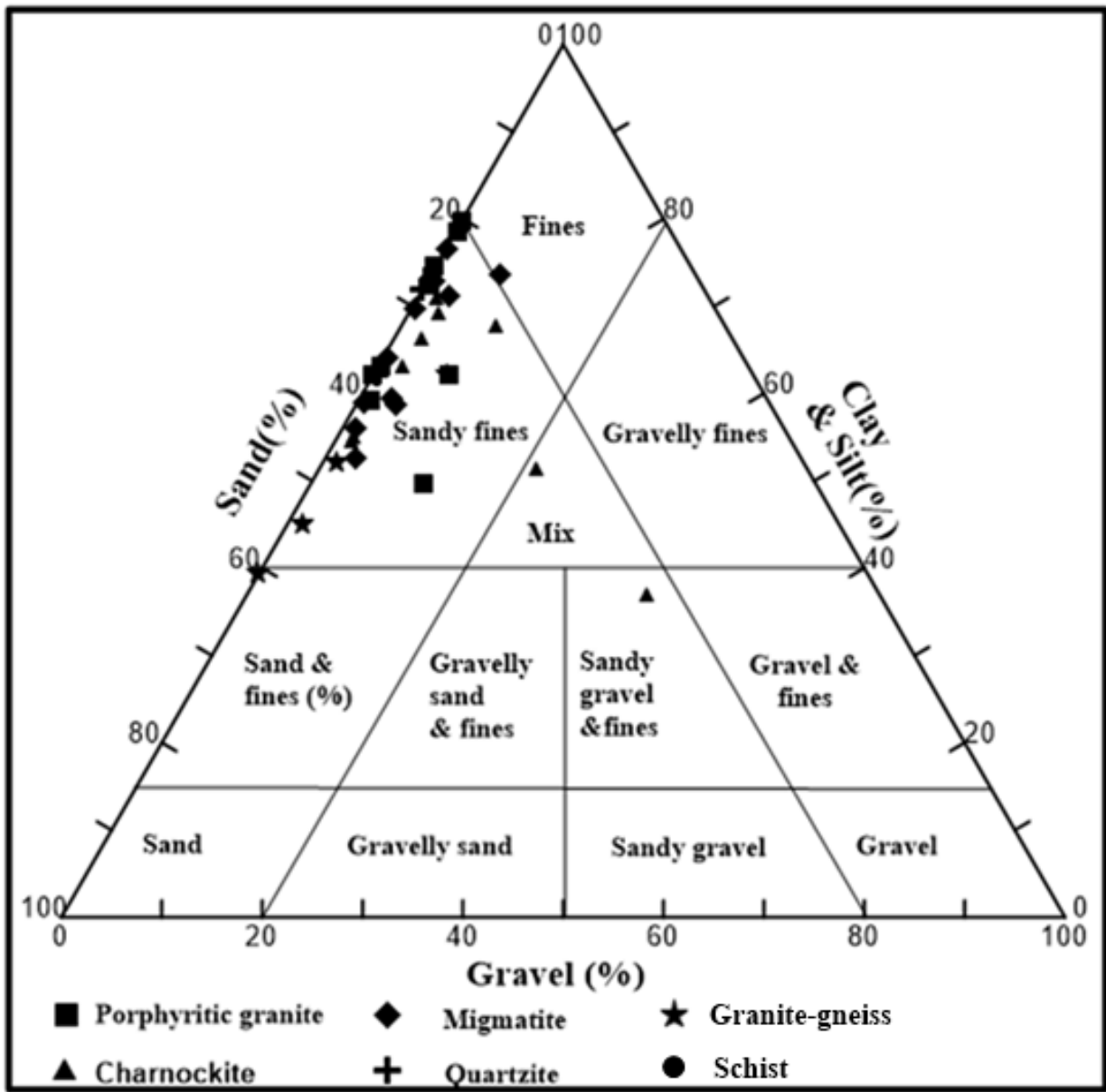


Figure 6.5. Classification of the lateritic soils (modified from Brink, 2015).

Table 6.1 Grain size distribution characteristics of the lateritic soils tested.

| Parent rocks | No. of Samples | | Clay (%) | Silt (%) | Sand (%) | Gravel (%) |
|---------------------|----------------|---------|-----------|-----------|-----------|------------|
| Porphyritic granite | 10 | average | 13.7 | 39.3 | 30.4 | 2.1 |
| | | range | 15.5-37.2 | 29.9-50.2 | 20.3-39.5 | 0.0-11.3 |
| Charnockite | 11 | average | 28.6 | 33 | 30.5 | 7.8 |
| | | range | 19.3-43.3 | 17.3-41.9 | 23.0-43.9 | 0.4-40 |
| Migmatite | 12 | average | 33.6 | 31.1 | 33.3 | 2 |
| | | range | 19.3-44.4 | 18.6-38.5 | 19.5-44.5 | 0.1-7.0 |
| Granite-gneiss | 4 | average | 27.7 | 22 | 47.8 | 2,6 |
| | | range | 20.3-40.3 | 15.9-31.1 | 30.5-60.6 | 0.0-7.3 |
| Quartzite | 2 | average | 30 | 27.5 | 41 | 1.5 |
| | | range | 27.0-28.0 | 27.0-28.0 | 40.0-42.0 | 1.0-2.0 |
| Schist | 1 | | 22 | 16 | 61 | 1 |

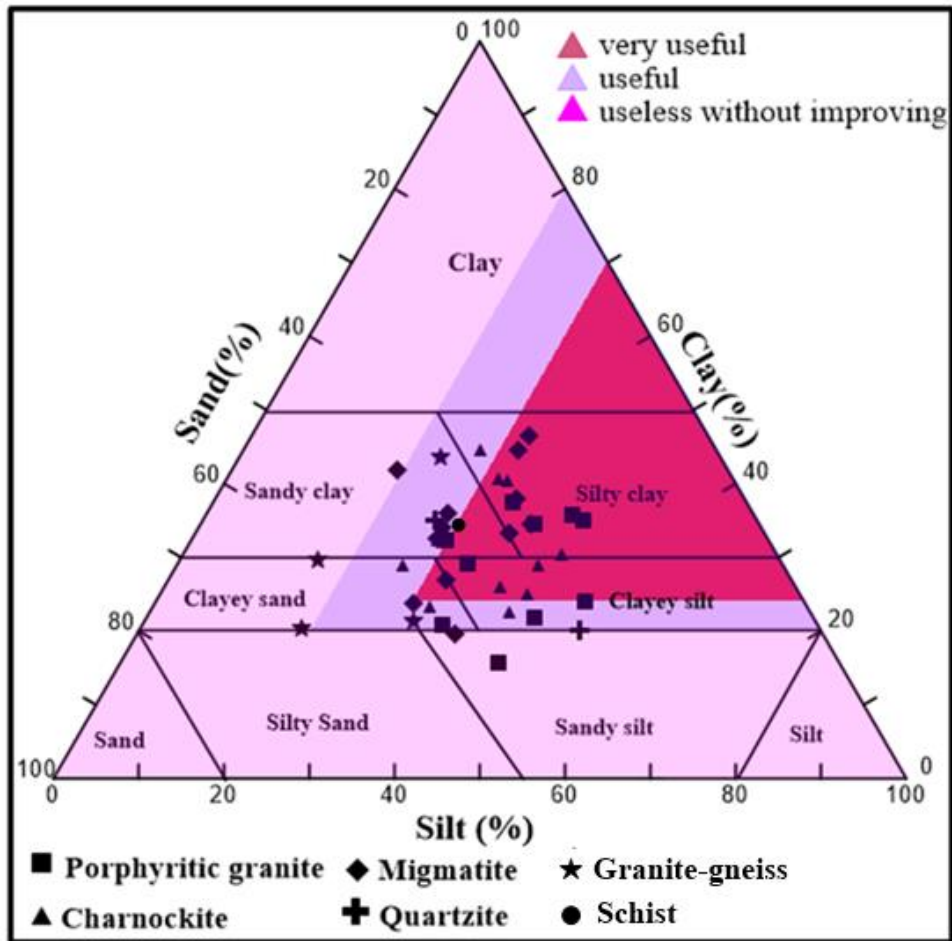


Figure 6.6. Position plots of the samples on the Matrix classification chart in relation to the requirements of soil liners (modified from Majer *et al.*, 2007).

6.3 Consistency limit

A summary of the Atterberg limits is presented in Table 6.2 whilst Figure 6.8 shows the position plots of the lateritic soils from the different rock units in the Cassagrande plasticity chart. The plots show that the soils plots below and above the arbitrary A-line and could thus be categorized as inorganic clays and silts of low to high compressibility and plasticity. A vast majority of the migmatite derived lateritic soils fall below the arbitrary A-line classifying them as inorganic silt with high plasticity while the charnockite derived soils plots above and below the A-line in the region of medium plasticity. Accordingly, this result is consistent with the results of Mesida (1987) and Adeyemi (1995) on the lateritic soils derived from similar parent materials. Favareti and Corsu (2018) recommended soils in the region above the A-line of the Cassagrande chart as suitable landfill liner materials and only fourteen of the samples fall into this category. Moreover, the soils plotting above the A-line have low silt content, which enables easy compaction and reduces their erodibility. Interestingly, many of these are charnockite derived soils with some porphyritic granite derived lateritic soils also fulfilling the condition while the plot of the average values indicates that only the charnockite derived soils plot above the A-line. The soils derived from quartzite recorded the lowest plastic and liquid limit, which is attributable to the high content of silt sized particle and some mica in the fine-grained fraction. Additionally, the lowest average plasticity index recorded by the granite gneiss derived lateritic soils can be linked to the occurrence of minimum amount of fines. Also, the average plasticity index of the lateritic soils is less than 35 which implies that they would possess low shrinkage (Daniel, 1993). Irrespective of the parent rocks, the average liquid limits of the studied lateritic soils are generally above the minimum (30%) recommended by TCEQ (2017) and significantly lower than the maximum (90%) specified by UKEPA (2009). Accordingly, the average plasticity index of the soils derived from the different parent rocks conform to the maximum limit stipulated by Declan and Paul (2009) and UKEPA (2014). Additionally, the average values are within the range ($10\% \leq PI \leq 30\%$) stipulated for plasticity index of liners by USEPA (2000). Figure 6.9 shows the Activity plots of the soils and indicates that a vast majority of the soils are inactive indicating a low expansion potential. All the lateritic soils derived from the different rock types gave average activity values which conform to the range (0.3-1.25) as specified by Oeltzschner (1992) and Rowe *et al.* (1995) for soils designated for landfill liners. Although, soils with higher activity values tend to yield low permeability, they are more vulnerable to contaminants. Consequently, Taha and Kabir (2005) advocated for the use of

less active soils as liners in containment facilities. Accordingly, the average activity values of the lateritic soils indicate that they are not likely to be vulnerable to contaminants. This is also desirable as it suggest the tendency to minimize the probability of desiccation cracking due to moisture changes within the liner. Thus, based on the average activity values, the soils could be adjudged as suitable for landfill liners. Moreover, following the classification of Ola (1980), the average values of the linear shrinkage indicate that the lateritic soils exhibit non-critical to marginal expansion potential indicating that the soils will not pose field compaction problems.

Table 6.2. Natural moisture content, specific gravity and consistency limits of the lateritic soils tested.

| | No. of Samples | | Natural moisture content | Specific gravity | Liquid limit | Plastic limit | Plasticity index | Linear shrinkage |
|---------------------|----------------|---------|--------------------------|------------------|--------------|---------------|------------------|------------------|
| | | | | | (%) | (%) | (%) | (%) |
| Porphyritic granite | 10 | average | 14 | 2.61 | 51 | 32 | 17 | 8.3 |
| | | range | 5-35 | 2.45-2.74 | 38-71 | 14-50 | 10-33 | 3.0-15.7 |
| Charnockite | 11 | average | 20 | 2.67 | 47 | 26 | 19 | 6.9 |
| | | range | 9-38 | 2.5-2.99 | 40-62 | 14-36 | 6-33 | 3.7-10 |
| Migmatite | 12 | average | 22 | 2.61 | 54 | 34 | 21 | 8.4 |
| | | range | 7-67 | 2.52-2.95 | 31-72 | 25-50 | 6-52 | 3.6-15.7 |
| Granite-gneiss | 4 | average | 16 | 2.62 | 39 | 27 | 12 | 5.5 |
| | | range | 9-26 | 2.56-2.73 | 32-44 | 13-38 | 3-20 | 2.1-7.5 |
| Quartzite | 2 | average | 25 | 2.65 | 31 | 4 | 20 | 4.7 |
| | | range | 25-25 | 2.6-2.7 | 23-39 | 4-4 | 20-20 | 1.5-7.9 |
| Schist | 1 | | 25 | 2.62 | 43.2 | - | - | 1.5 |

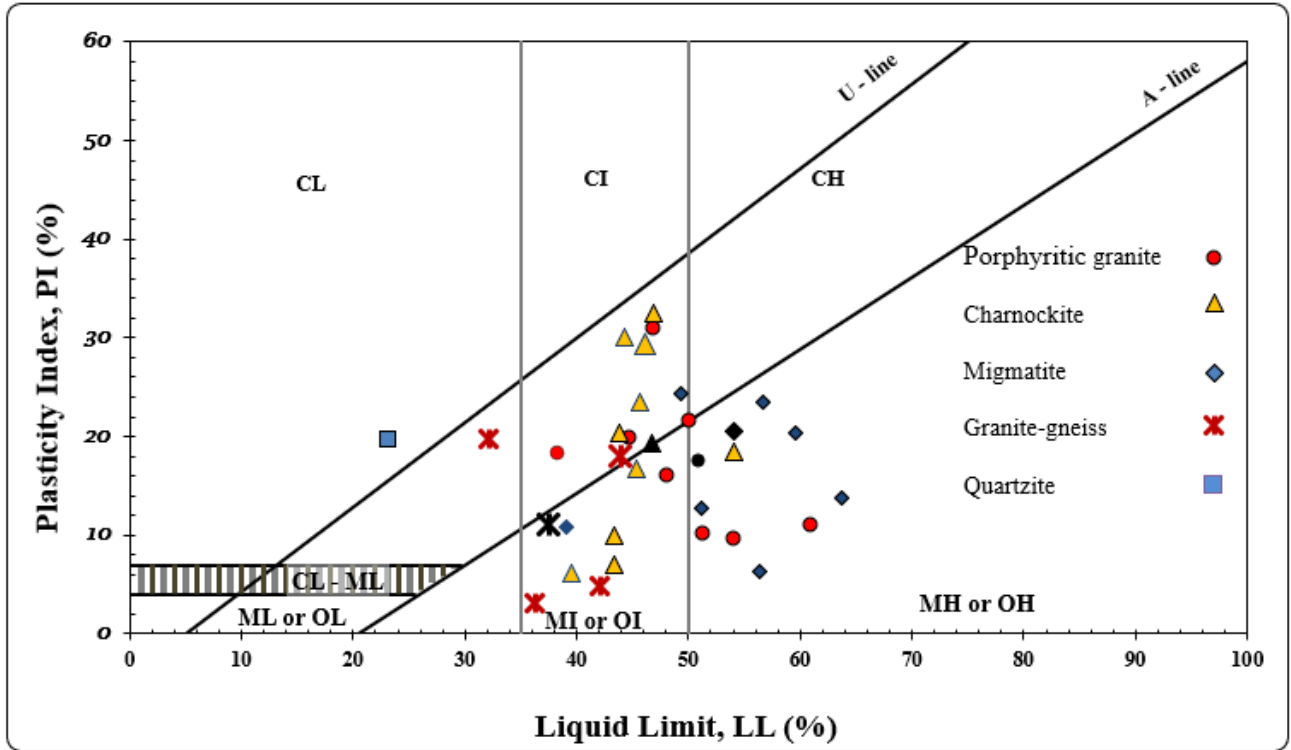


Figure 6.7. Position plot of the lateritic soils on the Cassagrande Plasticity chart (plots of the averages are colored black with the same symbols).

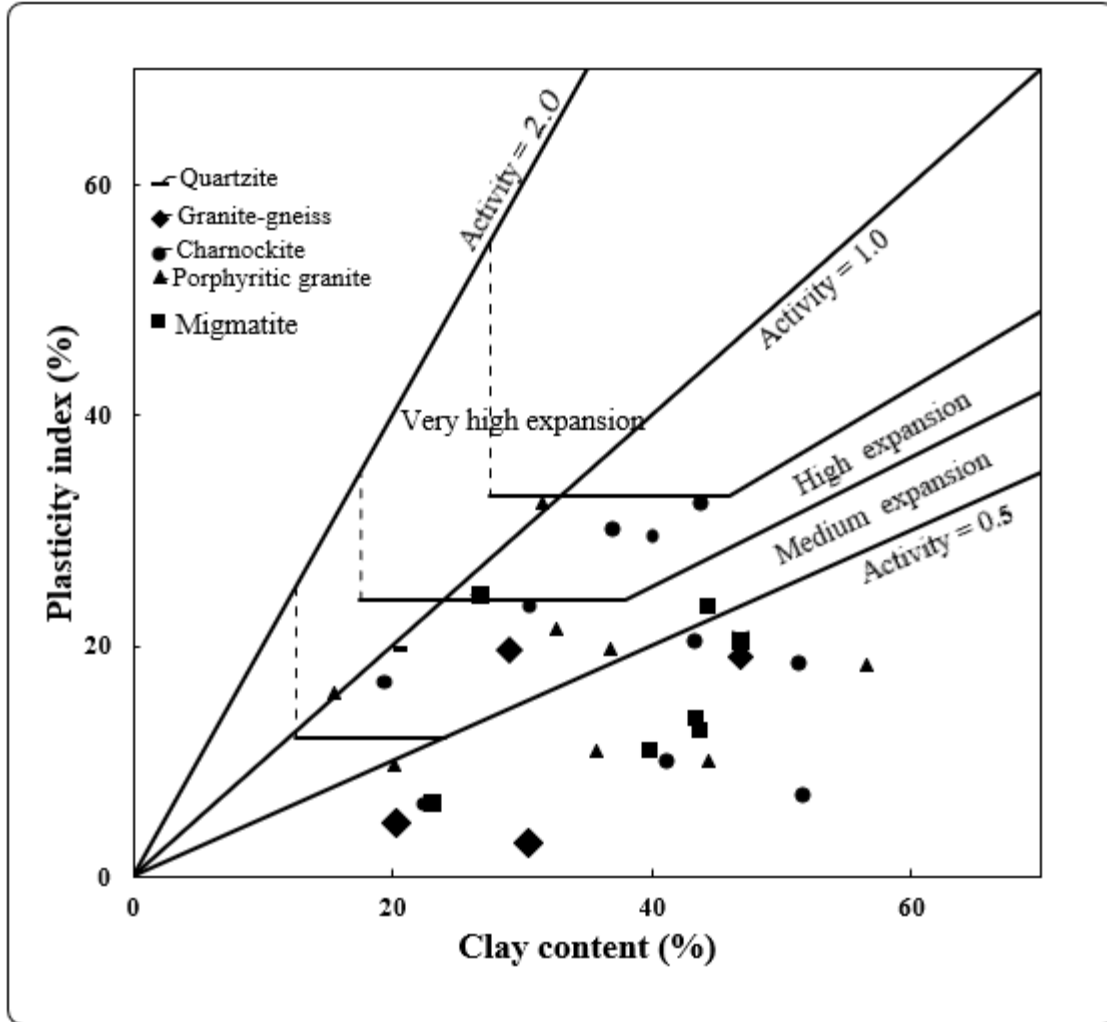


Figure 6.8. Activity Chart showing the position of the lateritic soils derived from the different parent materials (modified after Bell and Maud, 1995).

6.4 Specific gravity

The range of values of the specific gravity (Table 6.2) conforms to the range attributed to lateritic soils by Gidigasu (2012). The specific gravity of soils gives an indication of the degree of laterization as higher specific gravity implies a higher degree of laterization and strength of soils (Oyelami, 2017). The average values of the specific gravity of the soils derived from the different rock types are higher than the minimum 2.2 and 2.5 specified by USEPA (1982) and Ige (2013) respectively. Furthermore, the charnockite derived lateritic soils recorded the highest specific gravity, which may be attributed to the presence of pyroxene. Thus, on the basis of specific gravity of the soils, they can be adjudged as appropriate for landfill liner application.

6.5 Compaction

The results of the geotechnical properties obtained from the different tests of the lateritic soils derived from the diverse parent materials are presented in Table 6.3. The importance of the compaction characteristics of soils designated for landfill liners cannot be overemphasized as they directly influence their strength and hydraulic conductivity. The moisture-density relationships of the lateritic soils compacted at the West African and standard proctor energy level are shown in Figures 6.9a and 6.9b respectively. Particle size rearrangement in well graded soils during compaction yields high maximum dry density (MDD) while the significant occurrence of fine-grained particles result in the relatively high optimum moisture content (OMC) as observed in the soil (Endene *et al.*, 2020a and 2020b). The soils reflected a significant increase in the MDD and slight reduction in the OMC respectively as a result of increase in compactive efforts. This is because of the more parallel orientation of the finer particles resulting from higher compactive efforts, which yields a closer packing of the particles and an increased unit weight (Taha and Kabir, 2005). This could imply an increase in their shear strength characteristics because of the closer packing of the soil fabric that increased the bonding forces and reduced the void ratio. Soils with high MDD and low OMC are desirable for engineering construction (Daramola *et al.*, 2018; Oyelami *et al.*, 2022). Thus, the lateritic soils derived from granite gneiss showed the best compaction characteristics (highest MDD and lowest OMC). On the average, the lateritic soils from the various parent materials recorded MDD values lower than 1.7 Mg/m^3 recommended by Ogunsanwo (1996) for soils designated for liner applications. Nevertheless, Frempong & Yanful (2008) stated that soils with MDD values greater than 1.5 Mg/m^3 will yield adequate compaction and strength characteristics for landfill lining applications. Thus, the average MDD of the lateritic soils derived from charnockite and porphyritic granite fell short of this requirement. However, the soils derived from the different parent materials fulfill this requirement when compacted at the West African energy level.

Table 6.3. Summary of compaction results of the lateritic soils derived from different parent rocks.

| Rock types | No. of Samples | | Standard proctor | | West African | |
|---------------------|----------------|---------|------------------|--------------------------|--------------|--------------------------|
| | | | OMC (%) | MDD (Mg/m ³) | OMC (%) | MDD (Mg/m ³) |
| Porphyritic granite | 10 | average | 26.0 | 1.45 | 25.0 | 1.64 |
| | | range | 18.0 - 32.6 | 1.29 - 1.53 | 17.3 - 31.3 | 1.46 - 1.73 |
| Charnockite | 11 | average | 22.9 | 1.48 | 18.7 | 1.81 |
| | | range | 18.2 - 27.0 | 1.41-1.64 | 12.8 - 27.9 | 1.64 -1.98 |
| Migmatite | 12 | average | 21.4 | 1.50 | 22.0 | 1.67 |
| | | range | 13.0 - 27.3 | 1.40 - 1.61 | 17.5 - 26.0 | 1.59 - 1.86 |
| Granite gneiss | 4 | average | 19.5 | 1.61 | 20.6 | 1.69 |
| | | range | 13.3 - 29.0 | 1.46 - 1.75 | 12.5 - 26.3 | 1.59 - 1.82 |
| Quartzite | 2 | average | 22.0 | 1.53 | 21.2 | 1.73 |
| | | range | 22.0 - 22.0 | 1.50 - 1.56 | 21.2 - 21.2 | 1.70 - 1.76 |
| Schist | 1 | | 17.5 | 1.58 | 16.8 | 1.78 |

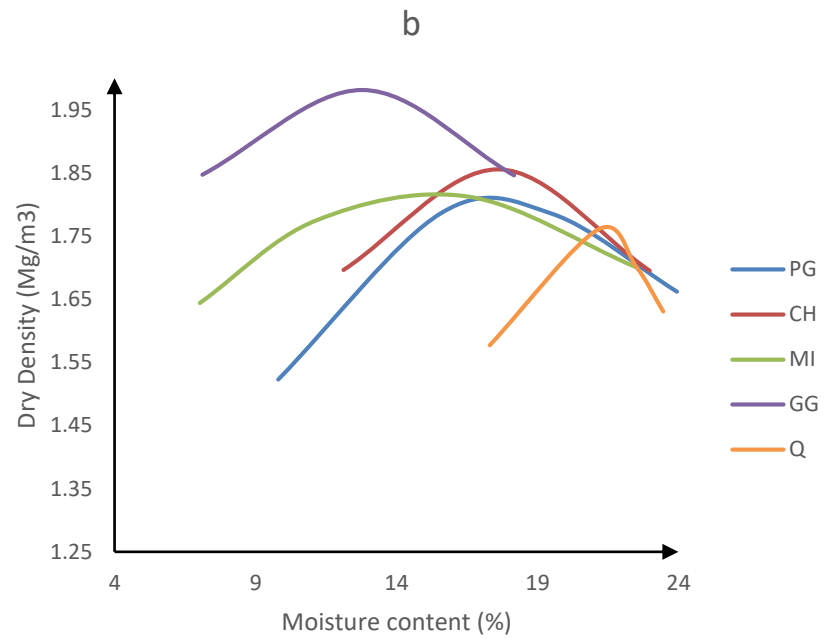
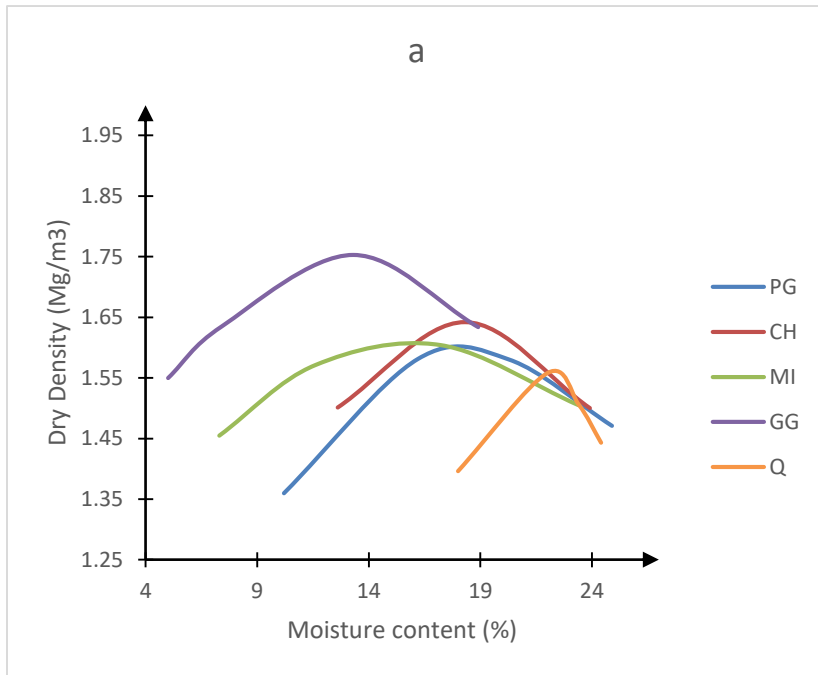


Figure 6.9. Moisture density relationship of the soils compacted at (a) Proctor and (b) West African Energy Level. PG = Porphyritic granite, CH = charnockite; MI = migmatite, GG = Granite-gneiss, Q = quartzite.

6.6 Permeability

The results of the coefficient of permeability are presented in Table 6.4. Notably, the charnockite derived soils recorded the minimum (3.5×10^{-10} m/s) and maximum (1.66×10^{-7} m/s) coefficient of permeability which indicates a wide range of variations in the permeability of the lateritic soils derived from this rock type. Furthermore, the higher coefficient of permeability of some of the charnockite derived soils coincides with higher gravel content in the lateritic soil samples identified as mix and sandy gravel and fines (Figure 6.5). Generally, the values of the coefficient of permeability of the lateritic soils indicate that they have very low permeability as the average hydraulic conductivity falls between 10^{-9} m/s and 10^{-8} m/s (Budhu, 2011). A coefficient of hydraulic conductivity of 10^{-9} m/s is frequently described as a margin demarcating the boundary between pervious and impervious soils (Lambe and Whiteman, 1959; Budhu, 2011; Adesina and Tijani, 2017). The very low degree of permeability exhibited by the lateritic soils could be attributed to the grading characteristics of the lateritic soils, which enabled the fines contents (clay and silt) to block the voids between the coarser grains, consequently reducing the amount and size of the pores controlling the flow thereby reducing the hydraulic conductivity. This is in line with the findings of Endene *et al.* (2020b) and Afolagboye *et al.* (2017) who pointed out that the modification of the fabric of soils due to compaction creates a more tortuous flow path for the movement of the permeant. Therefore, this suggests a poor to very poor drainage characteristics, which is desirable for compacted soil liners as it limits the migration of leachates into the surrounding soils thereby reducing the likelihood of contamination of the groundwater and surrounding environment. However, the average values of the hydraulic conductivity of the lateritic soils derived from the different parent rocks fail to satisfy the requirement of 1×10^{-9} m/s specified by UKEPA (2014), NSW EPA (2016), and USEPA (2021). Nevertheless, only four of the lateritic soil samples considered (two charnockite derived and two migmatite derived lateritic soils) satisfy the recommended maximum of 1×10^{-9} m/s. Despite prevailing standards, including those set by UKEPA (2014), NSW EPA (2016), and USEPA (2021), which establish the maximum required hydraulic conductivity at 1.0×10^{-9} m/s based on the standard Proctor energy level, the results indicate a notable reduction in hydraulic conductivity when the lateritic soils are compacted at the West African energy level. This could be attributed to the reduction and likely elimination in the occurrence of large pores (Acar and Oliveri, 1989; Taha and Kabir, 2005). However, in spite of the reduction, the average hydraulic conductivity values of the soils from various rocks fail to

meet the standard specified by UKEPA (2014), NSW EPA (2016), and USEPA (2021). In the light of this, the soils derived from granite-gneiss and charnockite have hydraulic conductivity values that are relatively lower than others but still marginally exceeds the standard requirements. Therefore, while the soils derived from granite-gneiss and charnockite may offer better performance compared to the soils derived from other parent rock types, it may not be sufficient to ensure long term containment unless some specific engineering solutions such as composite containment methods are adopted to improve on their higher hydraulic conductivity.

Table 6.4. Coefficient of permeability (hydraulic conductivity) of the lateritic soils compacted at two energy levels.

| Rock types | No. of Samples | | Coefficient of permeability(m/s) | |
|---------------------|----------------|---------|--|--|
| | | | Standard Proctor | West African Standard |
| Porphyritic granite | 10 | average | 1.1×10^{-8} | 1.0×10^{-8} |
| | | range | $1.2 \times 10^{-9} - 3.4 \times 10^{-8}$ | $9.5 \times 10^{-10} - 3.2 \times 10^{-8}$ |
| Charnockite | 11 | average | 1.9×10^{-8} | 1.8×10^{-8} |
| | | minimum | $3.5 \times 10^{-10} - 1.6 \times 10^{-7}$ | $3.3 \times 10^{-10} - 1.5 \times 10^{-7}$ |
| Migmatite | 12 | average | 1.7×10^{-8} | 1.5×10^{-8} |
| | | minimum | $5.6 \times 10^{-10} - 7.6 \times 10^{-8}$ | $5.2 \times 10^{-10} - 7.1 \times 10^{-8}$ |
| Granite-gneiss | 4 | average | 6.6×10^{-9} | 6.1×10^{-9} |
| | | minimum | $2.9 \times 10^{-9} - 1.1 \times 10^{-8}$ | $2.7 \times 10^{-9} - 1.0 \times 10^{-9}$ |
| Quartzite | 2 | average | 1.3×10^{-8} | 1.25×10^{-8} |
| | | minimum | $8.4 \times 10^{-9} - 1.8 \times 10^{-8}$ | $7.8 \times 10^{-9} - 1.7 \times 10^{-8}$ |
| Schist | 1 | | 1.58×10^{-9} | 1.73×10^{-9} |

6.7 Strength of the lateritic soils

The structural integrity and competence of liners are ascertained by ensuring that it has adequate shear strength. Bello & Osinubi (2009) noted that compacted soil liner must possess adequate shear strength and ample durability to resist the pressures of repeated freeze-thaw and wet-dry cycles. Table 6.5 presents the results of UCS and total shear strength parameters of the lateritic soils derived from different parent rock types. According to Bell (2007), the average UCS values obtained for the soils classify them as very stiff. This could be attributed to the significant occurrence of fine particles filling the voids and the interlocking of the coarse grains, thereby increasing their strength

characteristics. Furthermore, the classification of the lateritic soils as very stiff implies that they exhibit a considerably high resistance to deformation under compression, which indicates that the soils could withstand significant amount of load without excessive deformation. Accordingly, the lateritic soils possess UCS values that are desirable for soils designated for landfill liner applications, which must withstand compressive stresses imposed upon them by waste materials and the heavy construction and waste transportation equipment. Following the recommendation of a minimum of 200 kPa by Taha and Kabir (2005) and considering the average UCS values obtained from the laboratory tests, the soils derived from the different rock types could be considered suitable for use as landfill liners.

Table 6.5. Results of the UCS and the total shear strength parameters of the lateritic soil derived from different parent rocks

| Rock types | No. of Samples | | ϕ° | Cohesion (kPa) | UCS (kPa) |
|---------------------|----------------|---------|--------------|----------------|---------------|
| Porphyritic granite | 10 | average | 10.8 | 45.6 | 226.4 |
| | | range | 9.4 - 13 | 23 - 59.5 | 174 - 284.5 |
| Charnockite | 11 | average | 10.9 | 44.7 | 233.9 |
| | | range | 9.1 - 13 | 23 - 62.8 | 174 - 284.5 |
| Migmatite | 12 | average | 11.3 | 40.3 | 213.4 |
| | | range | 8.9 - 13 | 23 - 64.5 | 174 - 266 |
| Granite -gneiss | 4 | average | 11.1 | 42.7 | 213.4 |
| | | range | 9.7 - 12.5 | 28.1 - 56.4 | 184.2 - 240.9 |
| Quartzite | 2 | average | 9.6 | 35.2 | 208.5 |
| | | range | 6.2 - 13 | 23 - 47.3 | 174 - 243 |
| Schist | 1 | | 13 | 23 | 173.8 |

The total shear strength parameters play a prominent role in the assessment of the structural integrity and stability of landfill liner components during construction and in response to rapid loading conditions such as placement of waste and the movement of heavy equipment (Taha and Kabir, 2005; Yamusa *et al.*, 2022). The average values of the total cohesion revealed that the lateritic soils could be classified as medium stiff according to ECDF (2001) and Abdelsalam *et al.*

(2016). The average values of the total shear strength parameters for the lateritic soils derived from the various parent rocks are above the minimum of 35 kPa and 3° as specified by Majer *et al.* (2007) and Koś and Zawisza (2016) for landfill liners. Thus, based on the average values of the total shear strength parameters obtained from the laboratory tests, the soils derived from the different rock types could be considered suitable for utilization as landfill liners.

6.8 Stabilization of the lateritic soils

Natural soils for liner applications are carefully selected to conform to the minimum stipulated requirements. However, in cases where available soils are not up to the required standards, modification of the available soils seems the best option to adopt as this would save cost than importing suitable materials. Several authors (Farnezi & Leitie, 2007; Moradini and Leitie, 2010; Amadi & Eberemu, 2013; Gopinath *et al.*, 2018; Kumar *et al.*, 2021; Okeke *et al.*, 2021) have attempted to modify and improve the properties of potential soil liners using different materials such as fly ash, bentonite, sawdust, tailings, fibers, rice and maize husk ash. However, limited attention has been given to stabilizing lateritic soils with counterparts from diverse origins. Furthermore, the impact of these mixtures on the hydraulic conductivity, a critical soil property for landfill liner applications, has been overlooked in previous research. Therefore, the possibility of improving the marginally higher coefficient of permeability of some lateritic soils (Table 6.6) derived from various rock types was investigated by blending them with lateritic soils of derived from migmatite (SUN40) and charnockite (SUN33). The soils with marginally higher coefficient of permeability were thoroughly mixed with soils of lower coefficient of permeability in ratios of 1:10, 2:10, 3:10 and 4:10 respectively, in order to investigate the best ratio suited for blending. The result of blending the lateritic soils with various quantities of lateritic soils derived from various rock types is illustrated in Figure 6.10. The results indicate a notable reduction in the coefficient of permeability as shown in Figure 6.10. This could be attributed to the modification in the grain size characteristics of the resulting mixture. The higher fines content of the resultant mixture might have significantly increased the fines content of the soils thereby increasing the possibility of filling available pore spaces and reducing the permeability. Moreover, it is noteworthy that despite the reduction in the measured coefficient of permeability of the lateritic soils derived from porphyritic granite, granite-gneiss and quartzite, the values fail to satisfy the required minimum of 1×10^{-9} m/s specified by UKEPA (2014), NSW EPA (2016), and USEPA

(2021). Conversely, the measured coefficient of permeability of the lateritic soils derived from charnockite and migmatite conform to the specification when mixed at a ratio of 1:10. This suggests that a minimum mixing ratio of 1:10 could be adopted for effective utilization of the lateritic soils as landfill liners.

Table 6.6 Description of the lateritic soil samples blended.

| Sample ID | Parent Rock | Coefficient of permeability (m/s) |
|-----------|---------------------|-----------------------------------|
| SUN2 | Granite-gneiss | 4.58×10^{-9} |
| SUN3 | Migmatite | 1.20×10^{-9} |
| SUN8 | Charnockite | 1.09×10^{-9} |
| SUN12 | Porphyritic granite | 2.06×10^{-9} |
| SUN32 | Quartzite | 1.72×10^{-8} |
| SUN35 | Schist | 1.73×10^{-9} |

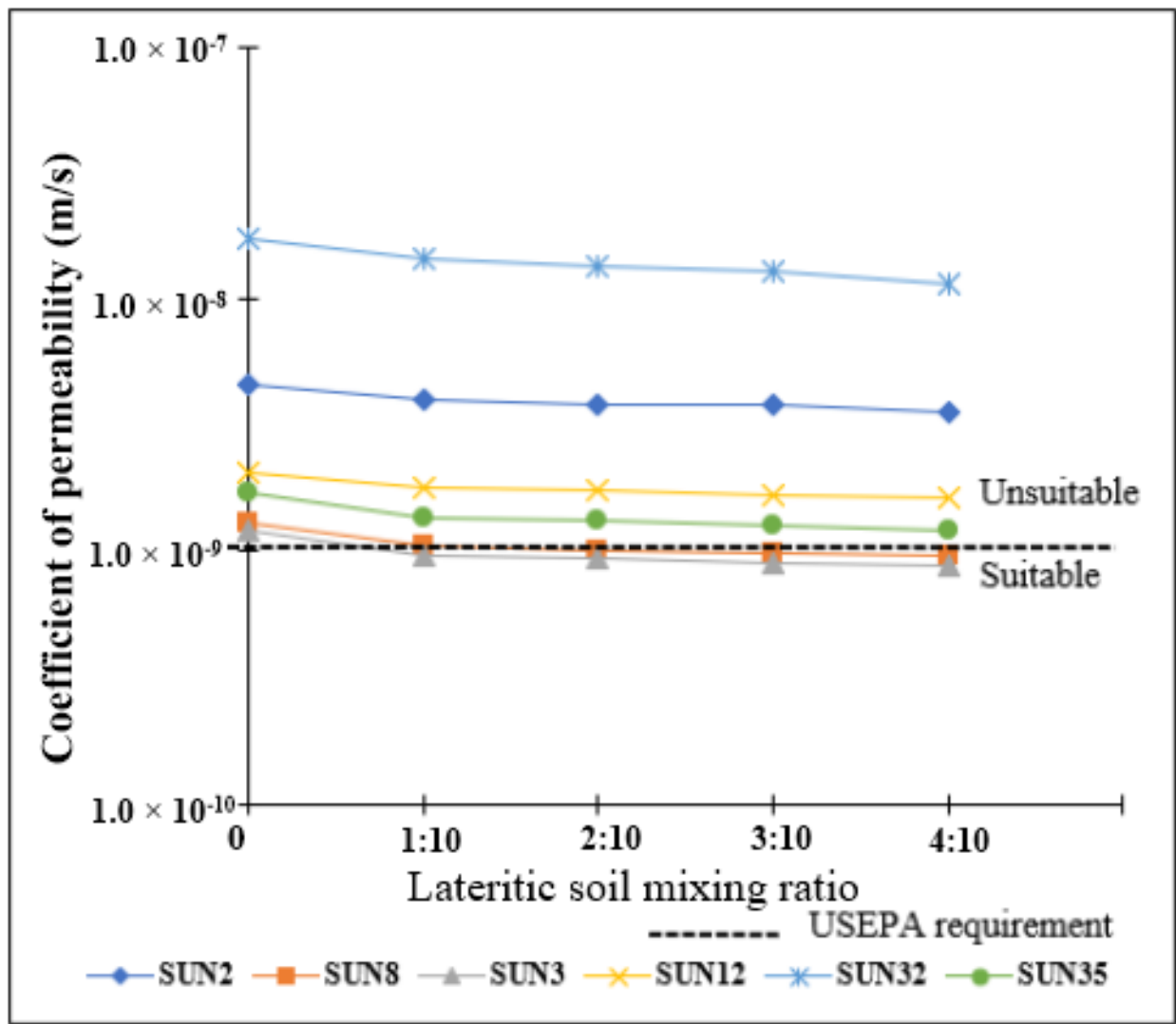


Figure 6.10. Plot showing the influence of the lateritic soils derived from charnockite on the hydraulic conductivity of lateritic soils derived from various parent rocks

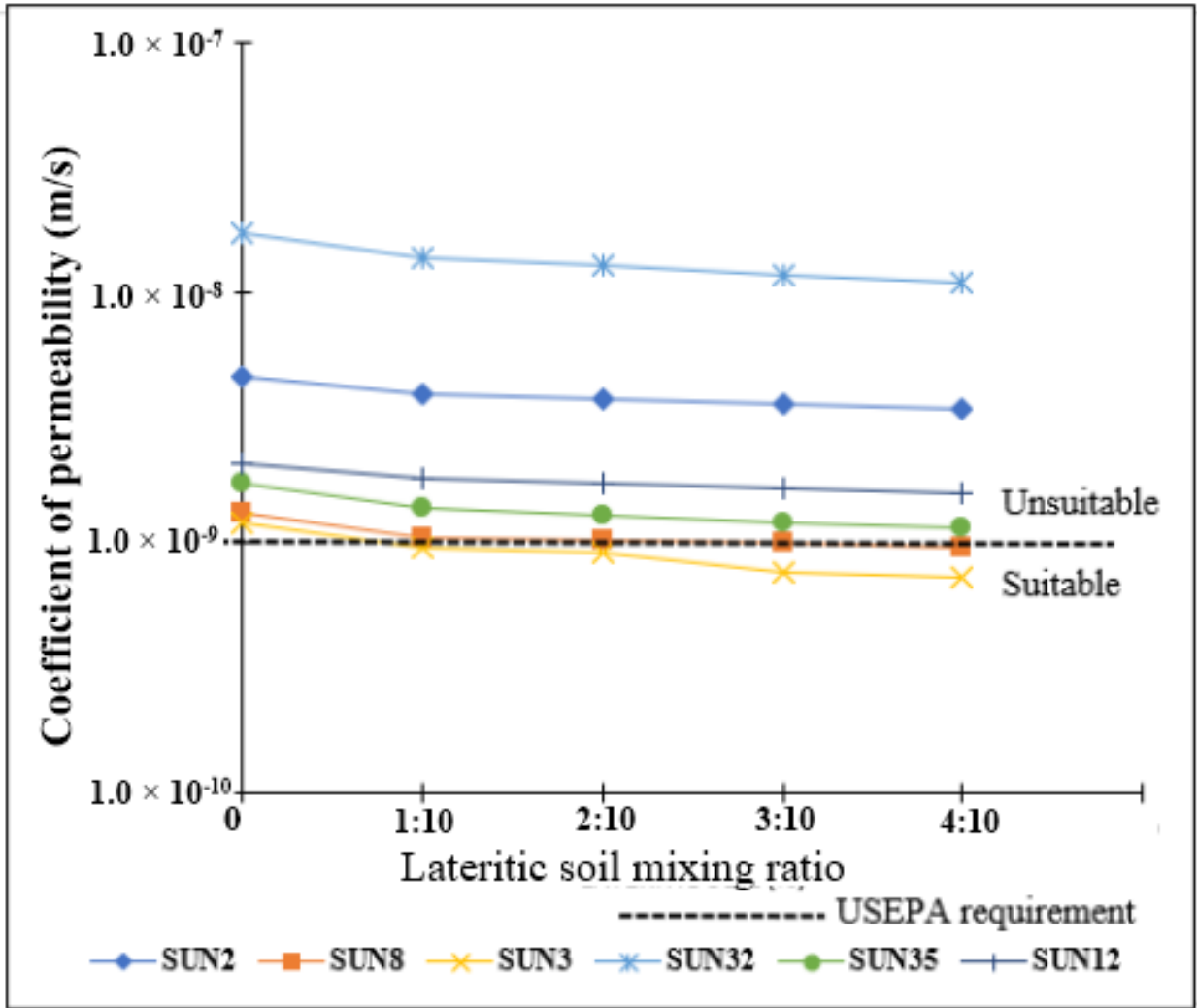


Figure 6.11. Plot showing the influence of the lateritic soils derived from migmatite on the hydraulic conductivity of lateritic soils derived from various parent rocks

6.9 Summary

The intrinsic characteristics of lateritic soils that render them valuable for landfill liner applications have been investigated. The assessment of the index properties comprising atterberg limits, particle size distribution and specific gravity establishes their potential for forming stable liner structures. Moreover, the examination of the geotechnical properties such as compaction, shear strength and permeability underscore their ability to minimize the migration of leachate and provide structural integrity. The lateritic soils derived from the different parent rocks are well-graded comprising cohesive soils and classified as inorganic clays and silts of with low, medium to high plasticity. Moreover, the lateritic soils demonstrated good compaction characteristics with the granite-gneiss

derived soils having the highest MDD at the lowest OMC. The average values of the UCS and other shear strength parameters were higher than the minimum recommended for landfill liners. Generally, the geotechnical properties of the lateritic soils derived from the different parent rocks are not significantly different.

CHAPTER SEVEN

MINERALOGICAL AND GEOCHEMICAL PROPERTIES OF THE LATERITIC SOILS FROM SOUTHWESTERN NIGERIA

7.1 Introduction

Lateritic soils have emerged as potential candidates for landfill liner materials due to their unique characteristics such as the presence of mineral phases that promote chemical stability. Understanding the intricate interplay of the various properties of lateritic soils is essential for optimizing landfill liner design and ensuring long-term environmental protection. The mineralogical, geochemical and physicochemical properties of lateritic soils are examined for use as landfill liner material is reported in this chapter. It aims to shed light on the feasibility and efficiency of lateritic soils under study as landfill liners, contributing to sustainable waste management.

7.2 Mineralogy of the lateritic soils

The mineralogical characteristic of a soil is of paramount importance in the selection of soils for landfill liners. This is because, clay minerals exhibit surface activities such as sorption and cation exchange capacity, which essentially contribute to the retention and attenuation of different contaminant species (Akgün *et al.*, 2017). Thus, the physical and chemical properties of a soil are dependent on the types and amount of clay minerals present in the soil (Saleh, 2005). The results of the mineralogical investigation of the soils derived from different parent rocks by XRD (Figure 7.1 and 7.2) reveals that the principal clay minerals are dickite (20-53%) and kaolinite (30-60%) while the non-clay minerals include quartz, muscovite, goethite, rutile, microcline, magnesite and anatase. The kandites form the most dominant part of residual soils and consist of large stacks of alternating aluminum octahedral and silicon tetrahedral sheets combined in a unit such that the edges of the silica tetrahedrons and the octahedral layer form a common sheet (Yong and Mulligan, 2019). Kaolinites are non-expandable, have very minute charge, and their cation exchange capacity (CEC) is low, ranging from 1 to 15 meq/100g (Van Olphen, 1977). Also, kaolinite is one of the most common two-layer clay minerals commonly encountered by soil engineers. They have a very strong, stable structure, with a very low swelling potential and the capacity to absorb minimum amount of water (Onana *et al.*, 2017; Ngo'o Ze *et al.*, 2019). According to Saleh (2005), kaolinite

exhibits low retarding characteristics and rarely attains a hydraulic conductivity that is less than 10^{-8} m/sec. However, the dominance of non-swelling clay minerals suggests a low swelling and shrinkage potential for majority of the soils. The dominant occurrence of the clay minerals of the kandite group further implies that the soils have good potential as landfill liners as they would not suffer a major extent of damage from the problem of reaction with municipal solid waste landfill. Additionally, the lateritic soils will tend to demonstrate low shrinkage on drying and low to marginal swelling due to wetting as kaolinite exhibit the minimum affinity for water amongst the different types of clay minerals. Furthermore, soils with low swelling potential do not crack on drying. Cracks reduce the performance of the landfill liner in terms of containment function, as it increases infiltration of surface water into the containment facility and enable the migration of leachates into surrounding soils and groundwater (McBean *et al.*, 1995, Taha and Kabir, 2005). Additionally, kaolinite rich soils are not known for any alteration to other clay minerals such as the smectite group, which may have much lesser amount of chemo-mechanical stability than illite-rich and kaolinite-rich soils which they are not originally derived from (Zhao *et al.*, 2007). Similarly, the dominance of kaolinite in these lateritic soils contributes to the low plasticity of the soils, which is an additional advantage as low plastic soils have a permeability that remains nearly constant even after several drying-wetting cycles. Kaolinite rich soils also exhibit predominant vertical deformation which presents a lesser threatening risk of developing desiccation cracks in a compacted soil liner instead of horizontal deformation commonly found in soils having high plasticity (Varghese and Anjana, 2015). In addition, the kandites do not imbibe larger amounts of water that reduces the strength of the soil, triggering slope failures in landfills (Wagner, 2013; Regadio *et al.*, 2020). Overall, the findings suggest that the sampled lateritic soils are suitable for landfill liners due to their low swelling potential and minimal cracking. Therefore, these soils should be prioritized in landfill liner design to enhance containment efficiency and durability.

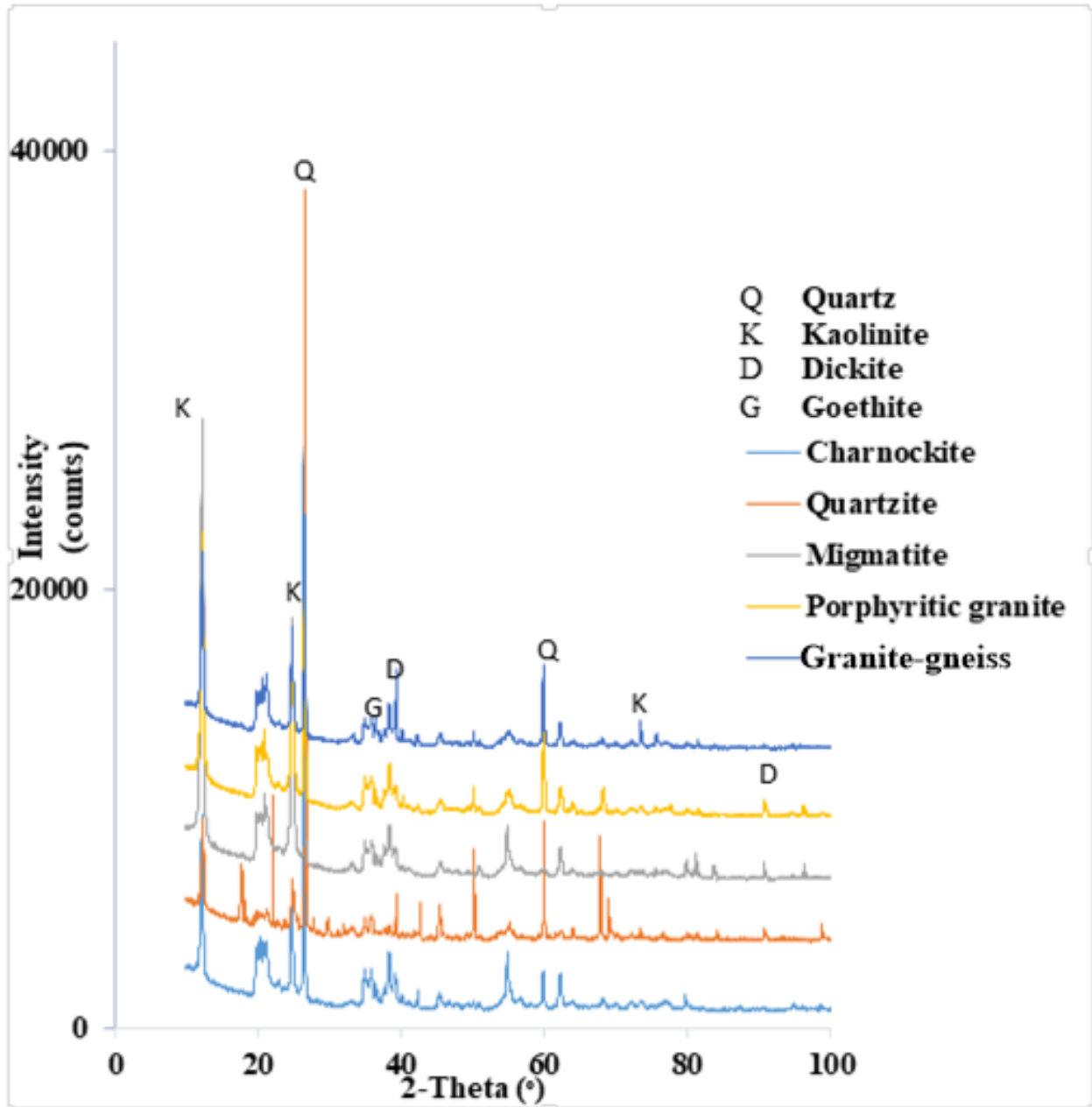


Figure 7.1. Typical XRD diffractograms of the lateritic soils derived from different parent rocks.

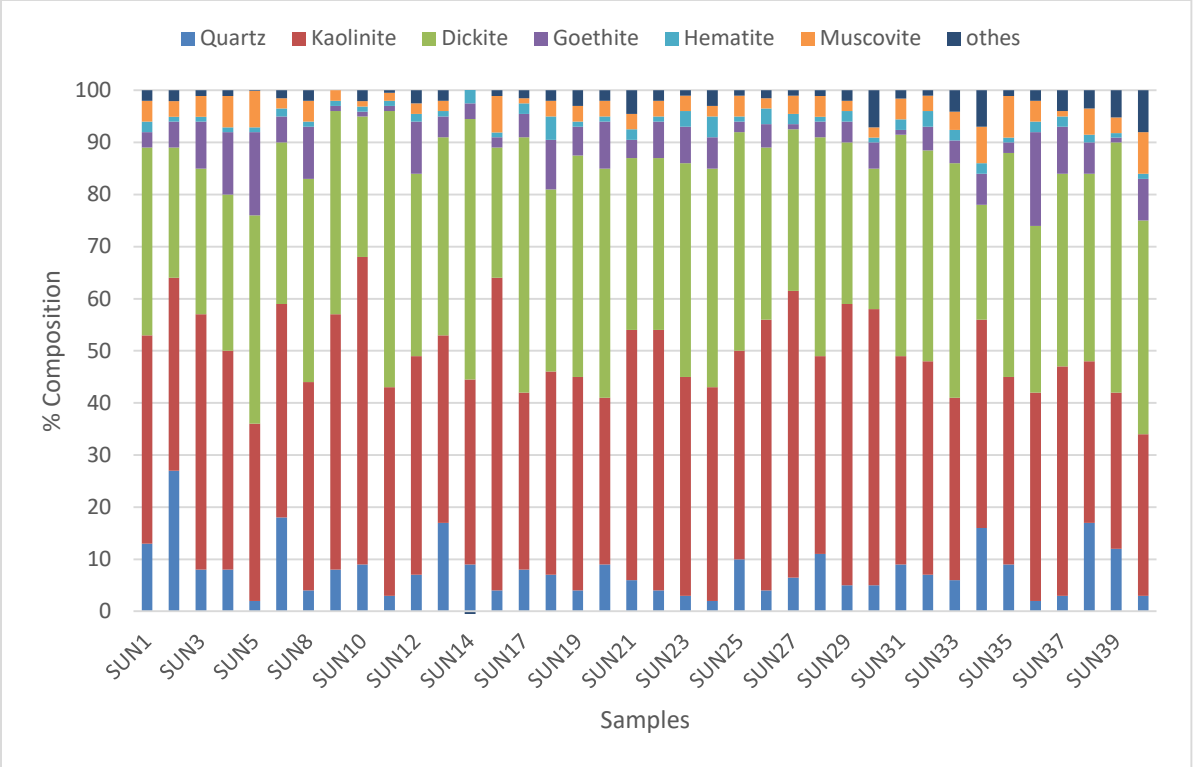


Figure 7.2. Distribution of the major and minor mineral phases in the soils.

7.3 Geochemical properties of the lateritic soils

The major oxides and trace element composition of the various selected lateritic soil samples are presented in Table 7.1. The geochemical data conform to the theoretical description of lateritic soils earlier given in the previous section. The results of the major oxides analysis indicate that oxides of silica, aluminum and iron are dominant in the sampled lateritic soils, constituting approximately 88 to 97% of the oxides present (Table 7.1). The samples are depleted in K_2O and Na_2O and minimal amount of MgO and CaO . The repeated occurrence of identical elements within comparable proportion ranges suggests a limited compositional variation of the parent rocks. Furthermore, the results depict compositional change resulting from the ongoing process of chemical weathering, which is apparent in the progressive degradation of alkalis and enhancement in sesquioxides of silica and alumina. This can be attributed to the differences in the mobility of the various chemical elements (e.g. Na, Ni, Ca, Cr, Cu, Sr, K, and Mg), which enables those derived from minerals that are less resistance to weathering such as feldspars and mica appear in lower quantities due to their mobility. Thus, the depletion of mobile elements can be explained by the influence of alternating dry and wet seasons on the development of lateritic soils. This causes a progressive leaching of the mineral constituents of the parent materials (rocks) during the wet season, causing the leaching of the mobile elements. Conversely, in the dry season, the originally leached ions are conveyed to the surface by capillary action where the salts evaporate and the residual elements are washed down during the following wet season (Oyelami and Van Rooy 2016a, Oyelami, 2017). The results indicate that the ratio of silica to sesquioxide (SSR) range from 0.5 to 1.96 in the soil samples. In the light of this, few of the soils are laterites while many of them are lateritic soils based on the SSR classification by Joachim and Kandiah (1941). However, plots of the lateritic soils geochemical data on the Schellman (1981) ternary diagram (Figure 7.3) indicate that the soils are weakly to moderately laterized. The trace element concentration shows that manganese (0.13-2.81ppm) and chromium (0.2-0.95 ppm) occur in higher concentrations while cadmium (0.01-0.06ppm) and lead (0.085-0.249ppm) occur at lower concentrations.

The clay mineral constituent of the studied lateritic soils reflects the parent material and the environment of formation of these soils. Since they were formed within the tropical climatic environment, they have been subjected to highly intense weathering that resulted in soils with a related mineralogy, comprising 1:1 alumino-silicate clays as well as oxides of iron and aluminium (Fontes and Gomes, 2003; Oyelami, 2017). The sampled lateritic soils have a silico–aluminous–

ferrugino composition. Furthermore, the mineralogical and major oxide compositions are similar to that of lateritic soils reported in various literature from southwestern Nigeria and Cameroon (eg. Adeyemi, 2003; Oyelami and VanRooy, 2018; Kamtchueng *et al.*, 2015). Additionally, these observations are in line with Nzabakurikiza *et al.* (2017) who reported that lateritic soils developed on felsic rocks exhibit silico–aluminous–ferrugino composition, whereas mafic rocks give rise to ferrugino–alumino– siliceous soils. Moreover, it is important to note that some of the lateritic soil samples contain the least iron oxide (4.69, 5.37, 7.46 and 6.37 wt%) and the most silica (53.39, 64.31, 56.16 and 57.82wt%). The high silica content suggests the high degree of leaching which may have left the more resistant silica in greater quantity. However, the silica content of the lateritic soils is lower than that of the parent rocks indicating that some of the silica has been removed as a result of weathering, leaching and desiccation (Elueze *et al.*, 2004). Additionally, the high silica, iron oxide and oxyhydroxide contents of these soils will provide better geomechanical properties that are required for different applications such as landfill liners (Bohi, 2008; Millogo *et al.*, 2008; Nzabakurikiza *et al.*, 2017). Moreover, sodium oxide concentration (≤ 0.01 wt%) is very small in all the lateritic soils; this is favourable for soils proposed for liner application as high concentration of sodium oxide in soils leads to the dispersion of soil particles which is detrimental to compacted soil liners (Osinubi *et al.*, 2014).

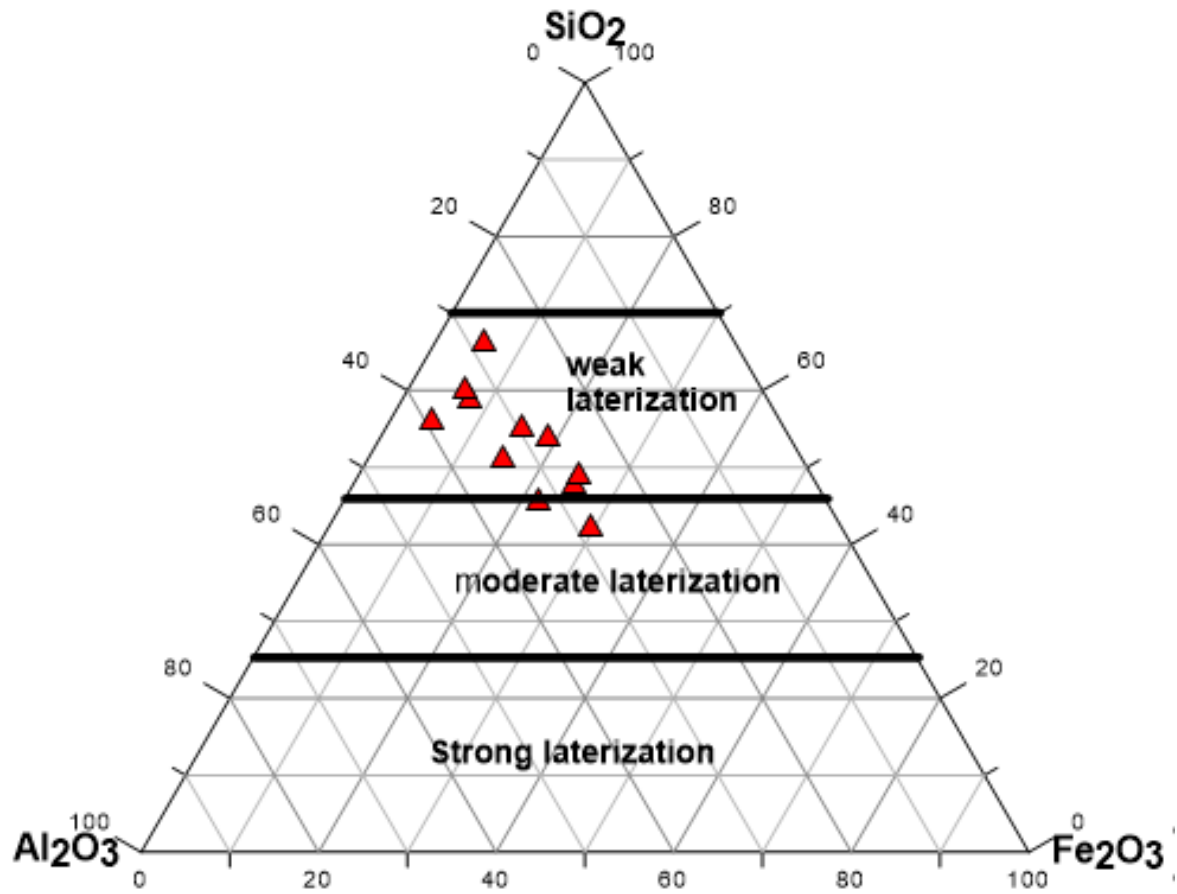


Figure 7.3. Ternary plot displaying the degree of laterization (modified from Schellmann, 1981).

Table 7.1 Major oxides (wt%) and trace element (ppm) composition of the lateritic soils.

| Sample ID | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | MgO | K ₂ O | Na ₂ O | TiO ₂ | V ₂ O ₅ | Cd | Cr | Cu | Mn | Pb | SSR |
|-----------|------------------|--------------------------------|--------------------------------|------|------|------------------|-------------------|------------------|-------------------------------|-------|-------|-------|-------|-------|------|
| SUN30 | 49.18 | 32.56 | 14.79 | 0.11 | 0.00 | 0.13 | 0.01 | 1.92 | 0.13 | 0.064 | 0.774 | 0.166 | 0.574 | 0.17 | 1.04 |
| SUN33 | 44.68 | 25.7 | 23.29 | 0.09 | 0.00 | 3.51 | 0.01 | 1.41 | 0.13 | 0.035 | 0.456 | 0.187 | 0.876 | 0.138 | 0.91 |
| SUN2 | 43.52 | 31.27 | 21.16 | 0.05 | 0.00 | 0.27 | 0.01 | 2.06 | 0.13 | 0.045 | 0.946 | 0.348 | 0.738 | 0.249 | 0.83 |
| SUN25 | 53.39 | 37.65 | 4.69 | 0.04 | 0.51 | 0.31 | 0.01 | 2.13 | 0.14 | 0.057 | 0.467 | 0.171 | 1.872 | 0.174 | 1.26 |
| SUN4 | 48.49 | 26.23 | 13.59 | 0.16 | 3.05 | 5.38 | 0.01 | 1.67 | 0.1 | 0.011 | 0.809 | 0.251 | 0.915 | 0.186 | 1.22 |
| SUN14 | 39.55 | 26.74 | 27.95 | 0.27 | 0.00 | 2.3 | 0.01 | 1.62 | 0.12 | 0.049 | 0.868 | 0.246 | 1.444 | 0.113 | 0.72 |
| SUN38 | 64.31 | 27.46 | 5.37 | 0.14 | 0.00 | 0.47 | 0.01 | 0.51 | 0.08 | 0.033 | 0.394 | 0.182 | 0.155 | 0.128 | 1.96 |
| SUN40 | 56.16 | 32.2 | 7.46 | 0.1 | 0.00 | 0.83 | 0.01 | 1.58 | 0.08 | 0.064 | 0.35 | 0.106 | 0.127 | 0.085 | 1.42 |
| SUN32 | 57.82 | 32.23 | 6.37 | 0.32 | 0.00 | 1.05 | 0 | 1.09 | 0.08 | 0.01 | 0.216 | 0.086 | 0.124 | 0.098 | 1.5 |
| SUN35 | 51.5 | 26.28 | 18.19 | 0.26 | 0.00 | 0.95 | 0.01 | 1.46 | 0.12 | 0.017 | 0.2 | 0.143 | 2.813 | 0.105 | 1.16 |

7.4 Summary

The investigation of the mineralogical and geochemical properties of lateritic soils for use as landfill liners has indicated their potential suitability for the intended applications. The XRD analysis shows that kaolinite and dickite are the dominant clay minerals present in the lateritic soils, implying low desiccation cracking and low shrink-swell behaviour. The geochemical analysis indicate that the lateritic soils are silico-alumino-feruginuous with average major oxide composition of SiO_2 , Al_2O_3 and Fe_2O_3 of 50.86 wt%, 29.83 wt% and 14.29 wt%), respectively. Additional oxides with lower abundance include TiO_2 (1.55 wt%), Na_2O (0.01wt%), MgO (0.36wt%), CaO (0.15wt%) and K_2O (1.52wt%). The lateritic soils contain trace amount of heavy metals with average concentrations of Cd (0.039 ppm), Pb (0.548 ppm), Cr (0.189 ppm), Cu (0.964 ppm), Mn (0.145 ppm). Furthermore, the low concentration of sodium oxide in the lateritic soils is indicative of the soil particles not susceptible to dispersion, while the presence of iron oxide and manganese signifies the heavy metal retention capacity of the soils. The mineralogical, geochemical and physicochemical characteristics of these lateritic soils provide important insights into their performance and long-term stability as landfill liners.

CHAPTER EIGHT
BATCH SORPTION CHARACTERISATION OF LATERITIC SOILS FROM
EKITI STATE, SOUTHWESTERN NIGERIA

8.1 Introduction

A comprehensive assessment of lateritic soils as landfill liners requires quantifying sorption-desorption reactions, as well as determining the reversibility or irreversibility of sorbed heavy metal cations that are known to occur in landfill leachates. This information is essential for predicting contaminant mobility, improving risk assessment, and developing effective remediation strategies. In this regard, batch equilibrium adsorption tests were conducted to characterize the lateritic soil samples taken across the study area including determination of their heavy metal retention capacities. This chapter presents and discusses the results of the sorption characteristics of lateritic soils derived from various parent rocks from the study area. A basic sample description of the sampled lateritic soils utilized for the batch equilibrium test is presented in Table 8.1.

Table 8.1. Description of the lateritic soil samples utilized for the batch equilibrium test.

| Sample ID | Sample description | | | |
|-----------|-----------------------------------|---------------------|---------|---------------------|
| | Color on the color chart | USCS classification | Texture | Parent Rock |
| SUN30 | Moderate red 5C 4/6 | CI | Clayey | Charnockite |
| SUN33 | Moderate red 5C 4/7 | MH | Clayey | Charnockite |
| SUN02 | Pale Red 10R 6/2 | CL | Silty | Porphyritic Granite |
| SUN25 | Moderate reddish brown 10R4/6 | MI | Sandy | Porphyritic Granite |
| SUN04 | Moderate brown 5YR 4/4 | MH | Clayey | Migmatite |
| SUN14 | Moderate brown 5YR 4/5 | MI | Clayey | Migmatite |
| SUN38 | Moderate red 5R 5/4 | MI | Sandy | Granite Gneiss |
| SUN40 | Light Red 5R 6/6 | MH | Sandy | Granite Gneiss |
| SUN32 | Orange Pink 5YR 7/2 | CL | Clayey | Quartzite |
| SUN35 | Moderate yellowish brown 10YR 5/4 | MI | Clayey | Schist |

8.2 Cation exchange capacity

The cation exchange capacity is a direct measure of the exchange and adsorption capacity of soils (Endene *et al.*, 2020b). Thus, it is a vital property that is commonly utilized in assessing the suitability of soils for the attenuation of contaminant, particularly with respect to heavy metals. It gives an estimate of the number of cations (meq) required to neutralize 100 g of soil (Yong and Mulligan, 2005; Regadio *et al.*, 2020). CEC is defined as the sum of the exchangeable cations in the soil (Endene *et al.*, 2020b). The range of the CEC (Table 8.2) are typical of kaolinite minerals; hence they are less vulnerable to structural alterations than the soils with higher CEC since the exchange of cation affect the double layer thickness which results in flocculation or dispersion which may cause some changes in hydraulic conductivity (Afolagboye *et al.*, 2017). The CEC of all the sampled lateritic soils is significantly higher than the minimum 10 meq/100g suggested by Taha and Kabir (2005) and Afolagboye *et al.* (2017). Hence, from CEC consideration the soils can be considered suitable provided they fulfill the other stipulated geotechnical requirements.

The range of the pH values (Table 8.2) is typical of soils found in tropical humid environments with high rainfall as it makes carbonic acid more available in the soil (Amusan *et al.*, 2006). The range of the pH values of the lateritic soils implies that the weathering medium is neutral to acidic (Oyediran and Adeyemi, 2012; Ko, 2014). The pH is not significantly influenced by the parent rock. This is because the pH of soils reflects the characteristics of the parent rock when freshly formed but with time, they become easily affected by the prevailing climatic conditions and vegetation (USDA, 2020). According to Shaheen *et al.* (2013), heavy metal sorption capacity is generally greater in alkaline soils than acidic soils because an increase in the pH of soil increases the retention of cationic trace element to soil surfaces by sorption and inner-sphere surface complexation. However, the soils under consideration can be suitably utilized for construction of liners as acid soils can still contribute to the retention of trace elements by sorption (Sunil and Fazilludin, 2015; Yong *et al.*, 2016). This is because the average pH values of the soils are in a range that still favour the adsorption of some common heavy metals such as lead and copper (Gomes *et al.*, 2001).

Table 8.2. Physicochemical properties of the lateritic soils.

| Sample ID | Rock Type | pH | Cation Exchange Capacity (meq/100) |
|-----------|---------------------|------|------------------------------------|
| SUN30 | Charnockite | 4.72 | 13.30 |
| SUN33 | Charnockite | 4.47 | 17.32 |
| SUN2 | Porphyritic granite | 4.65 | 17.89 |
| SUN25 | Porphyritic granite | 4.72 | 14.05 |
| SUN4 | Migmatite | 5.34 | 10.00 |
| SUN14 | Migmatite | 5.59 | 12.00 |
| SUN38 | Granite-gneiss | 5.69 | 10.70 |
| SUN40 | Granite-gneiss | 4.38 | 10.50 |
| SUN32 | Quartzite | 5.19 | 8.90 |
| SUN35 | Schist | 4.61 | 9.90 |

8.3 Adsorption characteristics

Compacted soil liners are known to have the tendency to attenuate leachate contaminants by sorption, redox transformations, filtration, precipitation and biodegradation (Allen, 2001; Regadio *et al.*, 2015; Regadio *et al.*, 2020; Yong and Mulligan, 2019). A combination of sorption, redox transformation, and precipitation processes leads to the attenuation of heavy metals in leachate. The aforementioned processes are usually supported by particular mineral phases, such as clay minerals, sulfate-bearing minerals, clay minerals, manganese as well as iron oxides, and oxyhydroxides (Fisher and Hudson, 1987; Regadio *et al.*, 2020). Furthermore, Wan Zuahiri (2003) and Yong and Mulligan (2019) indicated that the maximum sorption by soils is closely related to high clay content, organic carbon content, manganese and iron oxides as they provide the majority of the high energy binding spots for the sorption of trace metals. On the basis of this, all the soils analysed contain some quantity of iron oxide and manganese, which aids the retention of heavy metals.

The concentration (same quantity) of each of the heavy metal cations in the initial stock solution, and in the supernatant and residue at equilibrium are presented in Table 8.3. The adsorption isotherms are presented in Figure 8.1 and they show plots of the quantity of heavy metals adsorbed (i.e. removed from the solution per gram of the samples) as a function of the concentration of the solution at equilibrium. The differences in the sorption isotherms indicate that different soils exhibit different adsorption capacities for the various heavy metals considered in this study. Moreover, it is generally observed that the equilibrium concentration linearly increased with the

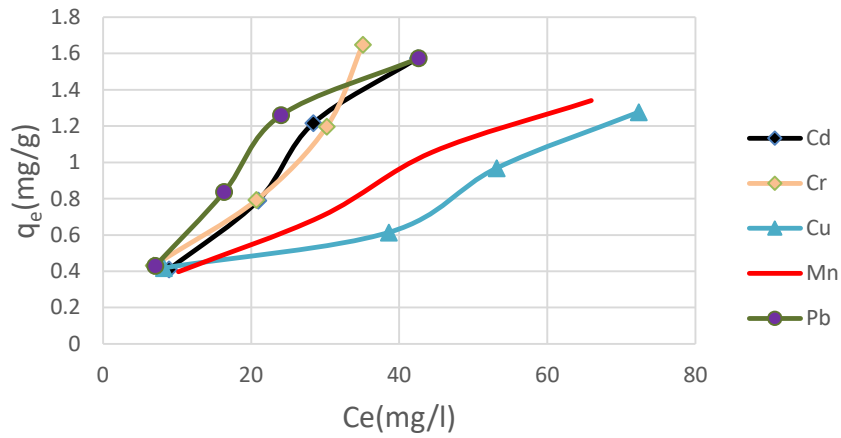
amount adsorbed on to the soil in the majority of the lateritic soil samples. Generally, the concentration of the solution at equilibrium was low for all the metal cations at lower initial concentrations applied, indicating that virtually all the metals were practically adsorbed by the lateritic soils. However, as the solution concentrations increased, the metals sustained their resilient affinity to the solid surfaces. These observations are consistent with the findings reported in Najim *et al.* (2009) and Amadi and Odedede (2009). These results explain that the adsorption is strongly influenced by the initial concentration of heavy metal ion. This is because the ratio of initial metal ions to accessible surface area is low at lower contamination concentrations and associated with highly selective sorption sites with fairly strong bonding energies. Subsequently, at high concentrations, fractional adsorption becomes independent of the initial concentration as potential adsorption sites become progressively occupied (Usman, 2007, Hamza *et al.*, 2013; Shaheen *et al.*, 2013).

It is worthy to note that the migmatite derived lateritic soils analyzed reacted to chromium differently as the amount of chromium adsorbed slightly reduced at lower applied concentrations (Figures 8.1) suggesting that they have been displaced from the surfaces. Furthermore, the isotherms also indicate that competition for sites of adsorption influenced the behavior of the heavy metals in such a way that most of the soils adsorbed more Cd, Pb, Cr and lesser Mn and Cu with increasing concentration. This indicates that the Mn and Cu are displaced from the adsorption complex and replaced by Cd, Cr and Pb (Figures 8.1). This observation agrees with the results of previous researchers (eg. Gomes *et al.*, 2001, Fontes and Gomes, 2003) who found out that these metals are favourably sorbed during simultaneous competition at lower pH.

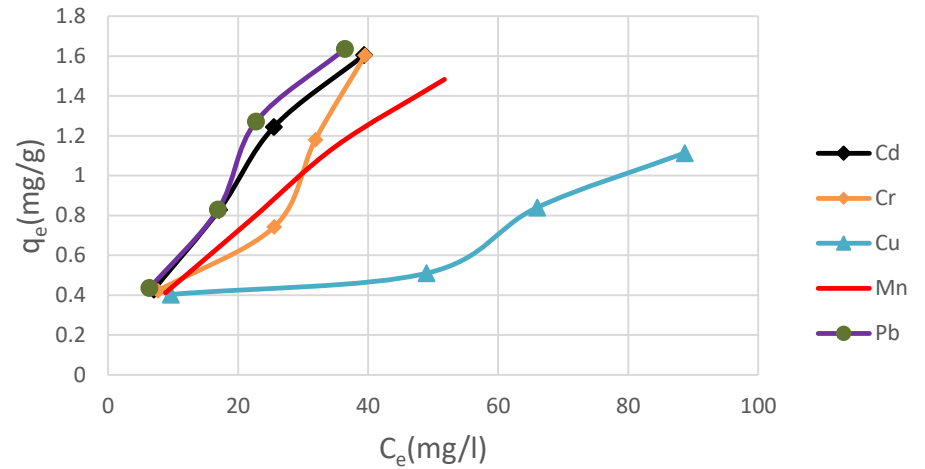
Table 8.3. Initial concentration (IC) of the metals in the stock solutions, equilibrium concentration of the metals in the supernatant solution (Ceq) and metal concentration in the residue (cf) after the supernatant solution is removed.

| Sample ID | IC (mg/l) | Cd (mg/l) | | Cr (mg/l) | | Cu (mg/l) | | Mn (mg/l) | | Pb (mg/l) | |
|-----------|-----------|-----------|----------------|-----------|----------------|-----------|----------------|-----------|----------------|-----------|----------------|
| | | Ceq | C _f | Ceq | C _f | Ceq | C _f | Ceq | C _f | Ceq | C _f |
| SUN30 | 50 | 8.92 | 1.95 | 6.83 | 5.33 | 8.22 | 5.55 | 10.20 | 5.13 | 7.04 | 6.58 |
| | 100 | 20.98 | 0.77 | 20.71 | 6.12 | 38.62 | 2.64 | 29.55 | 3.68 | 16.34 | 1.66 |
| | 150 | 28.41 | 2.24 | 30.24 | 5.27 | 53.18 | 4.89 | 44.42 | 4.38 | 24.03 | 7.24 |
| | 200 | 42.52 | 0.67 | 35.10 | 2.64 | 72.36 | 1.26 | 65.93 | 1.16 | 42.62 | 0.71 |
| SUN33 | 50 | 7.07 | 1.99 | 7.71 | 5.51 | 9.67 | 5.78 | 8.84 | 6.56 | 6.40 | 8.56 |
| | 100 | 17.13 | 0.79 | 25.60 | 5.54 | 49.03 | 4.06 | 22.03 | 5.90 | 16.94 | 3.56 |
| | 150 | 25.53 | 3.05 | 31.91 | 5.82 | 66.03 | 8.13 | 35.11 | 7.60 | 22.79 | 14.30 |
| | 200 | 39.42 | 4.34 | 39.58 | 5.66 | 88.70 | 7.66 | 51.73 | 7.55 | 36.44 | 7.17 |
| SUN02 | 50 | 6.73 | 1.38 | 11.66 | 5.09 | 12.89 | 5.22 | 12.83 | 12.37 | 5.52 | 8.73 |
| | 100 | 14.27 | 0.32 | 23.06 | 6.31 | 34.71 | 3.93 | 31.46 | 24.31 | 14.03 | 2.81 |
| | 150 | 24.24 | 2.43 | 32.12 | 5.50 | 51.48 | 9.37 | 46.11 | 14.51 | 23.83 | 18.13 |
| | 200 | 37.64 | 0.49 | 41.71 | 4.17 | 76.10 | 4.38 | 63.48 | 15.89 | 31.38 | 3.47 |
| SUN25 | 50 | 9.47 | 1.31 | 12.03 | 5.02 | 13.27 | 4.28 | 14.19 | 11.06 | 5.00 | 5.37 |
| | 100 | 23.76 | 0.62 | 30.52 | 5.55 | 48.02 | 3.29 | 43.15 | 7.82 | 16.62 | 4.33 |
| | 150 | 26.68 | 1.53 | 37.16 | 5.27 | 67.25 | 5.01 | 63.20 | 9.01 | 29.51 | 7.36 |
| | 200 | 43.78 | 2.16 | 50.01 | 5.26 | 82.58 | 4.99 | 84.61 | 7.37 | 39.21 | 5.53 |
| SUN4 | 50 | 5.91 | 2.24 | 3.14 | 5.37 | 6.35 | 9.29 | 10.73 | 6.82 | 7.38 | 10.96 |
| | 100 | 13.63 | 1.21 | 18.61 | 5.72 | 32.27 | 6.15 | 28.56 | 5.03 | 18.45 | 9.05 |
| | 150 | 24.02 | 2.83 | 28.21 | 5.97 | 42.50 | 9.21 | 52.40 | 6.99 | 27.34 | 17.47 |
| | 200 | 47.06 | 0.55 | 43.29 | 4.33 | 60.89 | 2.38 | 78.73 | 2.43 | 35.86 | 3.65 |
| SUN14 | 50 | 7.32 | 4.99 | 2.07 | 5.79 | 5.04 | 14.37 | 13.34 | 17.24 | 10.55 | 22.32 |
| | 100 | 21.52 | 2.84 | 16.61 | 6.35 | 34.89 | 12.87 | 54.01 | 10.95 | 26.89 | 17.07 |
| | 150 | 28.47 | 4.19 | 26.81 | 6.78 | 49.48 | 16.13 | 60.66 | 10.69 | 32.98 | 22.56 |
| | 200 | 44.60 | 1.31 | 48.40 | 5.20 | 57.58 | 3.49 | 80.15 | 3.91 | 42.30 | 4.35 |
| SUN38 | 50 | 11.21 | 0.86 | 12.96 | 4.12 | 10.93 | 3.02 | 7.52 | 2.33 | 6.84 | 2.42 |
| | 100 | 28.88 | 0.74 | 78.07 | 5.32 | 56.47 | 3.70 | 25.97 | 3.17 | 14.83 | 2.34 |
| | 150 | 32.29 | 3.30 | 85.87 | 4.69 | 67.76 | 2.75 | 42.59 | 2.41 | 24.44 | 7.93 |
| | 200 | 46.40 | 0.50 | 98.36 | 2.54 | 101.4 | 0.73 | 61.32 | 0.62 | 31.25 | 0.68 |
| SUN40 | 50 | 13.98 | 1.14 | 12.80 | 4.91 | 11.91 | 2.61 | 8.53 | 2.66 | 8.44 | 2.83 |
| | 100 | 35.09 | 1.13 | 68.39 | 6.27 | 48.32 | 3.81 | 28.76 | 3.11 | 20.63 | 3.23 |
| | 150 | 47.60 | 2.14 | 71.43 | 5.36 | 66.78 | 3.71 | 41.96 | 3.22 | 34.65 | 7.59 |
| | 200 | 65.86 | 3.03 | 88.89 | 3.96 | 85.59 | 4.27 | 69.71 | 4.89 | 47.94 | 2.81 |
| SUN32 | 50 | 9.11 | 2.50 | 7.81 | 5.58 | 8.54 | 6.48 | 7.83 | 4.56 | 7.05 | 7.29 |
| | 100 | 20.88 | 2.46 | 18.20 | 7.03 | 30.93 | 5.71 | 23.66 | 4.37 | 20.32 | 7.58 |
| | 150 | 33.45 | 3.29 | 42.17 | 7.71 | 46.69 | 6.49 | 36.60 | 4.92 | 30.26 | 13.16 |
| | 200 | 56.94 | 0.95 | 58.56 | 4.54 | 73.35 | 1.43 | 59.26 | 1.60 | 43.96 | 1.38 |
| SUN35 | 50 | 11.83 | 1.99 | 6.15 | 5.49 | 6.79 | 5.89 | 17.74 | 17.05 | 16.12 | 9.12 |
| | 100 | 29.57 | 2.64 | 26.12 | 5.96 | 46.33 | 6.13 | 56.32 | 20.25 | 31.47 | 15.09 |
| | 150 | 43.08 | 2.55 | 40.10 | 7.10 | 66.07 | 5.92 | 72.83 | 12.46 | 43.15 | 21.01 |
| | 200 | 63.35 | 1.90 | 57.84 | 5.65 | 79.18 | 2.97 | 90.67 | 14.42 | 62.21 | 5.21 |

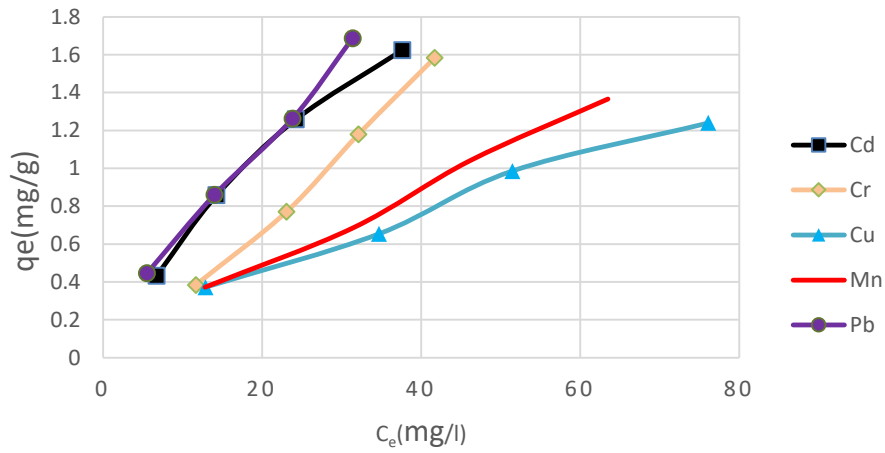
(a) SUN30



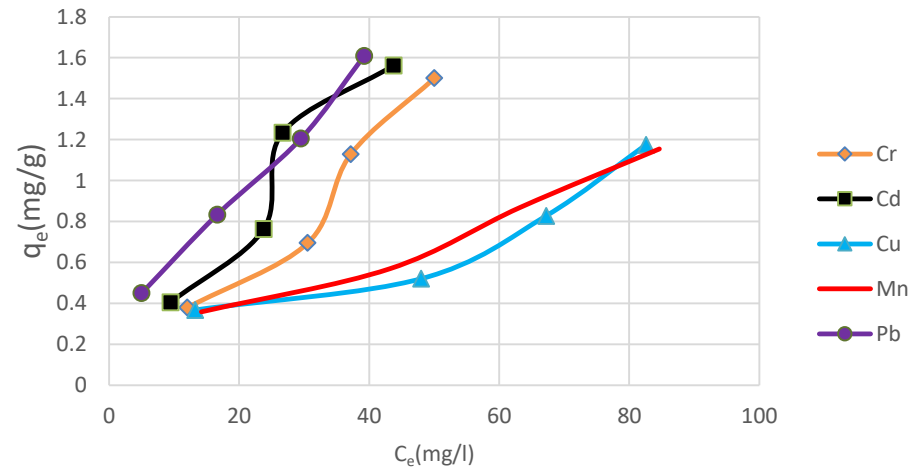
(b) SUN33



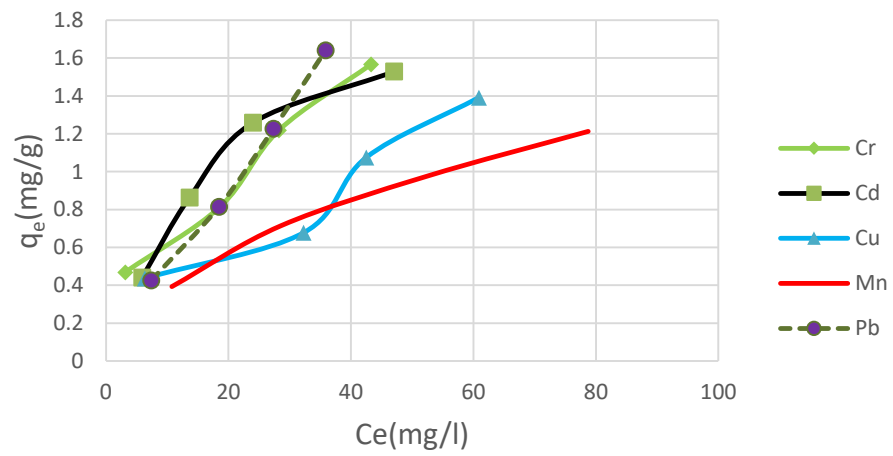
(c) SUN02



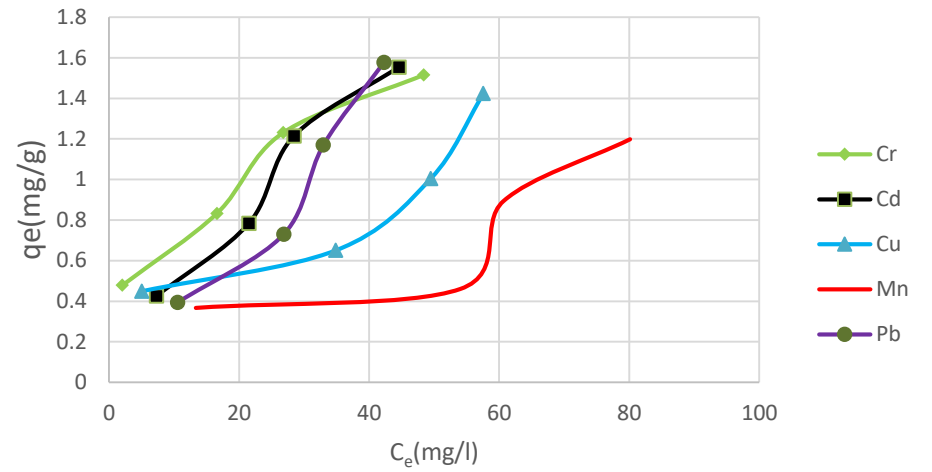
(d) SUN25



(e) SUN04



(f) SUN14



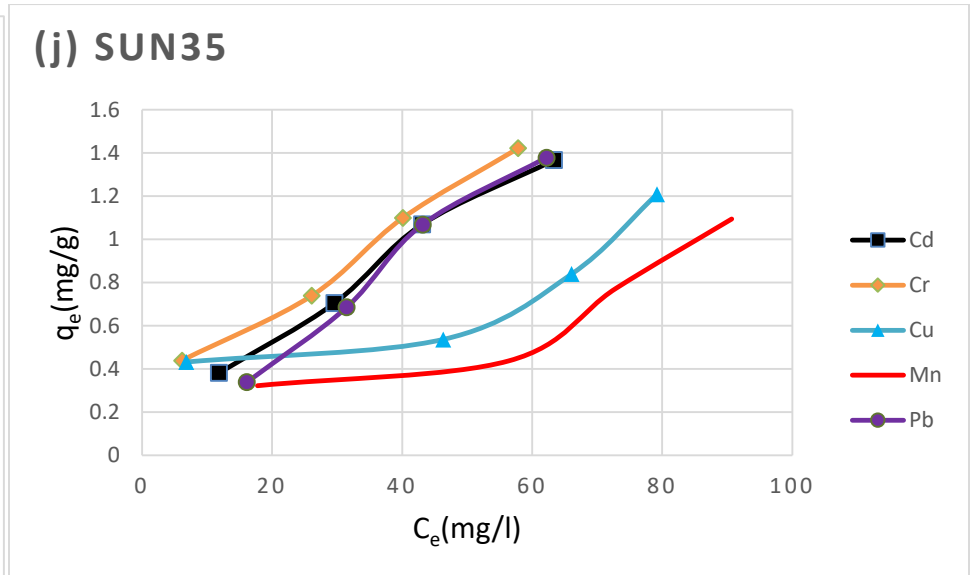
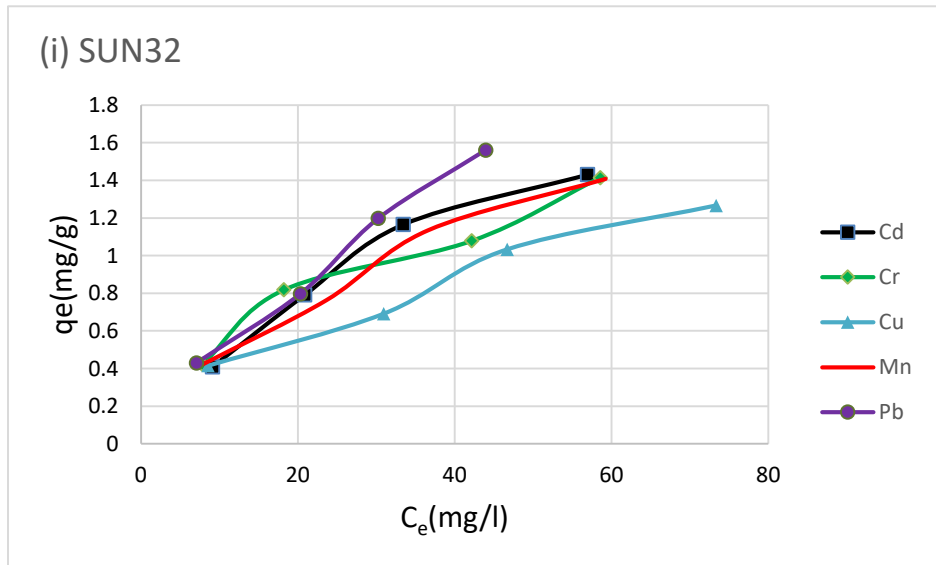
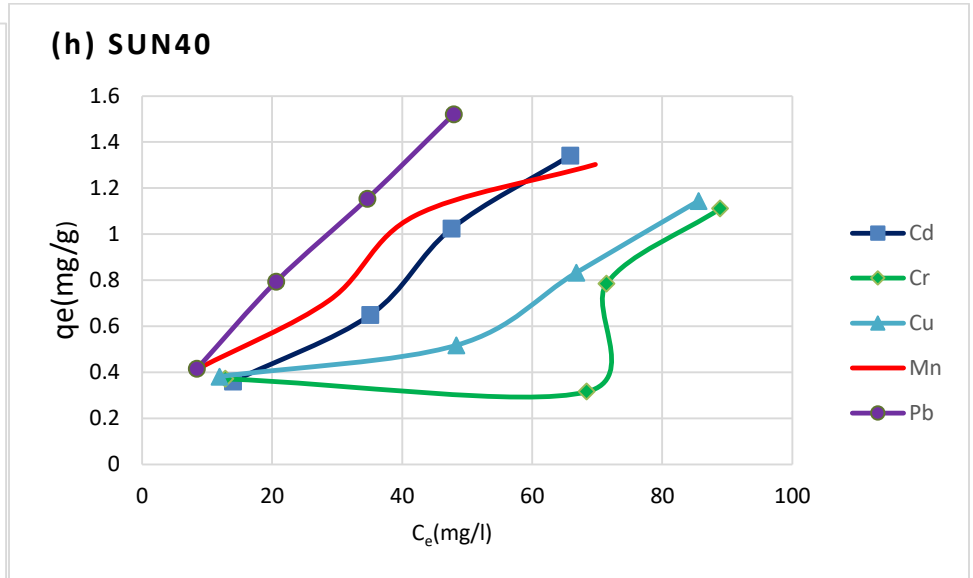
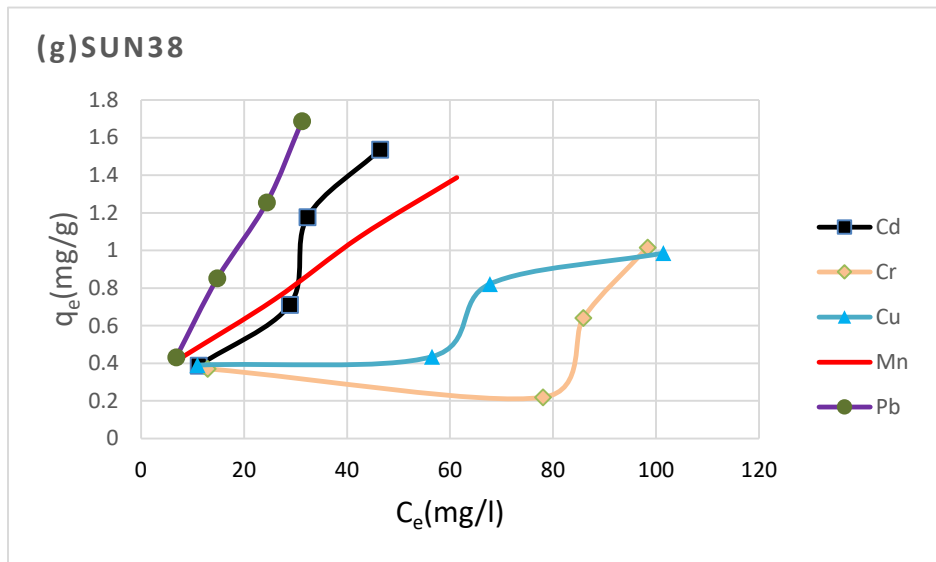


Figure 8.1. Adsorption Isotherms of the metals removed from solution per gram of soil

8.4 Maximum adsorption capacity

The data obtained from the batch equilibrium experiments were modelled using Freundlich and Langmuir isotherm equations. The Langmuir sorption isotherm is expressed using Equation 8.1 (Hamzoui *et al.*, 2018; Lu *et al.*, 2021):

$$\frac{1}{q_e} = \frac{1}{bq_m} \times \frac{1}{C_e} + \frac{1}{q_m} \quad (8.1)$$

Where, C_e (mg/l) and q_e (mg/g) denote the equilibrium concentrations of the adsorbate in the liquid and solid phases, respectively. The parameter q_m (mg/g) signifies the maximum adsorption capacity, while KL (Lm/g) represents the equilibrium constant for adsorption.

The Freundlich isotherm is expressed using Equation 8.2 (Lu *et al.*, 2021):

$$\ln q_e = \ln K_f + \frac{1}{n} \times \ln C_e \quad (8.2)$$

Where, K_f (mg/g) signifies the Freundlich constant associated with sorption capacity, while n denotes the heterogeneity factor. The maximum adsorption capacities and other isotherm parameters of the lateritic soils obtained by fitting the equations of Freundlich and Langmuir to the test results are presented in Table 8.4 while the corresponding plots with their linear regression values for the various metals for the lateritic soils are presented in Appendix 9. The values for goodness-of-fit (R^2) are generally greater than or equal to 0.7 in 97% of the lateritic soil samples tested. Interestingly, the goodness-of-fit indicates that the sorption of the trace elements is well described by both the Freundlich and Langmuir equations. This is consistent with findings of previous researchers (Chalermyanont *et al.*, 2009; Umeh *et al.*, 2019) on some tropical marine and lateritic soils. This is attributed to the complexity and heterogeneity of the sorption process as well as competitive interactions (Sparks, 2001; Violante *et al.*, 2010). The sorption constants determined from the Freundlich equation indicate that the sorption constant (k) values in the studied lateritic soils ranged from 0.018 to 0.22 (mg/kg) which implies good adsorption capacity. The value of k was the highest in SUN25 and the lowest in SUN35. The heterogeneity factor ($\frac{1}{n}$), a function of the strength of adsorption generally ranges from zero to one for all the sampled lateritic soils tested, thus indicating heterogenous surface, favourable, and normal adsorption.

Table 8.4. Sorption isotherm parameters identified for the heavy metals used in the lateritic soils sorption tests.

| Langmuir Parameters | | | | | | | | | | | | | | | |
|-----------------------|------------------|----------------|----------------|------------------|----------------|----------------|------------------|----------------|----------------|------------------|----------------|----------------|------------------|----------------|----------------|
| | Cd | | | Cr | | | Cu | | | Mn | | | Pb | | |
| | q _{max} | K _l | R ² | q _{max} | K _l | R ² | q _{max} | K _l | R ² | q _{max} | K _l | R ² | q _{max} | K _l | R ² |
| SUN30 | 5.539 | 0.009 | 0.990 | 2.493 | 0.030 | 0.954 | 1.128 | 0.070 | 0.832 | 1.870 | 0.026 | 0.772 | 3.841 | 0.018 | 0.995 |
| SUN33 | 3.699 | 0.018 | 0.995 | 2.250 | 0.029 | 0.920 | 0.892 | 0.082 | 0.693 | 2.768 | 0.020 | 0.995 | 3.373 | 0.023 | 0.983 |
| SUN02 | 4.541 | 0.016 | 0.999 | 8.411 | 0.004 | 0.999 | 1.919 | 0.018 | 0.977 | 3.027 | 0.011 | 0.986 | 3.095 | 0.030 | 0.993 |
| SUN25 | 6.156 | 0.007 | 0.960 | 5.330 | 0.006 | 0.957 | 1.100 | 0.036 | 0.813 | 1.374 | 0.024 | 0.925 | 1.884 | 0.062 | 0.974 |
| SUN04 | 2.721 | 0.033 | 0.997 | 1.392 | 0.159 | 0.918 | 1.247 | 0.083 | 0.858 | 1.636 | 0.029 | 0.997 | 3.929 | 0.016 | 0.987 |
| SUN14 | 2.494 | 0.028 | 0.968 | 1.290 | 0.281 | 0.918 | 1.086 | 0.138 | 0.780 | 1.025 | 0.040 | 0.650 | 6.009 | 0.007 | 0.958 |
| SUN38 | 6.300 | 0.006 | 0.945 | 0.441 | 0.350 | 0.018 | 0.778 | 0.088 | 0.536 | 1.547 | 0.049 | 0.961 | 6.280 | 0.011 | 0.998 |
| SUN40 | 3.146 | 0.009 | 0.972 | 0.640 | 0.104 | 0.200 | 1.000 | 0.050 | 0.775 | 1.546 | 0.042 | 0.958 | 2.871 | 0.020 | 0.996 |
| SUN32 | 3.045 | 0.017 | 0.998 | 2.016 | 0.034 | 0.991 | 1.381 | 0.049 | 0.946 | 1.866 | 0.037 | 0.980 | 2.379 | 0.031 | 0.979 |
| SUN35 | 2.775 | 0.013 | 0.987 | 1.404 | 0.072 | 0.929 | 0.871 | 0.141 | 0.642 | 1.122 | 0.022 | 0.772 | 0.766 | 0.003 | 0.997 |
| Freundlich Parameters | | | | | | | | | | | | | | | |
| | 1/n | k _f | R ² | 1/n | k _f | R ² | 1/n | k _f | R ² | 1/n | k _f | R ² | 1/n | K _f | R ² |
| SUN30 | 0.880 | 0.059 | 0.987 | 0.757 | 0.095 | 0.939 | 0.471 | 0.144 | 0.853 | 0.656 | 0.084 | 0.985 | 0.746 | 0.104 | 0.976 |
| SUN33 | 0.784 | 0.092 | 0.995 | 0.751 | 0.085 | 0.894 | 0.402 | 0.149 | 0.744 | 0.732 | 0.083 | 0.999 | 0.779 | 0.101 | 0.980 |
| SUN02 | 0.773 | 0.103 | 0.991 | 1.115 | 0.024 | 0.998 | 0.689 | 0.062 | 0.986 | 0.814 | 0.045 | 0.990 | 0.751 | 0.121 | 0.996 |
| SUN25 | 0.901 | 0.053 | 0.933 | 0.949 | 0.034 | 0.941 | 0.564 | 0.078 | 0.821 | 0.633 | 0.062 | 0.941 | 0.598 | 0.166 | 0.985 |
| SUN04 | 0.611 | 0.162 | 0.959 | 0.444 | 0.267 | 0.943 | 0.478 | 0.169 | 0.870 | 0.565 | 0.104 | 0.998 | 0.841 | 0.076 | 0.989 |
| SUN14 | 0.727 | 0.097 | 0.969 | 0.361 | 0.353 | 0.957 | 0.390 | 0.224 | 0.765 | 0.561 | 0.079 | 0.658 | 0.965 | 0.038 | 0.938 |
| SUN38 | 0.958 | 0.036 | 0.918 | 0.242 | 0.182 | 0.121 | 0.370 | 0.149 | 0.624 | 0.556 | 0.133 | 0.983 | 0.877 | 0.080 | 0.997 |
| SUN40 | 0.850 | 0.036 | 0.972 | 0.371 | 0.134 | 0.308 | 0.497 | 0.102 | 0.801 | 0.559 | 0.122 | 0.972 | 0.740 | 0.085 | 0.999 |
| SUN32 | 0.702 | 0.091 | 0.981 | 0.565 | 0.140 | 0.970 | 0.524 | 0.130 | 0.970 | 0.609 | 0.119 | 0.990 | 0.707 | 0.104 | 0.987 |
| SUN35 | 0.773 | 0.055 | 0.991 | 0.510 | 0.165 | 0.953 | 0.333 | 0.211 | 0.672 | 0.669 | 0.043 | 0.780 | 1.068 | 0.018 | 0.991 |

k_l = Langmuir constant, q_{max} = maximum sorbed mass per unit soil mass. 1/n = Freundlich constant, K_f = Freundlich sorption constant.

R² = Goodness-of-fit.

It also implies that the amount of metal adsorbed increased more rapidly than its concentration in soil solution. However, the value of $\frac{1}{n}$, exceeded 1 in only one sample (SH) implying a cooperative adsorption, in which an adsorbate that has already been adsorbed impacts and affects the adsorption of free adsorbates (Gosh and Dash, 2012; Nandiyantoa *et al.*, 2020). In all, the maximum adsorption capacity of the lateritic soils tested is within the range of those obtained by Chalermyanont *et al.* (2009) on some lateritic soils from Thailand. However, they are generally lower than those obtained from tropical soils from Brazil and Nigeria studied by Fontes and Gomes (2003) and Umeh *et al.* (2019) respectively. This could be linked to the acidic nature of the soils under consideration and the competitive nature of the sorption system (Shaheen *et al.*, 2013). Furthermore, the presence of relatively high amount of clay mineral types in these soils have very important role in retaining heavy metals (Sparks, 2001; Yong and Mulligan, 2019; Ugwu and Igbokwe, 2018). However, according to Shaheen *et al.* (2013), clay minerals including montmorillonite, amorphous allophanes, and vermiculite have the greatest sorption capacity compared to kaolinite and dickite of the kandite group of clay minerals. Accordingly, the relatively low sorption capacity exhibited by the lateritic soils under investigation in southwestern Nigeria may be attributed to the predominance of kaolinite and dickite (Table 8.5).

Table 8.5. Mineralogical composition of the lateritic soils.

| Sample ID | Mineral composition (%) | | | | | | | |
|-----------|-------------------------|--------|---------|----------|----------|--------|-----------|------------|
| | Kaolinite | Quartz | Dickite | Goethite | Hematite | Rutile | Muscovite | Microcline |
| SUN30 | 53 | 5 | 27 | 5 | <1 | <1 | 2 | 6 |
| SUN33 | 35 | 6 | 45 | 4.4 | 2 | <1 | 3.5 | 4 |
| SUN02 | 42 | 8 | 30 | 12 | <1 | 1 | 6 | 1 |
| SUN25 | 35.5 | 9 | 50 | 3 | 3 | <1 | 2 | 1 |
| SUN04 | 31 | 17 | 36 | 6 | 1.5 | <1 | 5 | 2 |
| SUN14 | 31 | 3 | 41 | 8 | 1 | <1 | 8 | 5 |
| SUN38 | 37 | 27 | 25 | 5 | <1 | 0 | 3 | <1 |
| SUN40 | 40 | 10 | 42 | 2 | 1 | <1 | 4 | 1 |
| SUN32 | 41 | 7 | 40.5 | 4.5 | 3 | 0 | 3 | 1 |
| SUN35 | 36 | 9 | 43 | 2 | <1 | <1 | 8 | 1 |

8.5 Sorption selectivity sequence

Although the Freundlich equation is widely used to draw conclusions about sorption mechanisms, its shortcoming is that it cannot predict the maximum sorption (Sparks, 2001; Covelo *et al.*, 2008). Thus, the maximum adsorption capacities derived from Langmuir equation were utilized for comparing the relative adsorption capacities of the studied lateritic soils. The adsorption capacity of the lateritic soils depends on the specific heavy metal species tested. Accordingly, the adsorption rankings generated from the maximum adsorption capacities are illustrated in Figure 8.2. The selectivity sequence for the lateritic soils derived from charnockite, porphyritic granite and granite-gneiss are $Cd > Pb > Cr > Mn > Cu$; $Pb > Cd > Mn > Cr > Cu$, and $Cd > Cr > Pb > Mn > Cu$ respectively. Furthermore, the selectivity sequence observed in the lateritic soils derived from migmatite, schist and quartzites are $Cd > Pb > Mn > Cu > Cr$, $Cd > Cr > Mn > Cu > Pb$ and $Cd > Pb > Cr > Mn > Cu$ respectively. All the soils showed poor capacity to sorb copper while they have the best adsorption capability for Cd as shown in Figure 8.2. The poor sorption capacity for copper can be linked to the acidic nature of the lateritic soils (Shaheen *et al.*, 2013; Djebbar and Djafri, 2016). Additionally, the poor sorption capacity of acidic soils for copper can be attributed to the formation of ion structure upon aqutation (Farrah and Pickering, 1977). Moreover, it is worth noting that the elements with the higher ionic radii (Cd and Pb) were the most sorbed in the lateritic soils. This observation aligns with Shaheen *et al.* (2013) that sorption selectivity sequence of metals is closely linked to their ionic radii. Furthermore, the high sorption affinity for Cd and Pb exhibited by the lateritic soils can be attributed to their mineralogical composition as a mixture of goethite and kaolinite are good sorbents for lead and cadmium (Unuabonah *et al.*, 2016; Ugwu and Igbokwe, 2018; Jabin *et al.*, 2021). However, the granite-gneiss derived lateritic soils presented a higher affinity towards chromium, which has a smaller ionic radius, than lead and cadmium. This anomaly may be due to the higher valence of chromium (Smith and McGrath, 1990; Nithya *et al.*, 2015).

Additionally, the results indicate that the lateritic soils differed significantly in their maximum adsorption capacity for heavy metals, implying that they may have different buffering capacities for these contaminants. Also, it is evident from Figure 8.2 that the lateritic soils derived from granite-gneiss and charnockites exhibit better sorption potential while those derived from schist, quartzite and migmatite (SUN14) showed poor sorption capacity for the metals considered. This is attributed to the goethite content of the sampled lateritic soils (Table 8.4). Thus, the soils derived

from granite-gneiss and charnockite could probably receive and retain higher heavy metal loadings indicating that they are optimal candidates for landfill liner applications. As a result of the low maximum adsorption capacity values, the lateritic soils derived from schist (SUN35), quartzite (SUN32) and migmatite (SUN14) will attain their critical load more easily and become more vulnerable to heavy metal inputs. Therefore, it is expedient to consider this soil characteristic during the planning stage of the location of landfills.

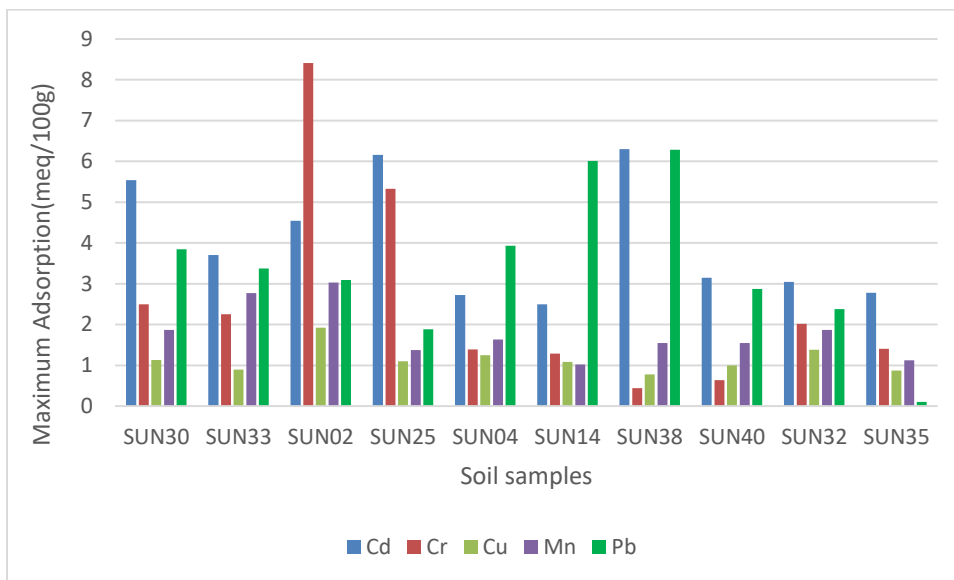


Figure 8.2. Plot of the maximum adsorption capacity of the lateritic soil samples for each trace metal.

8.6 Desorption characteristics of trace metals sorbed onto the lateritic soils

The desorption of trace metals from the adsorbed phase onto the lateritic soil samples were also investigated to understand the reversibility of the sorption process. The results of the desorption of trace metals from the lateritic soil samples revealed that the amount of metals desorbed consistently increased in proportion to the adsorbed quantity (Figure 8.3), which depicts the expected relationship between the quantity of adsorbed heavy metals and the relative amount that would desorb. Additionally, the amount of metals desorbed in the soils increased correspondingly with the increase in initial concentration of the heavy metals in the stock solution used for the sorption test. At lower initial heavy metal concentrations, there were only a relatively small amount

of high-energy sites on the solid surface that could be initially occupied. Consequently, preferential adsorption at the available high-energy spots of these soil particles successive desorption appears to become low. On the other hand, when the initial stock solution had higher metal concentrations, the limited available high-energy sites became saturated. This led to the occurrence of adsorption at lower energy sites as well, making the overall desorption to increase (Feng *et al.*, 2013; Song *et al.*, 2016). Furthermore, the amount of the metals desorbed were significantly less than the amount adsorbed in most of the lateritic soils. This indicates that the desorption of the metals from the soil samples was not complete and hence partially reversibility. These results agree well with observations reported in previous works (Zhao *et al.*, 2014; Borggaard *et al.*, 2019; Lu *et al.*, 2021). Additionally, the adsorption isotherm was generally displaced to the left as shown in Figures 8.3 compared to desorption, where there appears to be quite distinct differences between the sorption and desorption isotherms and that the reversibility of the sorption considerably varied among the lateritic soils. The extent of reversibility of the sorption is measured by using the hysteresis index presented in Table 8.6.

The hysteresis index HI is defined as:

$$HI = \frac{n_{desorb}}{n_{sorb}} \quad (8.3)$$

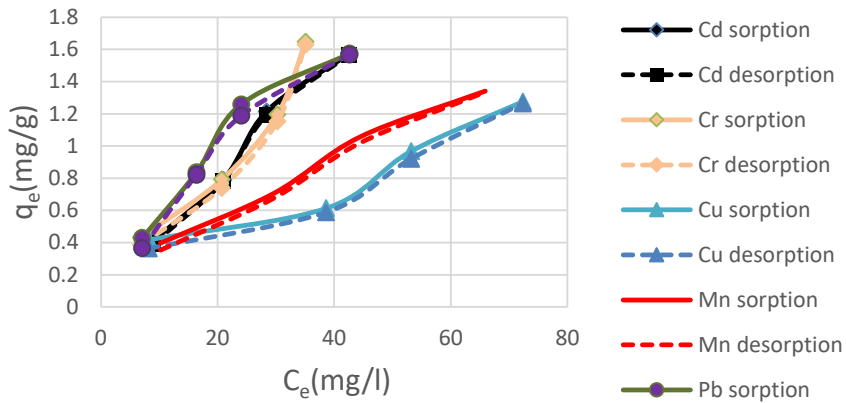
Where n_{desorb} and n_{sorb} are the exponents of fitted Freundlich equation of desorption and sorption respectively. A lower value of hysteresis index indicates an increased difficulty of the sorbed metal to desorb from the soil (Hamidpour *et al.*, 2010).

The desorption isotherms fit the Freundlich isotherm for all the trace metals in all the soils tested with regression coefficients that ranged from 0.61 to 0.997 (Table 8.7). The isotherm parameter n is greater than 1 in 92% of the tested soils, indicating a non-linear relationship between the heavy metal concentration in the initial solution and the desorption in the soils. This behaviour is associated with favourable desorption conditions, where the metal is less strongly bonded to the adsorbent. Furthermore, the Freundlich isotherm constant (K_f) for desorption were generally lower than those obtained for adsorption indicating that the metals desorbed more easily from the soils, which is also explained by the slight shifts in the plots between the sorption and desorption isotherm (Figures 8.3). The desorption curves of heavy metals from the lateritic soils exhibit varying degree of deviation from the respective adsorption curves, which is indicative of various extents of adsorption reversibility. Generally, n_{ads} (the exponent in the fitted Freundlich sorption equation) is greater than n_{des} (the exponent in the fitted Freundlich desorption equation) which

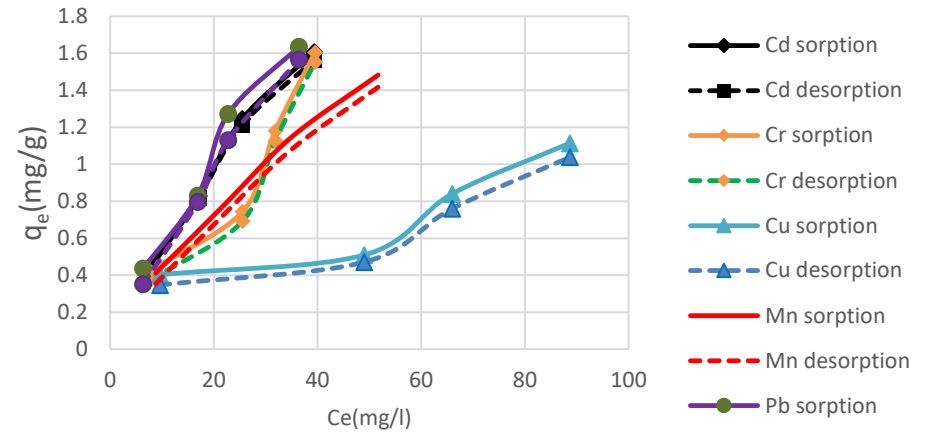
indicates a positive or normal hysteresis and suggests that a portion of the adsorbed metals were strongly bonded to the mineral soil surfaces and not readily desorbable.

A high HI value indicate easy reversibility while a low HI value signifies a low desorption metal from the adsorbent. The desorption isotherms of the lateritic soils diverge from the equivalent adsorption curves to varying degrees which is suggestive of various extents of adsorption reversibility. The hysteresis indices of the lateritic soils (Table 8.6) are very high and close to unity indicating a high reversibility of the sorption, hence high desorbability of these heavy metals on the lateritic soils. The order of desorption of the metals as shown in Table 8.6 indicates that Cd was consistently the most desorbed metal form all the soil samples, while Mn, Pb and Cu were the least in that order. Therefore, though a number of other lateritic soil information are to be considered, high HI values for Cd and Cr in most of the soils appear to imply that these trace toxic metals may have the potential to be released to the environment if relatively permeable compacted lateritic soil liners are used. Thus, careful design consideration should be taken into account if these soils are used in liner applications. As such, landfill liners utilizing these lateritic soils should be designed as a composite containment facility by integrating compacted soil liners, leachate collection systems and monitoring networks to ensure effective environmental protection. On the other hand, the higher tendency of the studied lateritic soils to retain Pb relatively well could be attributed to the high iron oxide and kaolinite content of the sampled soils (Yavuz *et al.*, 2003; Illera *et al.*, 2004; Covelo *et al.*, 2007). The variations in the degree of desorption (Table 8.6) suggest that these metals compete for strong binding sites on clay minerals and iron oxides. Furthermore, the high trace metals' HI values observed for the lateritic soils derived from migmatite parent rocks appear to be controlled by the low Fe oxide and high amount of silica content of these particular soil samples.

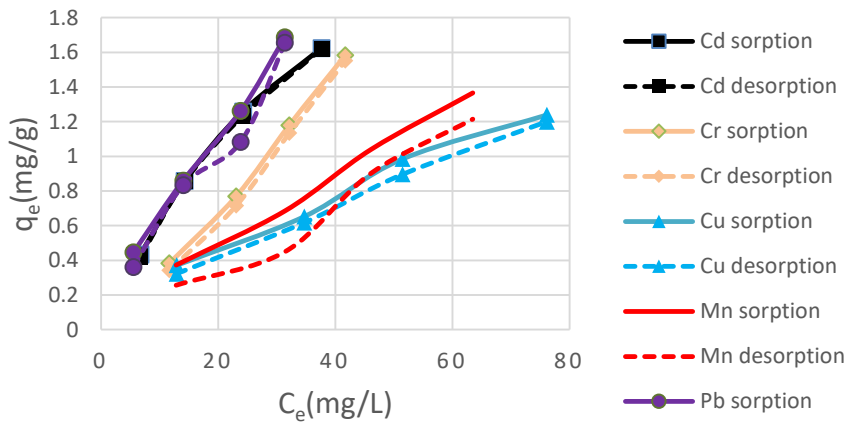
(a) SUN30



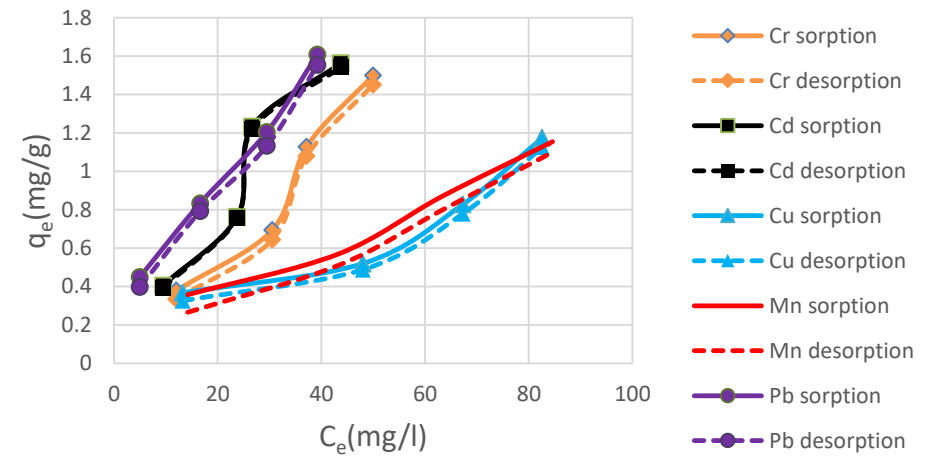
(b) SUN33



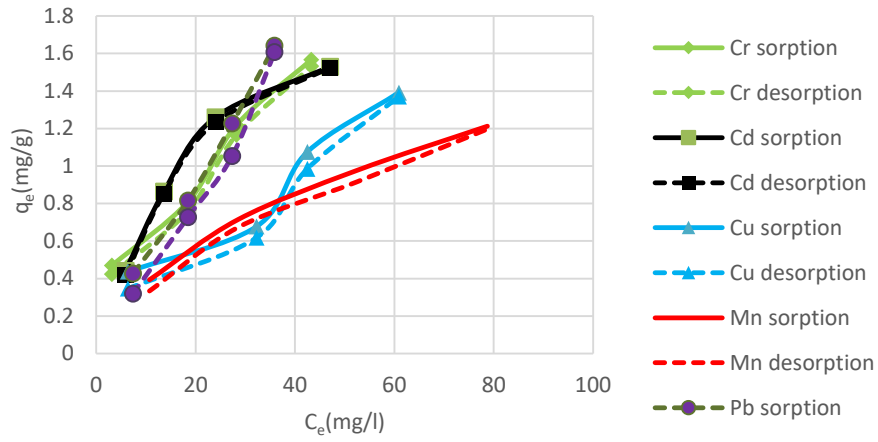
(c) SUN02



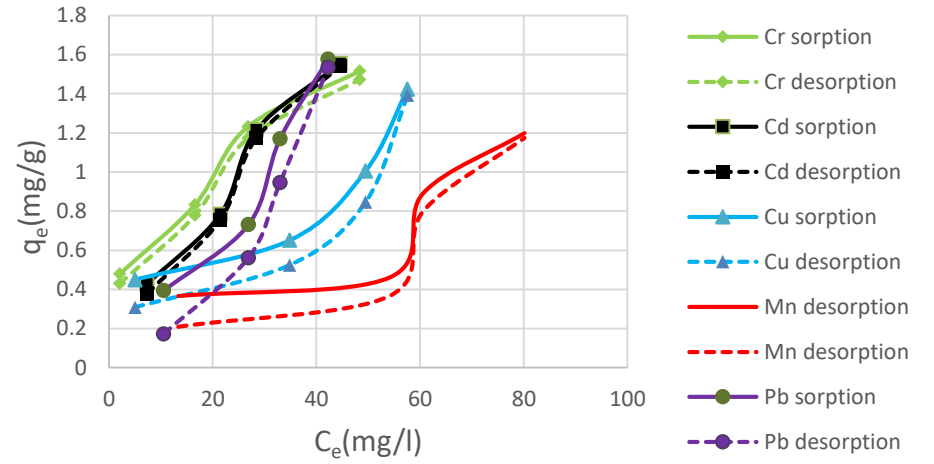
(d) SUN25



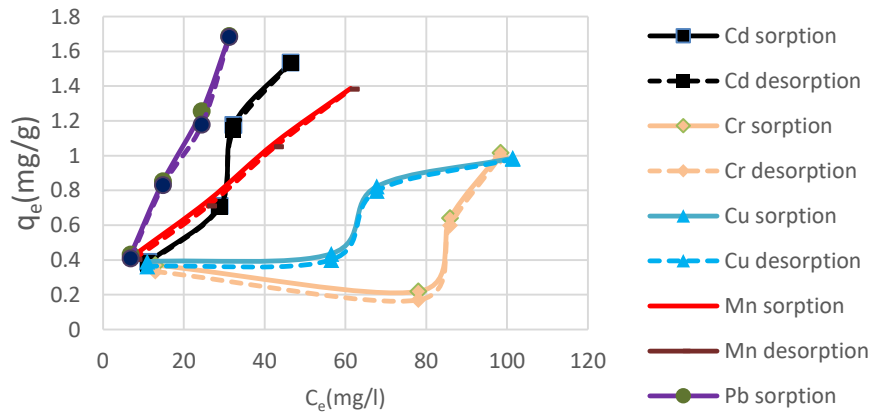
(e) SUN04



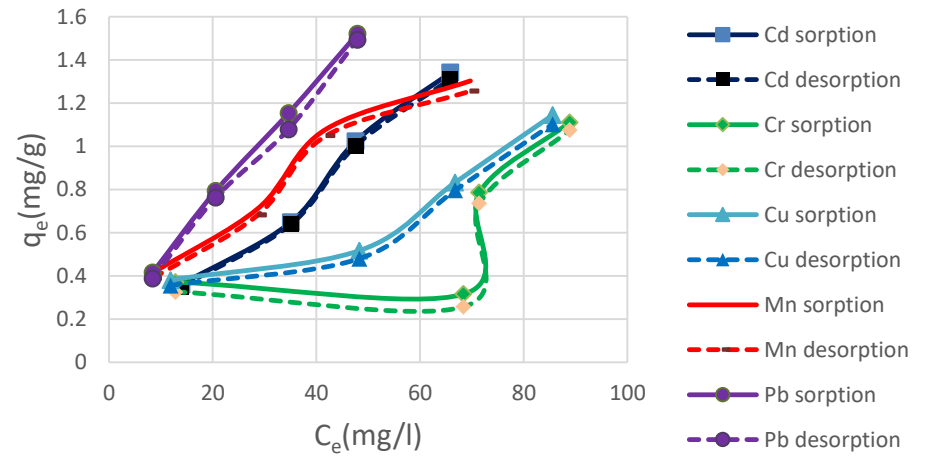
(f) SUN14



(g) SUN38



(h) SUN40



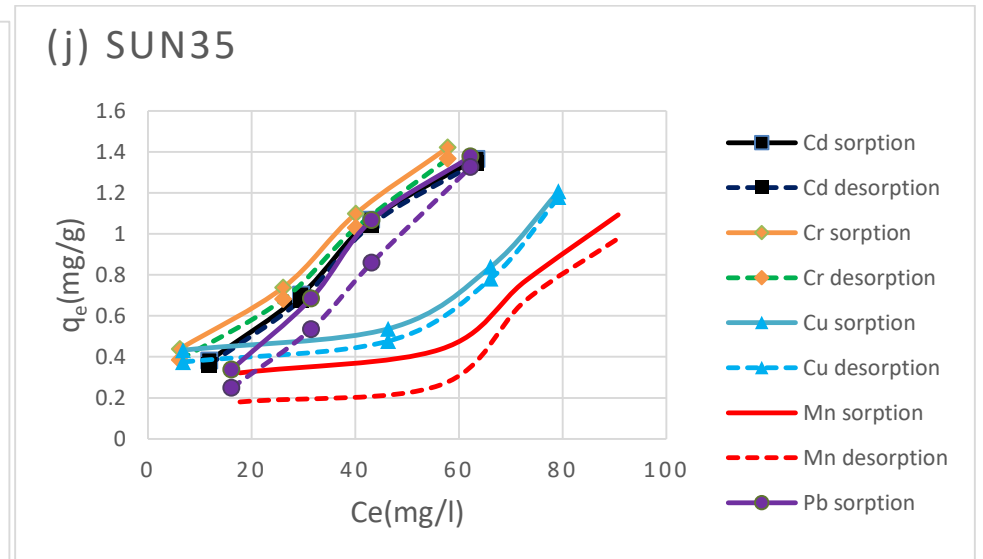
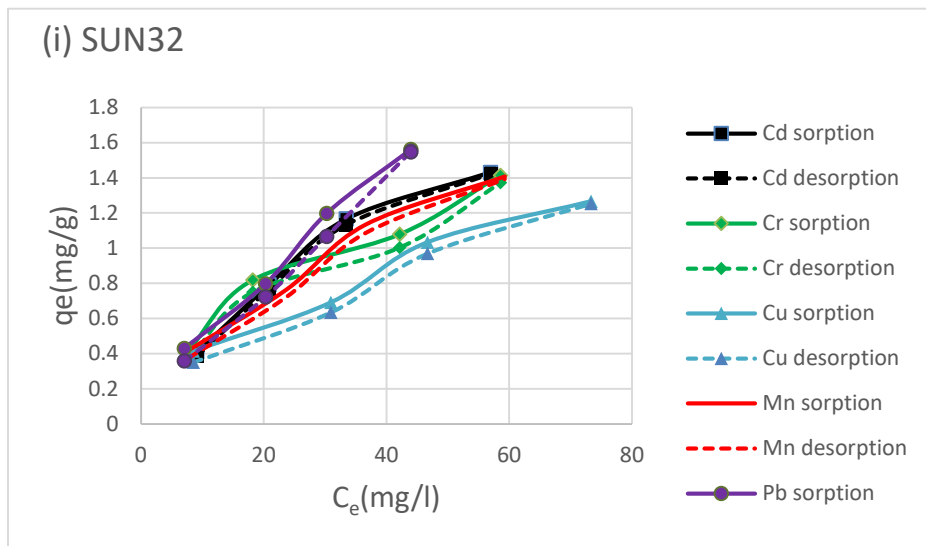


Figure 8.3. Desorption Isotherms (dashed lines) of the metals

Table 8.6. Hysteresis index (HI) of selected trace metals tested using the lateritic soil samples.

| | Cd | Cr | Mn | Cu | Pb | Ranking of the metals by HI |
|-------|-------|-------|-------|-------|-------|-----------------------------|
| SUN30 | 0.971 | 0.932 | 0.894 | 0.915 | 0.901 | Cd > Cr > Cu > Pb > Mn |
| SUN33 | 0.986 | 0.930 | 0.923 | 0.926 | 0.894 | Cd > Cr > Cu > Mn > Pb |
| SUN02 | 0.984 | 0.938 | 0.930 | 0.824 | 0.903 | Cd > Cr > Mn > Pb > Cu |
| SUN25 | 0.986 | 0.933 | 0.934 | 0.819 | 0.938 | Cd > Cr > Mn > Cu > Pb |
| SUN04 | 0.967 | 0.939 | 0.843 | 0.891 | 0.849 | Cd > Cr ≥ Cu > Pb > Mn |
| SUN14 | 0.919 | 0.937 | 0.770 | 0.658 | 0.630 | Cr > Cd > Mn > Cu > Pb |
| SUN38 | 0.990 | 0.981 | 0.937 | 0.962 | 0.979 | Cd > Cr > Pb > Cu > Mn |
| SUN40 | 0.993 | 0.939 | 0.974 | 0.975 | 0.974 | Cd > Cu > Pb = Mn > Cr |
| SUN32 | 0.960 | 0.925 | 0.883 | 0.927 | 0.896 | Cd > Cu > Cr > Pb > Mn |
| SUN35 | 0.971 | 0.931 | 0.898 | 0.705 | 0.854 | Cd > Cr > Mn > Pb > Cu |

Table 8.7. Freundlich desorption isotherm parameters of heavy metals in the lateritic soils.

| Sample ID | Cd | | | Cr | | | Mn | | | Cu | | | Pb | | |
|-----------|-------|-------|----------------|-------|-------|----------------|-------|-------|----------------|-------|-------|----------------|-------|-------|----------------|
| | kf | n | R ² | kf | n | R ² | kf | n | R ² | kf | n | R ² | kf | n | R ² |
| SUN30 | 0.053 | 1.103 | 0.990 | 0.076 | 1.230 | 0.937 | 1.111 | 1.897 | 0.853 | 0.065 | 1.394 | 0.990 | 0.077 | 1.208 | 0.978 |
| SUN33 | 0.087 | 1.257 | 0.995 | 0.067 | 1.238 | 0.902 | 0.119 | 2.293 | 0.783 | 0.064 | 1.265 | 0.999 | 0.070 | 1.147 | 0.996 |
| SUN02 | 0.098 | 1.272 | 0.990 | 0.018 | 0.841 | 0.997 | 0.047 | 1.349 | 0.995 | 0.019 | 1.012 | 0.950 | 0.088 | 1.202 | 0.981 |
| SUN25 | 0.050 | 1.094 | 0.936 | 0.025 | 0.983 | 0.943 | 1.063 | 1.655 | 0.842 | 0.032 | 1.294 | 0.968 | 0.139 | 1.569 | 0.988 |
| SUN04 | 0.149 | 1.584 | 0.960 | 0.233 | 2.115 | 0.945 | 1.113 | 1.762 | 0.900 | 0.076 | 1.577 | 0.995 | 0.043 | 1.009 | 0.989 |
| SUN14 | 0.076 | 1.165 | 0.978 | 0.310 | 2.592 | 0.957 | 1.126 | 1.976 | 0.783 | 0.021 | 1.173 | 0.775 | 0.004 | 0.653 | 0.979 |
| SUN38 | 0.035 | 1.033 | 0.923 | 0.160 | 4.049 | 0.096 | 0.129 | 2.532 | 0.611 | 0.120 | 1.730 | 0.983 | 0.073 | 1.116 | 0.991 |
| SUN40 | 0.035 | 1.169 | 0.974 | 0.109 | 2.530 | 0.277 | 0.092 | 1.958 | 0.791 | 1.111 | 1.744 | 0.980 | 0.076 | 1.316 | 0.997 |
| SUN32 | 0.080 | 1.367 | 0.983 | 0.112 | 1.635 | 0.968 | 0.094 | 1.685 | 0.976 | 1.096 | 1.521 | 0.992 | 0.074 | 1.268 | 0.988 |
| SUN35 | 0.049 | 1.256 | 0.990 | 0.135 | 1.827 | 0.956 | 1.169 | 2.697 | 0.670 | 0.010 | 1.054 | 0.760 | 0.008 | 0.800 | 0.998 |

n = the exponent of fitted Freundlich equation of desorption, K_f = Freundlich desorption constant. R² = Goodness-of-fit

8.7 Summary

The contaminant attenuation characteristic of lateritic soils in the study area is described with particular focus on exploring the sorption and desorption behavior of selected heavy metals (Cu, Cd, Pb, Mn, Cr) when interacting with lateritic soils in the context of their use as landfill liners. Furthermore, the process of sorption and desorption of heavy metals and their eventual release into the surrounding environment are discussed and presented. Understanding the capacity of lateritic soils to effectively retain heavy metals and potentially serve as liner materials so as to prevent the migration of leachates into environments is crucial as these soils are ubiquitous in tropical regions including southwestern Nigeria. The batch equilibrium sorption analysis showed that the lateritic soils derived from granite-gneiss and charnockite exhibit better sorption potential than those derived from schist and quartzite as indicated by their maximum adsorption capacity which is closely related to the goethite content in the soils. The sorption isotherms of the selected trace metals onto the lateritic soils are well described by the Langmuir equation and these isotherms deviate from the corresponding desorption isotherms to different degrees which is indicative of various extents of hysteresis. The sorption hysteresis indices for these trace metals range from 0.63 to 0.99. It appears that these trace metals may be re-released and leached to the surrounding soils and groundwater unless additional engineering interventions, including leachate collection systems are provided.

CHAPTER NINE

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The focus of this thesis was to explore the potential use of locally available lateritic soils as cost-effective landfill liner material in Ekiti State, southwestern Nigeria. The desirable geotechnical, mineralogical and geochemical properties of the lateritic soils with a special focus on the influence of geology on these desirable properties is investigated. As such, petrographic, geochemical, mineralogical, index and geotechnical studies have been undertaken to characterize and analyze the lateritic soils from Ekiti state, in southwestern Nigeria. The study revealed that the main parent rocks of the lateritic soils in the study area are migmatite, quartzite, schist, porphyritic granite and charnockite. Petrographic and geochemical investigation shows that the parent rocks are not appreciably different from one another in terms of the mineral composition observed. The rocks are dominantly quartzo-feldspathic with modest occurrence of mafic minerals mainly biotite, hornblende and pyroxene. The geochemical analysis indicates that the major oxide compositions of the rocks are dominated by SiO_2 , Al_2O_3 and Fe_2O_3 , while the oxides with lower abundance include TiO_2 , Na_2O , MgO , CaO and K_2O . Additionally, the plot of the modified alkali lime index versus SiO_2 classified the rocks into calcic-alkali and alkali-calcic and reveals the alkali character of the parent rocks. The plotting of the rocks in the AFM diagram reveals that rocks are calc-alkaline and tholeiitic indicating a mixed source of magma, thus suggesting that the rocks may have originated not only from calc-alkaline environments of the oceanic crust but also from subduction tectonic environment.

The lateritic soils developed from the different parent rocks are well graded comprising cohesive and cohesionless fractions in various quantities. The lateritic soils are classified as inorganic clays and silts with low, medium to high plasticity. Furthermore, the lateritic soils demonstrated good compaction characteristics with the granite-gneiss derived soils having the highest MDD at a low OMC. However, at the standard proctor energy level, the average MDD of the lateritic soils derived from charnockite and porphyritic granite fell short of the minimum considered for landfill liners. However, the soils derived from the various parent materials conform to this requirement at higher compactive effort (West African energy level). The average values of the UCS of the lateritic soils

are higher than the minimum recommended value for liner applications. This is desirable for soils designated for landfill liner applications, which must withstand compressive stresses imposed upon them by the waste materials. The total shear strength parameters indicate that the average values of the total cohesion of the soils derived from porphyritic granite, charnockite, migmatite, granite-gneiss and quartzite are 45.6 kPa, 44.7 kPa, 40.3 kPa, 42.7 kPa and 35.2 kPa, respectively. The average total angle of internal friction obtained for the lateritic soils derived from porphyritic granite, charnockite, migmatite, granite-gneiss and quartzite friction are 10.8°, 10.9°, 11.3°, 11.1° and 9.6°, respectively. Thus, the lateritic soils derived from the various parent rocks presented average total shear strength parameters that are greater than the minimum specified for landfill liners. The soils exhibit low permeability characteristics, which is desirable for soils designated for landfill liners. However, a slightly lower hydraulic conductivity was observed when compacted at the West African energy of compaction. Generally, the soils reflected subtle differences in their geotechnical properties, which is attributed to the similarities in the mineralogical composition of the parent materials. Comparatively, the soils derived from the different rock types fulfill the recommendations for index and shear strength properties while the soils derived from porphyritic granite and charnockite fail to meet the requirements for the maximum dry density when used as compacted soil liners. However, the average coefficients of permeability of the lateritic soils are higher than the specified maximum of 10^{-9} m/s, regardless of the parent rock. The soils having marginally higher hydraulic conductivities were mixed at various proportions including 1:10, 2:10, 3:10 and 4:10 by weight of the two soils (SUN33 and SUN 40) that have lower coefficient of permeability resulted in a notable reduction in the hydraulic conductivity of the soils. The reduction in the measured hydraulic conductivity of the lateritic soils derived from porphyritic granite, granite-gneiss and quartzite fail to satisfy the required maximum of 1×10^{-9} m/s specified by USEPA (2021). On the other hand, the measured hydraulic conductivity of the lateritic soils derived from charnockite and migmatite conform to the specification when mixed with soils of lower hydraulic conductivity in the ratio of 1:10.

The results of geochemical analysis indicate that iron and manganese oxides, which are crucial for the retention of heavy metals, are present in all of the lateritic soil samples investigated. Additionally, the low concentration of sodium oxide in the lateritic soils indicates that they may be favourably utilized as landfill liners as they would not be prone to soil particle dispersion, which can be detrimental to compacted soil liners. The XRD analysis results show that the lateritic soils

are dominated by clay minerals of the kandite group (kaolinite and dickite) and non-clay mineral phases of quartz, muscovite and goethite. As a result, these lateritic soils are unlikely to present a risk of desiccation cracking and high shrink-swell behavior when utilized as compacted liner in landfills. All the soils have pH (average, 4.5) and cation exchange capacity (average, 12.9) indicating their capacity for contaminant attenuation.

The adsorption of Cr, Cd, Pb, Cu and Mn onto these lateritic soils is effectively described by Langmuir and Freundlich isotherms. The lateritic soils exhibited a pronounced tendency for the sorption of Pb and Cd, indicating the effectiveness of these soils to adsorb these toxic heavy metals in leachate. However, an evaluation of the sorption reversibility through hysteresis index reveals a notably high desorption potential, particularly for Cr and Cd in all the soils, unlike Cu, Pb and Mn, which showed relatively greater irreversibility for all the lateritic soils.

The study reveals that the lateritic soils derived from granite-gneiss and charnockite are the optimal candidates for landfill liner application due to their favourable mineralogical and chemical properties while the sorption tests reinforce their potential to attenuate leachate pollutant through sorption. The high hysteresis index observed for Cr and Cd in several of the lateritic soils implies that they may be re-released to the surrounding soils and groundwater. Thus, it is recommended that landfill liners utilizing these lateritic soils are designed as a composite containment facility by integrating compacted soil liners, leachate collection systems and monitoring networks to ensure effective environmental protection.

9.2 Limitations of the study

This study has some limitations that should be acknowledged. Firstly, the sampling of the lateritic soils was restricted to borrow-pits and road cuts. As such, it would have been ideal to explore complete lateritic profiles in order to unravel the vertical variations in the relevant geotechnical and geochemical properties related to their utilization as landfill liners. Furthermore, the unavailability of standard engineered landfill with proper drainage collection systems in the study area restricted access to leachate samples, which could have been used to evaluate the compatibility and long-term performance of the lateritic soils. Also, resource constraints disallowed the building of laboratory scale model of a landfill which could have further established the long-term performance of the lateritic soils in an ideal landfill system. Moreover, the batch

equilibrium tests utilized small sample sizes, potentially limiting the representativeness of the results for larger, more heterogeneous environments. However, despite these limitations, this research significantly contributes to new knowledge in the domain of landfill liner materials by providing a comprehensive assessment of the geo-hydraulic performance of lateritic soils. The study offers valuable insights into the physical, chemical and mineralogical properties of lateritic soils, highlighting their potential and limitations as CSLs. The integration of geotechnical, geochemical, and batch equilibrium tests presents a holistic approach to evaluating landfill liner materials, setting a foundation for future studies in this field.

9.3 Recommendations

The recommendations emerging from this study advocates for a comprehensive evaluation of the suitability of lateritic soils for lining applications by considering various factors that influence their engineering properties. Geotechnical properties of lateritic soils should be adequately studied for horizontal variations within deposits and across profiles to ascertain the variability in the desired geotechnical properties of landfill liners. Furthermore, determining the appropriate compaction condition which can yield a minimum required hydraulic conductivity of lateritic soils with respect to the parent rock types is essential. Moreover, exploring the optimal blend or ratio of mixing lateritic soils derived from different parent materials with a focus on determining their suitability for landfill liner is recommended for further investigation. Additionally, the effectiveness of the blending the lateritic soils, especially those mixed with other materials including bentonite should be checked relative to the climatic conditions of the study area. e to find the right blend or ratio of mixing soils form different parent materiasl that would render the mixture suitable as liner. By this, to meet the requirements for permeability and other properties

Furthermore, laboratory scale models should be built to evaluate the long-term performance, efficiency, durability and compatibility of these soils with leachates while considering local climatic variations. This should also be done for various blends of materials mixed for lining purposes. The batch equilibrium sorption tests should be carried out at different pH levels to determine the effect pH may have on the adsorption properties os the soils.

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APPENDICES

Appendix 1. Index and Geotechnical properties of lateritic soils compiled from various sources including scientific papers, academic thesis and technical reports

| Country | Parent Rock | Clay (%) | Silt (%) | Fines (%) | Sand (%) | Gravel (%) | LL | PI | SG | C (kPa) | ϕ° | MDD (Mg/m ³) | OMC (%) | K(m/s) | UCS (kPa) | References |
|-------------|-------------|----------|----------|-----------|----------|------------|------|------|-----|---------|--------------|--------------------------|---------|--------|-------------|-----------------------------|
| Burkinafaso | | 27.5 | 30.7 | 57.5 | 42.5 | | 42.9 | 28.3 | | | | 1.8 | 17.2 | | | Lawane <i>et al.</i> , 2018 |
| Burkinafaso | | 10.0 | 51. | 61.4 | 38.5 | | 31.5 | 18.1 | | | | 1.9 | 14.5 | | | |
| Nigeria | | | | 20.0 | 8.0 | 71.0 | 32.0 | 21.0 | 2.6 | 138.0 | 15.0 | 1.8 | 12.0 | | | Nwadike and Nweke, 2017 |
| | | | | 33.1 | 6.0 | 61.1 | 37.1 | 24.0 | 2.5 | 130.1 | 20.0 | 1.8 | 18.0 | | | |
| | | | | 9.0 | 2.0 | 89.0 | 33.0 | 23.0 | 2.6 | 146.0 | 15.0 | 2.0 | 9.1 | | | |
| | | | | 20.0 | 10.0 | 69.9 | 33.0 | 22.0 | 2.6 | 139.0 | 15.0 | 1.9 | 14.0 | | | |
| | | | | 12.0 | 5.0 | 82.9 | 33.0 | 25.1 | 2.6 | 136.0 | 15.0 | 1.9 | 10.1 | | | |
| | | | | 35.0 | 7.0 | 58.1 | 38.0 | 25.1 | 2.6 | 140.0 | 20.0 | 1.9 | 20.0 | | | |
| | | | | 9.0 | 7.0 | 84.0 | 32.0 | 24.1 | 2.6 | 132.0 | 15.0 | 1.8 | 10.2 | | | |
| | | | 65.2 | 32.8 | 2.0 | 56.5 | 22.6 | 2.6 | | | | | | | Amadi, 2015 | |
| Sudan | | | | | | | 25.0 | 9.0 | | | | 2.1 | 9.7 | | | Elarabi and Elkhawad, 2013 |
| | | | | | | | 24.0 | 11.0 | | | | 2.1 | 9.9 | | | |
| | | | | | | | 25.0 | 11.1 | | | | 2.1 | 10.0 | | | |
| | | | | | | | | | | | | 2.1 | 7.5 | | | |
| | | | | | | | 43.0 | 23.0 | | | | 2.1 | 9.6 | | | |
| | | | | | | | 22.0 | 9.0 | | | | 2.1 | 9.5 | | | |
| | | | | | | | 34.0 | 15.0 | | | | 2.2 | 7.4 | | | |
| | | | | | | | 26.0 | 11.0 | | | | 2.0 | 10.5 | | | |
| | | | | | | | 34.0 | 15.0 | | | | 2.2 | 9.3 | | | |
| | | | | | | | 32.0 | 12.0 | | | | 2.1 | 10.8 | | | |

| | | | | | | | | | | | | | | | | |
|---------|---------------------|--|--|--|------|------|------|------|------|------|------|-----|------|--|--|----------------------------------|
| | | | | | | | 35.0 | 12.0 | | | | 2.1 | 11.2 | | | |
| | | | | | | | 38.0 | 16.0 | | | | 2.0 | 13.1 | | | |
| | | | | | | | | 16.0 | | | | 1.9 | 16.6 | | | |
| Nigeria | Migmatite gneiss | | | | | | 50.0 | 27.9 | 2.6 | 30.0 | 22.0 | 1.7 | 14.0 | | | Okunlola <i>et al.</i> , 2014 |
| | | | | | | | 54.0 | 35.0 | 2.6 | 20.0 | 24.0 | 1.7 | 16.0 | | | |
| | | | | | | | | | 2.7 | 10.0 | 32.0 | 1.9 | 11.0 | | | |
| | | | | | | | 53.0 | 26.0 | 2.7 | 15.0 | 30.0 | 1.8 | 14.0 | | | |
| | | | | | | | 49.0 | 25.3 | 2.6 | 20.0 | 31.0 | 1.8 | 14.0 | | | |
| | | | | | | | | | 2.6 | 10.0 | 30.0 | 1.8 | 13.0 | | | |
| | | | | | | | 51.0 | 28.1 | 2.6 | 10.0 | 28.0 | 1.8 | 14.0 | | | |
| | | | | | | | 50.0 | 31.9 | 2.7 | 30.0 | 30.0 | 1.8 | 14.0 | | | |
| | | | | | | | 58.0 | 32.2 | 2.5 | 20.0 | 24.0 | 1.7 | 16.0 | | | |
| | | | | | | | 44.0 | 22.2 | 2.7 | 30.0 | 27.0 | 1.8 | 13.0 | | | |
| | | | | | | | 46.0 | 21.5 | 2.6 | 10.0 | 30.0 | 1.9 | 13.0 | | | |
| | | | | | | | 43.0 | 22.9 | 2.5 | 20.0 | 24.0 | 1.8 | 15.0 | | | |
| | | | | | | | 40.0 | 17.7 | 2.6 | 30.0 | 25.0 | 1.8 | 15.0 | | | |
| | | | | | | | 46.0 | 23.2 | 2.6 | 20.0 | 26.0 | 1.7 | 15.0 | | | |
| | | | | | | | 44.0 | 22.2 | 2.5 | 30.0 | 26.0 | 1.8 | 13.0 | | | |
| | | | | | | | 43.0 | 26.0 | 2.7 | 10.0 | 31.0 | 1.8 | 16.0 | | | |
| | | | | | | | 51.0 | 33.4 | 2.7 | 20.0 | 23.0 | 1.6 | 14.0 | | | |
| | | | | | | | 45.0 | 23.6 | 2.6 | 30.0 | 23.0 | 1.7 | 14.0 | | | |
| | | | | | | | 48.0 | 23.6 | 2.5 | 20.0 | 28.0 | 1.8 | 14.0 | | | |
| | | | | | | | 48.0 | 22.4 | 2.6 | 20.0 | 23.0 | 1.7 | 14.0 | | | |
| | | | | | 44.0 | 23.5 | 2.6 | 20.0 | 27.0 | 1.8 | 14.0 | | | | | |

| | | | | | | | | | | | | | | | | | |
|---------|-----------------|------|------|------|------|------|------|------|-----|------|------|-----|------|--|--|--------------|---------------------------------|
| | | | | | | | 40.0 | 22.0 | 2.7 | 25.0 | 28.0 | 1.8 | 12.0 | | | | |
| Nigeria | Granite | 6.0 | 30.0 | 36.0 | 59.0 | 5.0 | 36.6 | 24.6 | | | | | | | | | Adebisi <i>et al.</i> , 2013 |
| | | 5.0 | 35.0 | 40.0 | 53.0 | 7.0 | 36.0 | 16.0 | | | | | | | | | |
| | | 4.0 | 12.0 | 16.0 | 78.0 | 5.0 | 42.1 | 15.1 | | | | | | | | | |
| | | 3.0 | 8.0 | 11.0 | 82.0 | 7.0 | 37.3 | 11.3 | | | | | | | | | |
| | | 5.0 | 13.0 | 18.0 | 77.0 | 5.0 | 39.5 | 18.0 | | | | | | | | | |
| | | 5.0 | 23.0 | 28.0 | 85.0 | 12.0 | 32.0 | 23.0 | | | | | | | | | |
| | | 2.0 | 20.0 | 22.0 | 68.0 | 10.0 | 28.8 | 11.8 | | | | | | | | | |
| | | 5.0 | 28.0 | 33.0 | 59.0 | 8.0 | 32.0 | 13.9 | | | | | | | | | |
| | | 6.0 | 18.0 | 24.0 | 54.2 | 22.0 | 42.6 | 21.6 | | | | | | | | | |
| | | 3.0 | 37.0 | 40.0 | 38.0 | 22.0 | 44.7 | 19.7 | | | | | | | | | |
| | | 10.0 | 23.0 | 33.0 | 64.0 | 3.0 | 28.0 | 9.2 | | | | | | | | | |
| | | 5.0 | 39.0 | 44.0 | 54.0 | 1.0 | 29.9 | 12.9 | | | | | | | | | |
| | | 8.0 | 39.0 | 47.0 | 51.0 | 2.0 | 45.0 | 7.0 | | | | | | | | | |
| | | 5.0 | 37.0 | 42.0 | 28.0 | 30.0 | 41.2 | 5.7 | | | | | | | | | |
| | | 2.0 | 14.0 | 16.0 | 51.0 | 33.0 | 28.0 | 15.0 | | | | | | | | | |
| | Migmatite | | | 5.6 | 43.3 | 0.6 | 47.1 | 27.1 | 2.7 | | | 1.5 | 28.3 | | | Falowo, 2018 | |
| | | | | 68.3 | 31.7 | | 53.8 | 29.3 | 2.7 | | | 1.3 | 32.7 | | | | |
| | | | | 74.1 | 25.9 | | 59.7 | 35.6 | 2.7 | | | 1.3 | 33.7 | | | | |
| | Charnockite | | | 22.0 | 76.8 | 1.2 | 32.4 | 13.5 | 2.7 | | | 1.9 | 16.2 | | | | |
| | | | | 20.5 | 78.0 | 1.6 | 34.0 | 15.1 | 2.7 | | | 1.9 | 15.3 | | | | |
| | | | | 15.3 | 83.5 | 1.2 | 28.0 | 9.9 | 2.7 | | | 2.0 | 14.2 | | | | |
| | Biotite-granite | | | 60.3 | 38.8 | 1.0 | 47.1 | 23.0 | 2.7 | | | 1.3 | 32.4 | | | | |
| | | | | 62.5 | 37.5 | | 44.2 | 19.1 | 2.7 | | | 1.3 | 33.4 | | | | |

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|----------|---------------------|------|------|------|------|------|------|------|-----|------|------|-----|------|------------------------|------|-----------------------------|
| | | | | 35.3 | 64.7 | | 43.4 | 17.0 | 2.7 | | | 1.9 | 16.2 | | | |
| | Migmatite gneiss | 24.0 | 22.0 | 46.0 | 38.0 | 16.0 | 38.3 | 19.1 | 2.7 | | | 1.7 | 19.2 | 8.34×10^{-12} | | Daramola & Ilesanmi, 2019 |
| | | 30.0 | 18.0 | 48.0 | 36.0 | 16.0 | 37.0 | 20.4 | 2.7 | | | 1.8 | 17.2 | 4.01×10^{-12} | | |
| | | 37.0 | 28.0 | 65.0 | 19.0 | 16.0 | 44.0 | 22.2 | 2.6 | | | 1.8 | 17.2 | 2.95×10^{-12} | | |
| | | 28.0 | 24.0 | 52.0 | 34.0 | 14.0 | 46.0 | 27.2 | 2.7 | | | 1.7 | 18.2 | 6.1×10^{-12} | | |
| | | 31.0 | 21.0 | 52.0 | 33.0 | 15.0 | 39.0 | 20.0 | 2.6 | | | 1.8 | 17.2 | 3.48×10^{-12} | | |
| | | 32.0 | 25.0 | 57.0 | 33.0 | 10.0 | 42.0 | 23.6 | 2.6 | | | 1.8 | 18.2 | 5.65×10^{-12} | | Osinubi, 2012 |
| | | | | 60.9 | 39.1 | | 48.9 | 22.0 | 2.7 | 95.0 | 35.0 | 1.7 | 17.3 | | | |
| Cameroon | Gneiss | 5.0 | 13.0 | 18.0 | 9.0 | 73.0 | 54.0 | 21.0 | | | | 2.8 | 10.7 | | | Onana <i>et al.</i> , 2017 |
| Nigeria | | | | | | | 40.0 | 22.0 | 2.6 | | | 1.9 | 16.1 | | 4.23 | Ugwuanyi and Qnyelope, 2019 |
| | | | | | | | 44.0 | 14.0 | 2.6 | | | 1.9 | 15.6 | | 5.5 | |
| Taiwan | Andesite | 42.9 | 45.6 | 88.5 | 11.5 | | | | | | | | | | | Ko, 2014 |
| | Pleistocene deposit | 41.8 | 43.8 | 85.6 | 14.4 | | | | | | | | | | | |
| | Diluvium | 51.5 | 34.2 | 85.7 | 14.3 | | | | | | | | | | | |
| | Shale | 49.7 | 26.8 | 76.5 | 23.5 | | | | | | | | | | | |
| | Basalt | 60.2 | 22.1 | 82.3 | 17.6 | | | | | | | | | | | |
| Nigeria | Nsukka Formation | 14.0 | 22.1 | 36.1 | 45.9 | 18.0 | 38.0 | 14.3 | | | | 2.1 | 9.5 | | | Ehujuo <i>et al.</i> , 2017 |

| | | | | | | | | | | | | | | | | |
|-------------|----------------|------|------|------|------|------|------|------|------|------|-------|------|------|-----------------------|-----|------------------------------------|
| | Ajali | 18.0 | 1.7 | 19.7 | 62.3 | 8.0 | 28.0 | 9.9 | | | | 2.0 | 11.2 | | | |
| | Mamu | 5.0 | 31.7 | 36.7 | 49.3 | 14.0 | 54.2 | 18.1 | | | | 1.9 | 14.5 | | | |
| Burkinafaso | | 5.0 | 4.0 | 9.0 | 17.0 | 74.0 | 22.5 | 10.5 | | | | 2.2 | 6.6 | | | Milogo <i>et al.</i> , 2011 |
| Nigeria | | | | 2.0 | 96.0 | 2.0 | 42.3 | 19.0 | | 34.0 | 22.0 | 2.0 | 15.0 | | | Ayeni 2016 |
| Senegal | Marl | | | 9.0 | 9.0 | 82.0 | 39.5 | 18.4 | | | | 2.1 | 12.0 | | | Diop <i>et al.</i> , 2015 |
| | | | | 12.0 | 6.0 | 82.0 | 39.0 | 19.0 | | | | 2.0 | 12.2 | | | |
| Nigeria | Sandstone | 18.0 | 18.0 | 36.0 | 64.0 | | 40.0 | 25.4 | | 50.0 | 17.0 | 1.7 | 11.0 | 3.09×10 ⁻⁸ | | Aweda <i>et al.</i> , 2017 |
| | Siltstone | 42.0 | 44.0 | 86.0 | 11.0 | 3.0 | 44.0 | 23.6 | | 26.0 | 30.0 | 1.7 | 12.0 | 1.19×10 ⁻⁸ | | |
| | Sandstone | 9.0 | 24.0 | 33.0 | 54.0 | 3.0 | 30.0 | 17.0 | | 85.0 | 21.0 | 1.8 | 12.6 | 2.46×10 ⁻⁸ | | |
| Thailand | | | | | | | 39.1 | 15.9 | 2.7 | 35.0 | 37.0 | 1.9 | 12.6 | 2.26×10 ⁻⁷ | | Indratana, 1991 |
| Nigeria | Charnockite | | | 32.7 | 59.1 | 8.2 | 39.0 | 17.0 | 2.5 | | | 1.9 | 12.7 | 3.14×10 ⁻⁴ | | Oni & Jimoh, 2016 |
| | | | | 34.7 | 60.4 | 4.9 | 42.0 | 17.5 | 2.4 | | | 2.0 | 10.5 | 2.06×10 ⁻⁴ | | |
| | | | | 33.8 | 59.3 | 6.9 | 40.0 | 19.0 | 2.7 | | | 1.9 | 14.1 | 4.15×10 ⁻⁴ | | |
| | | | | 29.2 | 65.5 | 5.3 | 41.0 | 18.9 | 2.6 | | | 1.8 | 15.0 | 3.58×10 ⁻⁴ | | |
| | | | | | 65.0 | 26.8 | 8.0 | 45.0 | 24.0 | | 153.0 | 34.0 | 1.8 | 12.7 | | Ojo, 2013 |
| | Biotite-gneiss | | | 61.0 | 32.0 | 7.0 | 45.0 | 24.3 | 2.7 | 85.0 | 11.0 | 1.7 | 16.0 | | | Baiyegunhi <i>et al.</i> , 2014 |
| Malaysia | | 32.0 | 30.0 | 62.0 | 33.0 | 5.0 | 75.0 | 34.0 | 2.7 | | | 1.3 | 34.0 | | 270 | Nima <i>et al</i> 2015 |
| Sri Lanka | | | | 32.0 | 52.0 | 16.0 | 28.3 | 6.6 | 2.5 | 5.5 | 3.2 | 1.8 | 14.4 | | | Nawagamuwa <i>et a.,l</i> 2015 |
| Cameroon | Granite | 7.0 | 8.0 | 15.0 | 20.0 | 63.0 | 61.0 | 27.0 | 2.8 | | | 2.0 | 12.2 | | | Nzabakimikiza <i>et al.</i> , 2016 |
| | | 8.0 | 9.0 | 17.0 | 14.0 | 68.0 | 55.0 | 29.0 | 2.9 | | | 2.1 | 11.0 | | | |
| Brazil | | | | 94.0 | | | 35.0 | 21.0 | 2.8 | | | 1.5 | 26.5 | 9.7×10 ⁻⁹ | | |

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|-----------|---------------------|------|------|------|------|------|------|------|-----|------|------|------|------|-----------------------|----|-----------------------------------|
| | | | | 69.0 | | | 58.0 | 30.0 | 2.9 | | | 1.4 | 29.8 | 1.25×10^{-9} | | De Brito <i>et al.</i> , 2004 |
| Malaysia | | | | 21.6 | 77.5 | 0.9 | 58.6 | 6.2 | 2.6 | | | 1.8 | 13.5 | 4.96×10^{-4} | | Aziz <i>et al.</i> , 2019 |
| China | | | | 40.0 | 60.0 | | 30.0 | | | | | 1.6 | 22.0 | | | Liu & Bae, 2004 |
| Nigeria | Sandstone | 10.0 | 16.0 | 26.0 | 61.0 | 13.0 | 39.0 | 14.0 | 2.6 | | | 2.0 | 12.8 | | 41 | Okogbue <i>et al.</i> , 2020 |
| | | 2.0 | 8.0 | 10.0 | 74.0 | 16.0 | 36.0 | 12.0 | 2.6 | | | 2.0 | 10.1 | | 40 | |
| | Limestone | 6.0 | 9.0 | 15.0 | 75.0 | 10.0 | 38.0 | 14.0 | 2.6 | | | 2.1 | 11.2 | | 43 | |
| | | 6.0 | 12.0 | 18.0 | 74.0 | 8.0 | 43.0 | 20.0 | 2.6 | | | 1.9 | 13.3 | | 38 | |
| | Granite | 11.0 | 14.0 | 25.0 | 70.0 | 5.0 | 35.0 | 12.0 | 2.5 | | | 1.8 | 10.4 | | 22 | |
| | | 10.0 | 12.0 | 22.0 | 72.0 | 6.0 | 36.0 | 14.0 | 2.5 | | | 1.7 | 9.4 | | 20 | |
| | Granite | 12.0 | 14.0 | 26.0 | 71.0 | 3.0 | 40.0 | 15.0 | 2.5 | | | 1.7 | 13.1 | | 23 | |
| | | 9.0 | 20.0 | 29.0 | 61.0 | 10.0 | 40.0 | 12.0 | 2.6 | | | 2.0 | 12.6 | | 39 | |
| | Basalt | 5.0 | 10.0 | 15.0 | 74.0 | 11.0 | 46.0 | 21.0 | 2.7 | | | 1.9 | 16.4 | | 27 | |
| | | 4.0 | 18.0 | 22.0 | 76.0 | 2.0 | 42.0 | 21.0 | 2.6 | | | 1.9 | 16.4 | | 27 | |
| Migmatite | 6.0 | 13.0 | 19.0 | 74.0 | 7.0 | 42.0 | 19.0 | 2.6 | | | 2.0 | 14.2 | | 37 | | |
| | 3.0 | 4.0 | 7.0 | 88.0 | 5.0 | 45.0 | 17.0 | 2.6 | | | 1.9 | 12.2 | | 40 | | |
| India | | | | 22.4 | 47.5 | 30.2 | 28.3 | 16.7 | | | | 1.9 | 12.5 | | | Biswal <i>et al.</i> , 2008 |
| | | | | 19.0 | 43.4 | 37.7 | 41.3 | 12.9 | | | | 2.2 | 10.7 | | | |
| | | | | 15.5 | 39.0 | 45.6 | 36.5 | 15.9 | | | | 2.2 | 9.6 | | | |
| Nigeria | Migmatite gneiss | | | 41.2 | 57.0 | 1.8 | 38.5 | 17.4 | 2.6 | 32.0 | 28.0 | 1.8 | 14.8 | 1.83×10^{-7} | | Adepelumi <i>et al.</i> , 2015 |
| | | | | 36.1 | 57.4 | 6.5 | 34.0 | 22.6 | 2.7 | 36.0 | 21.0 | 1.7 | 15.0 | 2.22×10^{-7} | | |
| | | | | 30.0 | 64.9 | 4.9 | 37.0 | 20.7 | 2.7 | 34.0 | 24.0 | 1.8 | 12.0 | 2.53×10^{-7} | | |
| | | | | 25.3 | 66.9 | 7.9 | 37.5 | 13.5 | 2.6 | 20.0 | 22.0 | 1.9 | 14.0 | 2.43×10^{-7} | | |

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|--|------------------|------|------|------|------|------|------|------|-----|------|------|-----|------|------------------------|--|--------------------------|
| | | | | 35.2 | 56.9 | 7.9 | 43.0 | 24.5 | 2.6 | 24.5 | 27.0 | 1.9 | 11.0 | 2.38×10 ⁻⁷ | | |
| | Granite-gneiss | 29.0 | 24.0 | 53.0 | 35.0 | 12.0 | 47.9 | 28.2 | 2.7 | | | 1.7 | 19.3 | 1.48×10 ⁻⁷ | | Ogunsanwo, 1989 |
| | Amphibolite | 38.0 | 36.0 | 74.0 | 23.0 | 3.0 | 55.5 | 30.1 | 2.8 | | | 1.5 | 26.5 | | | |
| | | 33.0 | 29.0 | 62.0 | 37.0 | 0.3 | 43.0 | 20.0 | 2.7 | | | 1.7 | 19.0 | | | |
| | | 33.0 | 37.0 | 70.0 | 29.0 | 0.6 | 41.0 | 19.0 | 2.7 | | | 1.7 | 17.0 | | | |
| | | 33.0 | 26.0 | 59.0 | 37.0 | 3.8 | 40.0 | 18.0 | 2.7 | | | 1.6 | 18.0 | | | |
| | Granite | 70.0 | 11.0 | 81.0 | 15.0 | 3.0 | 68.4 | 44.4 | 2.6 | | | 2.2 | 16.1 | 2.80×10 ⁻¹⁰ | | Ige & Ogunsanwo, 2009 |
| | | 11.0 | 9.0 | 22.0 | 20.0 | 6.0 | 21.6 | 13.5 | 2.7 | | | 2.0 | 12.3 | 3.30×10 ⁻⁹ | | Ige <i>et al.</i> , 2011 |
| | | 23.0 | 13.0 | 32.0 | 36.0 | 1.0 | 42.2 | 20.8 | 2.6 | | | 1.8 | 14.4 | 3.15×10 ⁻⁹ | | |
| | | 37.0 | 30.0 | 50.0 | 67.0 | 1.0 | 37.5 | 24.7 | 2.5 | | | 1.7 | 16.9 | 6.03×10 ⁻⁹ | | |
| | | 41.0 | 20.0 | 71.0 | 61.0 | 3.0 | 46.3 | 26.0 | 2.7 | | | 1.7 | 16.0 | 1.97×10 ⁻⁹ | | |
| | | 13.0 | 32.0 | 45.0 | 54.0 | 1.0 | 34.7 | 22.5 | 2.6 | | | 1.8 | 15.3 | 2.55×10 ⁻¹⁰ | | Ogunsanwo, 1996 |
| | Sandstone | 21.0 | 19.0 | 40.0 | 57.0 | 3.0 | 49.9 | 26.4 | 2.7 | | | 1.8 | 17.5 | 1.00×10 ⁻¹⁰ | | |
| | Granite-gneiss | 34.0 | 45.0 | 79.0 | 20.0 | 1.0 | 51.4 | 31.7 | 2.6 | | | 1.7 | 19.3 | 6.60×10 ⁻¹² | | |
| | Quartz-schist | 12.0 | 40.0 | 52.0 | 46.0 | 2.0 | 35.0 | 11.0 | 2.8 | | | 1.8 | 16.9 | 8.3×10 ⁻¹⁰ | | Ogunsanwo, 1989 |
| | Mica schist | 5.0 | 60.0 | 65.0 | 35.0 | | 42.0 | 6.0 | 2.8 | | | 1.7 | 18.5 | 7.48×10 ⁻⁹ | | |
| | Granulite schist | 29.0 | 24.0 | 53.0 | 35.0 | 12.0 | 48.0 | 28.0 | 2.7 | | | 1.7 | 19.3 | 1.48×10 ⁻¹⁰ | | |

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|----------|-------------|------|------|------|------|------|------|------|-----|--|--|-----|------|------------------------|--|---------------------------------|
| | Amphibolite | 38.0 | 36.0 | 74.0 | 23.0 | 3.0 | 56.0 | 31.0 | 2.8 | | | 1.5 | 26.5 | 1.17×10 ⁻⁹ | | |
| | Sandstone | 35.0 | 15.0 | 50.0 | 48.0 | 2.0 | 50.0 | 29.0 | 2.7 | | | 1.7 | 18.5 | 4.23×10 ⁻¹⁰ | | |
| | | | | | | | 50.0 | 33.7 | 2.6 | | | 1.7 | 17.2 | 4.00×10 ⁻⁴ | | Ola, 1989 |
| | | | | | | | 95.0 | 72.9 | 2.7 | | | 1.5 | 26.2 | 8.00×10 ⁻⁶ | | |
| | | | | | | | 70.0 | 47.6 | 2.5 | | | 1.7 | 17.2 | 1.8×10 ⁻⁵ | | |
| Cameroon | | | | 27.1 | 27.7 | 45.5 | 52.0 | 22.0 | 2.7 | | | 1.9 | 14.0 | | | Mvidi <i>et al.</i> , (2017) |
| Cameroon | | | | 24.1 | 21.2 | 54.9 | 44.0 | 20.0 | 2.7 | | | 2.0 | 13.0 | | | |
| Cameroon | | | | 26.8 | 29.9 | 45.9 | 45.0 | 20.0 | 2.7 | | | 2.0 | 11.6 | | | |
| Cameroon | | | | 22.9 | 28.4 | 50.4 | 48.0 | 21.0 | 2.7 | | | 1.9 | 11.7 | | | |
| Cameroon | | | | 26.4 | 25.3 | 47.7 | 50.0 | 22.0 | 2.6 | | | 2.0 | 13.4 | | | |
| Cameroon | | | | 22.2 | 26.0 | 44.0 | 41.0 | 19.0 | 2.7 | | | 2.0 | 10.3 | | | |
| Cameroon | | | | 33.8 | 32.1 | 38.3 | 71.0 | 36.0 | 2.5 | | | 1.8 | 15.7 | | | |
| Cameroon | | | | 33.5 | 41.1 | 30.7 | 69.0 | 35.0 | 2.6 | | | 1.9 | 15.8 | | | |
| Cameroon | | | | 29.7 | 40.6 | 32.0 | 49.0 | 23.0 | 2.6 | | | 2.0 | 11.9 | | | |
| Cameroon | | | | 26.1 | 26.5 | 48.0 | 48.0 | 21.0 | 2.7 | | | 1.9 | 12.9 | | | |
| Cameroon | | | | 26.3 | 28.6 | 45.7 | 48.0 | 21.0 | 2.6 | | | 2.0 | 11.0 | | | |
| Cameroon | | | | 21.1 | 22.3 | 58.1 | 45.0 | 19.0 | 2.7 | | | 2.0 | 10.9 | | | |
| Cameroon | | | | 19.8 | 19.0 | 63.2 | 46.0 | 19.0 | 2.8 | | | 2.1 | 11.3 | | | |
| Cameroon | | | | 21.1 | 13.3 | 66.0 | 48.0 | 20.0 | 2.8 | | | 2.1 | 11.9 | | | |
| Cameroon | | | | 22.1 | 15.5 | 65.4 | 48.0 | 21.0 | 2.8 | | | 2.0 | 12.4 | | | |
| Cameroon | | | | 22.0 | 14.0 | 66.4 | 48.0 | 21.0 | 2.8 | | | 2.0 | 13.0 | | | |
| Cameroon | | | | 18.9 | 11.1 | 71.1 | 49.0 | 20.0 | 2.9 | | | 2.1 | 10.8 | | | |
| Cameroon | | | | 21.1 | 13.7 | 65.8 | 49.0 | 21.0 | 2.8 | | | 2.1 | 12.3 | | | |

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|----------|--------|------|------|------|------|------|------|------|-----|--|--|-----|------|--|--|---------------------------------|
| Cameroon | | 18.6 | | | 30.0 | | 69.0 | 34.0 | 2.8 | | | 2.2 | 8.6 | | | Onana <i>et al.</i> , (2017) |
| Cameroon | | 34.7 | | | 59.8 | | 81.0 | 44.0 | 2.9 | | | 2.0 | 14.5 | | | |
| Cameroon | | 23.1 | | | 41.0 | | 57.0 | 26.0 | 2.8 | | | 2.2 | 10.2 | | | |
| Cameroon | | 28.2 | | | 50.9 | | 76.0 | 33.0 | 2.7 | | | 2.0 | 14.3 | | | |
| Cameroon | | 14.0 | | | 20.3 | | 65.0 | 31.0 | 2.9 | | | 2.2 | 9.8 | | | |
| Cameroon | | 9.0 | | | 15.1 | | 77.0 | 32.0 | 2.9 | | | 2.2 | 9.8 | | | |
| Cameroon | | 15.0 | | | 35.0 | | 73.0 | 38.0 | 2.8 | | | 2.1 | 10.4 | | | |
| Cameroon | | 24.0 | | | 40.9 | | 73.0 | 35.0 | 2.8 | | | 1.9 | 14.5 | | | |
| Cameroon | | 17.7 | | | 30.0 | | 95.0 | 55.0 | 2.8 | | | 2.0 | 12.8 | | | |
| Cameroon | | 9.9 | | | 41.0 | | 85.0 | 39.0 | 2.9 | | | 2.3 | 13.0 | | | |
| Cameroon | | 19.4 | | | 36.4 | | 75.1 | 36.7 | 2.8 | | | 2.1 | 11.8 | | | |
| Cameroon | Schist | 46.8 | 17.1 | 63.9 | 38.6 | 1.1 | 60.8 | 30.1 | | | | 1.7 | 20.8 | | | |
| Cameroon | Schist | 44.2 | 16.1 | 60.3 | 35.9 | 2.8 | 58.3 | 27.9 | | | | 1.6 | 18.3 | | | |
| Cameroon | Schist | 47.8 | 13.5 | 61.3 | 19.1 | 58.2 | 62.6 | 30.5 | | | | 1.7 | 16.5 | | | |
| Cameroon | Schist | 15.4 | 7.3 | 22.7 | 26.9 | 45.1 | 59.8 | 28.4 | | | | 2.1 | 11.2 | | | |
| Cameroon | Schist | 18.4 | 9.6 | 28.0 | 15.4 | 65.7 | 55.9 | 25.3 | | | | 2.0 | 13.7 | | | |
| Cameroon | Schist | 14.6 | 4.3 | 18.9 | 35.0 | 6.4 | 50.9 | 22.7 | | | | 2.1 | 11.8 | | | |
| Cameroon | Schist | 43.5 | 15.1 | 58.6 | 29.2 | 5.7 | 62.4 | 30.5 | | | | 1.8 | 18.9 | | | |
| Cameroon | Schist | 47.4 | 17.7 | 65.1 | 32.5 | 2.4 | 61.2 | 28.1 | | | | 1.7 | 19.5 | | | |
| Cameroon | Schist | 44.3 | 16.1 | 60.4 | 29.8 | 9.8 | 66.7 | 32.9 | | | | 1.7 | 15.4 | | | |
| China | | 44.0 | | | | | 54.0 | 27.0 | 2.8 | | | 1.9 | | | | Gao, 1960 |
| China | | 48.0 | | | | | 74.0 | 46.0 | 2.8 | | | 1.7 | | | | Gao, 1961 |
| China | | 57.0 | | | | | 61.0 | 33.0 | 2.8 | | | | | | | Gao, 1962 |
| China | | 80.0 | | | | | 82.0 | 47.0 | 2.8 | | | | | | | Gao, 1963 |

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|------------|--|------|--|------|------|------|------|------|-----|-------|------|-----|------|--|-------|---------------|
| China | | 72.0 | | | | | 53.0 | 36.0 | 2.8 | | | | | | | Gao, 1964 |
| China | | 50.0 | | | | | 74.0 | 35.0 | 2.8 | 52.0 | 17.0 | | | | | Gao, 1965 |
| China | | 64.0 | | | | | 69.0 | 40.0 | 2.7 | | | | | | | Gao, 1966 |
| China | | 87.0 | | | | | 87.0 | 52.0 | 2.9 | | | | | | | Gao, 1967 |
| China | | | | | | | 28.0 | 11.0 | 2.8 | 111.8 | 16.0 | | | | | Gao, 1968 |
| China | | | | | | | 58.0 | 24.0 | 2.8 | 125.5 | 18.0 | | | | | Gao, 1969 |
| China | | | | | | | 37.0 | 12.0 | | 25.5 | 11.0 | | | | | Gao, 1970 |
| China | | | | | | | 83.0 | 41.0 | | 45.1 | 18.0 | | | | | Gao, 1971 |
| China | | 62.0 | | | | | 50.0 | 18.0 | 2.9 | | | | | | | Gao, 1972 |
| China | | 74.0 | | | | | 67.0 | 28.0 | | | | | | | | Gao, 1973 |
| China | | | | | | | 37.0 | 12.0 | 2.7 | | | | | | | Gao, 1974 |
| China | | | | | | | 42.0 | 16.0 | | | | | | | | Gao, 1975 |
| China | | 38.0 | | | | | 51.0 | 19.0 | 2.7 | 74.5 | 30.0 | | | | | Gao, 1976 |
| China | | | | | | | 35.0 | 13.0 | 2.8 | 62.8 | 25.0 | | | | | Gao, 1977 |
| China | | | | | | | 43.0 | 17.0 | | | | | | | | Gao, 1978 |
| China | | 41.0 | | | | | 46.0 | 26.0 | 2.8 | 70.6 | 34.0 | | | | | Gao, 1979 |
| China | | 37.0 | | | | | 31.0 | 13.0 | | 33.3 | 20.0 | | | | | Gao, 1980 |
| China | | 50.0 | | | | | 56.0 | 22.0 | 2.8 | | | | | | | Gao, 1981 |
| India | | 20.0 | | | | | 31.0 | 15.0 | 3.0 | 36.3 | 20.0 | | | | | Gao, 1982 |
| India | | 25.0 | | | | | 45.0 | 19.0 | | 39.2 | 26.0 | | | | | Gao, 1983 |
| Madagascar | | 23.0 | | | | | 59.0 | 23.0 | | 39.2 | 17.0 | | | | | Gao, 1984 |
| Madagascar | | 40.0 | | | | | 81.0 | 40.0 | | 49.0 | 19.0 | | | | | Gao, 1985 |
| Malaysia | | | | 14.4 | 75.7 | 10.0 | 18.0 | 4.6 | 2.7 | | | 1.7 | 19.0 | | 38.8 | Sujeeth, 2015 |
| Malaysia | | | | 4.6 | 92.0 | 3.4 | 28.0 | 15.2 | 3.0 | | | 1.6 | 19.0 | | 45.61 | |

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|----------|--|------|------|------|------|------|------|------|-----|------|------|-----|------|--|-------|----------------|---------------------------|
| Malaysia | | | | 7.0 | 91.4 | 1.6 | 21.0 | 16.5 | 2.7 | | | 1.6 | 17.0 | | 134.2 | | |
| Malaysia | | | | 21.7 | 71.7 | 6.7 | 17.0 | 12.0 | 3.1 | | | 1.7 | 11.0 | | 79.61 | | |
| Malaysia | | | | 10.1 | 87.9 | 2.0 | 21.0 | 8.9 | 2.8 | | | 1.6 | 16.0 | | 43.1 | | |
| Ethiopia | | 3.4 | 9.8 | 13.2 | 12.7 | 74.1 | 56.0 | 20.0 | 3.0 | | | 1.7 | 23.2 | | | Zelalem, 2005 | |
| Ethiopia | | 4.4 | 9.9 | 14.3 | 6.5 | 79.2 | 56.0 | 18.0 | 2.9 | | | 1.7 | 24.0 | | | | |
| Ethiopia | | 7.8 | 16.5 | 24.3 | 9.9 | 65.8 | 59.0 | 22.0 | 2.9 | | | 1.6 | 25.0 | | | | |
| Ethiopia | | 6.7 | 19.1 | 25.8 | 10.8 | 63.4 | 67.0 | 24.0 | 3.0 | | | 1.5 | 26.4 | | | | |
| Ethiopia | | 3.6 | 11.1 | 14.7 | 6.9 | 78.5 | 54.0 | 20.0 | 3.0 | | | 1.4 | 32.2 | | | | |
| Ethiopia | | 8.3 | 21.5 | 29.8 | 13.4 | 56.8 | 58.0 | 21.0 | 2.8 | | | 1.8 | 20.2 | | | | |
| Ethiopia | | 20.5 | 53.6 | 74.1 | 25.9 | | 59.0 | 20.0 | 2.8 | | | 1.8 | 22.0 | | | | |
| Ethiopia | | 20.6 | 59.2 | 79.8 | 20.2 | | 54.0 | 20.0 | 2.9 | | | 1.5 | 24.0 | | | | |
| Hawai | | 30.3 | 38.7 | 69.0 | 31.0 | | 49.1 | 10.6 | 2.9 | | | 1.4 | | | | | Tuncer and Ihones, (1982) |
| Hawai | | 43.8 | 45.5 | 89.3 | 10.7 | | 51.3 | 15.3 | 3.0 | | | 1.5 | | | | | |
| Hawai | | 14.0 | 16.7 | 30.7 | 69.3 | | 67.1 | 16.7 | 3.0 | | | 1.4 | | | | | |
| Hawai | | 33.0 | 39.2 | 72.2 | 27.8 | | 57.1 | 17.8 | 3.1 | | | 1.3 | | | | | |
| Hawai | | 58.8 | 28.8 | 87.6 | 12.4 | | 72.6 | 17.7 | 3.1 | | | 1.3 | | | | | |
| Hawai | | 35.6 | 39.9 | 75.5 | 24.5 | | 44.0 | 3.7 | 3.3 | | | 1.3 | | | | | |
| Hawai | | 34.3 | 41.7 | 76.0 | 24.0 | | 52.0 | 10.0 | 3.5 | | | 1.2 | | | | | |
| Hawai | | 20.5 | 34.4 | 54.9 | 45.9 | | 40.0 | 4.6 | 3.0 | | | 1.2 | | | | | |
| Ghana | | | 4.0 | | 68.0 | 18.0 | 55.8 | 29.0 | | 40.0 | 14.0 | 1.7 | 19.0 | | | Frempong, 1994 | |
| Ghana | | 24.0 | 26.0 | 50.0 | 50.0 | | 54.0 | 29.8 | | 55.0 | 20.0 | 1.8 | 14.8 | | | | |
| Ghana | | 31.0 | 21.0 | 52.0 | 36.0 | 12.0 | 57.3 | 26.7 | | 60.0 | 22.0 | 1.8 | 15.3 | | | | |
| Ghana | | 6.0 | 36.0 | 43.0 | 54.0 | 2.0 | 51.4 | 18.7 | | 30.0 | 7.0 | 1.8 | 17.8 | | | | |

| | | | | | | | | | | | | | | | | |
|--------------------|--------------------|------|------|------|------|-------|------|------|-----|-------|------|------|------|------------------------|-------|--------------------------------|
| Malaysia | | 9.2 | 15.2 | 24.4 | 54.6 | 22.0 | 37.6 | 1.9 | 2.6 | 14.8 | 49.0 | 1.9 | 14.5 | 7.43×10^{-10} | | |
| Malaysia | | 1.3 | 37.2 | 38.4 | 47.1 | 14.5 | 43.2 | 14.1 | 2.7 | 21.5 | 48.5 | 1.8 | 15.0 | 6.09×10^{-9} | | |
| Malaysia | | 5.1 | 50.6 | 54.7 | 32.4 | 11.9 | 59.4 | 13.0 | 2.5 | 25.9 | 48.5 | 1.5 | 20.0 | 6.51×10^{-10} | | Rosli <i>et al.</i> , 2019 |
| Malaysia | | | | 30.0 | 40.0 | 30.0 | 75.0 | 34.0 | | | | 1.4 | 30.0 | 1.90×10^8 | | Yamusa <i>et al.</i> , 2018 |
| Malaysia | | 12.0 | 49.5 | 61.5 | 34.5 | 4.0 | 45.1 | 20.2 | 2.7 | | | 1.8 | 15.5 | 1.30×10^{-7} | 295 | Alhassan, (2008) |
| Min | Min | 1.3 | 1.7 | 2.0 | 2.0 | 0.3 | 17.0 | 1.9 | 2.4 | 5.5 | 3.2 | 1.2 | 6.6 | 2.95×10^{-12} | 4.23 | |
| Max | Max | 87.0 | 60.0 | 94.0 | 96.0 | 89.0 | 95.0 | 72.9 | 3.5 | 153.0 | 49.0 | 2.8 | 34.0 | 4.96×10^{-4} | 295.0 | |
| Mean | Mean | 24.6 | 24.2 | 39.1 | 40.6 | 24.1 | 47.1 | 22.0 | 2.7 | 49.8 | 24.1 | 1.8 | 15.4 | 5.04×10^{-5} | 62.53 | |
| Standard Deviation | Standard deviation | 19.3 | 13.4 | 22.7 | 22.7 | 26.5 | 14.3 | 9.5 | 0.2 | 41.7 | 8.7 | 0.2 | 5.3 | 1.29×10^{-4} | 76.10 | |
| Cov | COV | 78.4 | 55.4 | 58.0 | 55.9 | 110.1 | 30.5 | 43.3 | 5.7 | 83.7 | 36.1 | 12.7 | 34.6 | 256.8 | 121.7 | |

OMC = Optimum moisture content; LS= Linear Shrinkage MDD = Maximum dry density; UCS = Unconfined compressive strength; UCS = Unconfined compressive strength;

Appendix 2. Details of the soil sampling location and description

| Sample Code | Latitude | Longitude | Depth(m) | Soil description | Rock Type |
|-------------|----------|-----------|----------|---|---------------------|
| SUN1 | 7°38.07' | 5°12.23' | 5.8 | Moist, light red firm silty clay | Porphyritic granite |
| SUN2 | 7°39.25' | 5°11.59' | 1.3 | Slightly moist, moderately red firm to slightly stiff sandy clays | Granite-gneiss |
| SUN3 | 7°36.93' | 5°11.86' | 2 | Moist, greyish orange, soft to firm, sandy clay | Charnockite |
| SUN4 | 7°38.07' | 5°12.23' | 5.1 | Slightly moist, pale red, firm saprolitic silty clay | Porphyritic Granite |
| SUN5 | 7°38.94' | 5°13.02' | 6.3 | Slightly moist, dark yellowish firm mottled silty clay | Porphyritic granite |
| SUN6 | 7°46.53' | 5°14.95' | 2.1 | moist light brown moderately firm sandy clay | Migmatite |
| SUN7 | 7°36.93' | 5°11.86' | 4.3 | Moist, moderate red moderately firm sandy silty clay | Charnockite |
| SUN8 | 7°41.29' | 5°15.09' | 1.8 | Moist dark yellowish orange sandy clay | Migmatite |
| SUN9 | 7°29.95' | 5°14.69' | 3.3 | moist grayish pink soft silty clay with sand | Charnockite |
| SUN10 | 7°29.95' | 5°14.69' | 5.2 | moist grayish pink soft silty clay with sand | Charnockite |
| SUN11 | 7°29.95' | 5°14.69' | 1.3 | Moist dark yellowish orange firm sandy clay | Charnockite |
| SUN12 | 7°38.07' | 5°12.23' | 6.3 | Slightly moist light brown firm sandy clay | Porphyritic granite |
| SUN13 | 7°39.25' | 5°11.59' | 3.1 | Moist light red firm silty sandy clay | Granite-gneiss |
| SUN14 | 7°38.94' | 5°13.02' | 5.7 | Moist moderate reddish brown firm silty sandy clay | Porphyritic Granite |

| | | | | | |
|-------|----------|----------|-----|--|------------------------|
| SUN15 | 7°29.95' | 5°14.69' | 4.2 | Moist dark yellowish orange firm silty sandy clay | Charnockite |
| SUN16 | 7°41.29' | 5°15.09' | 2.6 | Slightly moist, dark reddish brown silty sandy clay | Migmatite |
| SUN17 | 7°47.61' | 5°16.54' | 2.6 | moist moderate reddish brown firm silty clay | Migmatite |
| SUN18 | 7°47.61' | 5°16.54' | 1.4 | moist pale reddish brown firm sandy silty clay | Migmatite |
| SUN19 | 7°36.93' | 5°11.86' | 3.6 | Moist moderate red firm silty clay with sand | Charnockite |
| SUN20 | 7°38.07' | 5°12.23' | 2 | Moist pale red firm sandy silt | Porphyritic Granite |
| SUN21 | 7°39.25' | 5°11.59' | 2.1 | Slightly moist light red soft to firm sandy clay | Granite-gneiss |
| SUN22 | 7°38.07' | 5°12.23' | 6.1 | slightly moist dark yellowish firm orange sandy silty clay | Porphyritic Granite |
| SUN23 | 7°46.53' | 5°14.95' | 2.7 | moist mottled moderate reddish brown firm sandy silty clay | Migmatite |
| SUN24 | 7°46.53' | 5°14.95' | 3.9 | moist moderate reddish orange soft to firm silty clay | Migmatite |
| SUN25 | 7°39.25' | 5°11.59' | 2.3 | moist light red moderately firm sandy silty clay | Granite-gneiss |
| SUN26 | 7°38.07' | 5°12.23' | 1.2 | Moist moderate red firm silty clay | Porphyritic granite |
| SUN27 | 7°38.07' | 5°12.23' | 4.5 | moist light red soft to firm clayey silt | Porphyritic Granite |
| SUN28 | 7°46.53' | 5°14.95' | 1.6 | moist dark yellowish orange sandy silty clay | Migmatite |
| SUN29 | 7°38.07' | 5°12.23' | 5.8 | moist dark yellowish orange sandy silty clay | Porphyritic granite |
| SUN30 | 7°36.93' | 5°11.86' | 1.4 | Slightly moist moderate red firm clay | Charnockite |

| | | | | | |
|-------|----------|----------|-----|--|-------------|
| SUN31 | 7°27.05' | 5°02.25' | 1.2 | Slightly moist light brown firm sandy clayey silt | Migmatite |
| SUN32 | 7°38.09' | 5°06.37' | 1.5 | Slightly moist orange pink firm clayey sandy silt | Quartzite |
| SUN33 | 7°29.95' | 5°14.69' | 1.1 | Moist moderate red firm sandy clay | Charnockite |
| SUN34 | 7°38.09' | 5°06.37' | 2.3 | moist, moderate brown clayey sand | Quartzite |
| SUN35 | 7°47.50' | 5°06.37' | 1.4 | Slightly moist, moderate yellowish brown firm sandy silty clay | Schist |
| SUN36 | 7°46.50' | 5°24.17' | 1.1 | Dry moderate brown hard gravelly with concretions | Charnockite |
| SUN37 | 7°46.50' | 5°24.17' | 2.3 | Moist moderate brown soft to firm sandy clay | Charnockite |
| SUN38 | 7°38.09' | 5°24.27' | 1.2 | Moist moderate brown firm sandy clay | Migmatite |
| SUN39 | 7°38.09' | 5°24.27' | 3.1 | Slightly moist moderate orange pink, firm sandy silty clay | Migmatite |
| SUN40 | 7°42.95' | 5°23.35' | 1.2 | Moist moderate brown slightly firm silty clay with sand | Migmatite |

Appendix 3. Grain size Distribution

| SUN1 | | SUN4 | | SUN5 | | SUN12 | | SUN14 | |
|------------------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|-----------|
| Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing |
| 9.5000 | | 9.5000 | | 9.5000 | | 9.5000 | 100.00 | 9.5000 | 100.00 |
| 4.7500 | | 4.7500 | | 4.7500 | 100.00 | 4.7500 | 99.96 | 4.7500 | 91.54 |
| 2.3600 | 99.96 | 2.3600 | 100.00 | 2.3600 | 99.86 | 2.3600 | 99.82 | 2.3600 | 88.72 |
| 1.1800 | 99.22 | 1.1800 | 99.06 | 1.1800 | 98.86 | 1.1800 | 98.70 | 1.1800 | 83.52 |
| 0.6000 | 92.92 | 0.6000 | 95.22 | 0.6000 | 97.54 | 0.6000 | 96.58 | 0.6000 | 74.14 |
| 0.4250 | 84.70 | 0.4250 | 92.18 | 0.4250 | 95.90 | 0.4250 | 94.50 | 0.4250 | 68.38 |
| 0.3000 | 76.78 | 0.3000 | 88.06 | 0.3000 | 92.16 | 0.3000 | 89.90 | 0.3000 | 62.28 |
| 0.1500 | 67.48 | 0.1500 | 80.54 | 0.1500 | 85.48 | 0.1500 | 80.80 | 0.1500 | 53.94 |
| 0.0750 | 62.02 | 0.0750 | 74.60 | 0.0750 | 78.60 | 0.0750 | 73.46 | 0.0750 | 49.70 |
| 0.0580 | 56.86 | 0.0507 | 68.30 | 0.0552 | 64.98 | 0.0570 | 72.64 | 0.0594 | 49.31 |
| 0.0416 | 53.41 | 0.0366 | 65.63 | 0.0396 | 61.56 | 0.0408 | 65.10 | 0.0426 | 45.37 |
| 0.0297 | 51.69 | 0.0276 | 56.25 | 0.0287 | 56.43 | 0.0290 | 60.38 | 0.0305 | 41.42 |
| 0.0190 | 48.24 | 0.0183 | 48.22 | 0.0185 | 51.30 | 0.0185 | 56.60 | 0.0195 | 37.48 |
| 0.0112 | 43.07 | 0.0110 | 41.52 | 0.0109 | 47.88 | 0.0107 | 50.94 | 0.0113 | 35.51 |
| 0.0080 | 42.21 | 0.0079 | 36.16 | 0.0078 | 44.46 | 0.0077 | 47.17 | 0.0081 | 31.56 |
| 0.0057 | 37.91 | 0.0057 | 30.80 | 0.0056 | 41.04 | 0.0054 | 45.28 | 0.0058 | 27.62 |
| 0.0040 | 34.46 | 0.0040 | 29.46 | 0.0040 | 39.33 | 0.0039 | 41.51 | 0.0042 | 23.67 |
| 0.0029 | 32.74 | 0.0029 | 25.45 | 0.0028 | 37.62 | 0.0028 | 37.74 | 0.0030 | 21.70 |
| 0.0012 | 29.29 | 0.0012 | 22.77 | 0.0012 | 35.91 | 0.0011 | 32.08 | 0.0012 | 17.75 |

| SUN20 | | SUN22 | | SUN26 | | SUN27 | | SUN29 | |
|-------------------------|-----------|-------------------------|-----------|-------------------------|-----------|-------------------------|-----------|-------------------------|-----------|
| Particle diameter, (mm) | % Passing | Particle diameter, (mm) | % Passing | Particle diameter, (mm) | % Passing | Particle diameter, (mm) | % Passing | Particle diameter, (mm) | % Passing |
| 9.5000 | 100.00 | 9.5000 | | 9.5000 | 100.00 | 9.5000 | | 9.5000 | |
| 4.7500 | 99.68 | 4.7500 | 100.00 | 4.7500 | 93.78 | 4.7500 | 100.00 | 4.7500 | 100.00 |
| 2.3600 | 98.70 | 2.3600 | 99.72 | 2.3600 | 92.50 | 2.3600 | 99.48 | 2.3600 | 100.00 |
| 1.1800 | 95.68 | 1.1800 | 98.54 | 1.1800 | 89.32 | 1.1800 | 97.68 | 1.1800 | 99.64 |
| 0.6000 | 87.98 | 0.6000 | 96.12 | 0.6000 | 84.14 | 0.6000 | 94.58 | 0.6000 | 98.84 |
| 0.4250 | 81.90 | 0.4250 | 87.96 | 0.4250 | 80.60 | 0.4250 | 90.18 | 0.4250 | 92.80 |
| 0.3000 | 75.00 | 0.3000 | 78.34 | 0.3000 | 76.04 | 0.3000 | 84.34 | 0.3000 | 87.08 |
| 0.1500 | 64.90 | 0.1500 | 70.66 | 0.1500 | 68.06 | 0.1500 | 77.12 | 0.1500 | 83.24 |
| 0.0750 | 59.22 | 0.0750 | 63.04 | 0.0750 | 62.20 | 0.0750 | 72.30 | 0.0750 | 79.72 |
| 0.0593 | 49.99 | 0.0564 | 59.53 | 0.0590 | 59.75 | 0.0587 | 69.91 | 0.0489 | 72.95 |
| 0.0427 | 45.68 | 0.0409 | 54.40 | 0.0429 | 52.28 | 0.0417 | 69.02 | 0.0364 | 69.19 |
| 0.0313 | 36.20 | 0.0295 | 50.52 | 0.0316 | 41.08 | 0.0302 | 63.64 | 0.0260 | 64.57 |
| 0.0202 | 31.03 | 0.0189 | 48.19 | 0.0208 | 34.88 | 0.0200 | 52.88 | 0.0176 | 55.35 |
| 0.0120 | 23.27 | 0.0114 | 38.08 | 0.0121 | 30.01 | 0.0116 | 51.09 | 0.0103 | 52.27 |
| 0.0085 | 22.41 | 0.0081 | 36.53 | 0.0085 | 27.07 | 0.0082 | 50.19 | 0.0074 | 49.20 |
| 0.0060 | 22.41 | 0.0058 | 35.75 | 0.0061 | 26.14 | 0.0059 | 45.71 | 0.0053 | 46.12 |
| 0.0043 | 19.82 | 0.0041 | 34.20 | 0.0043 | 24.27 | 0.0042 | 42.13 | 0.0038 | 41.51 |
| 0.0030 | 18.10 | 0.0029 | 31.09 | 0.0031 | 22.41 | 0.0030 | 40.33 | 0.0027 | 38.44 |
| 0.0012 | 17.24 | 0.0012 | 30.31 | 0.0013 | 20.54 | 0.0012 | 37.65 | 0.0011 | 36.90 |

| SUN30 | | SUN7 | | SUN9 | | SUN10 | | SUN11 | |
|------------------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|-----------|
| Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing |
| 9.5000 | | 9.5000 | 100.00 | 9.5000 | | 9.5000 | 100.00 | 9.5000 | 100.00 |
| 4.7500 | 100.00 | 4.7500 | 99.26 | 4.7500 | 100.00 | 4.7500 | 99.48 | 4.7500 | 99.02 |
| 2.3600 | 99.5 | 2.3600 | 98.28 | 2.3600 | 98.18 | 2.3600 | 96.88 | 2.3600 | 97.16 |
| 1.1800 | 95.7 | 1.1800 | 96.98 | 1.1800 | 88.38 | 1.1800 | 91.52 | 1.1800 | 92.52 |
| 0.6000 | 88.9 | 0.6000 | 93.36 | 0.6000 | 76.94 | 0.6000 | 84.72 | 0.6000 | 84.20 |
| 0.4250 | 85.2 | 0.4250 | 84.96 | 0.4250 | 71.44 | 0.4250 | 80.68 | 0.4250 | 79.80 |
| 0.3000 | 81.0 | 0.3000 | 74.50 | 0.3000 | 66.02 | 0.3000 | 76.36 | 0.3000 | 75.28 |
| 0.1500 | 75.3 | 0.1500 | 61.64 | 0.1500 | 58.72 | 0.1500 | 71.54 | 0.1500 | 69.06 |
| 0.0750 | 72.1 | 0.0750 | 54.64 | 0.0750 | 54.24 | 0.0750 | 69.04 | 0.0750 | 66.02 |
| 0.0593 | 69.15 | 0.0582 | 45.81 | 0.0596 | 53.83 | 0.0505 | 68.03 | 0.0579 | 66.63 |
| 0.0423 | 67.12 | 0.0418 | 42.75 | 0.0429 | 49.49 | 0.0363 | 64.45 | 0.0413 | 64.78 |
| 0.0303 | 63.05 | 0.0299 | 39.70 | 0.0309 | 45.14 | 0.0258 | 62.66 | 0.0293 | 63.85 |
| 0.0193 | 61.02 | 0.0194 | 33.59 | 0.0197 | 42.54 | 0.0170 | 53.71 | 0.0186 | 62.93 |
| 0.0112 | 58.98 | 0.0114 | 30.54 | 0.0115 | 40.80 | 0.0099 | 51.03 | 0.0108 | 62.00 |
| 0.0081 | 54.91 | 0.0081 | 29.01 | 0.0082 | 39.07 | 0.0071 | 48.34 | 0.0076 | 61.07 |
| 0.0058 | 50.85 | 0.0058 | 27.48 | 0.0058 | 39.07 | 0.0050 | 46.55 | 0.0054 | 59.22 |
| 0.0041 | 46.78 | 0.0041 | 25.96 | 0.0041 | 39.07 | 0.0036 | 44.76 | 0.0039 | 57.37 |
| 0.0030 | 42.71 | 0.0029 | 24.43 | 0.0029 | 38.20 | 0.0026 | 42.97 | 0.0028 | 53.67 |
| 0.0012 | 40.68 | 0.0012 | 23.67 | 0.0012 | 36.46 | 0.0010 | 41.18 | 0.0011 | 51.82 |

| SUN15 | | SUN | | SUN3 | | SUN36 | | SUN19 | |
|------------------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|-----------|
| Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing |
| 9.5000 | 100.00 | 9.5000 | 100.00 | 9.5000 | 100.00 | 9.5000 | 100.00 | 9.5000 | 100.00 |
| 4.7500 | 100.00 | 4.7500 | 93.96 | 4.7500 | 83.63 | 4.7500 | 99.12 | 4.7500 | 78.72 |
| 2.3600 | 99.56 | 2.3600 | 90.50 | 2.3600 | 78.30 | 2.3600 | 97.88 | 2.3600 | 60.00 |
| 1.1800 | 96.94 | 1.1800 | 86.36 | 1.1800 | 73.77 | 1.1800 | 94.64 | 1.1800 | 51.52 |
| 0.6000 | 91.98 | 0.6000 | 81.52 | 0.6000 | 68.97 | 0.6000 | 86.34 | 0.6000 | 45.76 |
| 0.4250 | 88.32 | 0.4250 | 78.76 | 0.4250 | 66.07 | 0.4250 | 81.74 | 0.4250 | 43.64 |
| 0.3000 | 83.72 | 0.3000 | 75.32 | 0.3000 | 62.00 | 0.3000 | 77.88 | 0.3000 | 41.56 |
| 0.1500 | 76.90 | 0.1500 | 70.70 | 0.1500 | 55.27 | 0.1500 | 73.34 | 0.1500 | 38.48 |
| 0.0750 | 73.02 | 0.0750 | 67.48 | 0.0750 | 51.23 | 0.0750 | 70.66 | 0.0750 | 36.62 |
| 0.0468 | 71.10 | 0.0570 | 62.28 | 0.0635 | 47.75 | 0.0544 | 66.43 | 0.0607 | 34.00 |
| 0.0334 | 69.48 | 0.0407 | 60.55 | 0.0455 | 44.07 | 0.0388 | 64.73 | 0.0433 | 31.74 |
| 0.0240 | 66.25 | 0.0290 | 58.82 | 0.0320 | 42.91 | 0.0277 | 63.03 | 0.0308 | 30.23 |
| 0.0155 | 63.02 | 0.0187 | 53.63 | 0.0208 | 38.56 | 0.0176 | 61.32 | 0.0196 | 28.71 |
| 0.0090 | 61.40 | 0.0110 | 50.17 | 0.0121 | 35.81 | 0.0103 | 59.62 | 0.0114 | 27.20 |
| 0.0066 | 54.94 | 0.0078 | 48.44 | 0.0086 | 34.89 | 0.0073 | 57.92 | 0.0081 | 25.69 |
| 0.0047 | 53.33 | 0.0056 | 46.71 | 0.0061 | 33.05 | 0.0052 | 56.21 | 0.0058 | 24.18 |
| 0.0034 | 50.09 | 0.0039 | 46.71 | 0.0043 | 32.14 | 0.0037 | 55.36 | 0.0041 | 22.67 |
| 0.0024 | 45.25 | 0.0028 | 44.98 | 0.0031 | 31.22 | 0.0026 | 52.81 | 0.0029 | 21.16 |
| 0.0010 | 40.40 | 0.0011 | 44.98 | 0.0013 | 29.38 | 0.0011 | 51.10 | 0.0012 | 19.65 |

| SUN24 | | SUN28 | | SUN38 | | SUN39 | | SUN40 | |
|------------------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|-----------|
| Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing |
| 9.5000 | 100.00 | 9.5000 | 100.00 | 9.5000 | 100.00 | 9.5000 | 100.00 | 9.5000 | |
| 4.7500 | 96.54 | 4.7500 | 99.90 | 4.7500 | 99.98 | 4.7500 | 99.48 | 4.7500 | 99.98 |
| 2.3600 | 92.96 | 2.3600 | 99.90 | 2.3600 | 99.80 | 2.3600 | 96.04 | 2.3600 | 99.68 |
| 1.1800 | 90.04 | 1.1800 | 98.22 | 1.1800 | 98.76 | 1.1800 | 86.86 | 1.1800 | 98.12 |
| 0.6000 | 86.46 | 0.6000 | 89.02 | 0.6000 | 95.20 | 0.6000 | 74.22 | 0.6000 | 90.30 |
| 0.4250 | 83.90 | 0.4250 | 83.08 | 0.4250 | 92.38 | 0.4250 | 69.68 | 0.4250 | 84.10 |
| 0.3000 | 81.00 | 0.3000 | 77.90 | 0.3000 | 88.96 | 0.3000 | 65.80 | 0.3000 | 80.64 |
| 0.1500 | 76.68 | 0.1500 | 69.64 | 0.1500 | 81.70 | 0.1500 | 61.16 | 0.1500 | 75.82 |
| 0.0750 | 73.94 | 0.0750 | 62.70 | 0.0750 | 76.50 | 0.0750 | 58.78 | 0.0750 | 69.76 |
| 0.0564 | 72.12 | 0.0584 | 56.62 | 0.0364 | 72.26 | 0.0593 | 56.84 | 0.0555 | 65.49 |
| 0.0402 | 70.27 | 0.0416 | 54.96 | 0.0260 | 70.72 | 0.0422 | 55.00 | 0.0396 | 63.77 |
| 0.0295 | 61.95 | 0.0295 | 54.12 | 0.0176 | 58.42 | 0.0301 | 53.17 | 0.0282 | 62.04 |
| 0.0189 | 58.25 | 0.0188 | 53.29 | 0.0103 | 55.35 | 0.0191 | 51.33 | 0.0180 | 60.32 |
| 0.0110 | 56.40 | 0.0109 | 52.46 | 0.0074 | 52.27 | 0.0111 | 49.50 | 0.0105 | 58.60 |
| 0.0078 | 54.55 | 0.0077 | 52.46 | 0.0053 | 49.20 | 0.0079 | 47.67 | 0.0075 | 56.87 |
| 0.0056 | 53.63 | 0.0055 | 51.63 | 0.0038 | 47.66 | 0.0056 | 45.83 | 0.0053 | 55.15 |
| 0.0040 | 50.85 | 0.0039 | 49.96 | 0.0027 | 46.12 | 0.0040 | 44.00 | 0.0038 | 53.43 |
| 0.0029 | 46.23 | 0.0028 | 45.80 | 0.0011 | 44.59 | 0.0029 | 42.17 | 0.0027 | 50.84 |
| 0.0012 | 38.83 | 0.0011 | 44.96 | 0.0011 | 44.59 | 0.0012 | 38.50 | 0.0011 | 48.26 |

| SUN6 | | SUN16 | | SUN17 | | SUN18 | | SUN23 | |
|------------------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|-----------|
| Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing |
| 9.5000 | 100.00 | 9.5000 | 100.00 | 9.5000 | 100.00 | 9.5000 | 100.00 | 9.5000 | 100.00 |
| 4.7500 | 99.94 | 4.7500 | 100.00 | 4.7500 | 98.14 | 4.7500 | 99.90 | 4.7500 | 98.94 |
| 2.3600 | 98.80 | 2.3600 | 99.30 | 2.3600 | 96.78 | 2.3600 | 99.60 | 2.3600 | 97.04 |
| 1.1800 | 93.00 | 1.1800 | 96.08 | 1.1800 | 94.20 | 1.1800 | 97.60 | 1.1800 | 89.38 |
| 0.6000 | 81.20 | 0.6000 | 89.86 | 0.6000 | 83.88 | 0.6000 | 90.76 | 0.6000 | 77.66 |
| 0.4250 | 75.90 | 0.4250 | 81.64 | 0.4250 | 76.76 | 0.4250 | 86.48 | 0.4250 | 72.48 |
| 0.3000 | 70.50 | 0.3000 | 73.72 | 0.3000 | 70.68 | 0.3000 | 81.20 | 0.3000 | 66.66 |
| 0.1500 | 61.70 | 0.1500 | 64.42 | 0.1500 | 63.46 | 0.1500 | 70.70 | 0.1500 | 58.12 |
| 0.0750 | 56.20 | 0.0750 | 58.96 | 0.0750 | 59.38 | 0.0750 | 64.02 | 0.0750 | 52.54 |
| 0.0613 | 53.04 | 0.0526 | 48.91 | 0.0580 | 59.07 | 0.0621 | 61.65 | 0.0634 | 49.37 |
| 0.0439 | 49.50 | 0.0377 | 46.04 | 0.0413 | 57.28 | 0.0445 | 57.54 | 0.0455 | 45.42 |
| 0.0323 | 38.89 | 0.0273 | 41.72 | 0.0301 | 50.12 | 0.0322 | 51.37 | 0.0328 | 39.50 |
| 0.0206 | 37.13 | 0.0174 | 40.28 | 0.0194 | 44.75 | 0.0204 | 50.34 | 0.0210 | 35.55 |
| 0.0120 | 35.36 | 0.0102 | 35.97 | 0.0114 | 41.17 | 0.0118 | 50.34 | 0.0122 | 34.56 |
| 0.0085 | 33.59 | 0.0073 | 34.53 | 0.0081 | 37.59 | 0.0084 | 46.23 | 0.0086 | 34.56 |
| 0.0061 | 31.82 | 0.0053 | 30.21 | 0.0058 | 37.59 | 0.0060 | 46.23 | 0.0061 | 33.57 |
| 0.0043 | 28.29 | 0.0037 | 28.77 | 0.0041 | 36.70 | 0.0042 | 46.23 | 0.0044 | 29.62 |
| 0.0031 | 22.98 | 0.0027 | 27.33 | 0.0029 | 36.70 | 0.0030 | 45.21 | 0.0031 | 26.66 |
| 0.0013 | 19.45 | 0.0011 | 21.58 | 0.0012 | 36.70 | 0.0012 | 45.21 | 0.0013 | 24.69 |

| SUN2 | | SUN13 | | SUN21 | | SUN25 | | SUN35 | |
|------------------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|-----------|
| Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing | Particle diameter (mm) | % Passing |
| 9.5000 | 100.00 | 9.5000 | 100.00 | 9.5000 | 100.00 | 9.5000 | | 9.5000 | 100.00 |
| 4.7500 | 99.50 | 4.7500 | 99.68 | 4.7500 | 94.66 | 4.7500 | | 4.7500 | 99.10 |
| 2.3600 | 98.5 | 2.3600 | 98.58 | 2.3600 | 92.74 | 2.3600 | 100.00 | 2.3600 | 98.72 |
| 1.1800 | 94.6 | 1.1800 | 93.40 | 1.1800 | 88.42 | 1.1800 | 97.81 | 1.1800 | 98.08 |
| 0.6000 | 82.2 | 0.6000 | 78.38 | 0.6000 | 83.72 | 0.6000 | 91.69 | 0.6000 | 96.80 |
| 0.4250 | 72.8 | 0.4250 | 70.40 | 0.4250 | 79.82 | 0.4250 | 80.23 | 0.4250 | 95.18 |
| 0.3000 | 63.7 | 0.3000 | 63.72 | 0.3000 | 74.44 | 0.3000 | 65.96 | 0.3000 | 89.10 |
| 0.1500 | 50.7 | 0.1500 | 55.70 | 0.1500 | 66.56 | 0.1500 | 50.16 | 0.1500 | 70.92 |
| 0.0750 | 45.1 | 0.0750 | 52.08 | 0.0750 | 62.22 | 0.0750 | 39.36 | 0.0750 | 62.32 |
| 0.0617 | 44.40 | 0.0628 | 48.96 | 0.0532 | 60.50 | 0.0644 | 37.99 | 0.0550 | 60.02 |
| 0.0438 | 43.51 | 0.0447 | 46.92 | 0.0382 | 57.48 | 0.0458 | 36.18 | 0.0392 | 58.48 |
| 0.0310 | 42.63 | 0.0318 | 44.88 | 0.0273 | 55.96 | 0.0326 | 34.37 | 0.0279 | 56.94 |
| 0.0199 | 39.07 | 0.0203 | 42.84 | 0.0174 | 54.45 | 0.0208 | 32.56 | 0.0178 | 55.40 |
| 0.0116 | 37.30 | 0.0118 | 40.80 | 0.0101 | 52.94 | 0.0121 | 30.75 | 0.0104 | 53.87 |
| 0.0082 | 35.52 | 0.0084 | 38.76 | 0.0072 | 50.67 | 0.0086 | 28.94 | 0.0074 | 52.33 |
| 0.0059 | 33.75 | 0.0060 | 36.72 | 0.0051 | 49.91 | 0.0061 | 27.13 | 0.0053 | 50.79 |
| 0.0042 | 31.97 | 0.0042 | 34.68 | 0.0037 | 48.40 | 0.0043 | 25.32 | 0.0037 | 49.25 |
| 0.0030 | 30.19 | 0.0030 | 32.64 | 0.0026 | 48.40 | 0.0031 | 22.61 | 0.0027 | 47.71 |
| 0.0012 | 28.42 | 0.0012 | 32.64 | 0.0011 | 46.89 | 0.0013 | 19.90 | 0.0011 | 44.63 |

Appendix 4. Atteberg limits

| ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318) | | | | | | |
|--|--------|------------------------|--------|-------------|-------------------------|-----------------|
| Sample No.: | | SUN1 | | Boring No.: | | |
| Soil Description : | | Casagrande method | | | | |
| LIQUID LIMIT, LL TEST | | | | LL = 44.8 % | | |
| Test No. | 1 | 2 | 3 | 4 | | |
| Container No. | A | B | C | D | | |
| Wet Soil & Container g | 34.51 | 34.12 | 35.50 | 34.51 | | |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 | | |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 | | |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 | | |
| Loss of Water g | 5.91 | 6.02 | 6.80 | 6.91 | | |
| Moisture Content % | 41.63 | 43.34 | 45.04 | 47.31 | | |
| Number of Blows | 46 | 33 | 24 | 16 | | |
| PLASTIC LIMIT, PL TEST | | | | | | |
| Test No. | 1 | 2 | | | | |
| Container No. | A | B | | | | |
| Wet Soil & Container g | 9.80 | 9.80 | | | | |
| Dry Soil & Container g | 9.40 | 9.40 | | | | |
| Container Empty g | 7.80 | 7.80 | | | | |
| Dry Soil g | 1.60 | 1.60 | | | | |
| Loss of Water g | 0.40 | 0.40 | | | | |
| Moisture Content % | 25.00 | 25.00 | | | | |
| Plastic Limit, PL = | 25.0 % | | | | | |
| | | | | | | |
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | |
| | | Test No. | 1 | 2 | Plasticity Index | 19.82 |
| Original Length, L_o (mm) | 134 | Container No. | A | B | Consistency Index | 1.71 |
| | | Wet Soil & Container g | 286.20 | 286.20 | (Very stiff) | |
| Final Length, L_f (mm) | 126 | Dry Soil & Container g | 261.70 | 261.70 | | Liquidity Index |
| | | Container Empty g | 35.70 | 35.70 | | |
| Linear Shrinkage = | 6.0 | Dry Soil g | 226.00 | 226.00 | | |
| $(1-(L_f/L_o))*100$ | | Loss of Water g | 24.50 | 24.50 | Flow Index | 6.59 |
| Shrinkage limit = | 11.4 | Moisture Content % | 10.84 | 10.84 | | |
| | | Moisture Content % = | 10.8 % | | Swell Index | 0.24 |

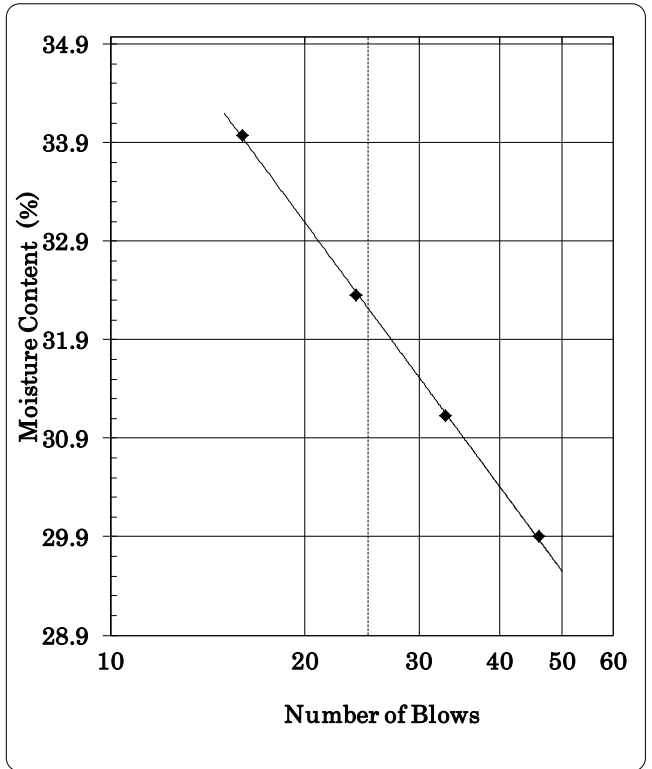
ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: SUN2

Boring No.:

Casagrande method

| LIQUID LIMIT, LL TEST | | LL = 32.2 % | | | |
|------------------------------|---|-------------|-------|-------|-------|
| Test No. | | 1 | 2 | 3 | 4 |
| Container No. | | A | B | C | D |
| Wet Soil & Container | g | 32.84 | 32.42 | 33.58 | 32.56 |
| Dry Soil & Container | g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty | g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil | g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water | g | 4.24 | 4.32 | 4.88 | 4.96 |
| Moisture Content | % | 29.88 | 31.11 | 32.33 | 33.95 |
| Number of Blows | | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | | |
|-------------------------------|---|--------|-------|
| Test No. | 1 | 2 | |
| Container No. | A | B | |
| Wet Soil & Container | g | 0.00 | 9.80 |
| Dry Soil & Container | g | 0.00 | 9.40 |
| Container Empty | g | 7.80 | 7.80 |
| Dry Soil | g | -7.80 | 1.60 |
| Loss of Water | g | 0.00 | 0.40 |
| Moisture Content | % | 0.00 | 25.00 |
| Plastic Limit, PL | = | 12.5 % | |

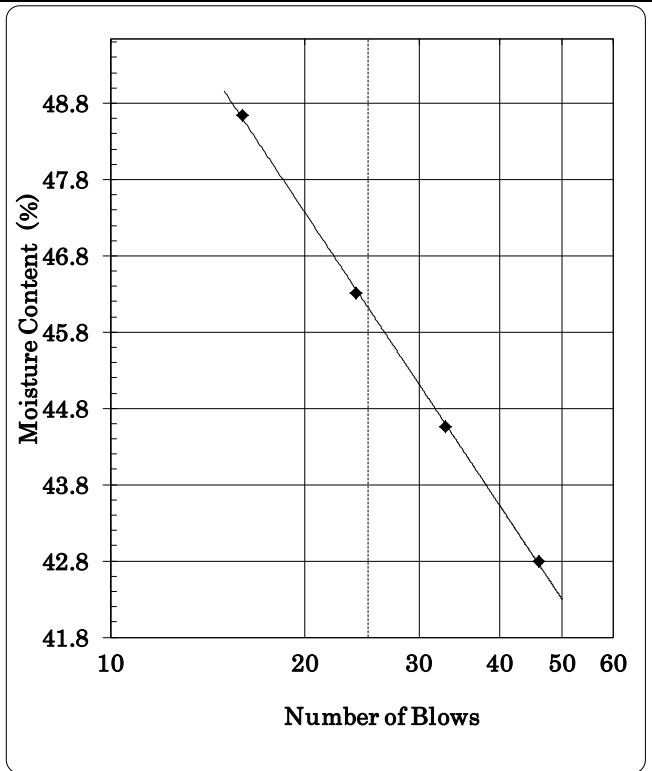
| LINEAR SHRINKAGE | | Moisture Content Test | | | | USCS GROUP SYMBOL: (OL) | |
|-----------------------------|------|------------------------------|-----|--------|------------------|--------------------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 19.67 | |
| Original Length, L_o (mm) | 140 | Container No. | A | B | | | |
| | | Wet Soil & Container | g | 315.50 | 315.50 | Consistency Index | 1.13 |
| Final Length, L_f (mm) | 136 | Dry Soil & Container | g | 290.10 | 290.10 | | (Very stiff) |
| | | Container Empty | g | 34.40 | 34.40 | Liquidity Index | -0.13 |
| Linear Shrinkage = | 2.9 | Dry Soil | g | 255.70 | 255.70 | | |
| $(1 - (L_f/L_o)) * 100$ | | Loss of Water | g | 25.40 | 25.40 | Flow Index | 6.59 |
| Shrinkage limit = | 13.4 | Moisture Content | % | 9.93 | 9.93 | | |
| | | Moisture Content | % = | 9.9 % | | Swell Index | 0.31 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: SUN3

Casagrande method

| LIQUID LIMIT, LL TEST | | | | LL = | 46.1 % |
|------------------------------|-------|-------|-------|-------|--------|
| Test No. | 1 | 2 | 3 | 4 | |
| Container No. | A | B | C | D | |
| Wet Soil & Container g | 34.68 | 34.30 | 35.70 | 34.70 | |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 | |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 | |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 | |
| Loss of Water g | 6.08 | 6.20 | 7.00 | 7.10 | |
| Moisture Content % | 42.82 | 44.58 | 46.33 | 48.66 | |
| Number of Blows | 46 | 33 | 24 | 16 | |



| PLASTIC LIMIT, PL TEST | | |
|-------------------------------|--------|-------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 15.10 | 15.10 |
| Dry Soil & Container g | 14.90 | 14.90 |
| Container Empty g | 13.70 | 13.70 |
| Dry Soil g | 1.20 | 1.20 |
| Loss of Water g | 0.20 | 0.20 |
| Moisture Content % | 16.67 | 16.67 |
| Plastic Limit, PL = | 16.7 % | |

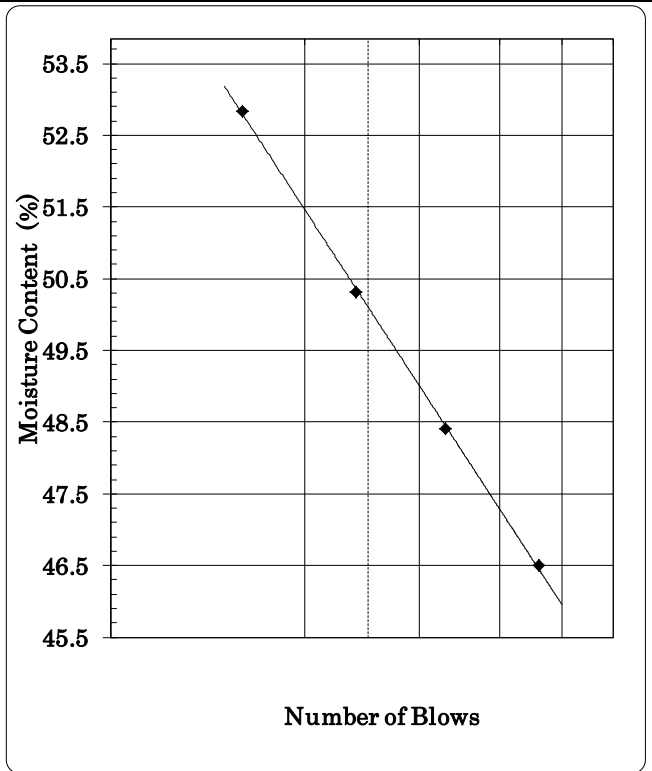
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | |
|-----------------------------|------|------------------------------|--------|--------|--------------------------------|--------|
| | | Test No. | 1 | 2 | Plasticity Index | 29.43 |
| Original Length, L_o (mm) | 134 | Container No. | A | B | | |
| | | Wet Soil & Container g | 283.60 | 283.60 | Consistency Index | 0.29 |
| Final Length, L_f (mm) | 125 | Dry Soil & Container g | 215.90 | 215.90 | | (Soft) |
| | | Container Empty g | 35.20 | 35.20 | Liquidity Index | 0.71 |
| Linear Shrinkage = | 6.7 | Dry Soil g | 180.70 | 180.70 | | |
| $(1 - (L_f/L_o)) * 100$ | | Loss of Water g | 67.70 | 67.70 | Flow Index | 6.59 |
| Shrinkage limit = | 10.9 | Moisture Content % | 37.47 | 37.47 | | |
| | | Moisture Content % = | 37.5 % | | Swell Index | 0.81 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: SUN4

Casagrande method

| LIQUID LIMIT, LL TEST | | LL = 50.1 % | | | |
|------------------------------|---|-------------|-------|-------|-------|
| Test No. | | 1 | 2 | 3 | 4 |
| Container No. | | A | B | C | D |
| Wet Soil & Container | g | 35.21 | 34.83 | 36.30 | 35.32 |
| Dry Soil & Container | g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty | g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil | g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water | g | 6.61 | 6.73 | 7.60 | 7.72 |
| Moisture Content | % | 46.53 | 48.44 | 50.34 | 52.87 |
| Number of Blows | | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | | |
|-------------------------------|---|--------|-------|
| Test No. | 1 | 2 | |
| Container No. | A | B | |
| Wet Soil & Container | g | 11.10 | 11.10 |
| Dry Soil & Container | g | 10.70 | 10.70 |
| Container Empty | g | 9.30 | 9.30 |
| Dry Soil | g | 1.40 | 1.40 |
| Loss of Water | g | 0.40 | 0.40 |
| Moisture Content | % | 28.57 | 28.57 |
| Plastic Limit, PL | = | 28.6 % | |

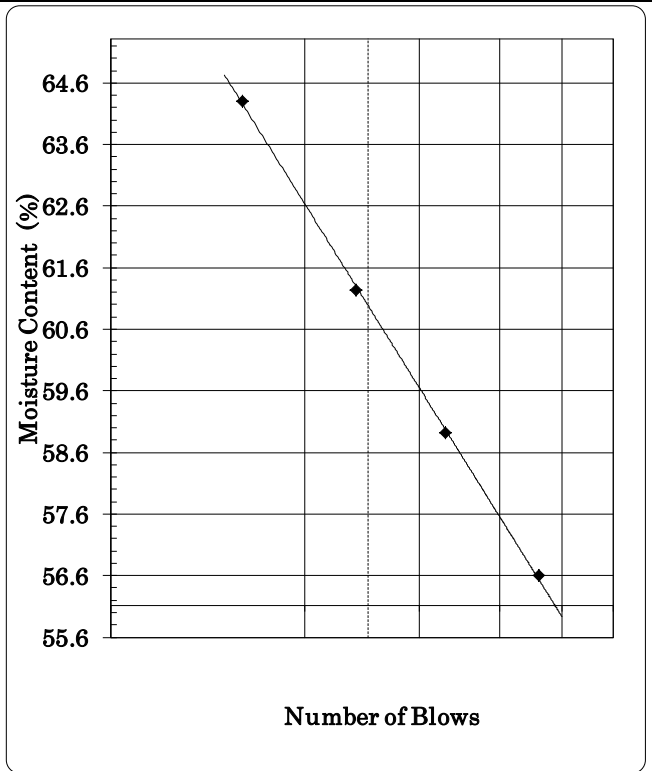
| LINEAR SHRINKAGE | | Moisture Content Test | | | | USCS GROUP SYMBOL: (0H) | |
|-----------------------------|------|------------------------------|-----|--------|------------------|--------------------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 21.52 | |
| Original Length, L_o (mm) | 140 | Container No. | A | B | | | |
| | | Wet Soil & Container | g | 262.00 | 262.00 | Consistency Index | 1.86 |
| Final Length, L_f (mm) | 129 | Dry Soil & Container | g | 240.10 | 240.10 | | (Very stiff) |
| | | Container Empty | g | 22.80 | 22.80 | Liquidity Index | -0.86 |
| Linear Shrinkage = | 7.9 | Dry Soil | g | 217.30 | 217.30 | | |
| $(1 - (L_f/L_o)) * 100$ | | Loss of Water | g | 21.90 | 21.90 | Flow Index | 6.59 |
| Shrinkage limit = | 10.1 | Moisture Content | % | 10.08 | 10.08 | | |
| | | Moisture Content | % = | 10.1 % | | Swell Index | 0.20 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: SUN5

Casagrande method

| LIQUID LIMIT, LL TEST | | | LL = 60.9 % | |
|------------------------|-------|-------|-------------|-------|
| Test No. | 1 | 2 | 3 | 4 |
| Container No. | A | B | C | D |
| Wet Soil & Container g | 36.64 | 36.29 | 37.95 | 36.99 |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water g | 8.04 | 8.19 | 9.25 | 9.39 |
| Moisture Content % | 56.60 | 58.92 | 61.23 | 64.31 |
| Number of Blows | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | |
|------------------------|--------|-------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 9.70 | 9.70 |
| Dry Soil & Container g | 9.30 | 9.30 |
| Container Empty g | 8.50 | 8.50 |
| Dry Soil g | 0.80 | 0.80 |
| Loss of Water g | 0.40 | 0.40 |
| Moisture Content % | 50.00 | 50.00 |
| Plastic Limit, PL = | 50.0 % | |

| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (0H) | |
|---|------|------------------------|--------|--------|-------------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 10.93 |
| Original Length, L _o (mm) | 134 | Container No. | A | B | | |
| | | Wet Soil & Container g | 270.20 | 270.20 | Consistency Index | 4.79 |
| Final Length, L _f (mm) | 130 | Dry Soil & Container g | 251.60 | 251.60 | | (Very stiff) |
| | | Container Empty g | 35.60 | 35.60 | Liquidity Index | -3.79 |
| Linear Shrinkage = | 3.0 | Dry Soil g | 216.00 | 216.00 | | |
| (1-(L _f /L _o))*100 | | Loss of Water g | 18.60 | 18.60 | Flow Index | 6.59 |
| Shrinkage limit = | 13.3 | Moisture Content % | 8.61 | 8.61 | | |
| | | Moisture Content % = | 8.6 % | | Swell Index | 0.14 |

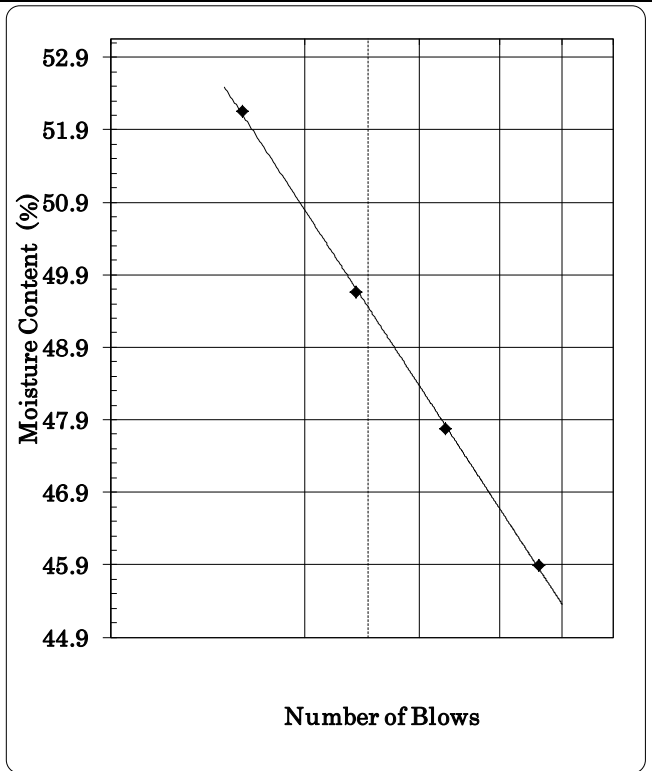
ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: SUN8

Casagrande method

| LIQUID LIMIT, LL TEST | | | LL = 49.4 % | |
|------------------------|-------|-------|-------------|-------|
| Test No. | 1 | 2 | 3 | 4 |
| Container No. | A | B | C | D |
| Wet Soil & Container g | 35.12 | 34.74 | 36.20 | 35.21 |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water g | 6.52 | 6.64 | 7.50 | 7.61 |
| Moisture Content % | 45.90 | 47.78 | 49.65 | 52.15 |
| Number of Blows | 46 | 33 | 24 | 16 |

| PLASTIC LIMIT, PL TEST | | |
|------------------------|--------|-------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 14.90 | 14.90 |
| Dry Soil & Container g | 14.70 | 14.70 |
| Container Empty g | 13.90 | 13.90 |
| Dry Soil g | 0.80 | 0.80 |
| Loss of Water g | 0.20 | 0.20 |
| Moisture Content % | 25.00 | 25.00 |
| Plastic Limit, PL = | 25.0 % | |



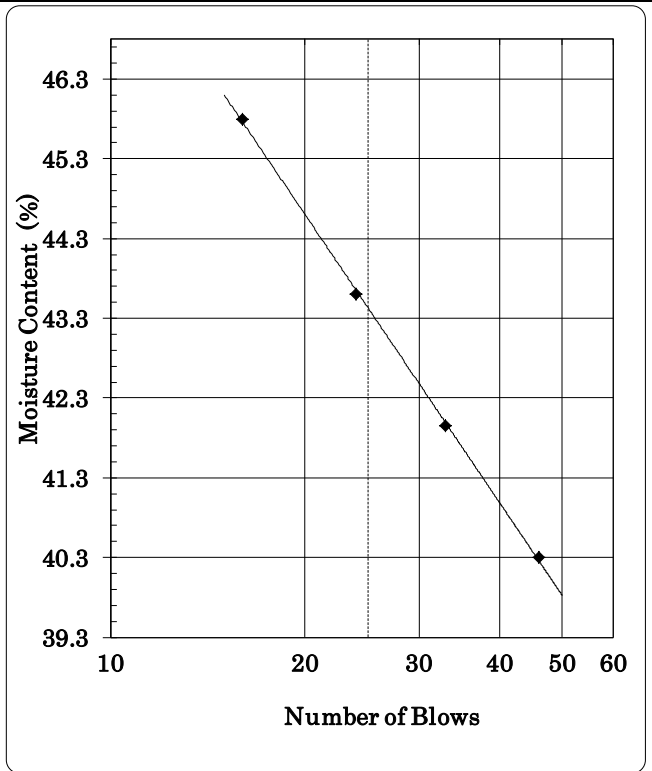
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | |
|-----------------------------|------|------------------------|--------|--------|-------------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 24.41 |
| Original Length, L_o (mm) | 140 | Container No. | A | B | | |
| | | Wet Soil & Container g | 271.10 | 271.10 | Consistency Index | 1.38 |
| Final Length, L_f (mm) | 118 | Dry Soil & Container g | 241.30 | 241.30 | | (Very stiff) |
| | | Container Empty g | 51.80 | 51.80 | Liquidity Index | -0.38 |
| Linear Shrinkage = | 15.7 | Dry Soil g | 189.50 | 189.50 | | |
| $(1 - (L_f/L_o)) * 100$ | | Loss of Water g | 29.80 | 29.80 | Flow Index | 6.59 |
| Shrinkage limit = | 4.9 | Moisture Content % | 15.73 | 15.73 | | |
| | | Moisture Content % = | 15.7 % | | Swell Index | 0.32 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: SUN10

Casagrande method

| LIQUID LIMIT, LL TEST | | | | LL = | 43.4 % |
|------------------------------|-------|-------|-------|-------|--------|
| Test No. | 1 | 2 | 3 | 4 | |
| Container No. | A | B | C | D | |
| Wet Soil & Container g | 34.33 | 33.94 | 35.29 | 34.29 | |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 | |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 | |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 | |
| Loss of Water g | 5.73 | 5.84 | 6.59 | 6.69 | |
| Moisture Content % | 40.34 | 42.00 | 43.65 | 45.84 | |
| Number of Blows | 46 | 33 | 24 | 16 | |



| PLASTIC LIMIT, PL TEST | | |
|-------------------------------|--------|-------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 10.10 | 10.10 |
| Dry Soil & Container g | 9.30 | 9.30 |
| Container Empty g | 7.10 | 7.10 |
| Dry Soil g | 2.20 | 2.20 |
| Loss of Water g | 0.80 | 0.80 |
| Moisture Content % | 36.36 | 36.36 |
| Plastic Limit, PL = | 36.4 % | |

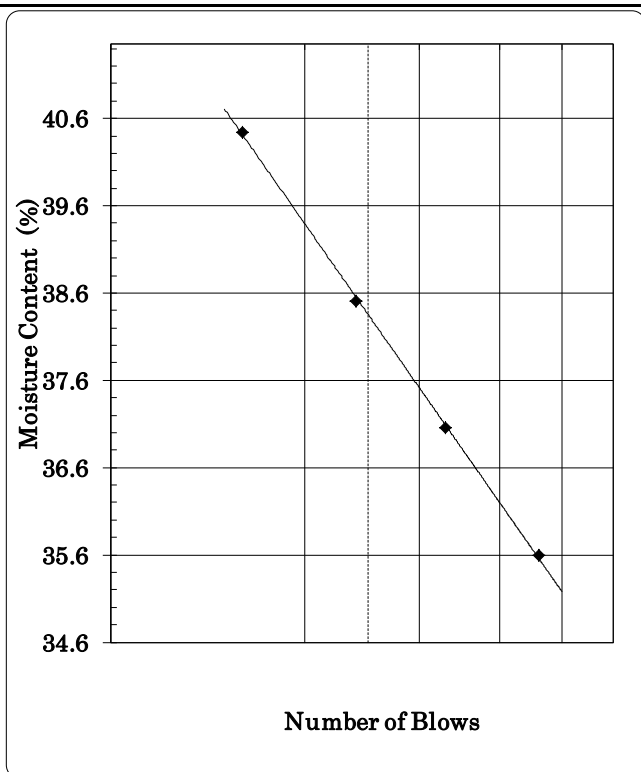
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | |
|-----------------------------|------|------------------------------|--------|--------|--------------------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 7.07 |
| Original Length, L_o (mm) | 134 | Container No. | A | B | | |
| | | Wet Soil & Container g | 290.50 | 290.50 | Consistency Index | 3.64 |
| Final Length, L_f (mm) | 125 | Dry Soil & Container g | 251.90 | 251.90 | | (Very stiff) |
| | | Container Empty g | 33.70 | 33.70 | Liquidity Index | -2.64 |
| Linear Shrinkage = | 6.7 | Dry Soil g | 218.20 | 218.20 | | |
| $(1 - (L_f/L_o)) * 100$ | | Loss of Water g | 38.60 | 38.60 | Flow Index | 6.59 |
| Shrinkage limit = | 10.9 | Moisture Content % | 17.69 | 17.69 | | |
| | | Moisture Content % = | 17.7 % | | Swell Index | 0.41 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: 12

Casagrande method

| LIQUID LIMIT, LL TEST | | | | LL = | 38.3 % |
|------------------------------|-------|-------|-------|-------|--------|
| Test No. | 1 | 2 | 3 | 4 | |
| Container No. | A | B | C | D | |
| Wet Soil & Container g | 33.65 | 33.25 | 34.51 | 33.50 | |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 | |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 | |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 | |
| Loss of Water g | 5.05 | 5.15 | 5.81 | 5.90 | |
| Moisture Content % | 35.58 | 37.03 | 38.49 | 40.43 | |
| Number of Blows | 46 | 33 | 24 | 16 | |



| PLASTIC LIMIT, PL TEST | | |
|-------------------------------|--------|-------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 9.10 | 9.10 |
| Dry Soil & Container g | 8.90 | 8.90 |
| Container Empty g | 7.90 | 7.90 |
| Dry Soil g | 1.00 | 1.00 |
| Loss of Water g | 0.20 | 0.20 |
| Moisture Content % | 20.00 | 20.00 |
| Plastic Limit, PL = | 20.0 % | |

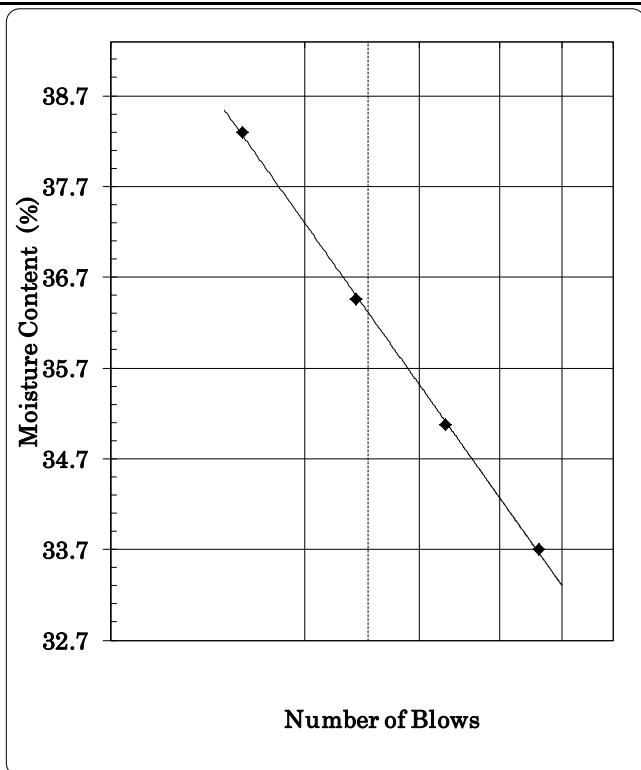
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | |
|-----------------------------|------|------------------------------|--------|--------|--------------------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 18.30 |
| Original Length, L_o (mm) | 140 | Container No. | A | B | | |
| | | Wet Soil & Container g | 260.20 | 260.20 | Consistency Index | 1.74 |
| Final Length, L_f (mm) | 133 | Dry Soil & Container g | 247.30 | 247.30 | | (Very stiff) |
| | | Container Empty g | 48.60 | 48.60 | Liquidity Index | -0.74 |
| Linear Shrinkage = | 5.0 | Dry Soil g | 198.70 | 198.70 | | |
| $(1 - (L_f/L_o)) * 100$ | | Loss of Water g | 12.90 | 12.90 | Flow Index | 6.59 |
| Shrinkage limit = | 12.0 | Moisture Content % | 6.49 | 6.49 | | |
| | | Moisture Content % = | 6.5 % | | Swell Index | 0.17 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: 13

Casagrande method

| LIQUID LIMIT, LL TEST | | | LL = 36.3 % | |
|------------------------|-------|-------|-------------|-------|
| Test No. | 1 | 2 | 3 | 4 |
| Container No. | A | B | C | D |
| Wet Soil & Container g | 33.39 | 32.98 | 34.21 | 33.20 |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water g | 4.79 | 4.88 | 5.51 | 5.60 |
| Moisture Content % | 33.73 | 35.11 | 36.49 | 38.32 |
| Number of Blows | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | |
|------------------------|--------|-------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 11.30 | 11.30 |
| Dry Soil & Container g | 11.00 | 11.00 |
| Container Empty g | 10.10 | 10.10 |
| Dry Soil g | 0.90 | 0.90 |
| Loss of Water g | 0.30 | 0.30 |
| Moisture Content % | 33.33 | 33.33 |
| Plastic Limit, PL = | 33.3 % | |

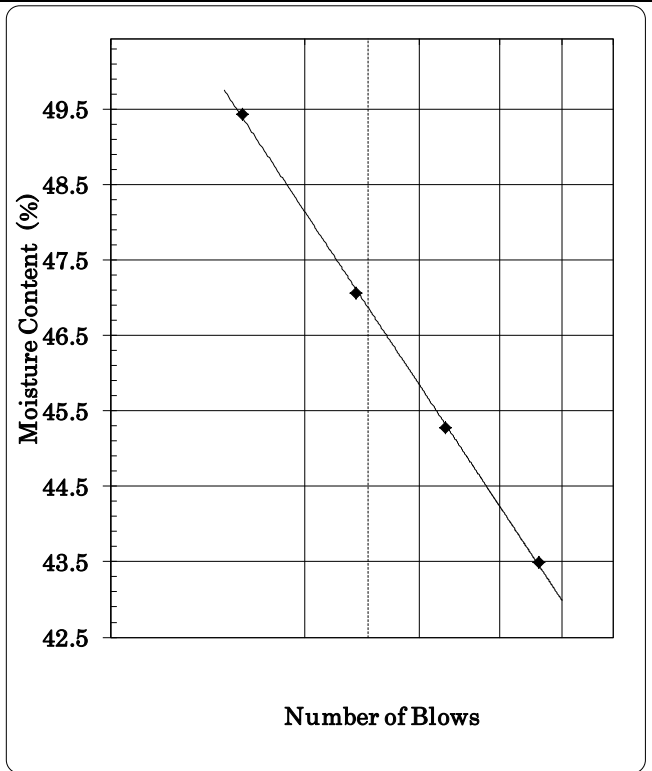
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | |
|---|------|------------------------|--------|--------|-------------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 2.98 |
| Original Length, L _o (mm) | 134 | Container No. | A | B | | |
| | | Wet Soil & Container g | 298.30 | 298.30 | Consistency Index | 3.50 |
| Final Length, L _f (mm) | 124 | Dry Soil & Container g | 241.50 | 241.50 | | (Very stiff) |
| | | Container Empty g | 22.20 | 22.20 | Liquidity Index | -2.50 |
| Linear Shrinkage = | 7.5 | Dry Soil g | 219.30 | 219.30 | | |
| (1-(L _f /L _o))*100 | | Loss of Water g | 56.80 | 56.80 | Flow Index | 6.59 |
| Shrinkage limit = | 10.4 | Moisture Content % | 25.90 | 25.90 | | |
| | | Moisture Content % = | 25.9 % | | Swell Index | 0.71 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: 15

Casagrande method

| LIQUID LIMIT, LL TEST | | | LL = 46.8 % | |
|------------------------|-------|-------|-------------|-------|
| Test No. | 1 | 2 | 3 | 4 |
| Container No. | A | B | C | D |
| Wet Soil & Container g | 34.78 | 34.40 | 35.81 | 34.82 |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water g | 6.18 | 6.30 | 7.11 | 7.22 |
| Moisture Content % | 43.51 | 45.29 | 47.07 | 49.44 |
| Number of Blows | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | |
|------------------------|--------|-------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 16.50 | 16.50 |
| Dry Soil & Container g | 16.40 | 16.40 |
| Container Empty g | 15.70 | 15.70 |
| Dry Soil g | 0.70 | 0.70 |
| Loss of Water g | 0.10 | 0.10 |
| Moisture Content % | 14.29 | 14.29 |
| Plastic Limit, PL = | 14.3 % | |

| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | |
|---|------|------------------------|--------|--------|-------------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 32.55 |
| Original Length, L _o (mm) | 134 | Container No. | A | B | | |
| | | Wet Soil & Container g | 259.10 | 259.10 | Consistency Index | 1.14 |
| Final Length, L _f (mm) | 124 | Dry Soil & Container g | 240.20 | 240.20 | | (Very stiff) |
| | | Container Empty g | 48.80 | 48.80 | Liquidity Index | -0.14 |
| Linear Shrinkage = | 7.5 | Dry Soil g | 191.40 | 191.40 | | |
| (1-(L _f /L _o))*100 | | Loss of Water g | 18.90 | 18.90 | Flow Index | 6.59 |
| Shrinkage limit = | 10.4 | Moisture Content % | 9.87 | 9.87 | | |
| | | Moisture Content % = | 9.9 % | | Swell Index | 0.21 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: SUN16

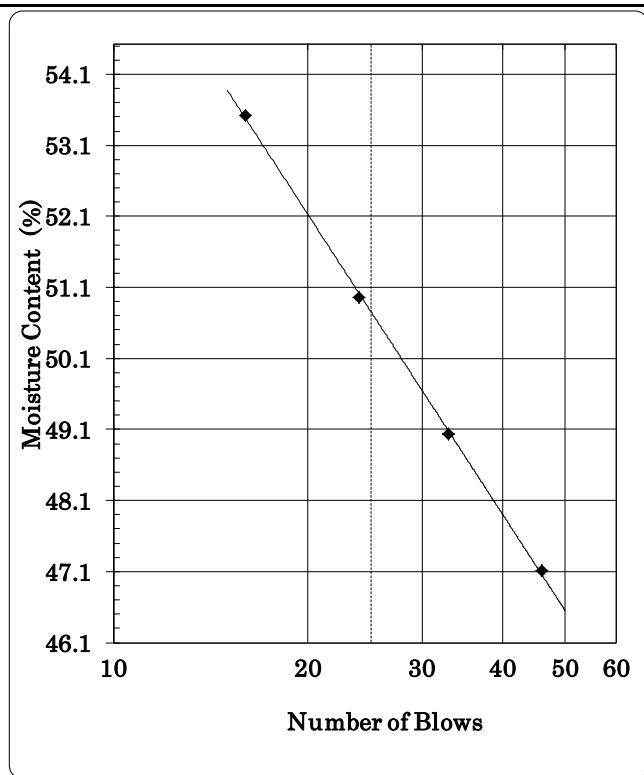
Boring No.:

Depth (mt):

Soil Description :

Casagrande method

| LIQUID LIMIT, LL TEST | | LL = 50.7 % | | | |
|-----------------------|---|-------------|-------|-------|-------|
| Test No. | | 1 | 2 | 3 | 4 |
| Container No. | | A | B | C | D |
| Wet Soil & Container | g | 35.29 | 34.91 | 36.39 | 35.41 |
| Dry Soil & Container | g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty | g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil | g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water | g | 6.69 | 6.81 | 7.69 | 7.81 |
| Moisture Content | % | 47.08 | 49.02 | 50.94 | 53.50 |
| Number of Blows | | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | | |
|------------------------|---|-------------|-------|
| Test No. | 1 | 2 | |
| Container No. | A | B | |
| Wet Soil & Container | g | 14.40 | 11.30 |
| Dry Soil & Container | g | 14.30 | 11.00 |
| Container Empty | g | 13.40 | 10.10 |
| Dry Soil | g | 0.90 | 0.90 |
| Loss of Water | g | 0.10 | 0.30 |
| Moisture Content | % | 11.11 | 33.33 |
| Plastic Limit, PL | = | Non plastic | |

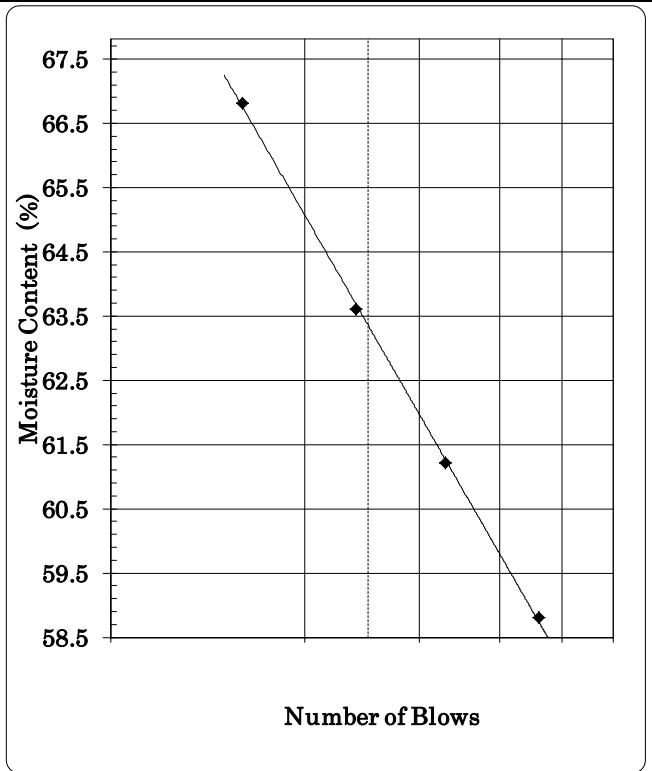
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OH) | | |
|-----------------------------|------|-----------------------|-----|--------|-------------------------|-------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 0.00 | |
| Original Length, L_o (mm) | 140 | Container No. | A | B | | | |
| | | Wet Soil & Container | g | 317.30 | 317.30 | Consistency Index | 31942.53 |
| Final Length, L_f (mm) | 118 | Dry Soil & Container | g | 270.90 | 270.90 | | (Very stiff) |
| | | Container Empty | g | 23.40 | 23.40 | Liquidity Index | #VALUE! |
| Linear Shrinkage = | 15.7 | Dry Soil | g | 247.50 | 247.50 | | |
| $(1-(L_f/L_o))*100$ | | Loss of Water | g | 46.40 | 46.40 | Flow Index | 2.19 |
| Shrinkage limit = | 4.9 | Moisture Content | % | 18.75 | 18.75 | | |
| | | Moisture Content | % = | 18.7 % | | Swell Index | 0.37 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: SUN17

Casagrande method

| LIQUID LIMIT, LL TEST | | LL = 63.3 % | | | |
|------------------------------|---|-------------|-------|-------|-------|
| Test No. | | 1 | 2 | 3 | 4 |
| Container No. | | A | B | C | D |
| Wet Soil & Container | g | 36.94 | 36.60 | 38.30 | 37.35 |
| Dry Soil & Container | g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty | g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil | g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water | g | 8.34 | 8.50 | 9.60 | 9.75 |
| Moisture Content | % | 58.76 | 61.17 | 63.57 | 66.77 |
| Number of Blows | | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | | |
|-------------------------------|---|--------|-------|
| Test No. | 1 | 2 | |
| Container No. | A | B | |
| Wet Soil & Container | g | 14.40 | 14.40 |
| Dry Soil & Container | g | 14.30 | 14.30 |
| Container Empty | g | 13.40 | 13.40 |
| Dry Soil | g | 0.90 | 0.90 |
| Loss of Water | g | 0.10 | 0.10 |
| Moisture Content | % | 11.11 | 11.11 |
| Plastic Limit, PL | = | 11.1 % | |

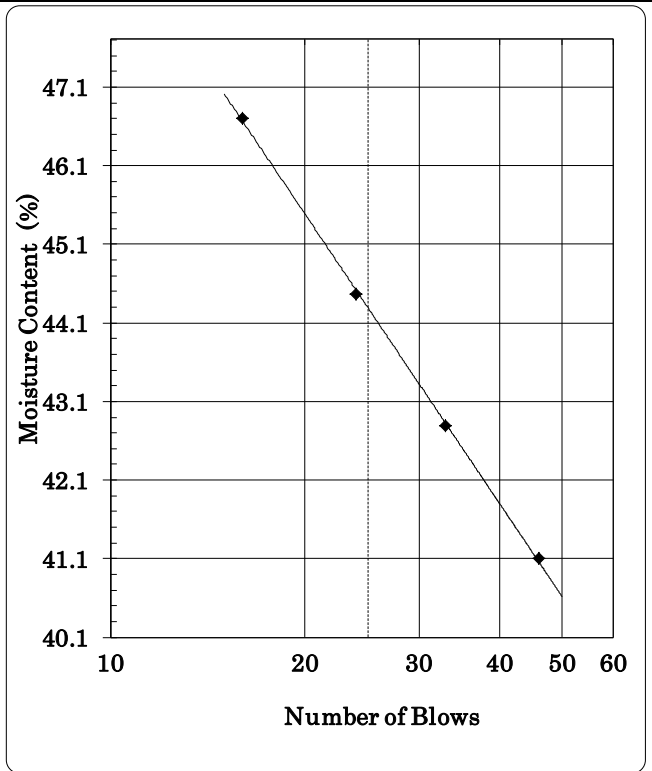
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (0H) | | |
|-----------------------------|------|------------------------------|-----|--------|--------------------------------|-------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 52.15 | |
| Original Length, L_o (mm) | 140 | Container No. | A | B | | | |
| | | Wet Soil & Container | g | 218.50 | 218.50 | Consistency Index | 1.01 |
| Final Length, L_f (mm) | 125 | Dry Soil & Container | g | 200.00 | 200.00 | | (Very stiff) |
| | | Container Empty | g | 22.10 | 22.10 | Liquidity Index | -0.01 |
| Linear Shrinkage = | 10.7 | Dry Soil | g | 177.90 | 177.90 | | |
| $(1 - (L_f/L_o)) * 100$ | | Loss of Water | g | 18.50 | 18.50 | Flow Index | 6.59 |
| Shrinkage limit = | 8.2 | Moisture Content | % | 10.40 | 10.40 | | |
| | | Moisture Content | % = | 10.4 % | | Swell Index | 0.16 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: SUN19

Casagrande method

| LIQUID LIMIT, LL TEST | | | | LL = | 44.3 % |
|------------------------------|-------|-------|-------|-------|--------|
| Test No. | 1 | 2 | 3 | 4 | |
| Container No. | A | B | C | D | |
| Wet Soil & Container g | 34.44 | 34.05 | 35.42 | 34.42 | |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 | |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 | |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 | |
| Loss of Water g | 5.84 | 5.95 | 6.72 | 6.82 | |
| Moisture Content % | 41.12 | 42.81 | 44.49 | 46.73 | |
| Number of Blows | 46 | 33 | 24 | 16 | |



| PLASTIC LIMIT, PL TEST | | |
|-------------------------------|--------|-------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 33.50 | 33.50 |
| Dry Soil & Container g | 33.40 | 33.40 |
| Container Empty g | 32.70 | 32.70 |
| Dry Soil g | 0.70 | 0.70 |
| Loss of Water g | 0.10 | 0.10 |
| Moisture Content % | 14.29 | 14.29 |
| Plastic Limit, PL = | 14.3 % | |

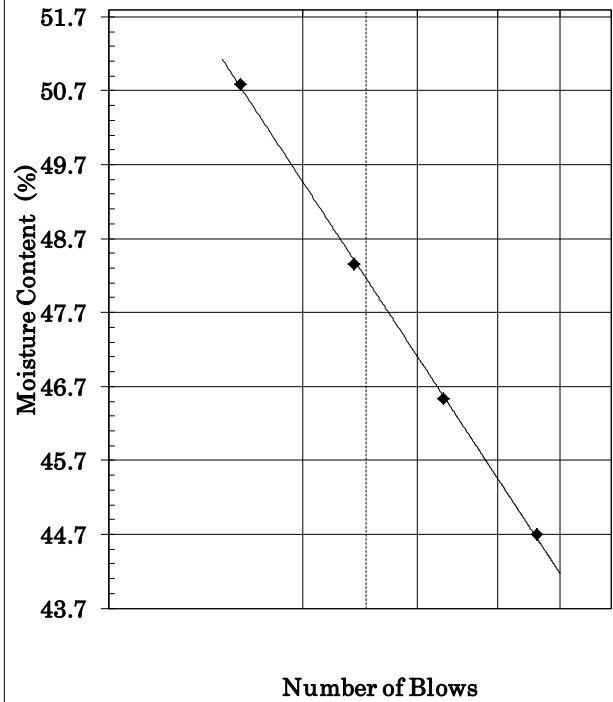
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | |
|-----------------------------|-----|------------------------------|--------|--------|--------------------------------|---------|
| | | Test No. | 1 | 2 | Plasticity Index | 29.98 |
| Original Length, L_o (mm) | 134 | Container No. | A | B | | |
| | | Wet Soil & Container g | 157.10 | 157.10 | Consistency Index | 0.77 |
| Final Length, L_f (mm) | 123 | Dry Soil & Container g | 130.90 | 130.90 | | (Stiff) |
| | | Container Empty g | 7.00 | 7.00 | Liquidity Index | 0.23 |
| Linear Shrinkage = | 8.2 | Dry Soil g | 123.90 | 123.90 | | |
| $(1 - (L_f/L_o)) * 100$ | | Loss of Water g | 26.20 | 26.20 | Flow Index | 6.59 |
| Shrinkage limit = | 9.9 | Moisture Content % | 21.15 | 21.15 | | |
| | | Moisture Content % = | 21.1 % | | Swell Index | 0.48 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: SUN20

Casagrande method

| LIQUID LIMIT, LL TEST | | LL = 48.1 % | | | |
|------------------------------|---|-------------|-------|-------|-------|
| Test No. | | 1 | 2 | 3 | 4 |
| Container No. | | A | B | C | D |
| Wet Soil & Container | g | 34.95 | 34.57 | 36.01 | 35.02 |
| Dry Soil & Container | g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty | g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil | g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water | g | 6.35 | 6.47 | 7.31 | 7.42 |
| Moisture Content | % | 44.72 | 46.55 | 48.38 | 50.81 |
| Number of Blows | | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | | |
|-------------------------------|---|--------|-------|
| Test No. | 1 | 2 | |
| Container No. | A | B | |
| Wet Soil & Container | g | 7.80 | 33.50 |
| Dry Soil & Container | g | 7.30 | 33.40 |
| Container Empty | g | 6.30 | 32.70 |
| Dry Soil | g | 1.00 | 0.70 |
| Loss of Water | g | 0.50 | 0.10 |
| Moisture Content | % | 50.00 | 14.29 |
| Plastic Limit, PL | = | 32.1 % | |

| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | | |
|-----------------------------|------|------------------------------|-----|--------|--------------------------------|-------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 16.00 | |
| Original Length, L_o (mm) | 140 | Container No. | A | B | | | |
| | | Wet Soil & Container | g | 235.40 | 235.40 | Consistency Index | 2.71 |
| Final Length, L_f (mm) | 132 | Dry Soil & Container | g | 225.00 | 225.00 | | (Very stiff) |
| | | Container Empty | g | 9.00 | 9.00 | Liquidity Index | -1.71 |
| Linear Shrinkage = | 5.7 | Dry Soil | g | 216.00 | 216.00 | | |
| $(1 - (L_f/L_o)) * 100$ | | Loss of Water | g | 10.40 | 10.40 | Flow Index | 6.59 |
| Shrinkage limit = | 11.5 | Moisture Content | % | 4.81 | 4.81 | | |
| | | Moisture Content | % = | 4.8 % | | Swell Index | 0.10 |

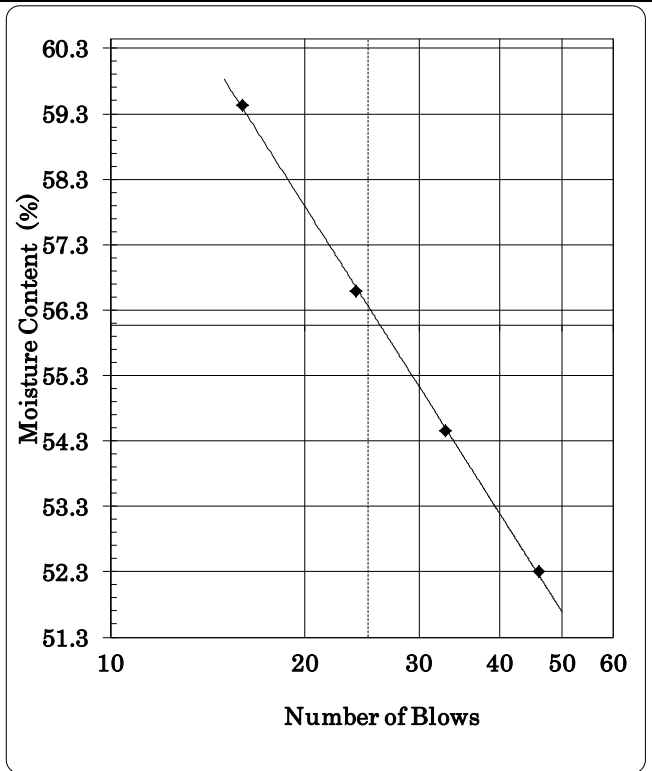
ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: 23

Casagrande method

| LIQUID LIMIT, LL TEST | | | LL = 56.4 % | |
|------------------------|-------|-------|-------------|-------|
| Test No. | 1 | 2 | 3 | 4 |
| Container No. | A | B | C | D |
| Wet Soil & Container g | 36.03 | 35.67 | 37.25 | 36.28 |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water g | 7.43 | 7.57 | 8.55 | 8.68 |
| Moisture Content % | 52.34 | 54.49 | 56.63 | 59.48 |
| Number of Blows | 46 | 33 | 24 | 16 |

| PLASTIC LIMIT, PL TEST | | |
|------------------------|--------|-------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 9.10 | 9.10 |
| Dry Soil & Container g | 8.70 | 8.70 |
| Container Empty g | 7.90 | 7.90 |
| Dry Soil g | 0.80 | 0.80 |
| Loss of Water g | 0.40 | 0.40 |
| Moisture Content % | 50.00 | 50.00 |
| Plastic Limit, PL = | 50.0 % | |



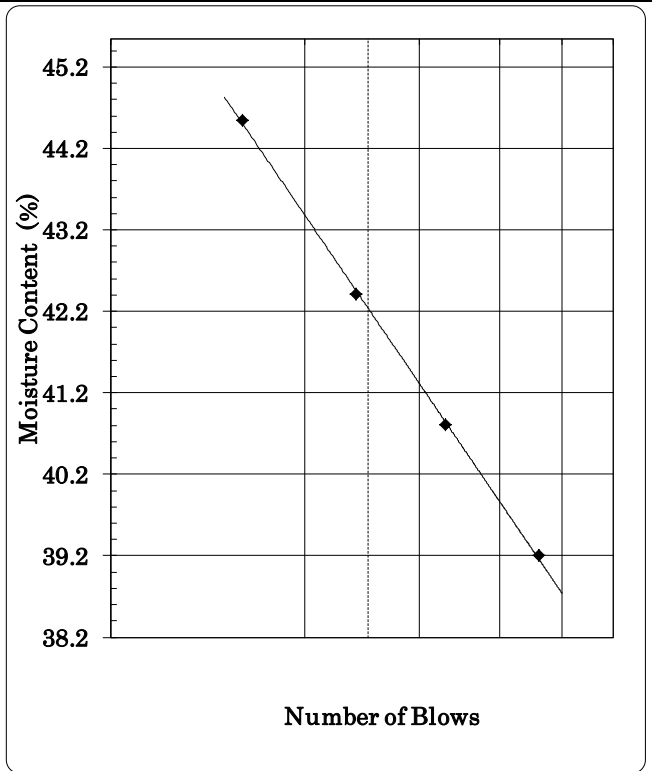
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (0H) | |
|---|------|------------------------|--------|--------|-------------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 6.35 |
| Original Length, L _o (mm) | 140 | Container No. | A | B | | |
| | | Wet Soil & Container g | 168.30 | 168.30 | Consistency Index | 6.76 |
| Final Length, L _f (mm) | 132 | Dry Soil & Container g | 150.00 | 150.00 | | (Very stiff) |
| | | Container Empty g | 13.80 | 13.80 | Liquidity Index | -5.76 |
| Linear Shrinkage = | 5.7 | Dry Soil g | 136.20 | 136.20 | | |
| (1-(L _f /L _o))*100 | | Loss of Water g | 18.30 | 18.30 | Flow Index | 6.59 |
| Shrinkage limit = | 11.5 | Moisture Content % | 13.44 | 13.44 | | |
| | | Moisture Content % = | 13.4 % | | Swell Index | 0.24 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: 25

Casagrande method

| LIQUID LIMIT, LL TEST | | | LL = 42.2 % | |
|------------------------|-------|-------|-------------|-------|
| Test No. | 1 | 2 | 3 | 4 |
| Container No. | A | B | C | D |
| Wet Soil & Container g | 34.16 | 33.77 | 35.10 | 34.10 |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water g | 5.56 | 5.67 | 6.40 | 6.50 |
| Moisture Content % | 39.18 | 40.79 | 42.39 | 44.52 |
| Number of Blows | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | |
|------------------------|--------|-------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 9.00 | 9.00 |
| Dry Soil & Container g | 8.70 | 8.70 |
| Container Empty g | 7.90 | 7.90 |
| Dry Soil g | 0.80 | 0.80 |
| Loss of Water g | 0.30 | 0.30 |
| Moisture Content % | 37.50 | 37.50 |
| Plastic Limit, PL = | 37.5 % | |

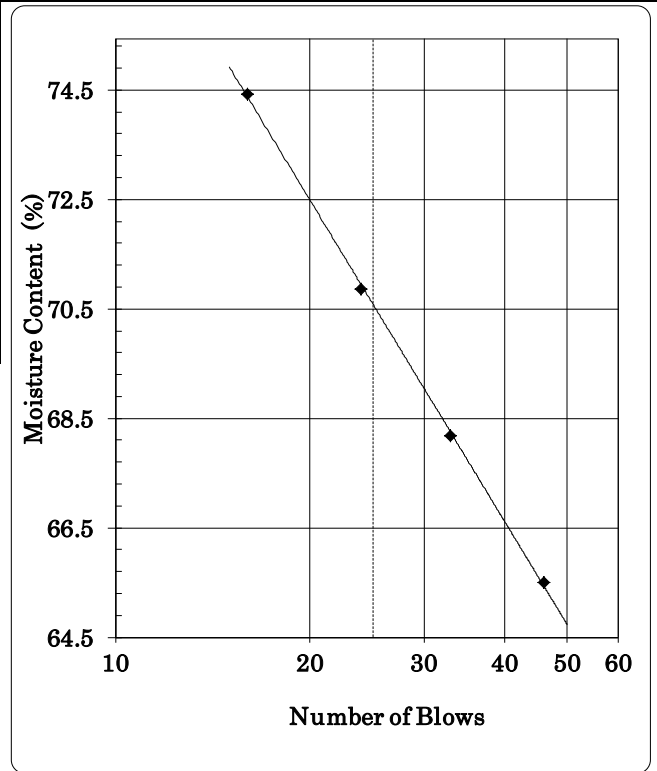
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | |
|---|------|------------------------|--------|--------|-------------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 4.68 |
| Original Length, L _o (mm) | 140 | Container No. | A | B | | |
| | | Wet Soil & Container g | 189.70 | 189.70 | Consistency Index | 4.61 |
| Final Length, L _f (mm) | 130 | Dry Soil & Container g | 167.10 | 167.10 | | (Very stiff) |
| | | Container Empty g | 57.40 | 57.40 | Liquidity Index | -3.61 |
| Linear Shrinkage = | 7.1 | Dry Soil g | 109.70 | 109.70 | | |
| (1-(L _f /L _o))*100 | | Loss of Water g | 22.60 | 22.60 | Flow Index | 6.59 |
| Shrinkage limit = | 10.6 | Moisture Content % | 20.60 | 20.60 | | |
| | | Moisture Content % = | 20.6 % | | Swell Index | 0.49 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: 27

Casagrande method

| LIQUID LIMIT, LL TEST | | | LL = 70.5 % | |
|------------------------|-------|-------|-------------|-------|
| Test No. | 1 | 2 | 3 | 4 |
| Container No. | A | B | C | D |
| Wet Soil & Container g | 37.90 | 37.58 | 39.40 | 38.47 |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water g | 9.30 | 9.48 | 10.70 | 10.87 |
| Moisture Content % | 65.51 | 68.20 | 70.88 | 74.44 |
| Number of Blows | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | |
|------------------------|-------------|-------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 11.30 | 11.30 |
| Dry Soil & Container g | 11.00 | 11.00 |
| Container Empty g | 10.10 | 10.10 |
| Dry Soil g | 0.90 | 0.90 |
| Loss of Water g | 0.30 | 0.30 |
| Moisture Content % | 33.33 | 33.33 |
| Plastic Limit, PL = | Non plastic | |

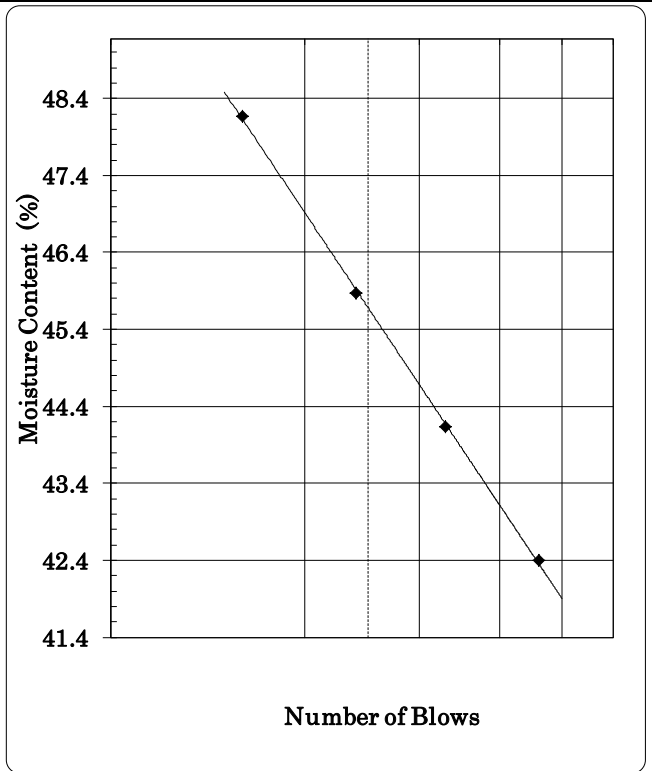
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (0H) | |
|---|------|------------------------|--------|-------|-------------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 0.00 |
| Original Length, L _o (mm) | 140 | Container No. | A | B | | |
| | | Wet Soil & Container g | 9.80 | 9.40 | Consistency Index | 45530.00 |
| Final Length, L _f (mm) | 118 | Dry Soil & Container g | 9.40 | 9.40 | | (Very stiff) |
| | | Container Empty g | 7.80 | 7.80 | Liquidity Index | #VALUE! |
| Linear Shrinkage = | 15.7 | Dry Soil g | 1.60 | 1.60 | | |
| (1-(L _f /L _o))*100 | | Loss of Water g | 0.40 | 0.40 | Flow Index | 2.19 |
| Shrinkage limit = | 4.9 | Moisture Content % | 25.00 | 25.00 | | |
| | | Moisture Content % = | 25.0 % | | Swell Index | 0.35 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: 30

Casagrande method

| LIQUID LIMIT, LL TEST | | LL = 45.6 % | | | |
|------------------------------|---|-------------|-------|-------|-------|
| Test No. | | 1 | 2 | 3 | 4 |
| Container No. | | A | B | C | D |
| Wet Soil & Container | g | 34.61 | 34.23 | 35.62 | 34.63 |
| Dry Soil & Container | g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty | g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil | g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water | g | 6.01 | 6.13 | 6.92 | 7.03 |
| Moisture Content | % | 42.35 | 44.08 | 45.82 | 48.12 |
| Number of Blows | | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | |
|-------------------------------|---|--------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container | g | 8.90 |
| Dry Soil & Container | g | 8.70 |
| Container Empty | g | 7.80 |
| Dry Soil | g | 0.90 |
| Loss of Water | g | 0.20 |
| Moisture Content | % | 22.22 |
| Plastic Limit, PL | = | 22.2 % |

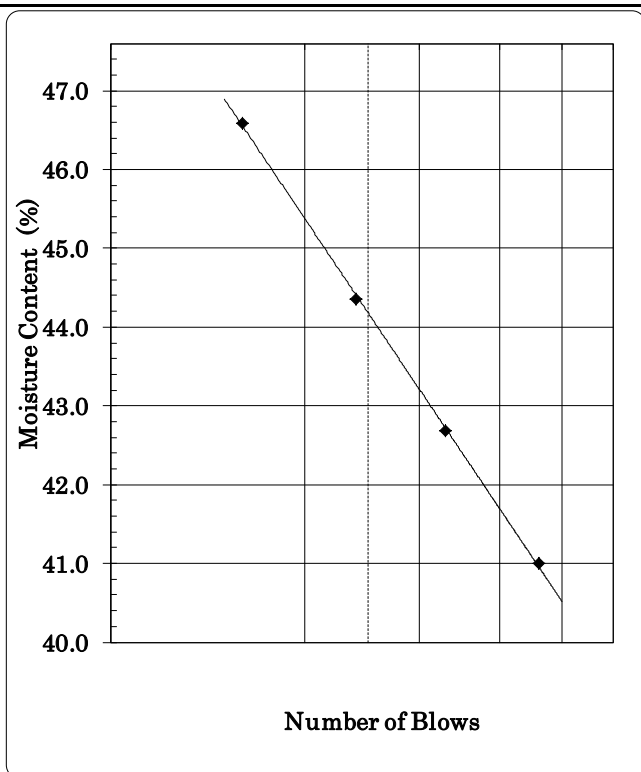
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | | |
|-----------------------------|-----|------------------------------|-----|--------|--------------------------------|-------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 23.37 | |
| Original Length, L_o (mm) | 140 | Container No. | A | B | | | |
| | | Wet Soil & Container | g | 241.90 | 241.90 | Consistency Index | 1.40 |
| Final Length, L_f (mm) | 127 | Dry Soil & Container | g | 220.00 | 220.00 | | (Very stiff) |
| | | Container Empty | g | 49.20 | 49.20 | Liquidity Index | -0.40 |
| Linear Shrinkage = | 9.3 | Dry Soil | g | 170.80 | 170.80 | | |
| $(1 - (L_f/L_o)) * 100$ | | Loss of Water | g | 21.90 | 21.90 | Flow Index | 6.59 |
| Shrinkage limit = | 9.1 | Moisture Content | % | 12.82 | 12.82 | | |
| | | Moisture Content | % = | 12.8 % | | Swell Index | 0.28 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: 32

Casagrande method

| LIQUID LIMIT, LL TEST | | | LL = 44.2 % | |
|------------------------|-------|-------|-------------|-------|
| Test No. | 1 | 2 | 3 | 4 |
| Container No. | A | B | C | D |
| Wet Soil & Container g | 34.43 | 34.04 | 35.40 | 34.41 |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water g | 5.83 | 5.94 | 6.70 | 6.81 |
| Moisture Content % | 41.03 | 42.71 | 44.39 | 46.62 |
| Number of Blows | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | |
|------------------------|-------|------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 9.20 | 9.20 |
| Dry Soil & Container g | 8.90 | 8.90 |
| Container Empty g | 0.30 | 0.30 |
| Dry Soil g | 8.60 | 8.60 |
| Loss of Water g | 0.30 | 0.30 |
| Moisture Content % | 3.49 | 3.49 |
| Plastic Limit, PL = | 3.5 % | |

| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | |
|-----------------------------|------|------------------------|--------|-------|-------------------------|--------|
| | | Test No. | 1 | 2 | Plasticity Index | 40.68 |
| Original Length, L_o (mm) | 140 | Container No. | A | B | | |
| | | Wet Soil & Container g | 9.80 | 9.40 | Consistency Index | 0.47 |
| Final Length, L_f (mm) | 129 | Dry Soil & Container g | 9.40 | 9.40 | | (Soft) |
| | | Container Empty g | 7.80 | 7.80 | Liquidity Index | 0.53 |
| Linear Shrinkage = | 7.9 | Dry Soil g | 1.60 | 1.60 | | |
| $(1 - (L_f/L_o)) * 100$ | | Loss of Water g | 0.40 | 0.40 | Flow Index | 6.59 |
| Shrinkage limit = | 10.1 | Moisture Content % | 25.00 | 25.00 | | |
| | | Moisture Content % = | 25.0 % | | Swell Index | 0.57 |

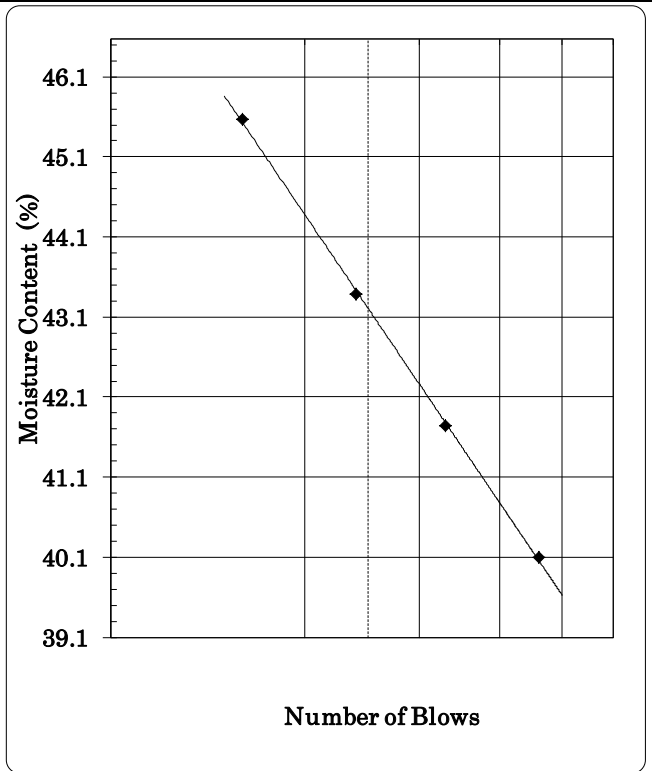
ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: 35

Casagrande method

| LIQUID LIMIT, LL TEST | | | LL = 43.2 % | |
|------------------------|-------|-------|-------------|-------|
| Test No. | 1 | 2 | 3 | 4 |
| Container No. | A | B | C | D |
| Wet Soil & Container g | 34.30 | 33.90 | 35.25 | 34.25 |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water g | 5.70 | 5.80 | 6.55 | 6.65 |
| Moisture Content % | 40.11 | 41.75 | 43.39 | 45.58 |
| Number of Blows | 46 | 33 | 24 | 16 |

| PLASTIC LIMIT, PL TEST | | |
|------------------------|-------------|-------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 9.50 | 9.50 |
| Dry Soil & Container g | 9.00 | 9.00 |
| Container Empty g | 7.60 | 7.60 |
| Dry Soil g | 1.40 | 1.40 |
| Loss of Water g | 0.50 | 0.50 |
| Moisture Content % | 35.71 | 35.71 |
| Plastic Limit, PL = | Non plastic | |



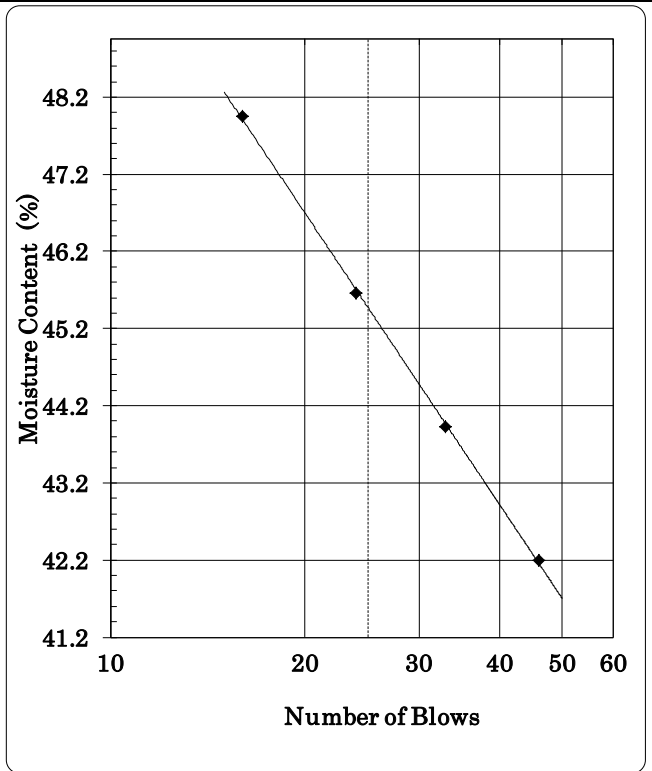
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | |
|---|------|------------------------|--------|-------|-------------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 0.00 |
| Original Length, L _o (mm) | 134 | Container No. | A | B | | |
| | | Wet Soil & Container g | 9.80 | 9.40 | Consistency Index | 18180.00 |
| Final Length, L _f (mm) | 132 | Dry Soil & Container g | 9.40 | 9.40 | | (Very stiff) |
| | | Container Empty g | 7.80 | 7.80 | Liquidity Index | #VALUE! |
| Linear Shrinkage = | 1.5 | Dry Soil g | 1.60 | 1.60 | | |
| (1-(L _f /L _o))*100 | | Loss of Water g | 0.40 | 0.40 | Flow Index | 2.19 |
| Shrinkage limit = | 14.3 | Moisture Content % | 25.00 | 25.00 | | |
| | | Moisture Content % = | 25.0 % | | Swell Index | 0.58 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: 36

Casagrande method

| LIQUID LIMIT, LL TEST | | | | LL = | 45.4 % |
|------------------------------|---|-------|-------|-------|--------|
| Test No. | 1 | 2 | 3 | 4 | |
| Container No. | A | B | C | D | |
| Wet Soil & Container | g | 34.59 | 34.20 | 35.59 | 34.60 |
| Dry Soil & Container | g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty | g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil | g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water | g | 5.99 | 6.10 | 6.89 | 7.00 |
| Moisture Content | % | 42.17 | 43.90 | 45.62 | 47.92 |
| Number of Blows | | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | | |
|-------------------------------|---|--------|-------|
| Test No. | 1 | 2 | |
| Container No. | A | B | |
| Wet Soil & Container | g | 11.00 | 11.00 |
| Dry Soil & Container | g | 10.60 | 10.60 |
| Container Empty | g | 9.20 | 9.20 |
| Dry Soil | g | 1.40 | 1.40 |
| Loss of Water | g | 0.40 | 0.40 |
| Moisture Content | % | 28.57 | 28.57 |
| Plastic Limit, PL | = | 28.6 % | |

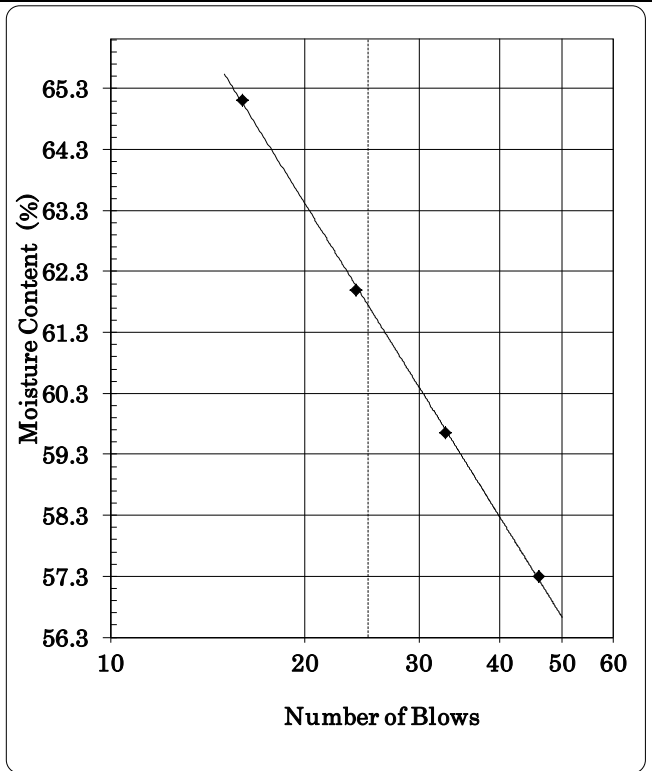
| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | | |
|-----------------------------|------|------------------------------|-----|--------|--------------------------------|-------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 16.83 | |
| Original Length, L_o (mm) | 140 | Container No. | A | B | | | |
| | | Wet Soil & Container | g | 9.80 | 9.40 | Consistency Index | 1.21 |
| Final Length, L_f (mm) | 131 | Dry Soil & Container | g | 9.40 | 9.40 | | (Very stiff) |
| | | Container Empty | g | 7.80 | 7.80 | Liquidity Index | -0.21 |
| Linear Shrinkage = | 6.4 | Dry Soil | g | 1.60 | 1.60 | | |
| $(1 - (L_f/L_o)) * 100$ | | Loss of Water | g | 0.40 | 0.40 | Flow Index | 6.59 |
| Shrinkage limit = | 11.0 | Moisture Content | % | 25.00 | 25.00 | | |
| | | Moisture Content | % = | 25.0 % | | Swell Index | 0.55 |

ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: 37

Casagrande method

| LIQUID LIMIT, LL TEST | | | | LL = | 61.7 % |
|------------------------------|-------|-------|-------|-------|--------|
| Test No. | 1 | 2 | 3 | 4 | |
| Container No. | A | B | C | D | |
| Wet Soil & Container g | 36.74 | 36.39 | 38.06 | 37.11 | |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 | |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 | |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 | |
| Loss of Water g | 8.14 | 8.29 | 9.36 | 9.51 | |
| Moisture Content % | 57.30 | 59.65 | 62.00 | 65.11 | |
| Number of Blows | 46 | 33 | 24 | 16 | |



| PLASTIC LIMIT, PL TEST | | |
|-------------------------------|-------------|-------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 11.00 | 11.00 |
| Dry Soil & Container g | 10.60 | 10.60 |
| Container Empty g | 9.20 | 9.20 |
| Dry Soil g | 1.40 | 1.40 |
| Loss of Water g | 0.40 | 0.40 |
| Moisture Content % | 28.57 | 28.57 |
| Plastic Limit, PL = | Non plastic | |

| LINEAR SHRINKAGE | | Moisture Content Test | | | | USCS GROUP SYMBOL: (0H) | |
|-----------------------------|------|------------------------------|--------|-------|-------------------|--------------------------------|--|
| | | Test No. | 1 | 2 | Plasticity Index | 0.00 | |
| Original Length, L_o (mm) | 134 | Container No. | A | B | | | |
| | | Wet Soil & Container g | 9.80 | 9.40 | Consistency Index | 36690.00 | |
| Final Length, L_f (mm) | 129 | Dry Soil & Container g | 9.40 | 9.40 | | (Very stiff) | |
| | | Container Empty g | 7.80 | 7.80 | Liquidity Index | #VALUE! | |
| Linear Shrinkage = | 3.7 | Dry Soil g | 1.60 | 1.60 | | | |
| $(1 - (L_f/L_o)) * 100$ | | Loss of Water g | 0.40 | 0.40 | Flow Index | 2.19 | |
| Shrinkage limit = | 12.8 | Moisture Content % | 25.00 | 25.00 | | | |
| | | Moisture Content % = | 25.0 % | | Swell Index | 0.41 | |

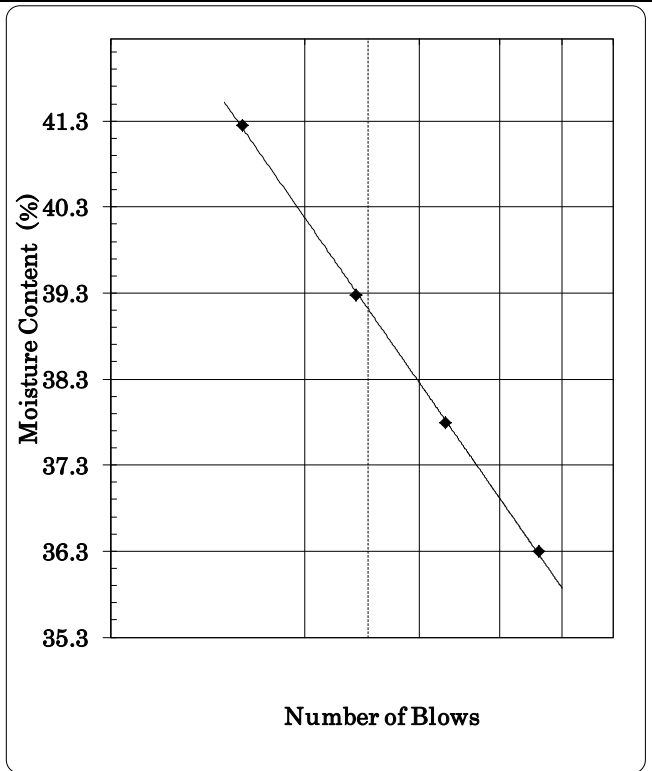
ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: 38

Boring No.:

Casagrande method

| LIQUID LIMIT, LL TEST | | | LL = 39.1 % | |
|------------------------|-------|-------|-------------|-------|
| Test No. | 1 | 2 | 3 | 4 |
| Container No. | A | B | C | D |
| Wet Soil & Container g | 33.76 | 33.36 | 34.63 | 33.63 |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water g | 5.16 | 5.26 | 5.93 | 6.03 |
| Moisture Content % | 36.32 | 37.81 | 39.29 | 41.27 |
| Number of Blows | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | |
|------------------------|---------|--------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 19.30 | 19.30 |
| Dry Soil & Container g | 11.10 | 11.10 |
| Container Empty g | 9.30 | 9.30 |
| Dry Soil g | 1.80 | 1.80 |
| Loss of Water g | 8.20 | 8.20 |
| Moisture Content % | 455.56 | 455.56 |
| Plastic Limit, PL = | 455.6 % | |

| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | |
|---|------|------------------------|--------|-------|-------------------------|-------------|
| | | Test No. | 1 | 2 | Plasticity Index | -416.46 |
| Original Length, L _o (mm) | 134 | Container No. | A | B | | |
| | | Wet Soil & Container g | 9.80 | 9.40 | Consistency Index | -0.03 |
| Final Length, L _f (mm) | 129 | Dry Soil & Container g | 9.40 | 9.40 | | (Very Soft) |
| | | Container Empty g | 7.80 | 7.80 | Liquidity Index | 1.03 |
| Linear Shrinkage = | 3.7 | Dry Soil g | 1.60 | 1.60 | | |
| (1-(L _f /L _o))*100 | | Loss of Water g | 0.40 | 0.40 | Flow Index | 6.59 |
| Shrinkage limit = | 12.8 | Moisture Content % | 25.00 | 25.00 | | |
| | | Moisture Content % = | 25.0 % | | Swell Index | 0.64 |

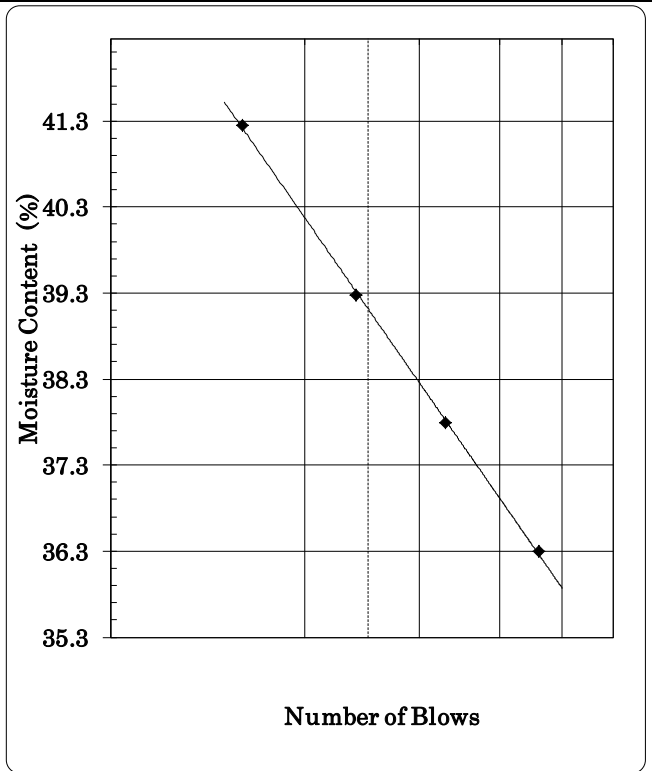
ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: SUN38

Boring No.:

Casagrande method

| LIQUID LIMIT, LL TEST | | | LL = 39.1 % | |
|------------------------|-------|-------|-------------|-------|
| Test No. | 1 | 2 | 3 | 4 |
| Container No. | A | B | C | D |
| Wet Soil & Container g | 33.76 | 33.36 | 34.63 | 33.63 |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water g | 5.16 | 5.26 | 5.93 | 6.03 |
| Moisture Content % | 36.32 | 37.81 | 39.29 | 41.27 |
| Number of Blows | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | |
|------------------------|---------|--------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 19.30 | 19.30 |
| Dry Soil & Container g | 11.10 | 11.10 |
| Container Empty g | 9.30 | 9.30 |
| Dry Soil g | 1.80 | 1.80 |
| Loss of Water g | 8.20 | 8.20 |
| Moisture Content % | 455.56 | 455.56 |
| Plastic Limit, PL = | 455.6 % | |

| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OI) | |
|---|------|------------------------|--------|-------|-------------------------|-------------|
| | | Test No. | 1 | 2 | Plasticity Index | -416.46 |
| Original Length, L _o (mm) | 134 | Container No. | A | B | | |
| | | Wet Soil & Container g | 9.80 | 9.40 | Consistency Index | -0.03 |
| Final Length, L _f (mm) | 129 | Dry Soil & Container g | 9.40 | 9.40 | | (Very Soft) |
| | | Container Empty g | 7.80 | 7.80 | Liquidity Index | 1.03 |
| Linear Shrinkage = | 3.7 | Dry Soil g | 1.60 | 1.60 | | |
| (1-(L _f /L _o))*100 | | Loss of Water g | 0.40 | 0.40 | Flow Index | 6.59 |
| Shrinkage limit = | 12.8 | Moisture Content % | 25.00 | 25.00 | | |
| | | Moisture Content % = | 25.0 % | | Swell Index | 0.64 |

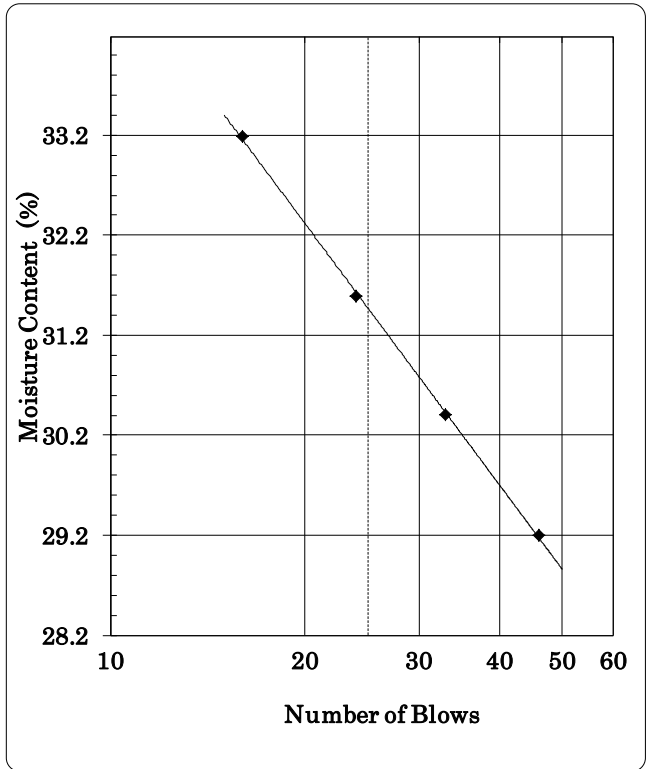
ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: SUN39

Boring No.:

Casagrande method

| LIQUID LIMIT, LL TEST | | | | LL = | 31.4 % |
|------------------------------|-------|-------|-------|-------|--------|
| Test No. | 1 | 2 | 3 | 4 | |
| Container No. | A | B | C | D | |
| Wet Soil & Container g | 32.75 | 32.32 | 33.47 | 32.44 | |
| Dry Soil & Container g | 28.60 | 28.10 | 28.70 | 27.60 | |
| Container Empty g | 14.40 | 14.20 | 13.60 | 13.00 | |
| Dry Soil g | 14.20 | 13.90 | 15.10 | 14.60 | |
| Loss of Water g | 4.15 | 4.22 | 4.77 | 4.84 | |
| Moisture Content % | 29.19 | 30.39 | 31.59 | 33.17 | |
| Number of Blows | 46 | 33 | 24 | 16 | |



| PLASTIC LIMIT, PL TEST | | |
|-------------------------------|-------------|--------|
| Test No. | 1 | 2 |
| Container No. | A | B |
| Wet Soil & Container g | 19.30 | 19.30 |
| Dry Soil & Container g | 11.10 | 11.10 |
| Container Empty g | 9.30 | 9.30 |
| Dry Soil g | 1.80 | 1.80 |
| Loss of Water g | 8.20 | 8.20 |
| Moisture Content % | 455.56 | 455.56 |
| Plastic Limit, PL = | Non plastic | |

| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OL) | |
|---|------|------------------------------|--------|-------|--------------------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 0.00 |
| Original Length, L _o (mm) | 140 | Container No. | A | B | | |
| | | Wet Soil & Container g | 9.80 | 9.40 | Consistency Index | 6430.00 |
| Final Length, L _f (mm) | 129 | Dry Soil & Container g | 9.40 | 9.40 | | (Very stiff) |
| | | Container Empty g | 7.80 | 7.80 | Liquidity Index | #VALUE! |
| Linear Shrinkage = | 7.9 | Dry Soil g | 1.60 | 1.60 | | |
| (1-(L _f /L _o))*100 | | Loss of Water g | 0.40 | 0.40 | Flow Index | 2.19 |
| Shrinkage limit = | 10.1 | Moisture Content % | 25.00 | 25.00 | | |
| | | Moisture Content % = | 25.0 % | | Swell Index | 0.80 |

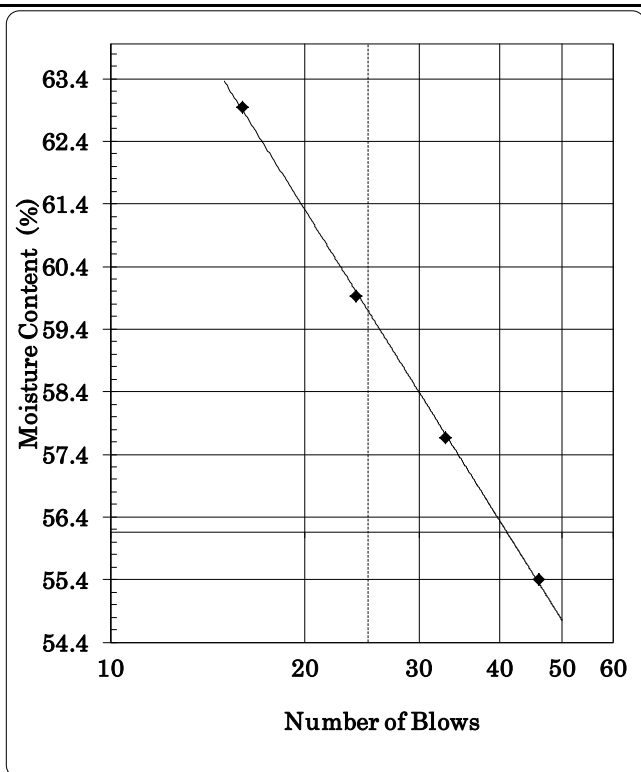
ATTERBERG LIMIT TEST- BS 1377-2:1990:4.5/4.6* (ASTM D4318)

Sample No.: SUN40

Boring No.:

Casagrande method

| LIQUID LIMIT, LL TEST | | LL = 59.6 % | | | |
|------------------------------|---|-------------|-------|-------|-------|
| Test No. | | 1 | 2 | 3 | 4 |
| Container No. | | A | B | C | D |
| Wet Soil & Container | g | 36.46 | 36.11 | 37.74 | 36.78 |
| Dry Soil & Container | g | 28.60 | 28.10 | 28.70 | 27.60 |
| Container Empty | g | 14.40 | 14.20 | 13.60 | 13.00 |
| Dry Soil | g | 14.20 | 13.90 | 15.10 | 14.60 |
| Loss of Water | g | 7.86 | 8.01 | 9.04 | 9.18 |
| Moisture Content | % | 55.36 | 57.63 | 59.90 | 62.91 |
| Number of Blows | | 46 | 33 | 24 | 16 |



| PLASTIC LIMIT, PL TEST | | | |
|-------------------------------|---|--------|-------|
| Test No. | 1 | 2 | |
| Container No. | A | B | |
| Wet Soil & Container | g | 12.60 | 10.70 |
| Dry Soil & Container | g | 11.80 | 10.30 |
| Container Empty | g | 9.90 | 9.20 |
| Dry Soil | g | 1.90 | 1.10 |
| Loss of Water | g | 0.80 | 0.40 |
| Moisture Content | % | 42.11 | 36.36 |
| Plastic Limit, PL | = | 39.2 % | |

| LINEAR SHRINKAGE | | Moisture Content Test | | | USCS GROUP SYMBOL: (OH) | | |
|-----------------------------|------|------------------------------|-----|--------|--------------------------------|-------------------|--------------|
| | | Test No. | 1 | 2 | Plasticity Index | 20.37 | |
| Original Length, L_o (mm) | 140 | Container No. | A | B | | | |
| | | Wet Soil & Container | g | 9.80 | 9.40 | Consistency Index | 1.70 |
| Final Length, L_f (mm) | 121 | Dry Soil & Container | g | 9.40 | 9.40 | | (Very stiff) |
| | | Container Empty | g | 7.80 | 7.80 | Liquidity Index | -0.70 |
| Linear Shrinkage = | 13.6 | Dry Soil | g | 1.60 | 1.60 | | |
| $(1 - (L_f/L_o)) * 100$ | | Loss of Water | g | 0.40 | 0.40 | Flow Index | 6.59 |
| Shrinkage limit = | 6.3 | Moisture Content | % | 25.00 | 25.00 | | |
| | | Moisture Content | % = | 25.0 % | | Swell Index | 0.42 |

Appendix 5. Unconfined compression test

UNCONFINED COMPRESSION TEST

AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. SUN1

| | | | | | | | | |
|--------------------------------|------|----|---------|-----|----|------------------------------------|---------|--------|
| Initial specimen height, H_0 | 7.20 | cm | Diam. = | 5.0 | cm | Load ring constant (1 load unit) = | 0.1466 | kg |
| Final specimen height, H_c | 6.93 | cm | | | | A_0 | 19.64 | cm^2 |
| | | | | | | A_c | 20.5106 | cm^2 |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:26:57 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:27:09 | 0:00:00 | 0.25 | 44.00 | 6.45 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 32.08 |
| 13:27:21 | 0:00:12 | 0.50 | 88.00 | 12.90 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 63.91 |
| 13:27:33 | 0:00:24 | 0.75 | 154.00 | 22.58 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 111.41 |
| 13:27:45 | 0:00:36 | 1.00 | 220.00 | 32.25 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 158.54 |
| 13:27:57 | 0:00:48 | 1.25 | 264.00 | 38.70 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 189.51 |
| 13:28:09 | 0:01:00 | 1.50 | 286.00 | 41.93 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 204.49 |
| 13:28:21 | 0:01:12 | 1.75 | 308.00 | 45.15 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 219.36 |
| 13:28:33 | 0:01:24 | 2.00 | 330.00 | 48.38 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 234.09 |
| 13:28:45 | 0:01:36 | 2.25 | 341.00 | 49.99 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 240.94 |
| 13:28:57 | 0:01:48 | 2.50 | 330.00 | 48.38 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 232.24 |
| 13:29:09 | 0:02:00 | 2.75 | 308.00 | 45.15 | 0.0423 | 4.2308 | 0.9577 | 20.5106 | 215.89 |

UNCONFINED COMPRESSION TEST

AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. SUN2

| | | | | | | | | | |
|--------------------------------|------|----|---------|-----|----|----------------------------------|---|---------|--------|
| Initial specimen height, H_o | 7.20 | cm | Diam. = | 5.0 | cm | Load ring constant (1 load unit) | = | 0.1466 | kg |
| Final specimen height, H_c | 6.85 | cm | | | | A_o | = | 19.64 | cm^2 |
| | | | | | | A_c | = | 20.7607 | cm^2 |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:26:54 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:27:06 | 0:00:00 | 0.25 | 40.00 | 5.86 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 29.16 |
| 13:27:18 | 0:00:12 | 0.50 | 119.00 | 17.45 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 86.43 |
| 13:27:30 | 0:00:24 | 0.75 | 185.00 | 27.12 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 133.84 |
| 13:27:42 | 0:00:36 | 1.00 | 225.00 | 32.99 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 162.14 |
| 13:27:54 | 0:00:48 | 1.25 | 254.00 | 37.24 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 182.33 |
| 13:28:06 | 0:01:00 | 1.50 | 288.00 | 42.22 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 205.92 |
| 13:28:18 | 0:01:12 | 1.75 | 312.00 | 45.74 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 222.20 |
| 13:28:30 | 0:01:24 | 2.00 | 323.00 | 47.35 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 229.13 |
| 13:28:42 | 0:01:36 | 2.25 | 333.00 | 48.82 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 235.29 |
| 13:28:54 | 0:01:48 | 2.50 | 339.00 | 49.70 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 238.57 |
| 13:29:06 | 0:02:00 | 2.75 | 344.00 | 50.43 | 0.0423 | 4.2308 | 0.9577 | 20.5106 | 241.12 |
| 13:29:18 | 0:02:12 | 3.00 | 344.00 | 50.43 | 0.0462 | 4.6154 | 0.9538 | 20.5933 | 240.15 |
| 13:29:30 | 0:02:24 | 3.25 | 333.00 | 48.82 | 0.0500 | 5.0000 | 0.9500 | 20.6767 | 231.54 |
| 13:29:42 | 0:02:36 | 3.50 | 317.00 | 46.47 | 0.0538 | 5.3846 | 0.9462 | 20.7607 | 219.52 |

UNCONFINED COMPRESSION TEST
AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. SUN4

| | | | | | | | | |
|--------------------------------|-------------|----|---------|-----|----|------------------------------------|----------------|--------|
| Initial specimen height, H_o | <u>7.20</u> | cm | Diam. = | 5.0 | cm | Load ring constant (1 load unit) = | 0.1466 | kg |
| Final specimen height, H_c | <u>6.90</u> | cm | | | | A_o | <u>19.64</u> | cm^2 |
| | | | | | | A_c | <u>20.5933</u> | cm^2 |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:26:49 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:27:01 | 0:00:00 | 0.25 | 45.00 | 6.60 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 32.81 |
| 13:27:13 | 0:00:12 | 0.50 | 102.00 | 14.95 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 74.08 |
| 13:27:25 | 0:00:24 | 0.75 | 165.00 | 24.19 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 119.37 |
| 13:27:37 | 0:00:36 | 1.00 | 222.00 | 32.55 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 159.98 |
| 13:27:49 | 0:00:48 | 1.25 | 258.00 | 37.82 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 185.20 |
| 13:28:01 | 0:01:00 | 1.50 | 288.00 | 42.22 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 205.92 |
| 13:28:13 | 0:01:12 | 1.75 | 315.00 | 46.18 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 224.34 |
| 13:28:25 | 0:01:24 | 2.00 | 330.00 | 48.38 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 234.09 |
| 13:28:37 | 0:01:36 | 2.25 | 345.00 | 50.58 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 243.76 |
| 13:28:49 | 0:01:48 | 2.50 | 351.00 | 51.46 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 247.02 |
| 13:29:01 | 0:02:00 | 2.75 | 345.00 | 50.58 | 0.0423 | 4.2308 | 0.9577 | 20.5106 | 241.82 |
| 13:29:13 | 0:02:12 | 3.00 | 330.00 | 48.38 | 0.0462 | 4.6154 | 0.9538 | 20.5933 | 230.38 |

UNCONFINED COMPRESSION TEST
AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. SUN6

| | | | | | | | | | |
|--------------------------------|-------------|----|---------|-----|----|----------------------------------|---|----------------|--------|
| Initial specimen height, H_o | <u>7.20</u> | cm | Diam. = | 5.0 | cm | Load ring constant (1 load unit) | = | 0.1466 | kg |
| Final specimen height, H_c | <u>6.90</u> | cm | | | | A_o | | <u>19.64</u> | cm^2 |
| | | | | | | A_c | | <u>20.5933</u> | cm^2 |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:26:44 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:26:56 | 0:00:00 | 0.25 | 19.00 | 2.79 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 13.85 |
| 13:27:08 | 0:00:12 | 0.50 | 58.00 | 8.50 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 42.12 |
| 13:27:20 | 0:00:24 | 0.75 | 105.00 | 15.39 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 75.96 |
| 13:27:32 | 0:00:36 | 1.00 | 163.00 | 23.90 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 117.46 |
| 13:27:44 | 0:00:48 | 1.25 | 198.00 | 29.03 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 142.13 |
| 13:27:56 | 0:01:00 | 1.50 | 223.00 | 32.69 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 159.45 |
| 13:28:08 | 0:01:12 | 1.75 | 233.00 | 34.16 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 165.94 |
| 13:28:20 | 0:01:24 | 2.00 | 242.00 | 35.48 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 171.67 |
| 13:28:32 | 0:01:36 | 2.25 | 246.00 | 36.06 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 173.81 |
| 13:28:44 | 0:01:48 | 2.50 | 242.00 | 35.48 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 170.31 |
| 13:28:56 | 0:02:00 | 2.75 | 228.00 | 33.42 | 0.0423 | 4.2308 | 0.9577 | 20.5106 | 159.81 |
| 13:29:08 | 0:02:12 | 3.00 | 209.00 | 30.64 | 0.0462 | 4.6154 | 0.9538 | 20.5933 | 145.91 |

UNCONFINED COMPRESSION TEST

AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. 8

| | | | | | | | | |
|--------------------------------|------|----|---------|-----|----|------------------------------------|---------|--------|
| Initial specimen height, H_o | 7.20 | cm | Diam. = | 5.0 | cm | Load ring constant (1 load unit) = | 0.1466 | kg |
| Final specimen height, H_c | 6.83 | cm | | | | A_o | 19.64 | cm^2 |
| | | | | | | A_c | 20.8455 | cm^2 |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | $1 - \epsilon$ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:26:38 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:26:50 | 0:00:00 | 0.25 | 15.00 | 2.20 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 10.94 |
| 13:27:02 | 0:00:12 | 0.50 | 36.00 | 5.28 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 26.15 |
| 13:27:14 | 0:00:24 | 0.75 | 66.00 | 9.68 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 47.75 |
| 13:27:26 | 0:00:36 | 1.00 | 112.00 | 16.42 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 80.71 |
| 13:27:38 | 0:00:48 | 1.25 | 163.00 | 23.90 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 117.01 |
| 13:27:50 | 0:01:00 | 1.50 | 230.00 | 33.72 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 164.45 |
| 13:28:02 | 0:01:12 | 1.75 | 281.00 | 41.19 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 200.13 |
| 13:28:14 | 0:01:24 | 2.00 | 306.00 | 44.86 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 217.07 |
| 13:28:26 | 0:01:36 | 2.25 | 332.00 | 48.67 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 234.58 |
| 13:28:38 | 0:01:48 | 2.50 | 347.00 | 50.87 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 244.20 |
| 13:28:50 | 0:02:00 | 2.75 | 362.00 | 53.07 | 0.0423 | 4.2308 | 0.9577 | 20.5106 | 253.74 |
| 13:29:02 | 0:02:12 | 3.00 | 367.00 | 53.80 | 0.0462 | 4.6154 | 0.9538 | 20.5933 | 256.21 |
| 13:29:14 | 0:02:24 | 3.25 | 367.00 | 53.80 | 0.0500 | 5.0000 | 0.9500 | 20.6767 | 255.18 |
| 13:29:26 | 0:02:36 | 3.50 | 362.00 | 53.07 | 0.0538 | 5.3846 | 0.9462 | 20.7607 | 250.68 |
| 13:29:38 | 0:02:48 | 3.75 | 352.00 | 51.60 | 0.0577 | 5.7692 | 0.9423 | 20.8455 | 242.76 |

UNCONFINED COMPRESSION TEST

AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. 9

| | | | | | | | | | |
|--------------------------------|------|----|---------|-----|----|----------------------------------|---|---------|--------|
| Initial specimen height, H_o | 7.20 | cm | Diam. = | 5.0 | cm | Load ring constant (1 load unit) | = | 0.1466 | kg |
| Final specimen height, H_c | 6.88 | cm | | | | A_o | = | 19.64 | cm^2 |
| | | | | | | A_c | = | 20.6767 | cm^2 |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:26:35 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:26:47 | 0:00:00 | 0.25 | 51.00 | 7.48 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 37.18 |
| 13:26:59 | 0:00:12 | 0.50 | 90.00 | 13.19 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 65.36 |
| 13:27:11 | 0:00:24 | 0.75 | 141.00 | 20.67 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 102.01 |
| 13:27:23 | 0:00:36 | 1.00 | 167.00 | 24.48 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 120.35 |
| 13:27:35 | 0:00:48 | 1.25 | 193.00 | 28.29 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 138.54 |
| 13:27:47 | 0:01:00 | 1.50 | 218.00 | 31.96 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 155.87 |
| 13:27:59 | 0:01:12 | 1.75 | 244.00 | 35.77 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 173.77 |
| 13:28:11 | 0:01:24 | 2.00 | 270.00 | 39.58 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 191.53 |
| 13:28:23 | 0:01:36 | 2.25 | 283.00 | 41.49 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 199.96 |
| 13:28:35 | 0:01:48 | 2.50 | 296.00 | 43.39 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 208.31 |
| 13:28:47 | 0:02:00 | 2.75 | 296.00 | 43.39 | 0.0423 | 4.2308 | 0.9577 | 20.5106 | 207.48 |
| 13:28:59 | 0:02:12 | 3.00 | 283.00 | 41.49 | 0.0462 | 4.6154 | 0.9538 | 20.5933 | 197.57 |
| 13:29:11 | 0:02:24 | 3.25 | 270.00 | 39.58 | 0.0500 | 5.0000 | 0.9500 | 20.6767 | 187.73 |

UNCONFINED COMPRESSION TEST

AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. SUN10

| | | | | | | | | |
|--------------------------------|------|----|---------|-----|----|------------------------------------|---------|-----------------|
| Initial specimen height, H_o | 7.20 | cm | Diam. = | 5.0 | cm | Load ring constant (1 load unit) = | 0.1466 | kg |
| Final specimen height, H_c | 6.95 | cm | | | | A_o | 19.64 | cm ² |
| | | | | | | A_c | 20.4286 | cm ² |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:26:33 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:26:45 | 0:00:00 | 0.25 | 49.00 | 7.18 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 35.73 |
| 13:26:57 | 0:00:12 | 0.50 | 82.00 | 12.02 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 59.55 |
| 13:27:09 | 0:00:24 | 0.75 | 131.00 | 19.20 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 94.77 |
| 13:27:21 | 0:00:36 | 1.00 | 181.00 | 26.53 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 130.44 |
| 13:27:33 | 0:00:48 | 1.25 | 213.00 | 31.23 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 152.90 |
| 13:27:45 | 0:01:00 | 1.50 | 246.00 | 36.06 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 175.89 |
| 13:27:57 | 0:01:12 | 1.75 | 263.00 | 38.56 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 187.31 |
| 13:28:09 | 0:01:24 | 2.00 | 279.00 | 40.90 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 197.92 |
| 13:28:21 | 0:01:36 | 2.25 | 279.00 | 40.90 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 197.13 |
| 13:28:33 | 0:01:48 | 2.50 | 263.00 | 38.56 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 185.09 |

UNCONFINED COMPRESSION TEST

AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. 12

| | | | | | |
|--------------------------------|-------------|----|---------|--------|--|
| Initial specimen height, H_o | <u>7.20</u> | cm | Diam. = | 5.0 cm | Load ring constant (1 load unit) = 0.1466 kg |
| Final specimen height, H_c | <u>6.85</u> | cm | | | A_o <u>19.64</u> cm^2 |
| | | | | | A_c <u>20.7607</u> cm^2 |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:26:27 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:26:39 | 0:00:00 | 0.25 | 39.00 | 5.72 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 28.43 |
| 13:26:51 | 0:00:12 | 0.50 | 117.00 | 17.15 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 84.97 |
| 13:27:03 | 0:00:24 | 0.75 | 181.00 | 26.53 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 130.94 |
| 13:27:15 | 0:00:36 | 1.00 | 220.00 | 32.25 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 158.54 |
| 13:27:27 | 0:00:48 | 1.25 | 249.00 | 36.50 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 178.74 |
| 13:27:39 | 0:01:00 | 1.50 | 282.00 | 41.34 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 201.63 |
| 13:27:51 | 0:01:12 | 1.75 | 306.00 | 44.86 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 217.93 |
| 13:28:03 | 0:01:24 | 2.00 | 316.00 | 46.33 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 224.16 |
| 13:28:15 | 0:01:36 | 2.25 | 326.00 | 47.79 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 230.34 |
| 13:28:27 | 0:01:48 | 2.50 | 332.00 | 48.67 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 233.64 |
| 13:28:39 | 0:02:00 | 2.75 | 337.00 | 49.40 | 0.0423 | 4.2308 | 0.9577 | 20.5106 | 236.21 |
| 13:28:51 | 0:02:12 | 3.00 | 337.00 | 49.40 | 0.0462 | 4.6154 | 0.9538 | 20.5933 | 235.27 |
| 13:29:03 | 0:02:24 | 3.25 | 326.00 | 47.79 | 0.0500 | 5.0000 | 0.9500 | 20.6767 | 226.67 |
| 13:29:15 | 0:02:36 | 3.50 | 311.00 | 45.59 | 0.0538 | 5.3846 | 0.9462 | 20.7607 | 215.36 |

UNCONFINED COMPRESSION TEST

AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. 15

| | | | | |
|--------------------------------|----------------|----------------|--|--|
| Initial specimen height, H_0 | <u>7.20</u> cm | Diam. = 5.0 cm | Load ring constant (1 load unit) = 0.1466 kg | |
| Final specimen height, H_c | <u>6.93</u> cm | | A_0 <u>19.64</u> cm ² | |
| | | | A_c <u>20.5106</u> cm ² | |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:26:17 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:26:29 | 0:00:00 | 0.25 | 52.00 | 7.62 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 37.91 |
| 13:26:41 | 0:00:12 | 0.50 | 104.00 | 15.25 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 75.53 |
| 13:26:53 | 0:00:24 | 0.75 | 182.00 | 26.68 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 131.67 |
| 13:27:05 | 0:00:36 | 1.00 | 260.00 | 38.12 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 187.37 |
| 13:27:17 | 0:00:48 | 1.25 | 312.00 | 45.74 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 223.96 |
| 13:27:29 | 0:01:00 | 1.50 | 338.00 | 49.55 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 241.67 |
| 13:27:41 | 0:01:12 | 1.75 | 364.00 | 53.36 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 259.24 |
| 13:27:53 | 0:01:24 | 2.00 | 390.00 | 57.17 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 276.66 |
| 13:28:05 | 0:01:36 | 2.25 | 403.00 | 59.08 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 284.74 |
| 13:28:17 | 0:01:48 | 2.50 | 390.00 | 57.17 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 274.46 |
| 13:28:29 | 0:02:00 | 2.75 | 364.00 | 53.36 | 0.0423 | 4.2308 | 0.9577 | 20.5106 | 255.14 |

UNCONFINED COMPRESSION TEST
AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. SUN18

| | | | | | | | | |
|--------------------------------|-------------|----|---------|-----|----|------------------------------------|----------------|--------|
| Initial specimen height, H_o | <u>7.20</u> | cm | Diam. = | 5.0 | cm | Load ring constant (1 load unit) = | 0.1466 | kg |
| Final specimen height, H_c | <u>6.85</u> | cm | | | | A_o | <u>19.64</u> | cm^2 |
| | | | | | | A_c | <u>20.7607</u> | cm^2 |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:26:07 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:26:19 | 0:00:00 | 0.25 | 18.00 | 2.64 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 13.12 |
| 13:26:31 | 0:00:12 | 0.50 | 39.00 | 5.72 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 28.32 |
| 13:26:43 | 0:00:24 | 0.75 | 60.00 | 8.80 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 43.41 |
| 13:26:55 | 0:00:36 | 1.00 | 91.00 | 13.34 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 65.58 |
| 13:27:07 | 0:00:48 | 1.25 | 130.00 | 19.06 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 93.32 |
| 13:27:19 | 0:01:00 | 1.50 | 158.00 | 23.16 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 112.97 |
| 13:27:31 | 0:01:12 | 1.75 | 193.00 | 28.29 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 137.45 |
| 13:27:43 | 0:01:24 | 2.00 | 210.00 | 30.79 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 148.97 |
| 13:27:55 | 0:01:36 | 2.25 | 228.00 | 33.42 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 161.10 |
| 13:28:07 | 0:01:48 | 2.50 | 238.00 | 34.89 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 167.49 |
| 13:28:19 | 0:02:00 | 2.75 | 245.00 | 35.92 | 0.0423 | 4.2308 | 0.9577 | 20.5106 | 171.73 |
| 13:28:31 | 0:02:12 | 3.00 | 249.00 | 36.50 | 0.0462 | 4.6154 | 0.9538 | 20.5933 | 173.83 |
| 13:28:43 | 0:02:24 | 3.25 | 242.00 | 35.48 | 0.0500 | 5.0000 | 0.9500 | 20.6767 | 168.26 |
| 13:28:55 | 0:02:36 | 3.50 | 228.00 | 33.42 | 0.0538 | 5.3846 | 0.9462 | 20.7607 | 157.89 |

UNCONFINED COMPRESSION TEST
AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. 19

Load ring constant (1 load unit) = 0.1466 kg

Initial specimen height, H_o 7.20 cm

Diam. = 5.0 cm

A_o 19.64 cm²

Final specimen height, H_c 6.88 cm

A_c 20.6767 cm²

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:26:03 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:26:15 | 0:00:00 | 0.25 | 68.00 | 9.97 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 49.58 |
| 13:26:27 | 0:00:12 | 0.50 | 119.00 | 17.45 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 86.43 |
| 13:26:39 | 0:00:24 | 0.75 | 188.00 | 27.56 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 136.01 |
| 13:26:51 | 0:00:36 | 1.00 | 222.00 | 32.55 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 159.98 |
| 13:27:03 | 0:00:48 | 1.25 | 256.00 | 37.53 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 183.76 |
| 13:27:15 | 0:01:00 | 1.50 | 290.00 | 42.51 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 207.35 |
| 13:27:27 | 0:01:12 | 1.75 | 324.00 | 47.50 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 230.75 |
| 13:27:39 | 0:01:24 | 2.00 | 358.00 | 52.48 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 253.96 |
| 13:27:51 | 0:01:36 | 2.25 | 375.00 | 54.98 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 264.96 |
| 13:28:03 | 0:01:48 | 2.50 | 392.00 | 57.47 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 275.87 |
| 13:28:15 | 0:02:00 | 2.75 | 392.00 | 57.47 | 0.0423 | 4.2308 | 0.9577 | 20.5106 | 274.77 |
| 13:28:27 | 0:02:12 | 3.00 | 375.00 | 54.98 | 0.0462 | 4.6154 | 0.9538 | 20.5933 | 261.79 |
| 13:28:39 | 0:02:24 | 3.25 | 358.00 | 52.48 | 0.0500 | 5.0000 | 0.9500 | 20.6767 | 248.92 |

UNCONFINED COMPRESSION TEST
AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. 20

| | | | |
|--------------------------------|----------------|----------------|--|
| Initial specimen height, H_o | <u>7.20</u> cm | Diam. = 5.0 cm | Load ring constant (1 load unit) = 0.1466 kg |
| Final specimen height, H_c | <u>6.95</u> cm | | A_o <u>19.64</u> cm ² |
| | | | A_c <u>20.4286</u> cm ² |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:26:00 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:26:12 | 0:00:00 | 0.25 | 57.00 | 8.36 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 41.56 |
| 13:26:24 | 0:00:12 | 0.50 | 95.00 | 13.93 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 69.00 |
| 13:26:36 | 0:00:24 | 0.75 | 151.00 | 22.14 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 109.24 |
| 13:26:48 | 0:00:36 | 1.00 | 208.00 | 30.49 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 149.89 |
| 13:27:00 | 0:00:48 | 1.25 | 246.00 | 36.06 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 176.58 |
| 13:27:12 | 0:01:00 | 1.50 | 284.00 | 41.63 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 203.06 |
| 13:27:24 | 0:01:12 | 1.75 | 303.00 | 44.42 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 215.79 |
| 13:27:36 | 0:01:24 | 2.00 | 322.00 | 47.21 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 228.42 |
| 13:27:48 | 0:01:36 | 2.25 | 322.00 | 47.21 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 227.51 |
| 13:28:00 | 0:01:48 | 2.50 | 303.00 | 44.42 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 213.24 |

UNCONFINED COMPRESSION TEST
AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. SUN22

Load ring constant (1 load unit) = 0.1466 kg

Initial specimen height, H_o 7.20 cm Diam. = 5.0 cm A_o 19.64 cm²
 Final specimen height, H_c 6.85 cm A_c 20.7607 cm²

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:25:53 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:26:05 | 0:00:00 | 0.25 | 47.00 | 6.89 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 34.27 |
| 13:26:17 | 0:00:12 | 0.50 | 141.00 | 20.67 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 102.40 |
| 13:26:29 | 0:00:24 | 0.75 | 219.00 | 32.11 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 158.44 |
| 13:26:41 | 0:00:36 | 1.00 | 266.00 | 39.00 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 191.69 |
| 13:26:53 | 0:00:48 | 1.25 | 300.00 | 43.98 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 215.35 |
| 13:27:05 | 0:01:00 | 1.50 | 341.00 | 49.99 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 243.82 |
| 13:27:17 | 0:01:12 | 1.75 | 369.00 | 54.10 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 262.80 |
| 13:27:29 | 0:01:24 | 2.00 | 382.00 | 56.00 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 270.98 |
| 13:27:41 | 0:01:36 | 2.25 | 394.00 | 57.76 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 278.39 |
| 13:27:53 | 0:01:48 | 2.50 | 401.00 | 58.79 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 282.20 |
| 13:28:05 | 0:02:00 | 2.75 | 407.00 | 59.67 | 0.0423 | 4.2308 | 0.9577 | 20.5106 | 285.28 |
| 13:28:17 | 0:02:12 | 3.00 | 407.00 | 59.67 | 0.0462 | 4.6154 | 0.9538 | 20.5933 | 284.13 |
| 13:28:29 | 0:02:24 | 3.25 | 394.00 | 57.76 | 0.0500 | 5.0000 | 0.9500 | 20.6767 | 273.95 |
| 13:28:41 | 0:02:36 | 3.50 | 376.00 | 55.12 | 0.0538 | 5.3846 | 0.9462 | 20.7607 | 260.38 |

UNCONFINED COMPRESSION TEST
AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. SUN23

| | | | | |
|--------------------------------|----------------|----------------|--|--|
| Initial specimen height, H_0 | <u>7.20</u> cm | Diam. = 5.0 cm | Load ring constant (1 load unit) = 0.1466 kg | |
| Final specimen height, H_c | <u>6.95</u> cm | | A_0 <u>19.64</u> cm ² | |
| | | | A_c <u>20.4286</u> cm ² | |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:25:50 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:26:02 | 0:00:00 | 0.25 | 44.00 | 6.45 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 32.08 |
| 13:26:14 | 0:00:12 | 0.50 | 87.00 | 12.75 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 63.19 |
| 13:26:26 | 0:00:24 | 0.75 | 131.00 | 19.20 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 94.77 |
| 13:26:38 | 0:00:36 | 1.00 | 174.00 | 25.51 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 125.39 |
| 13:26:50 | 0:00:48 | 1.25 | 218.00 | 31.96 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 156.49 |
| 13:27:02 | 0:01:00 | 1.50 | 247.00 | 36.21 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 176.61 |
| 13:27:14 | 0:01:12 | 1.75 | 262.00 | 38.41 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 186.59 |
| 13:27:26 | 0:01:24 | 2.00 | 276.00 | 40.46 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 195.79 |
| 13:27:38 | 0:01:36 | 2.25 | 275.00 | 40.32 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 194.30 |
| 13:27:50 | 0:01:48 | 2.50 | 262.00 | 38.41 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 184.38 |

UNCONFINED COMPRESSION TEST

AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. SUN34

| | | | | |
|--------------------------------|------|----|----------------|--|
| Initial specimen height, H_o | 7.20 | cm | Diam. = 5.0 cm | Load ring constant (1 load unit) = 0.1466 kg |
| Final specimen height, H_c | 6.90 | cm | | |
| | | | | $A_o = 19.64 \text{ cm}^2$ |
| | | | | $A_c = 20.5933 \text{ cm}^2$ |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:28:17 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:28:29 | 0:00:00 | 0.25 | 32.00 | 4.69 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 23.33 |
| 13:28:41 | 0:00:12 | 0.50 | 72.00 | 10.56 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 52.29 |
| 13:28:53 | 0:00:24 | 0.75 | 116.00 | 17.01 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 83.92 |
| 13:29:05 | 0:00:36 | 1.00 | 156.00 | 22.87 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 112.42 |
| 13:29:17 | 0:00:48 | 1.25 | 182.00 | 26.68 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 130.64 |
| 13:29:29 | 0:01:00 | 1.50 | 203.00 | 29.76 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 145.15 |
| 13:29:41 | 0:01:12 | 1.75 | 222.00 | 32.55 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 158.11 |
| 13:29:53 | 0:01:24 | 2.00 | 233.00 | 34.16 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 165.28 |
| 13:30:05 | 0:01:36 | 2.25 | 243.00 | 35.62 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 171.69 |
| 13:30:17 | 0:01:48 | 2.50 | 247.00 | 36.21 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 173.83 |
| 13:30:29 | 0:02:00 | 2.75 | 243.00 | 35.62 | 0.0423 | 4.2308 | 0.9577 | 20.5106 | 170.33 |
| 13:30:41 | 0:02:12 | 3.00 | 233.00 | 34.16 | 0.0462 | 4.6154 | 0.9538 | 20.5933 | 162.66 |

UNCONFINED COMPRESSION TEST

AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. SUN35

| | | | | | | | | |
|--------------------------------|-------------|----|---------|-----|----|------------------------------------|----------------|---------------|
| Initial specimen height, H_0 | <u>7.20</u> | cm | Diam. = | 5.0 | cm | Load ring constant (1 load unit) = | 0.1466 | kg |
| Final specimen height, H_c | <u>6.93</u> | cm | | | | A_0 | <u>19.64</u> | cm^2 |
| | | | | | | A_c | <u>20.5106</u> | cm^2 |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | $1 - \epsilon$ | Corrected Area, $A_{corr} = A/1 - \epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:28:15 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:28:27 | 0:00:00 | 0.25 | 32.00 | 4.69 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 23.33 |
| 13:28:39 | 0:00:12 | 0.50 | 64.00 | 9.38 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 46.48 |
| 13:28:51 | 0:00:24 | 0.75 | 111.00 | 16.27 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 80.30 |
| 13:29:03 | 0:00:36 | 1.00 | 159.00 | 23.31 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 114.58 |
| 13:29:15 | 0:00:48 | 1.25 | 191.00 | 28.00 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 137.10 |
| 13:29:27 | 0:01:00 | 1.50 | 207.00 | 30.35 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 148.01 |
| 13:29:39 | 0:01:12 | 1.75 | 222.00 | 32.55 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 158.11 |
| 13:29:51 | 0:01:24 | 2.00 | 238.00 | 34.89 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 168.83 |
| 13:30:03 | 0:01:36 | 2.25 | 246.00 | 36.06 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 173.81 |
| 13:30:15 | 0:01:48 | 2.50 | 238.00 | 34.89 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 167.49 |
| 13:30:27 | 0:02:00 | 2.75 | 222.00 | 32.55 | 0.0423 | 4.2308 | 0.9577 | 20.5106 | 155.61 |

UNCONFINED COMPRESSION TEST
AXIAL LOAD DATA

Type of material:

Date: 4/5/2023

Sample ID. SUN38

| | | | | |
|--------------------------------|-------------|----|----------------|--|
| Initial specimen height, H_o | <u>7.20</u> | cm | Diam. = 5.0 cm | Load ring constant (1 load unit) = 0.1466 kg |
| Final specimen height, H_c | <u>6.83</u> | cm | | A_o <u>19.64</u> cm^2 |
| | | | | A_c <u>20.8455</u> cm^2 |

| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain $\epsilon = \Delta H/H$ | % strain | 1 - ϵ | Corrected Area, $A_{corr} = A/1-\epsilon$ | Axial Stress = P / A_{corr} kPa |
|----------|-------------------|-------------------------------------|---------------------------|---------------|--------------------------------------|----------|----------------|---|-----------------------------------|
| 13:28:07 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:28:19 | 0:00:00 | 0.25 | 13.00 | 1.91 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 9.48 |
| 13:28:31 | 0:00:12 | 0.50 | 29.00 | 4.25 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 21.06 |
| 13:28:43 | 0:00:24 | 0.75 | 55.00 | 8.06 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 39.79 |
| 13:28:55 | 0:00:36 | 1.00 | 92.00 | 13.49 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 66.30 |
| 13:29:07 | 0:00:48 | 1.25 | 134.00 | 19.64 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 96.19 |
| 13:29:19 | 0:01:00 | 1.50 | 189.00 | 27.71 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 135.14 |
| 13:29:31 | 0:01:12 | 1.75 | 231.00 | 33.86 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 164.52 |
| 13:29:43 | 0:01:24 | 2.00 | 252.00 | 36.94 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 178.76 |
| 13:29:55 | 0:01:36 | 2.25 | 273.00 | 40.02 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 192.89 |
| 13:30:07 | 0:01:48 | 2.50 | 286.00 | 41.93 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 201.27 |
| 13:30:19 | 0:02:00 | 2.75 | 298.00 | 43.69 | 0.0423 | 4.2308 | 0.9577 | 20.5106 | 208.88 |
| 13:30:31 | 0:02:12 | 3.00 | 302.00 | 44.27 | 0.0462 | 4.6154 | 0.9538 | 20.5933 | 210.83 |
| 13:30:43 | 0:02:24 | 3.25 | 302.00 | 44.27 | 0.0500 | 5.0000 | 0.9500 | 20.6767 | 209.98 |
| 13:30:55 | 0:02:36 | 3.50 | 298.00 | 43.69 | 0.0538 | 5.3846 | 0.9462 | 20.7607 | 206.36 |
| 13:31:07 | 0:02:48 | 3.75 | 290.00 | 42.51 | 0.0577 | 5.7692 | 0.9423 | 20.8455 | 200.00 |

UNCONFINED COMPRESSION TEST
AXIAL LOAD DATA

Type of material:

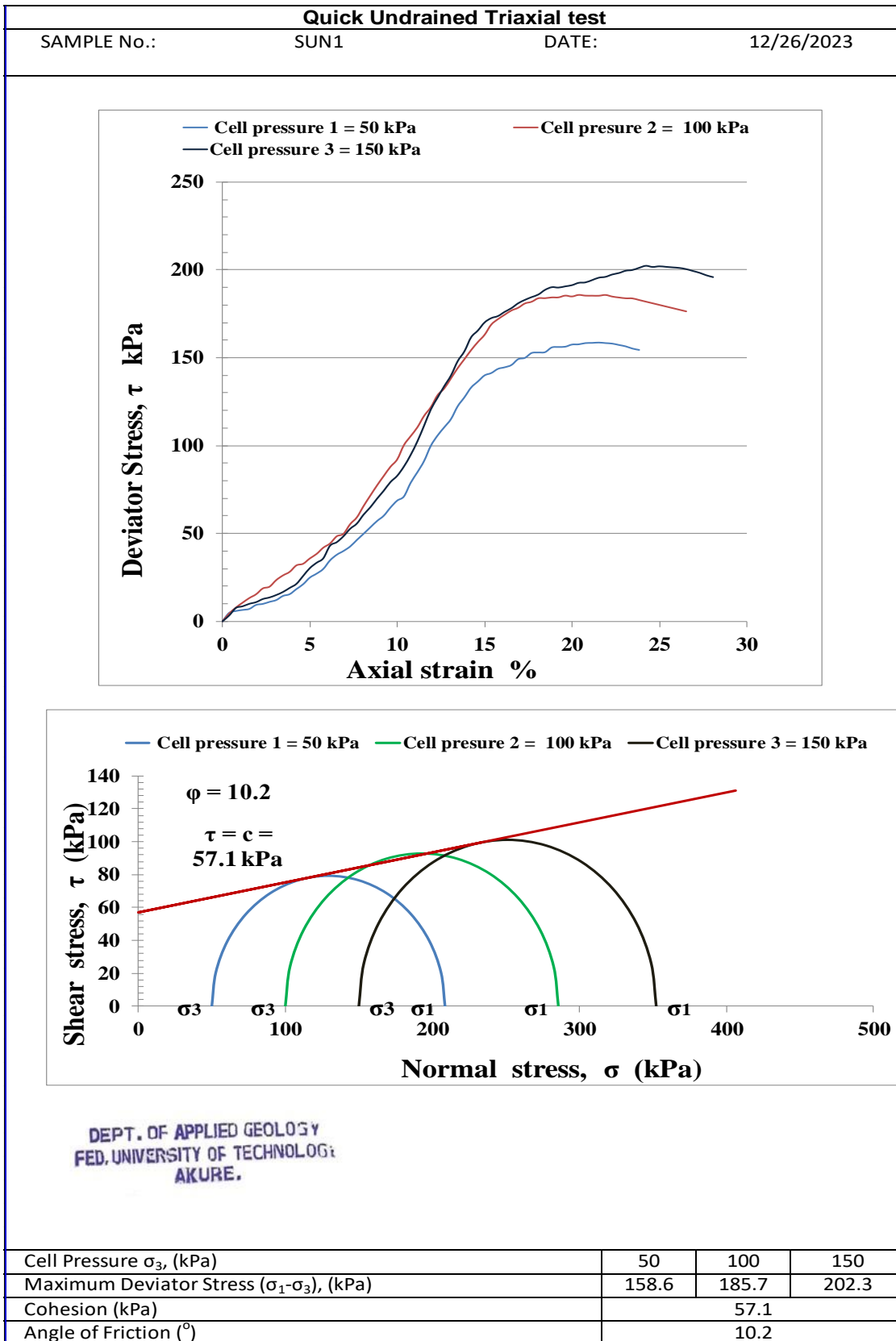
Date: 4/5/2023

Sample ID. SUN40

| | | | |
|---|----------------|--|---|
| | | Load ring constant (1 load unit) = 0.1466 kg | |
| Initial specimen height, H _o | <u>7.20</u> cm | Diam. = 5.0 cm | A _o <u>19.64</u> cm ² |
| Final specimen height, H _c | <u>6.95</u> cm | | A _c <u>20.4286</u> cm ² |

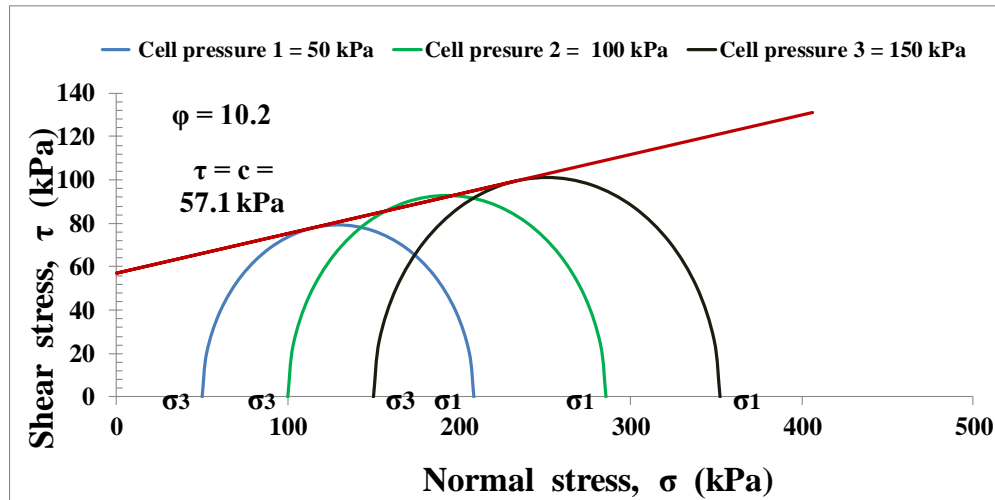
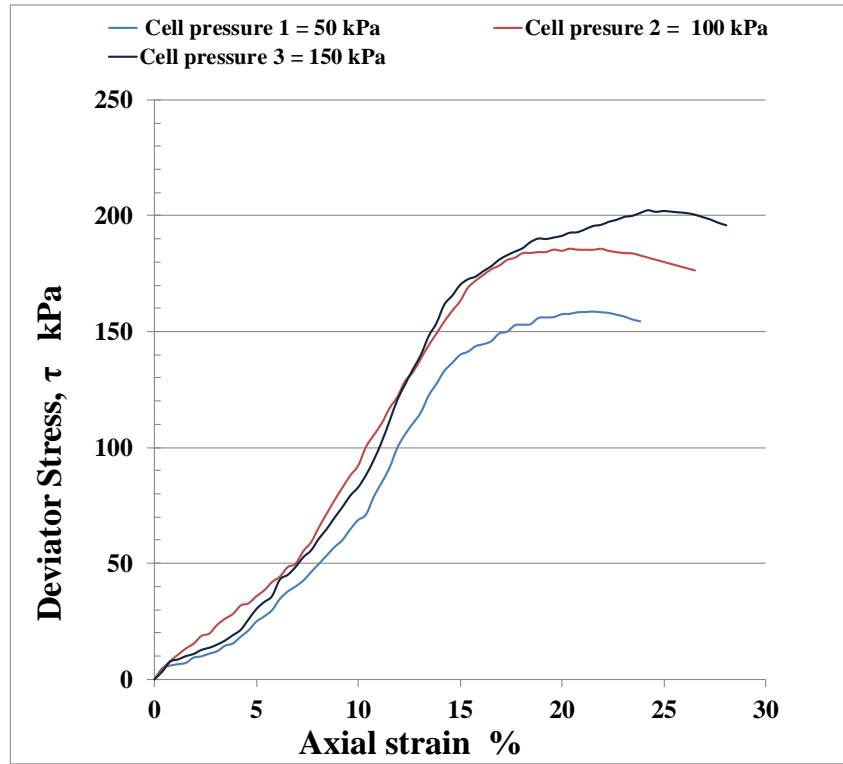
| Time | Elapsed Time sec. | Cumulative change (ΔH) mm | Load dial readings (unit) | Axial Load kg | Axial Strain ε = ΔH/H | % strain | 1 - ε | Corrected Area, A _{corr} = A/1-ε | Axial Stress = P / A _{corr} kPa |
|----------|-------------------|---------------------------|---------------------------|---------------|-----------------------|----------|--------|---|--|
| 13:27:00 | 0:00:00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.0000 | 1.0000 | 19.6429 | 0.00 |
| 13:27:12 | 0:00:00 | 0.25 | 61.00 | 8.94 | 0.0038 | 0.3846 | 0.9962 | 19.7187 | 44.47 |
| 13:27:24 | 0:00:12 | 0.50 | 101.00 | 14.81 | 0.0077 | 0.7692 | 0.9923 | 19.7951 | 73.35 |
| 13:27:36 | 0:00:24 | 0.75 | 162.00 | 23.75 | 0.0115 | 1.1538 | 0.9885 | 19.8722 | 117.20 |
| 13:27:48 | 0:00:36 | 1.00 | 222.00 | 32.55 | 0.0154 | 1.5385 | 0.9846 | 19.9498 | 159.98 |
| 13:28:00 | 0:00:48 | 1.25 | 263.00 | 38.56 | 0.0192 | 1.9231 | 0.9808 | 20.0280 | 188.79 |
| 13:28:12 | 0:01:00 | 1.50 | 303.00 | 44.42 | 0.0231 | 2.3077 | 0.9769 | 20.1069 | 216.65 |
| 13:28:24 | 0:01:12 | 1.75 | 323.00 | 47.35 | 0.0269 | 2.6923 | 0.9731 | 20.1863 | 230.04 |
| 13:28:36 | 0:01:24 | 2.00 | 343.00 | 50.28 | 0.0308 | 3.0769 | 0.9692 | 20.2664 | 243.32 |
| 13:28:48 | 0:01:36 | 2.25 | 343.00 | 50.28 | 0.0346 | 3.4615 | 0.9654 | 20.3472 | 242.35 |
| 13:29:00 | 0:01:48 | 2.50 | 323.00 | 47.35 | 0.0385 | 3.8462 | 0.9615 | 20.4286 | 227.31 |

Appendix 6. Quick undrained triaxial test



Quick Undrained Triaxial test

SAMPLE No.: SUN1 DATE: 12/26/2023



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

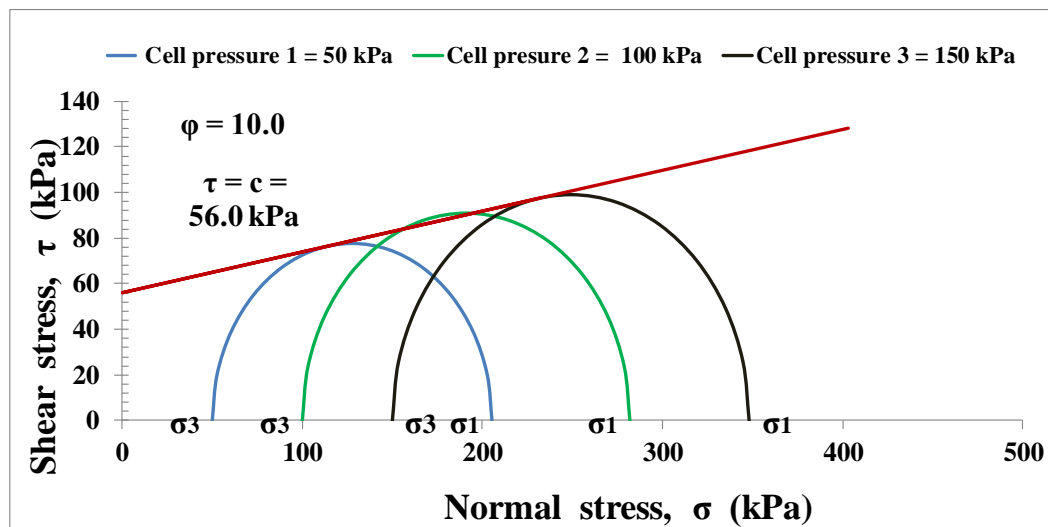
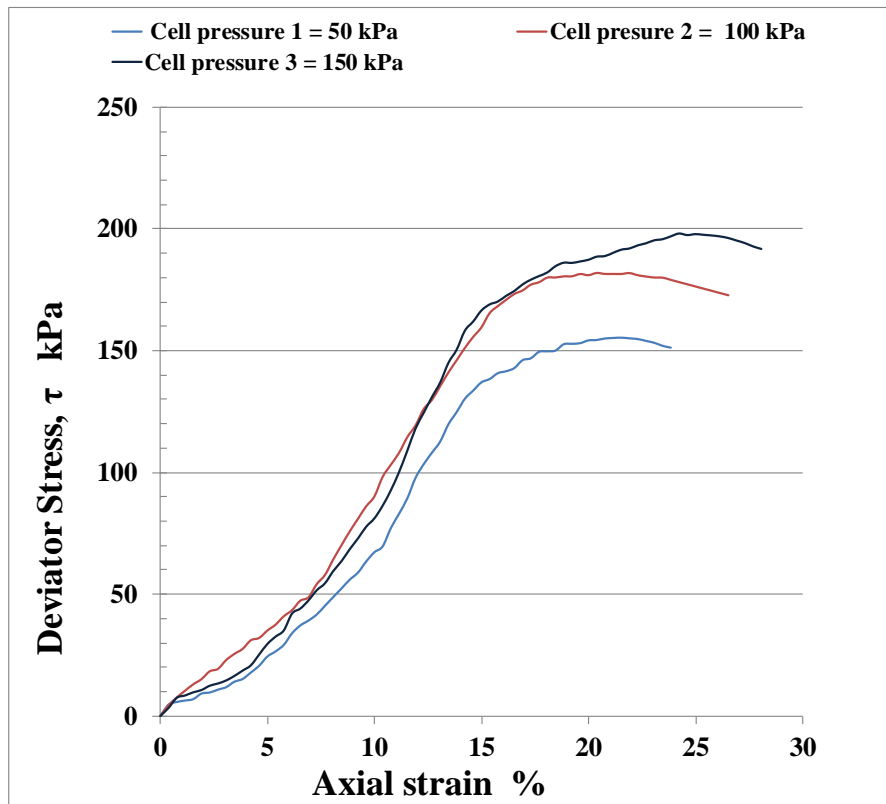
| | | | |
|--|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress ($\sigma_1 - \sigma_3$), (kPa) | 158.6 | 185.7 | 202.3 |
| Cohesion (kPa) | 57.1 | | |
| Angle of Friction ($^\circ$) | 10.2 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN2



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

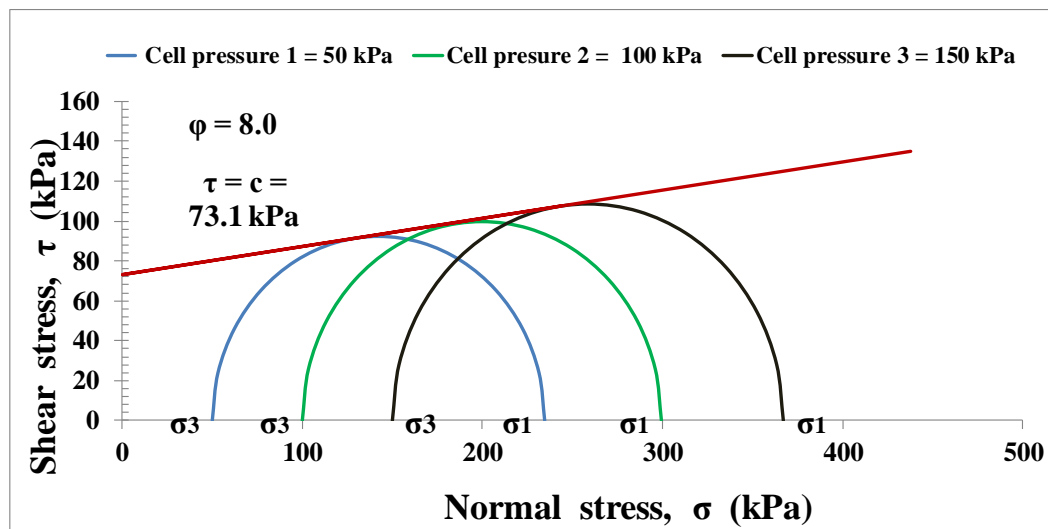
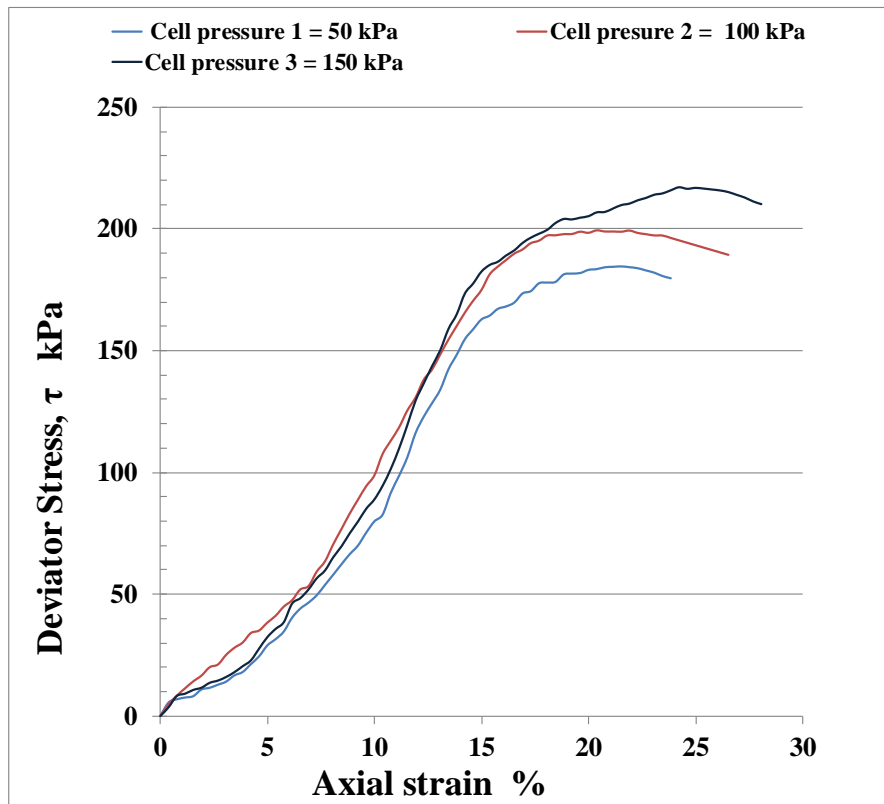
| | | | |
|--|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress ($\sigma_1 - \sigma_3$), (kPa) | 155.3 | 181.9 | 198.1 |
| Cohesion (kPa) | 56.0 | | |
| Angle of Friction ($^\circ$) | 10.0 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

3



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

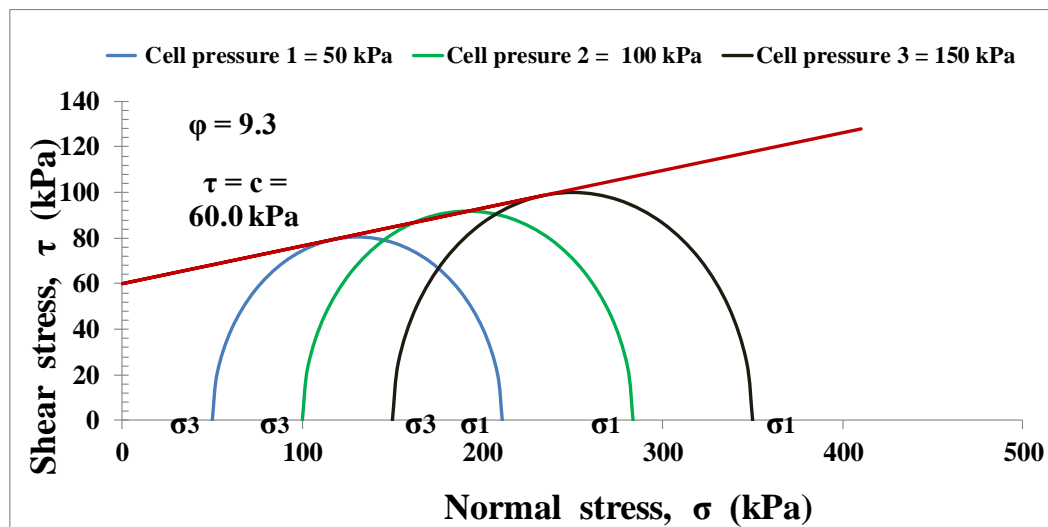
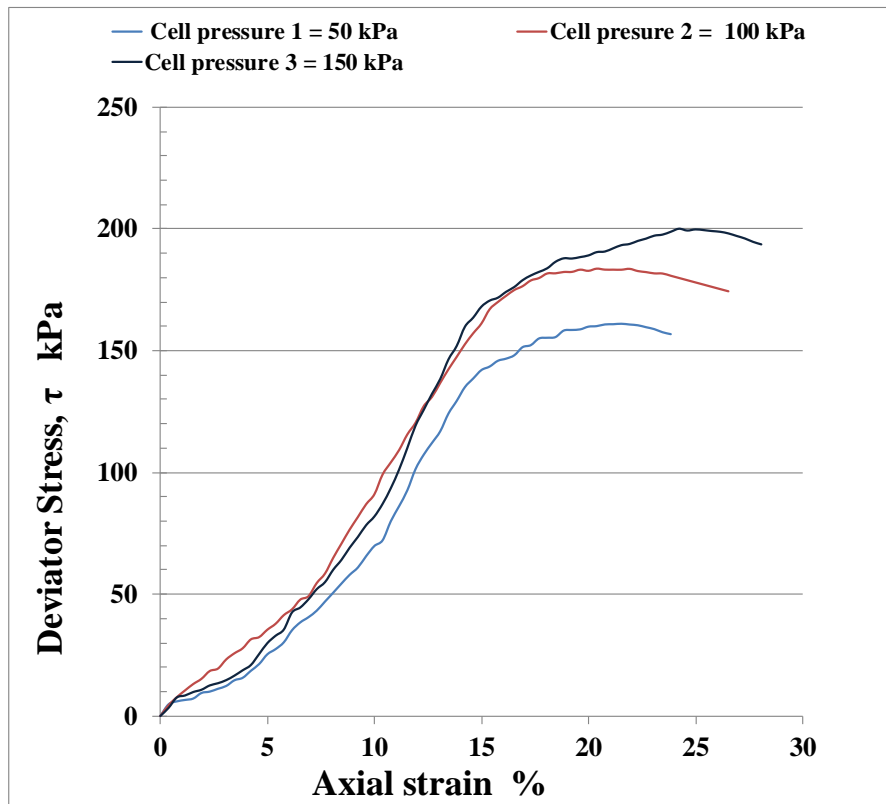
| | | | |
|--|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress ($\sigma_1 - \sigma_3$), (kPa) | 184.6 | 199.4 | 217.1 |
| Cohesion (kPa) | 73.1 | | |
| Angle of Friction ($^\circ$) | 8.0 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN4



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

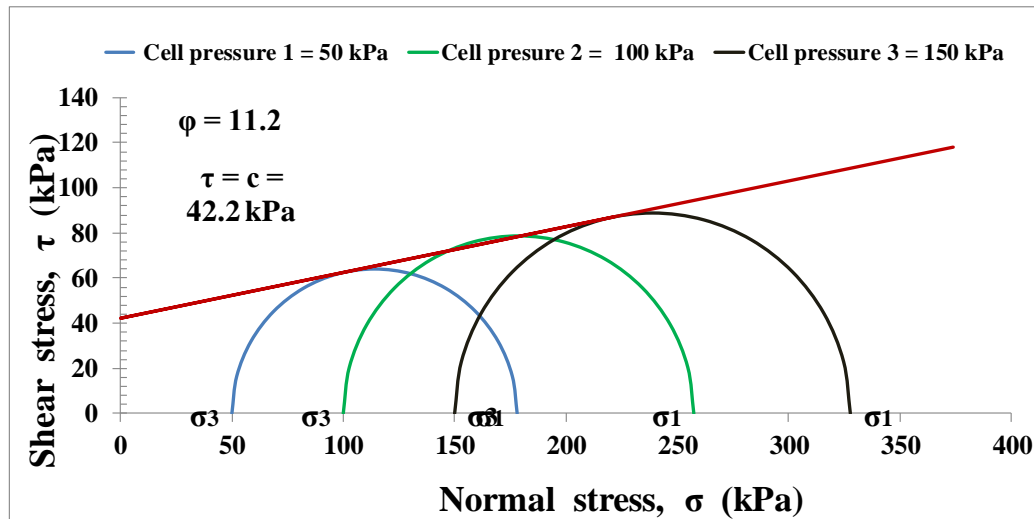
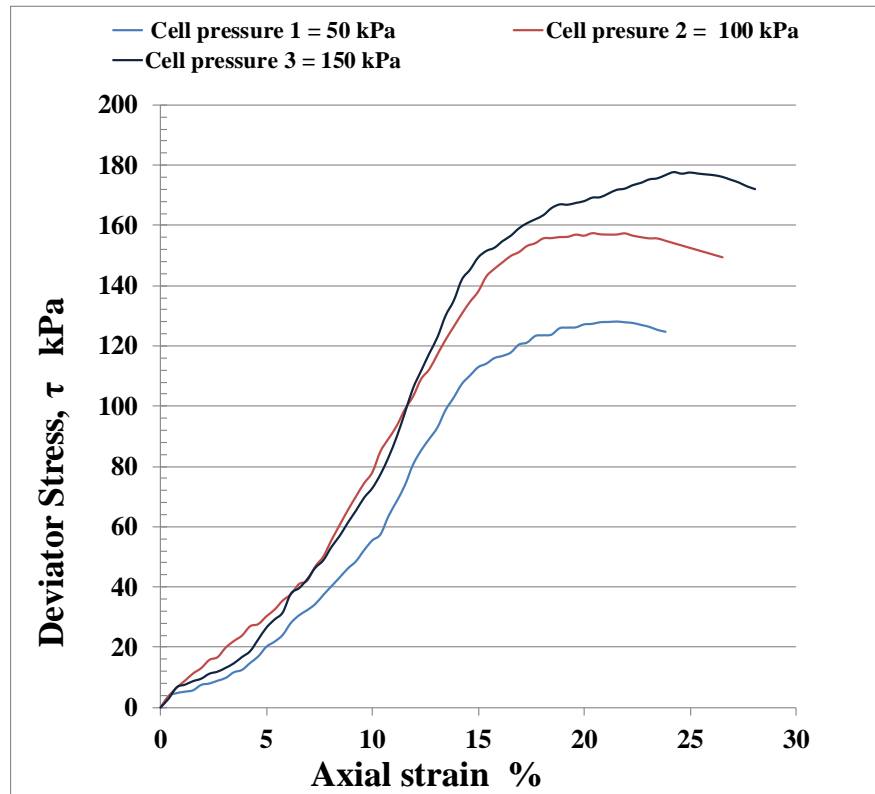
| | | | |
|---|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 161.0 | 183.7 | 200.1 |
| Cohesion (kPa) | 60.0 | | |
| Angle of Friction ($^\circ$) | 9.3 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN5



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

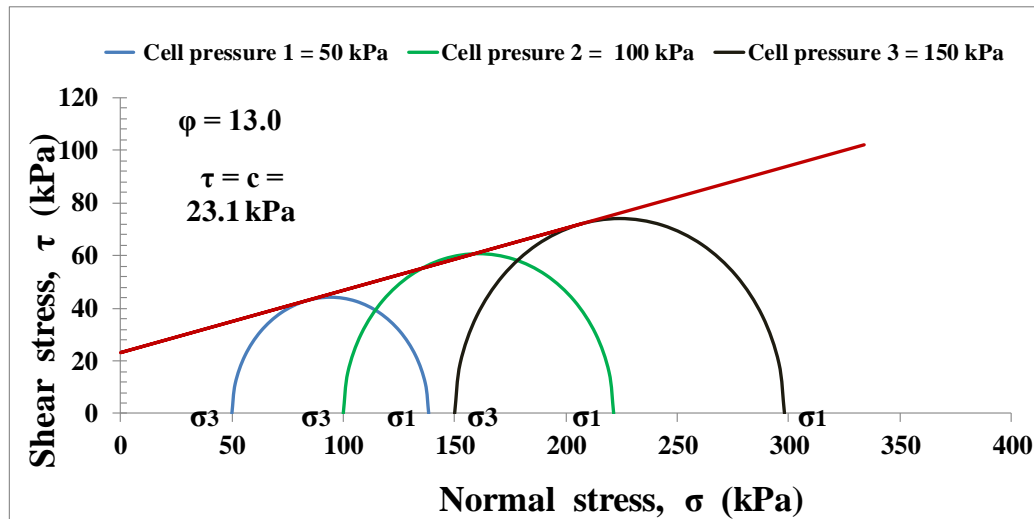
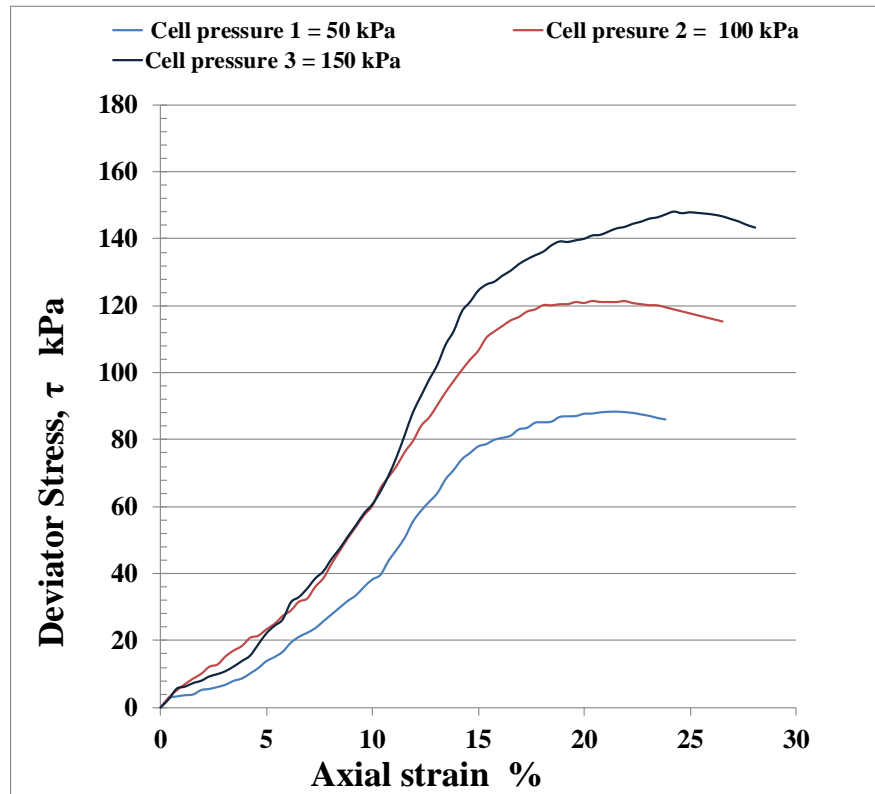
| | | | |
|---|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 128.1 | 157.4 | 177.7 |
| Cohesion (kPa) | 42.2 | | |
| Angle of Friction ($^\circ$) | 11.2 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN6



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

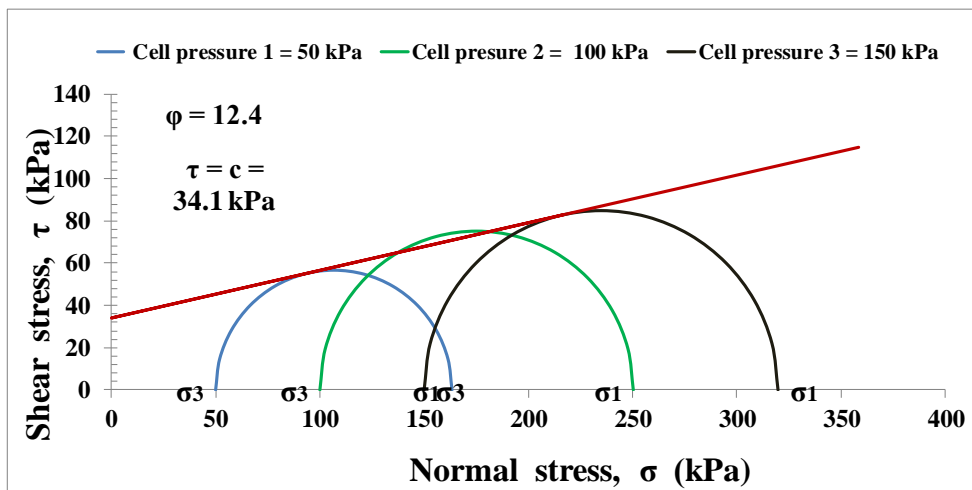
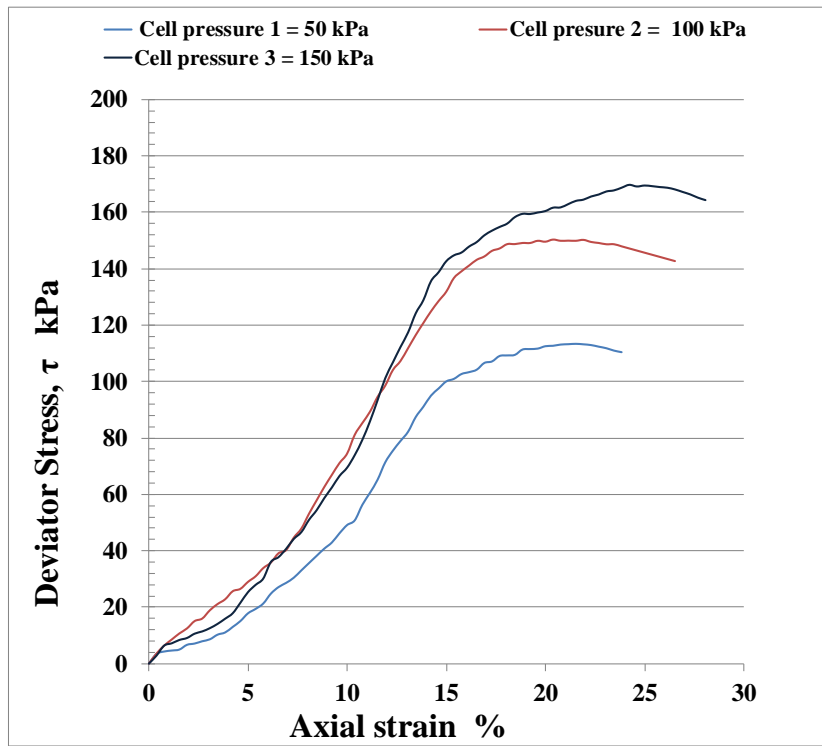
| | | | |
|---|------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 88.4 | 121.4 | 148.1 |
| Cohesion (kPa) | 23.1 | | |
| Angle of Friction ($^\circ$) | 13.0 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN7



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

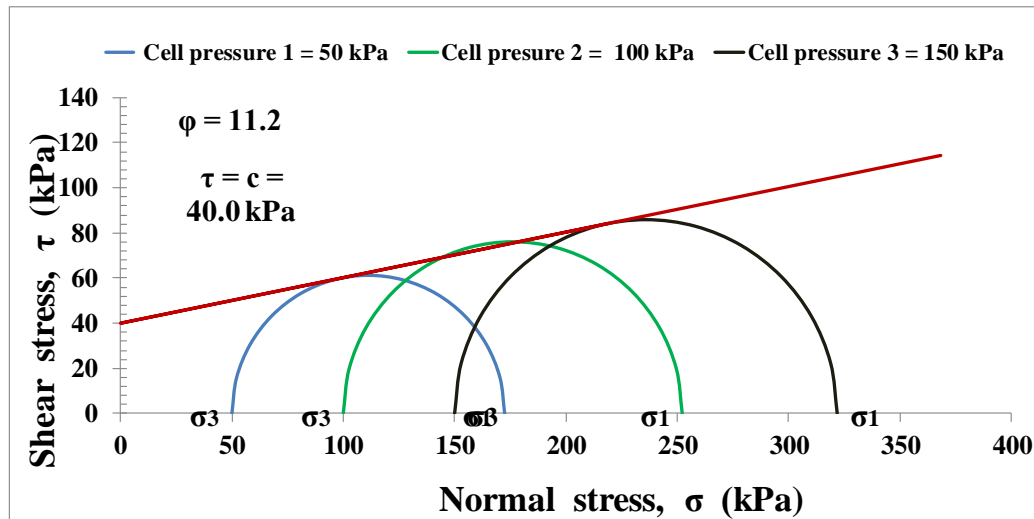
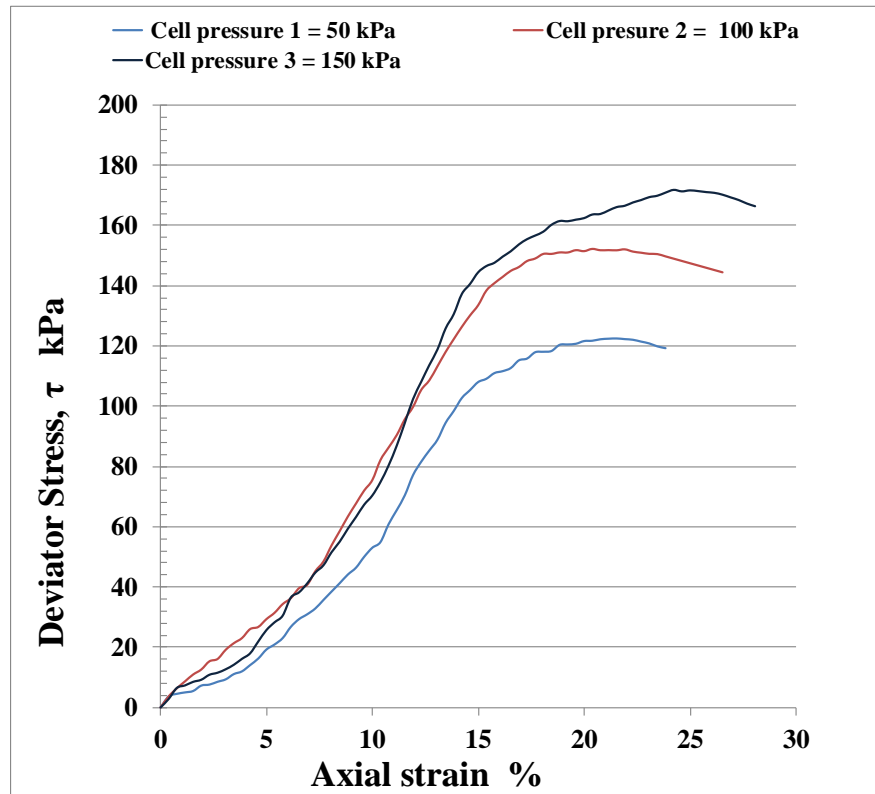
| | | | |
|---|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 113.4 | 150.3 | 169.7 |
| Cohesion (kPa) | 34.1 | | |
| Angle of Friction ($^\circ$) | 12.4 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN9



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

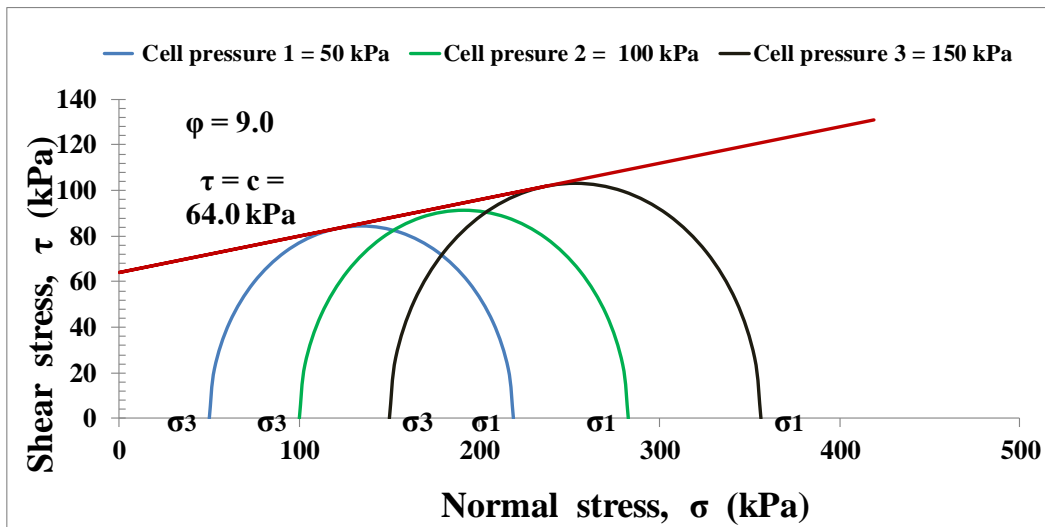
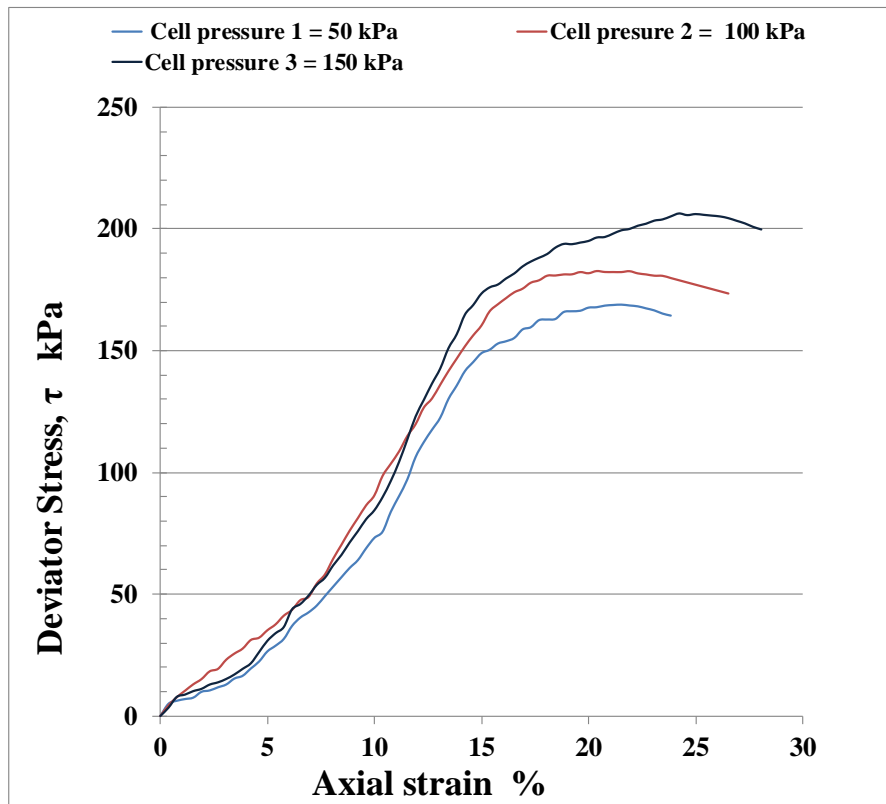
| | | | |
|---|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 122.5 | 152.2 | 171.8 |
| Cohesion (kPa) | 40.0 | | |
| Angle of Friction ($^\circ$) | 11.2 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN8



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

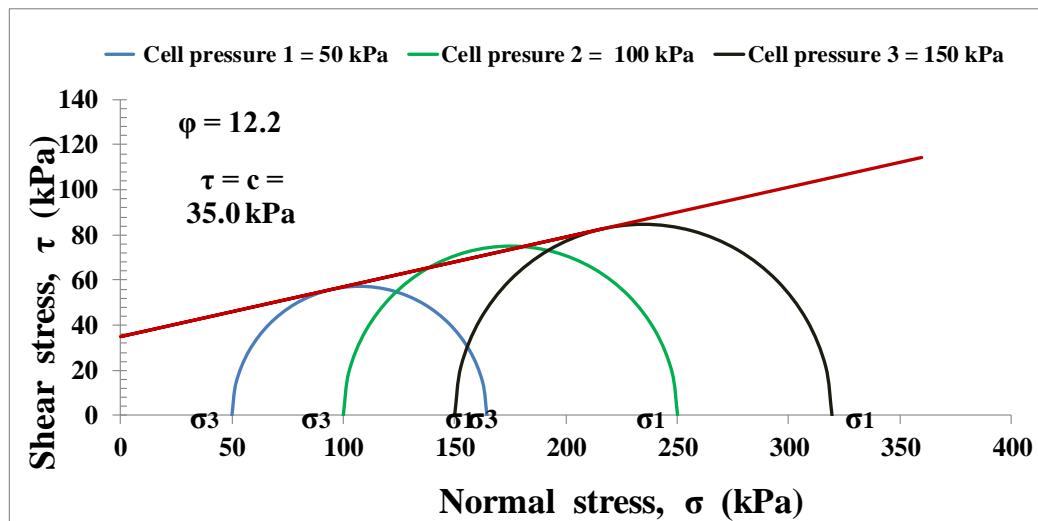
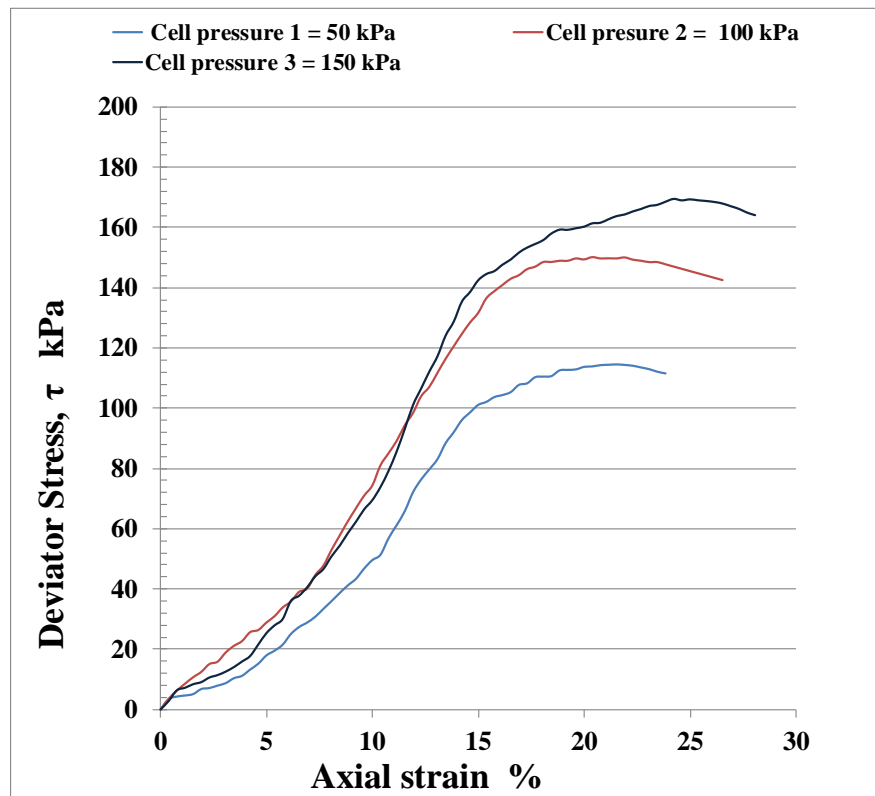
| | | | |
|--|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress ($\sigma_1 - \sigma_3$), (kPa) | 168.9 | 182.7 | 206.3 |
| Cohesion (kPa) | 64.0 | | |
| Angle of Friction ($^\circ$) | 9.0 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN10



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

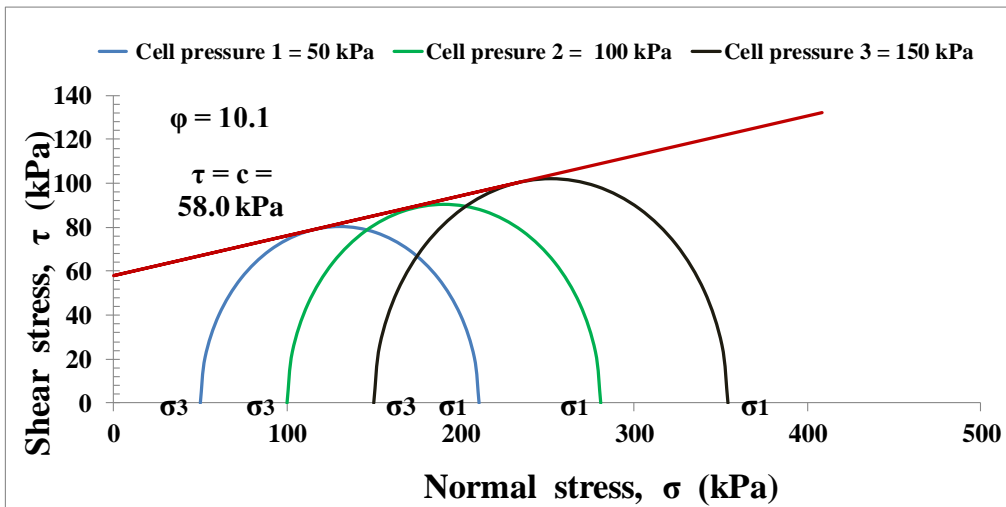
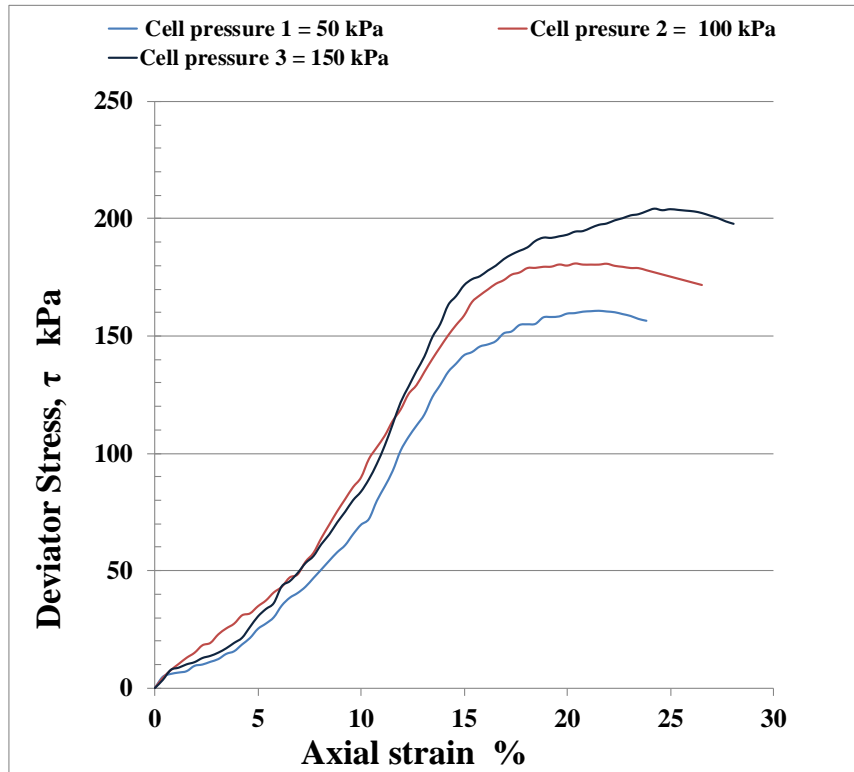
| | | | |
|---|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 114.5 | 150.1 | 169.5 |
| Cohesion (kPa) | 35.0 | | |
| Angle of Friction ($^\circ$) | 12.2 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN11



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

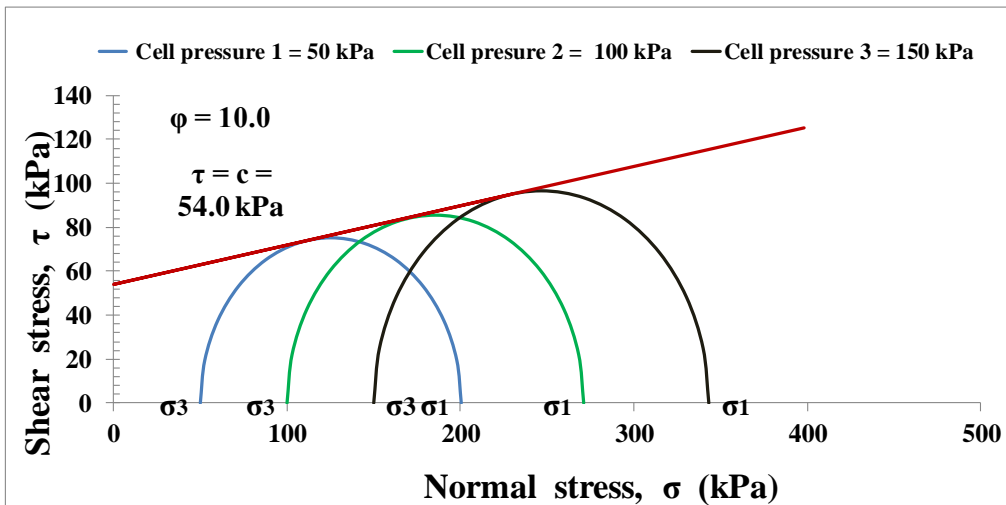
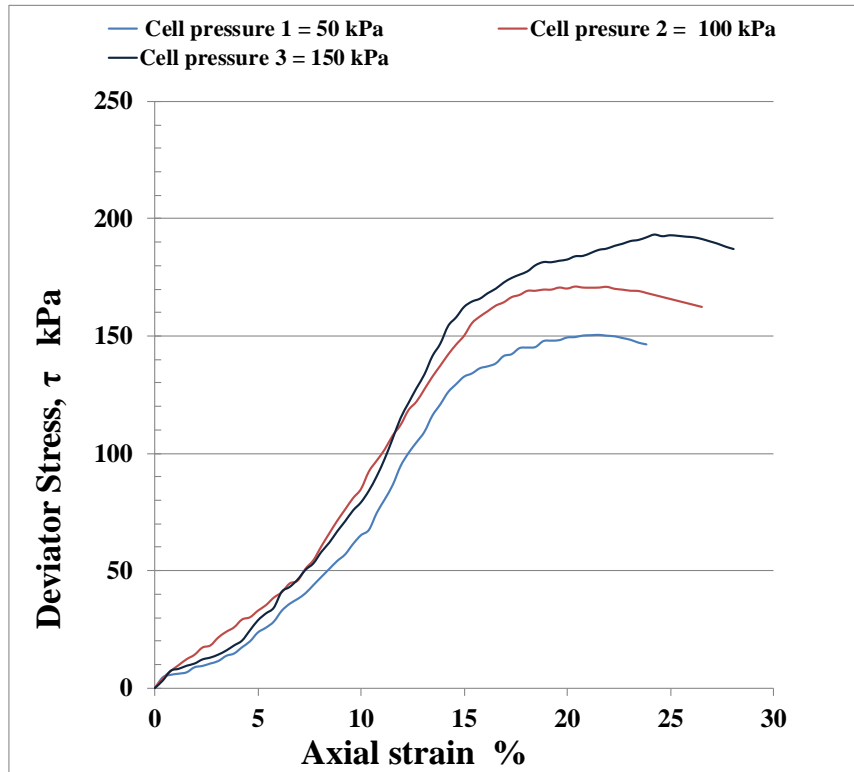
| | | | |
|---|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 160.7 | 180.9 | 204.3 |
| Cohesion (kPa) | 58.0 | | |
| Angle of Friction ($^\circ$) | 10.1 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN12



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

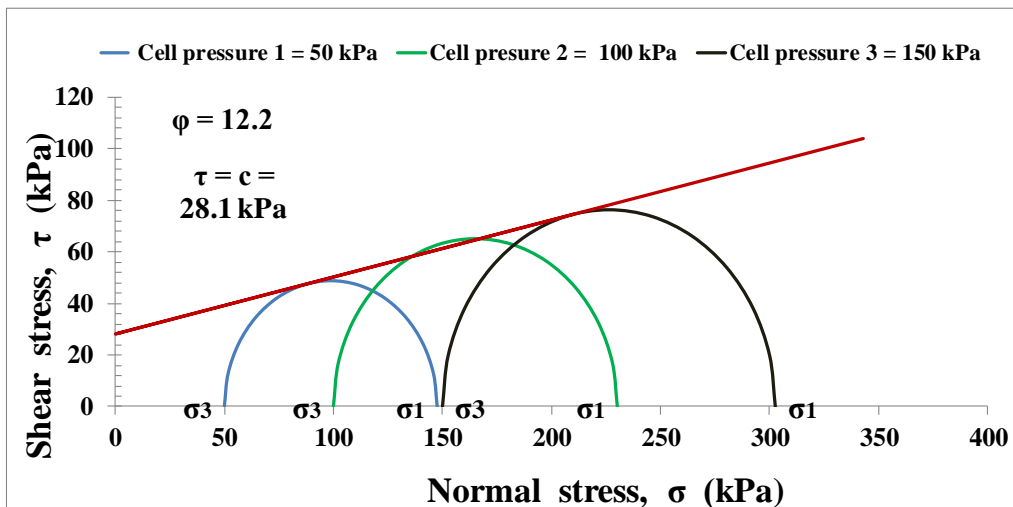
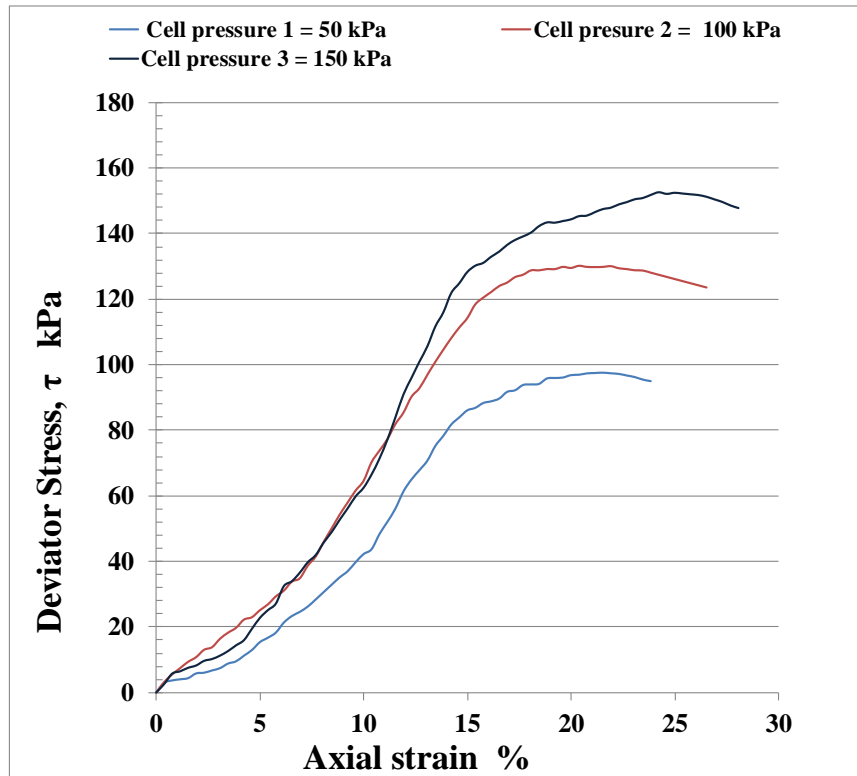
| | | | |
|---|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 150.5 | 171.1 | 193.2 |
| Cohesion (kPa) | 54.0 | | |
| Angle of Friction ($^\circ$) | 10.0 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

13



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

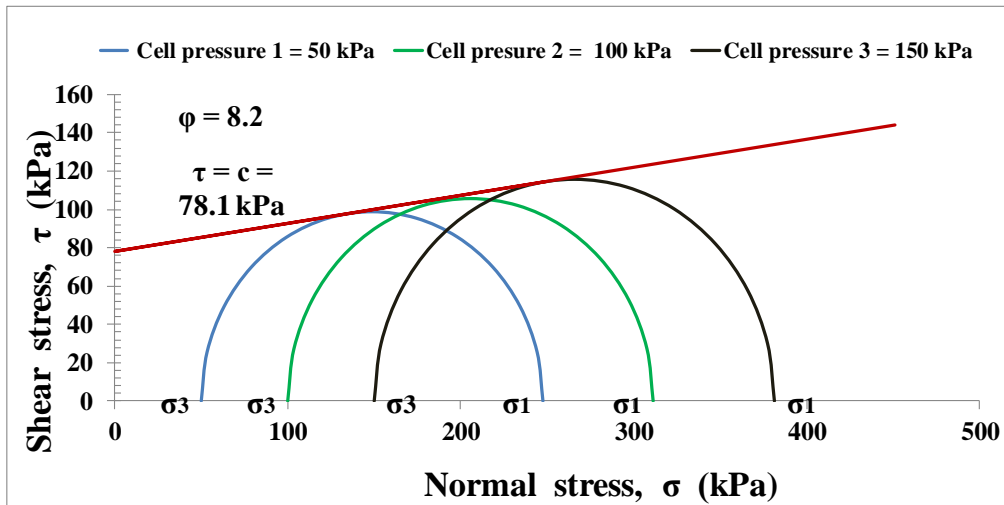
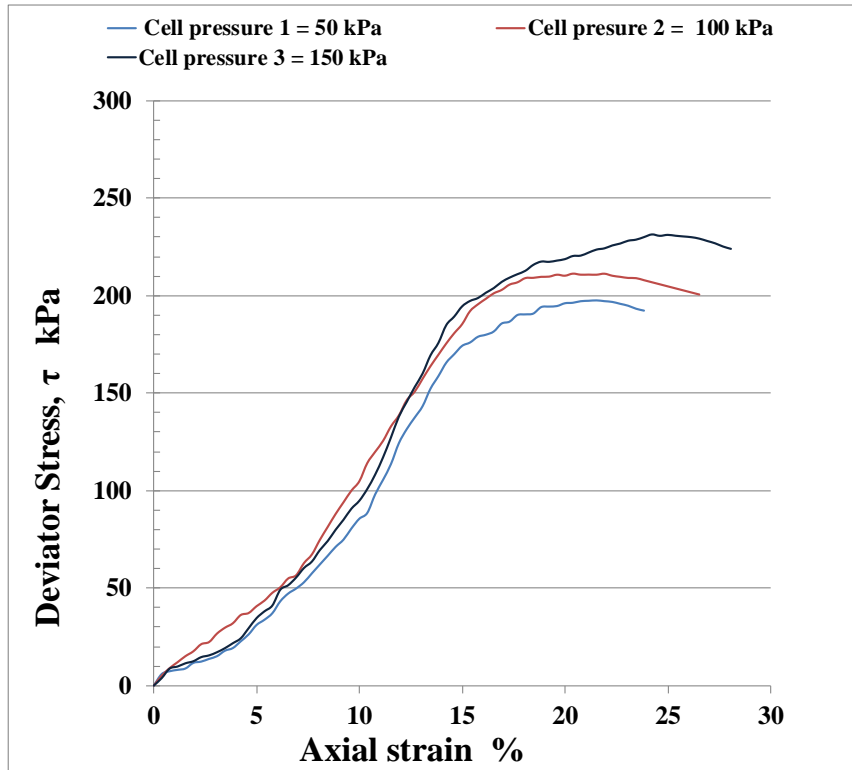
| | | | |
|---|------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 97.6 | 130.2 | 152.6 |
| Cohesion (kPa) | 28.1 | | |
| Angle of Friction ($^\circ$) | 12.2 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN15



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

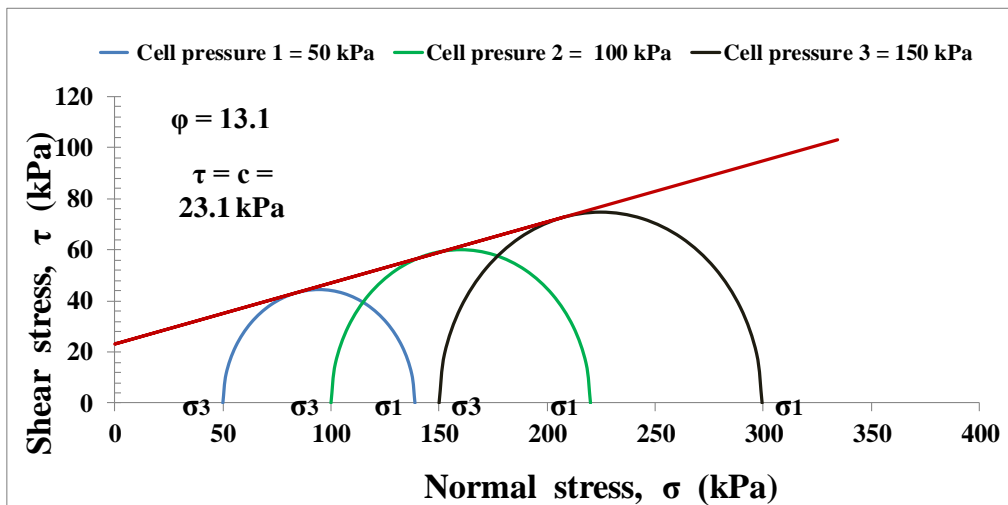
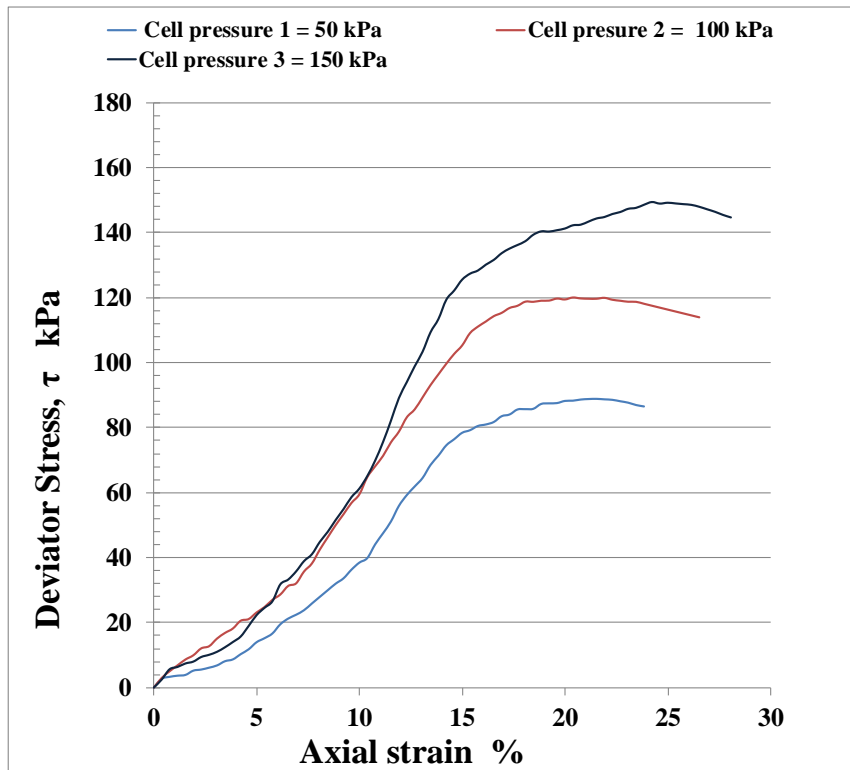
| | | | |
|---|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 197.6 | 211.3 | 231.4 |
| Cohesion (kPa) | 78.1 | | |
| Angle of Friction ($^\circ$) | 8.2 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN14



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

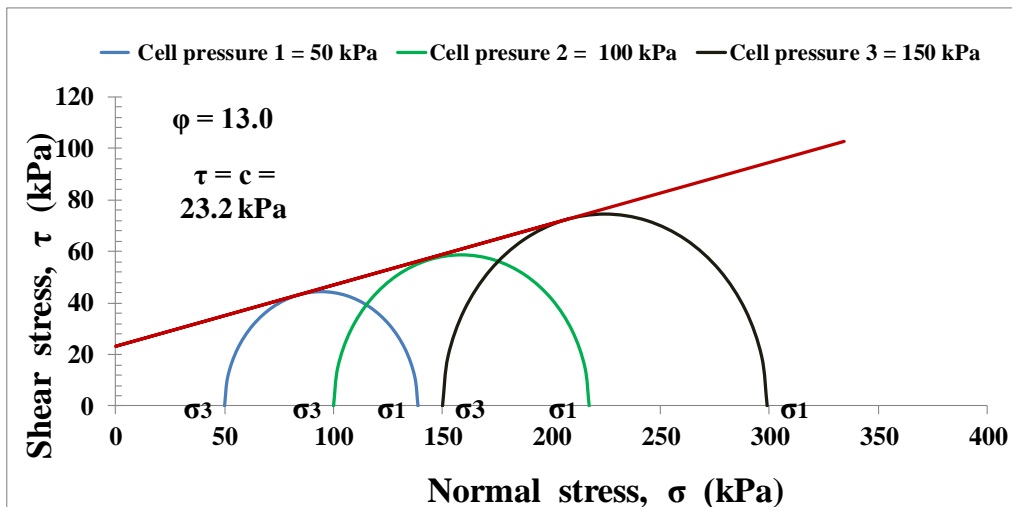
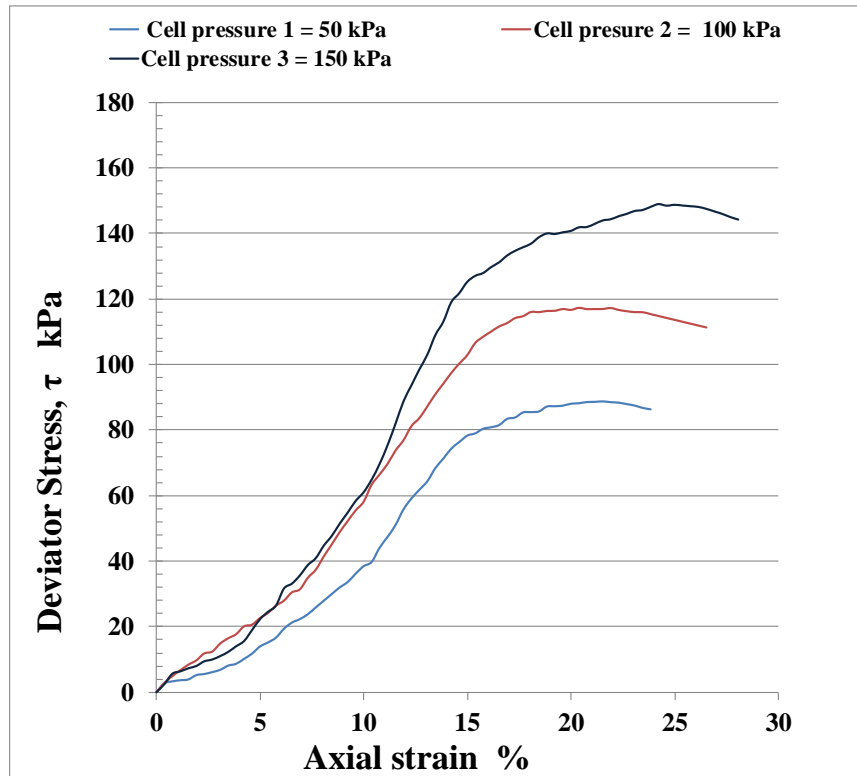
| | | | |
|---|------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 88.9 | 120.0 | 149.4 |
| Cohesion (kPa) | 23.1 | | |
| Angle of Friction ($^\circ$) | 13.1 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN16



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

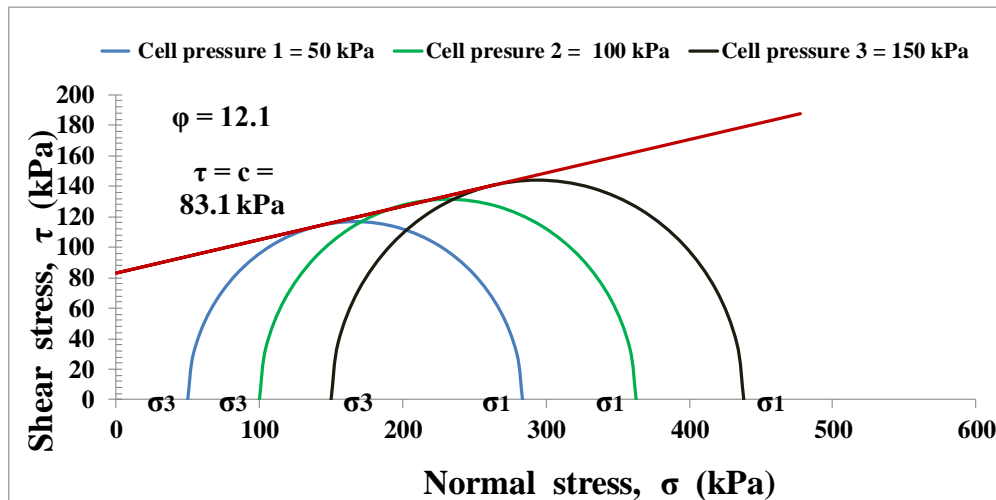
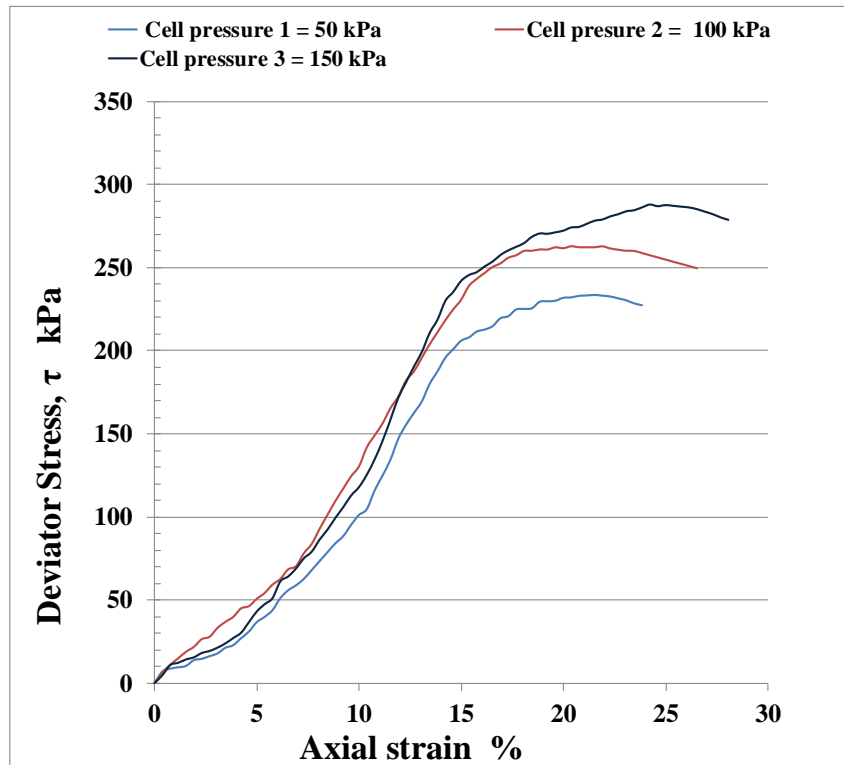
| | | | |
|---|------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 88.8 | 117.3 | 149.0 |
| Cohesion (kPa) | 23.2 | | |
| Angle of Friction ($^\circ$) | 13.0 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN17



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

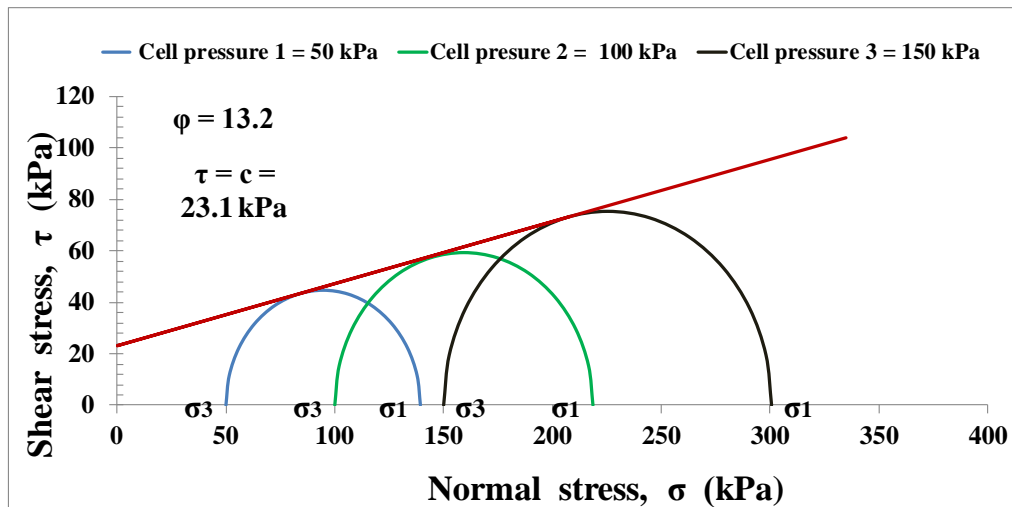
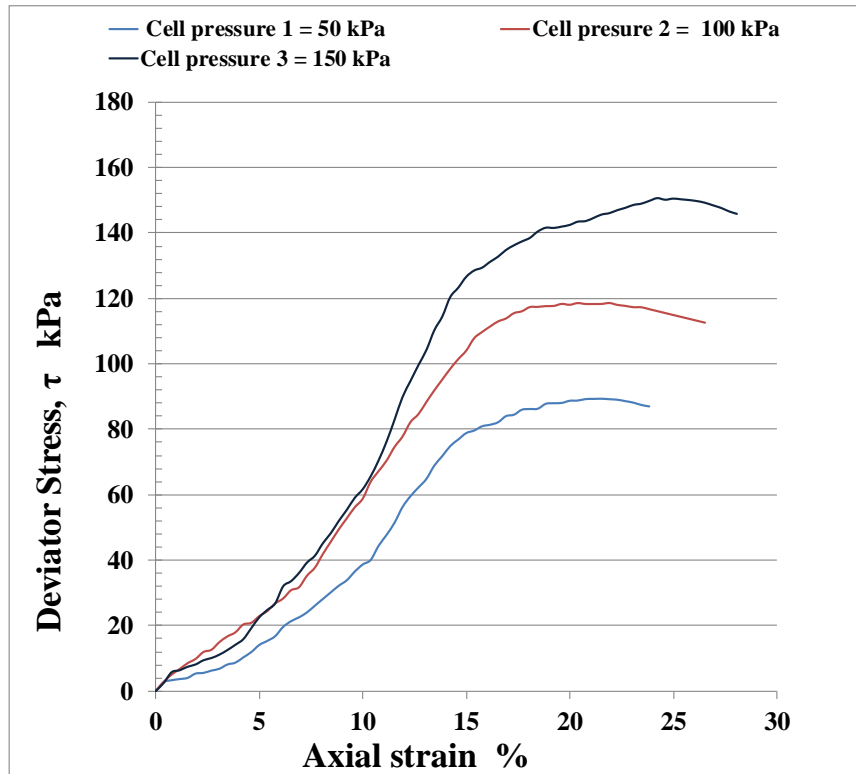
| | | | |
|---|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 233.6 | 262.9 | 288.0 |
| Cohesion (kPa) | 83.1 | | |
| Angle of Friction ($^\circ$) | 12.1 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN18



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

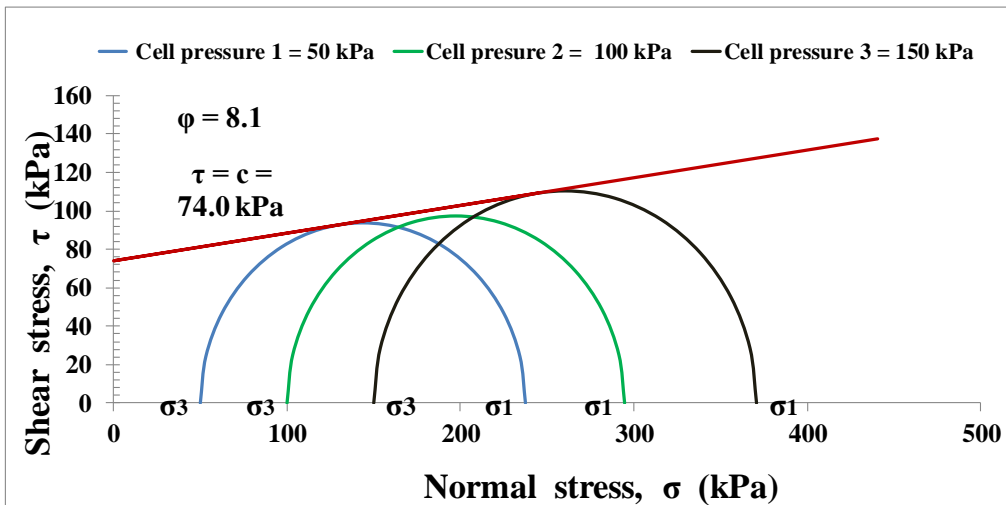
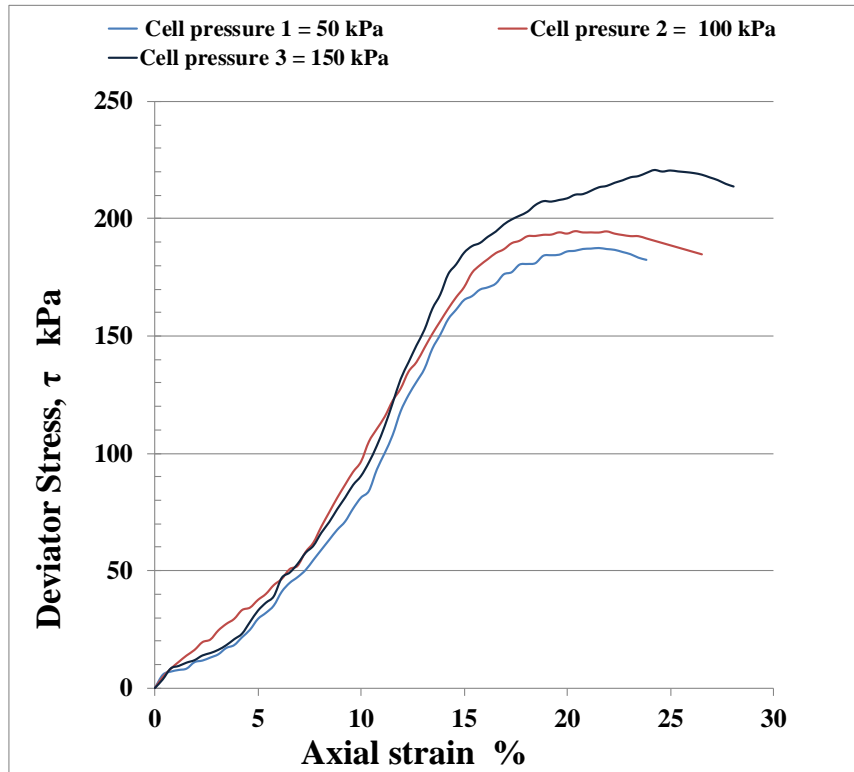
| | | | |
|---|------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 89.3 | 118.6 | 150.6 |
| Cohesion (kPa) | 23.1 | | |
| Angle of Friction ($^\circ$) | 13.2 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN19



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

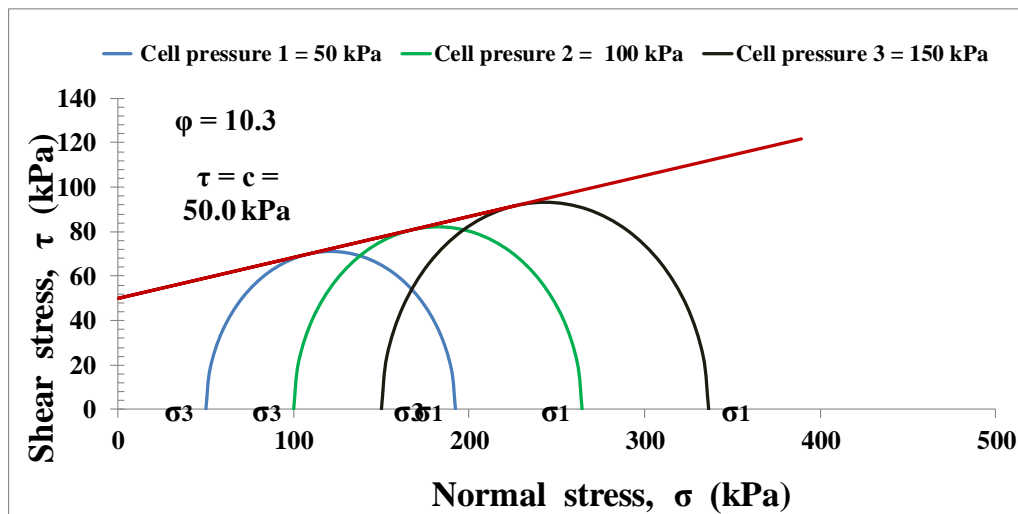
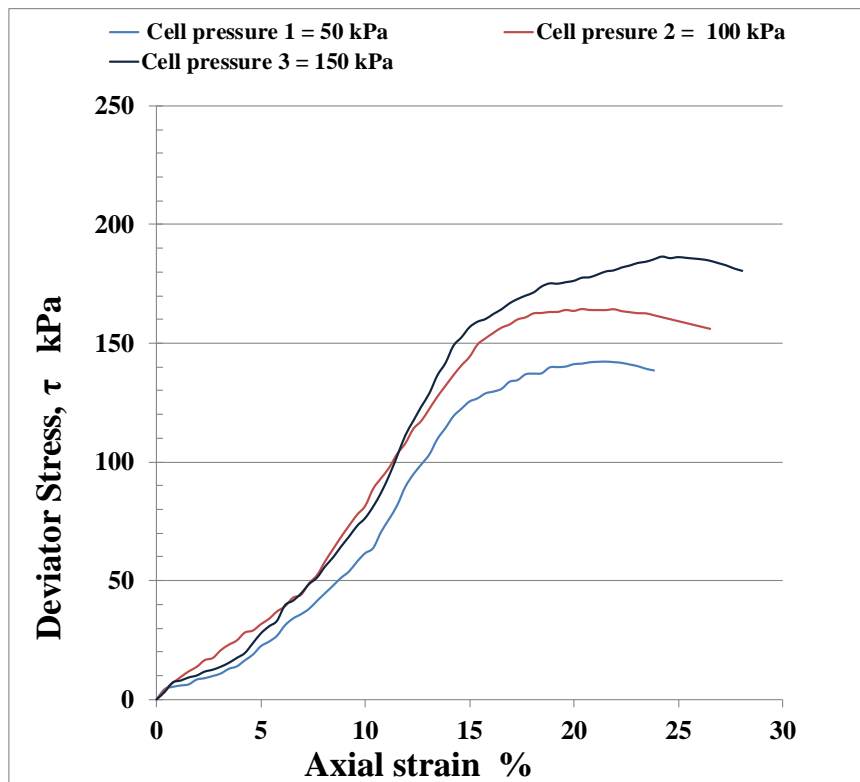
| | | | |
|---|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 187.5 | 194.7 | 220.7 |
| Cohesion (kPa) | 74.0 | | |
| Angle of Friction ($^\circ$) | 8.1 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN20



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

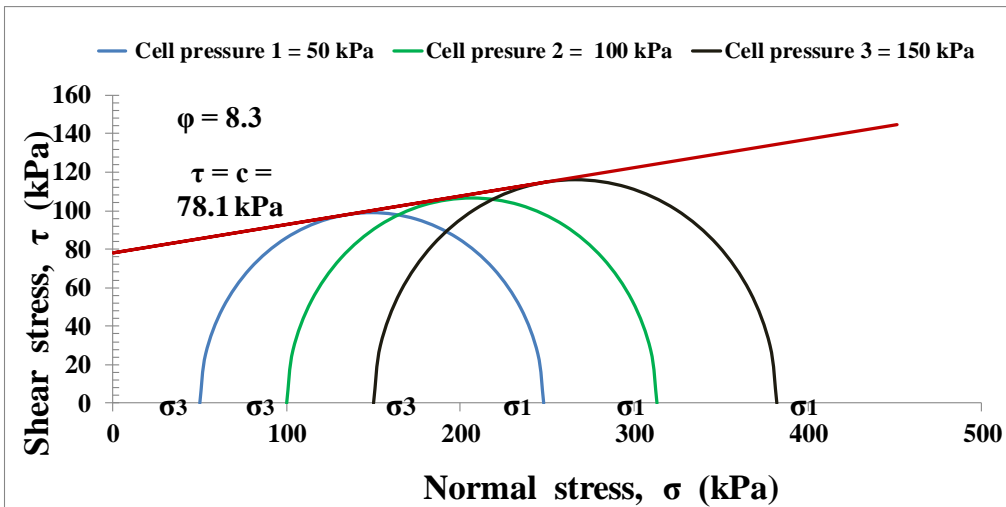
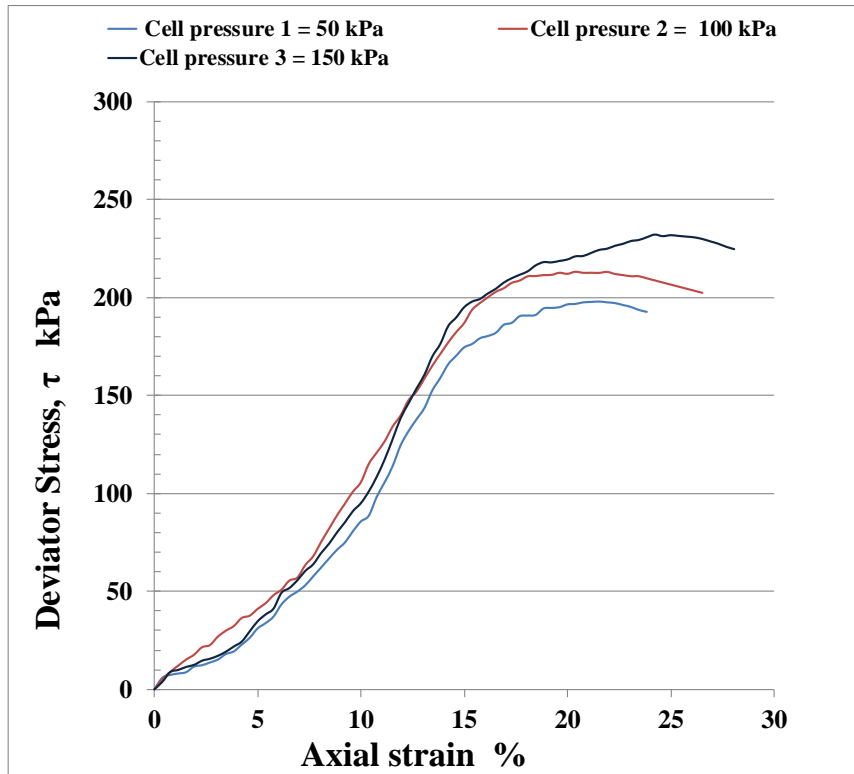
| | | | |
|--|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress ($\sigma_1 - \sigma_3$), (kPa) | 142.2 | 164.4 | 186.5 |
| Cohesion (kPa) | 50.0 | | |
| Angle of Friction ($^\circ$) | 10.3 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN22



DEPT. OF APPLIED GEOLOGY
 FED. UNIVERSITY OF TECHNOLOGY
 AKURE.

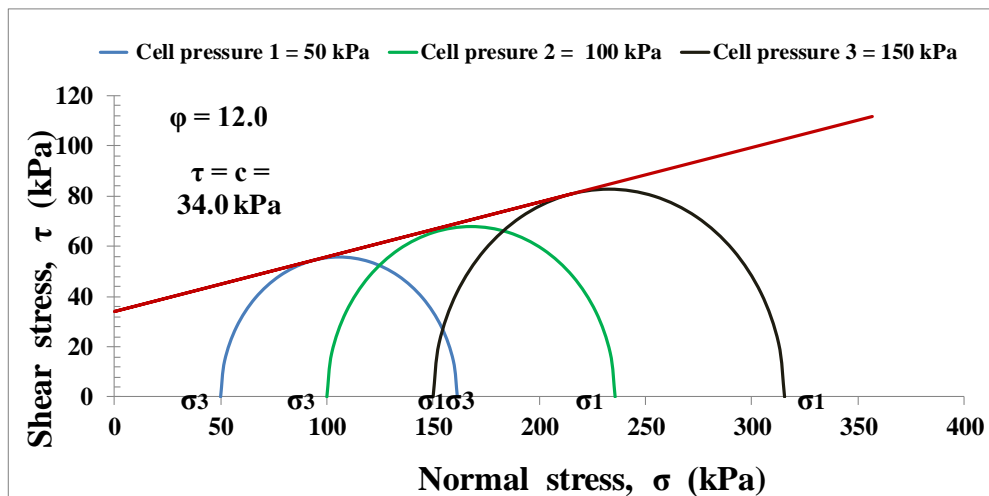
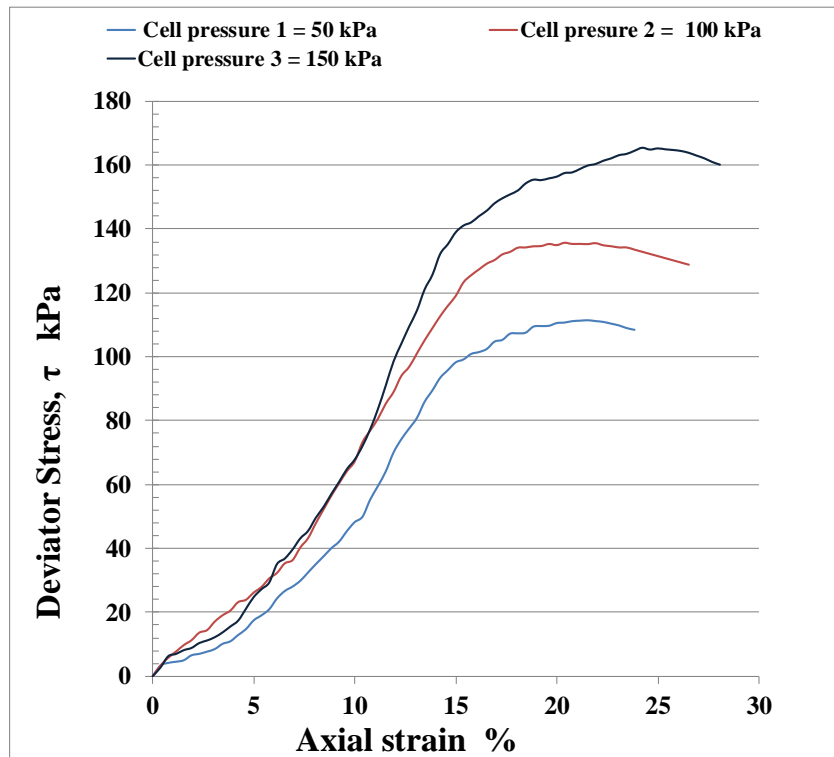
| | | | |
|---|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 198.0 | 213.2 | 232.1 |
| Cohesion (kPa) | 78.1 | | |
| Angle of Friction ($^\circ$) | 8.3 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN23



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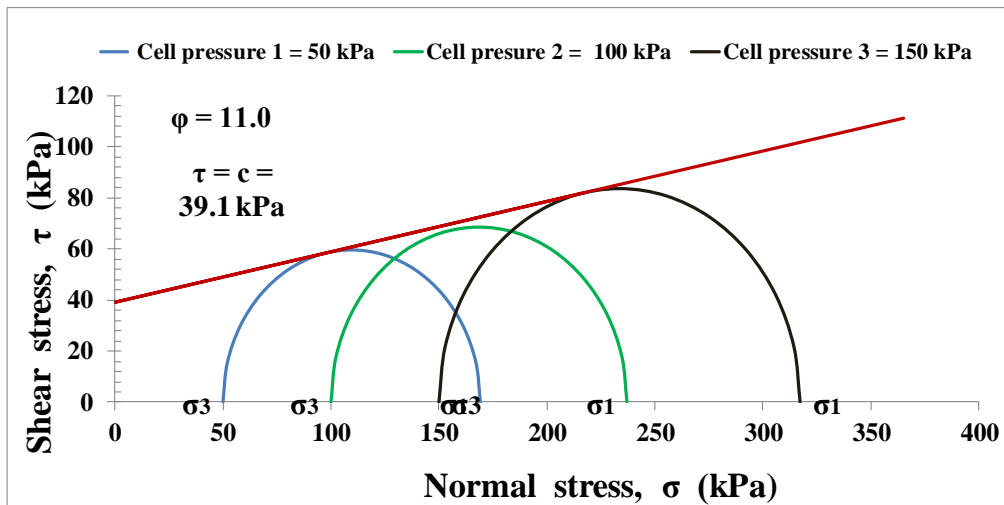
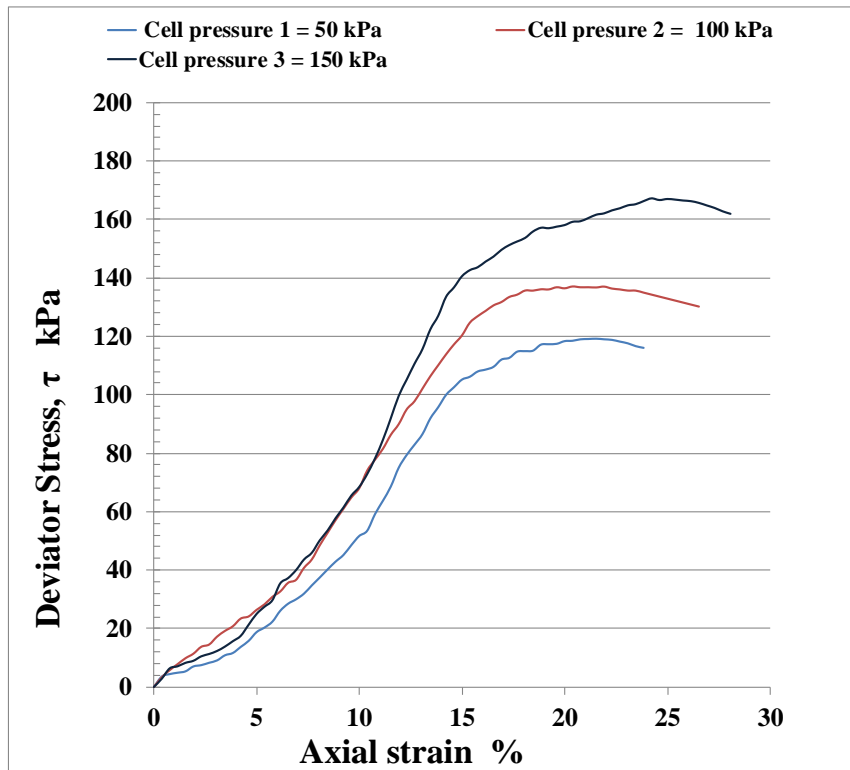
| | | | |
|--|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress ($\sigma_1 - \sigma_3$), (kPa) | 111.4 | 135.7 | 165.4 |
| Cohesion (kPa) | 34.0 | | |
| Angle of Friction ($^\circ$) | 12.0 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN26



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 AKURE.

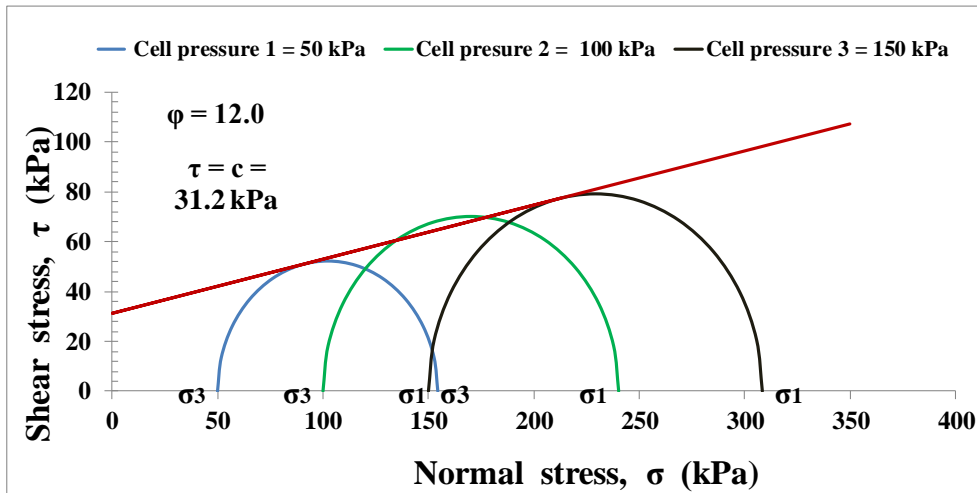
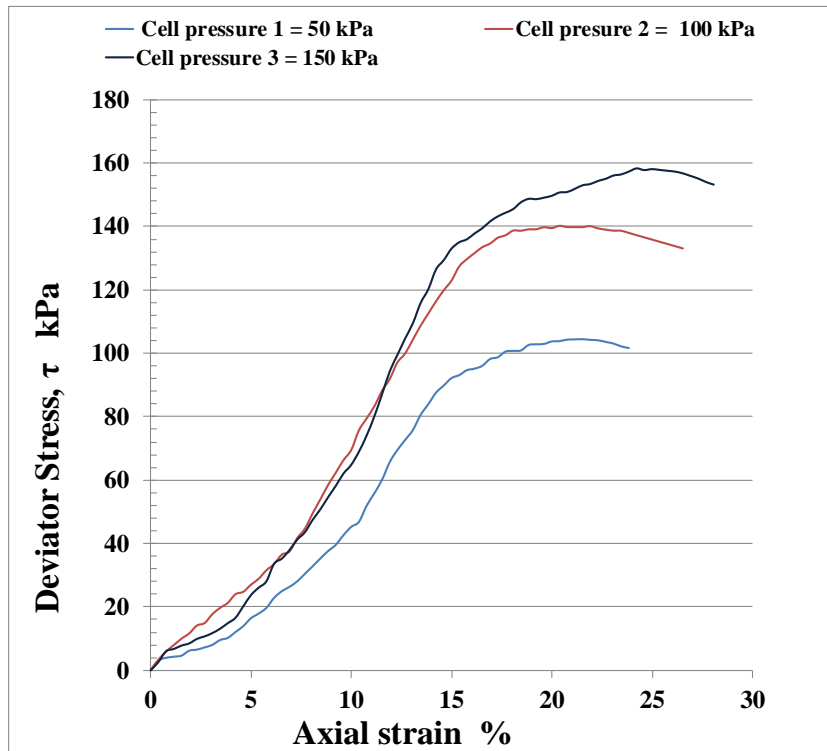
| | | | |
|---|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 119.2 | 137.1 | 167.2 |
| Cohesion (kPa) | 39.1 | | |
| Angle of Friction ($^\circ$) | 11.0 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN25



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 AKURE.

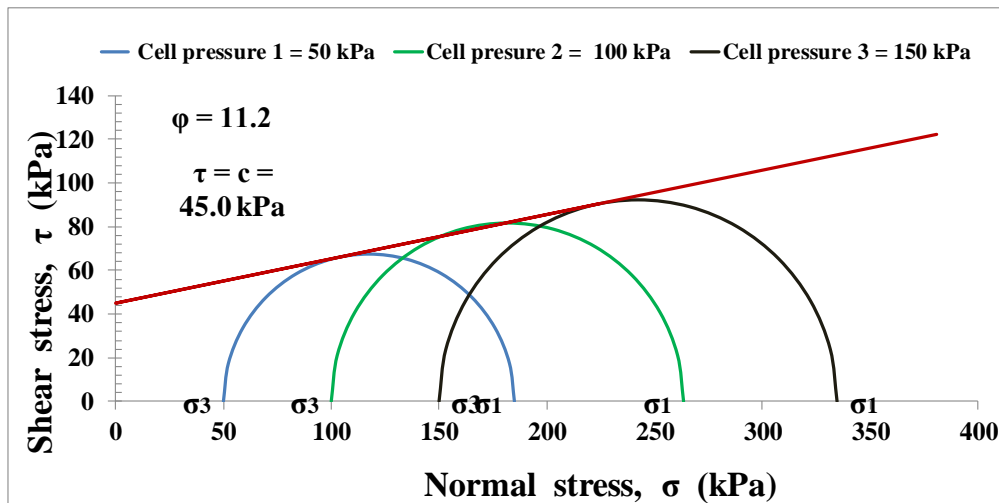
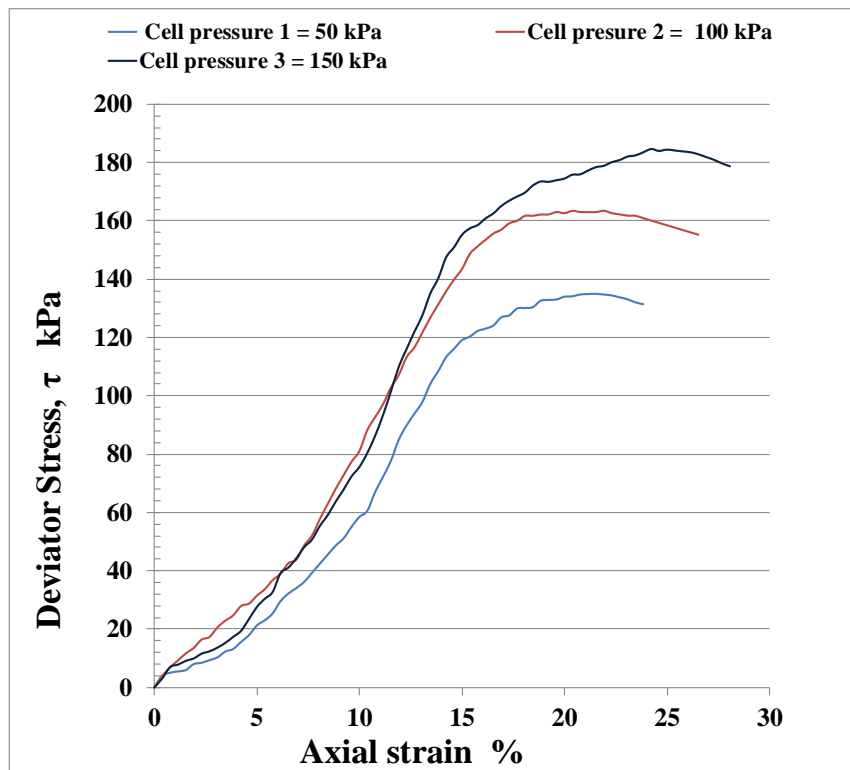
| | | | |
|--|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress ($\sigma_1 - \sigma_3$), (kPa) | 104.5 | 140.2 | 158.3 |
| Cohesion (kPa) | 31.2 | | |
| Angle of Friction ($^\circ$) | 12.0 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN28



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 AKURE.

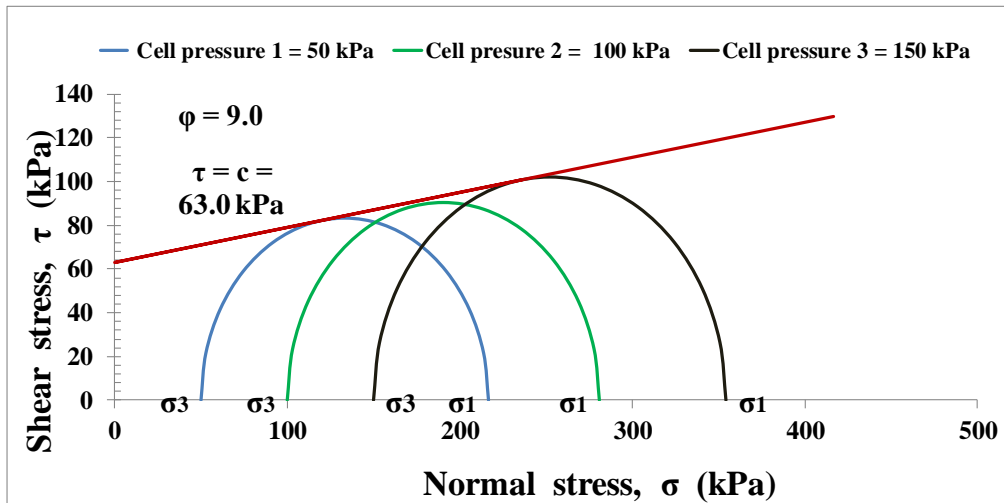
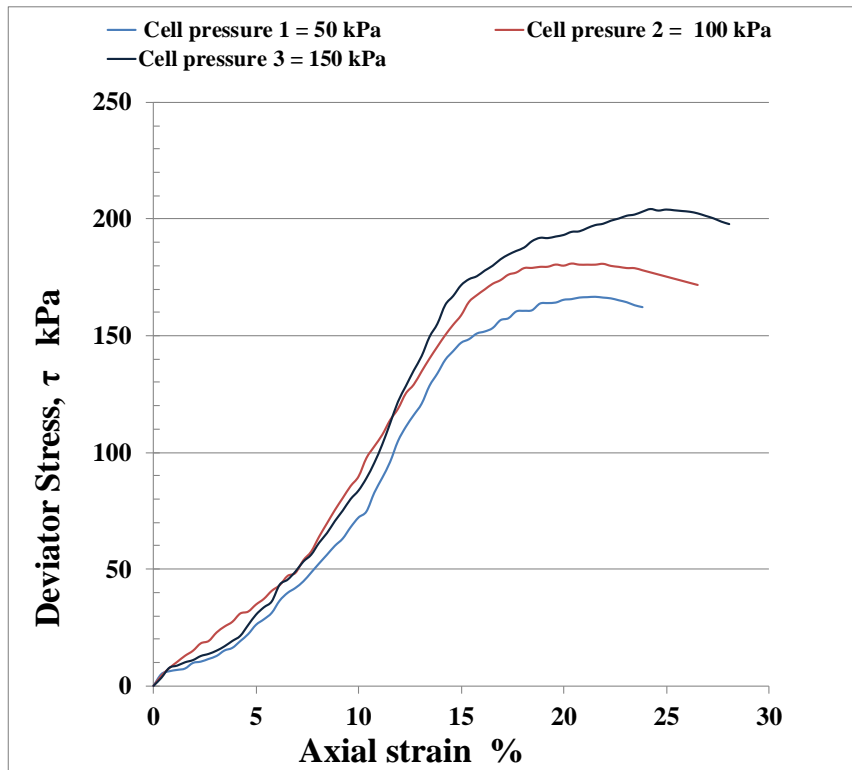
| | | | |
|--|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress ($\sigma_1 - \sigma_3$), (kPa) | 135.0 | 163.4 | 184.6 |
| Cohesion (kPa) | 45.0 | | |
| Angle of Friction ($^\circ$) | 11.2 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN30



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 AKURE.

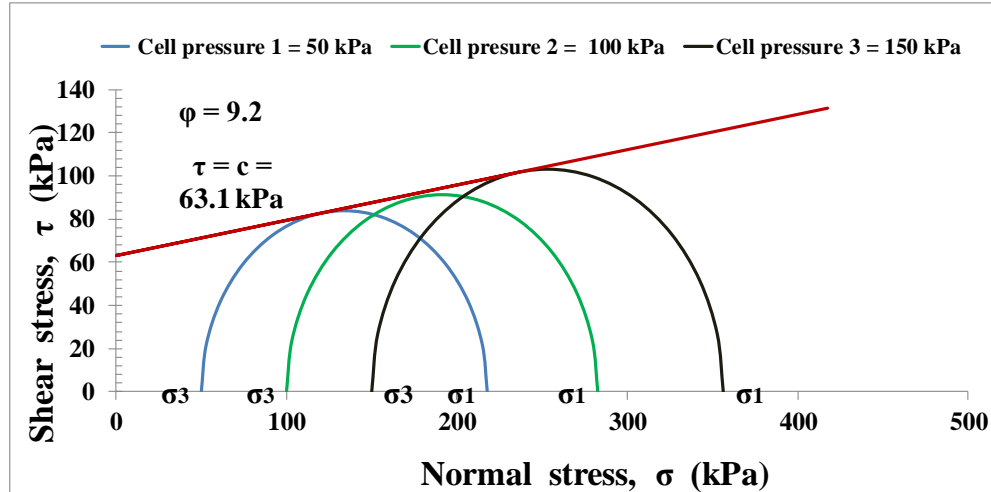
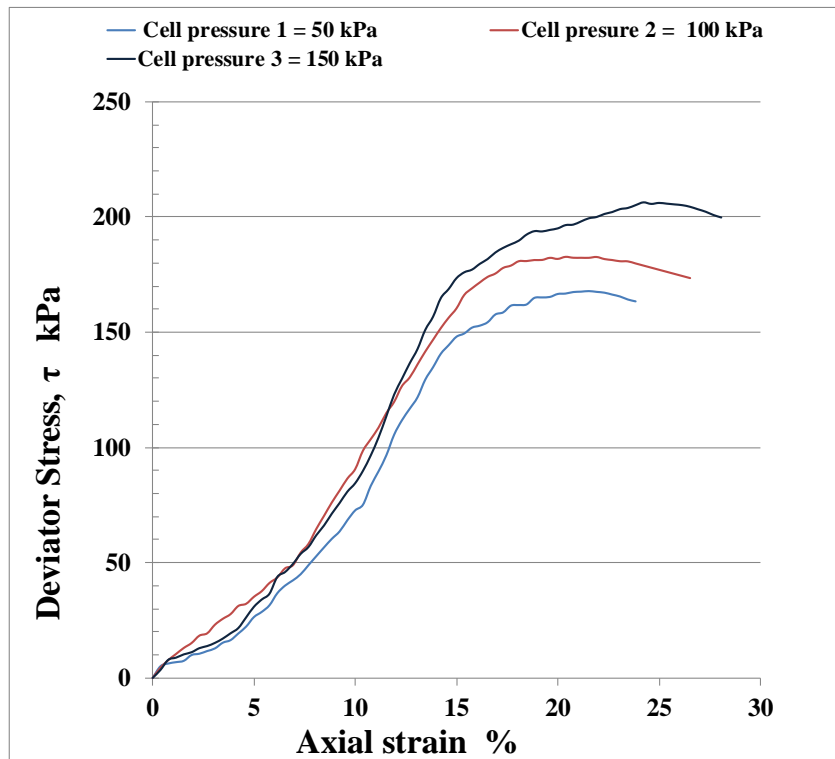
| | | | |
|---|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 166.7 | 180.9 | 204.3 |
| Cohesion (kPa) | 63.0 | | |
| Angle of Friction ($^\circ$) | 9.0 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN31



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 AKURE.

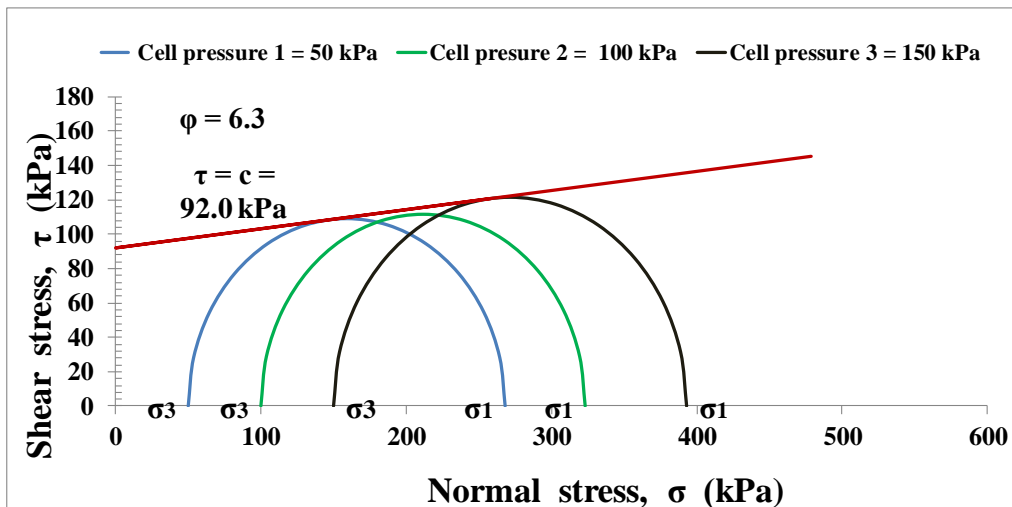
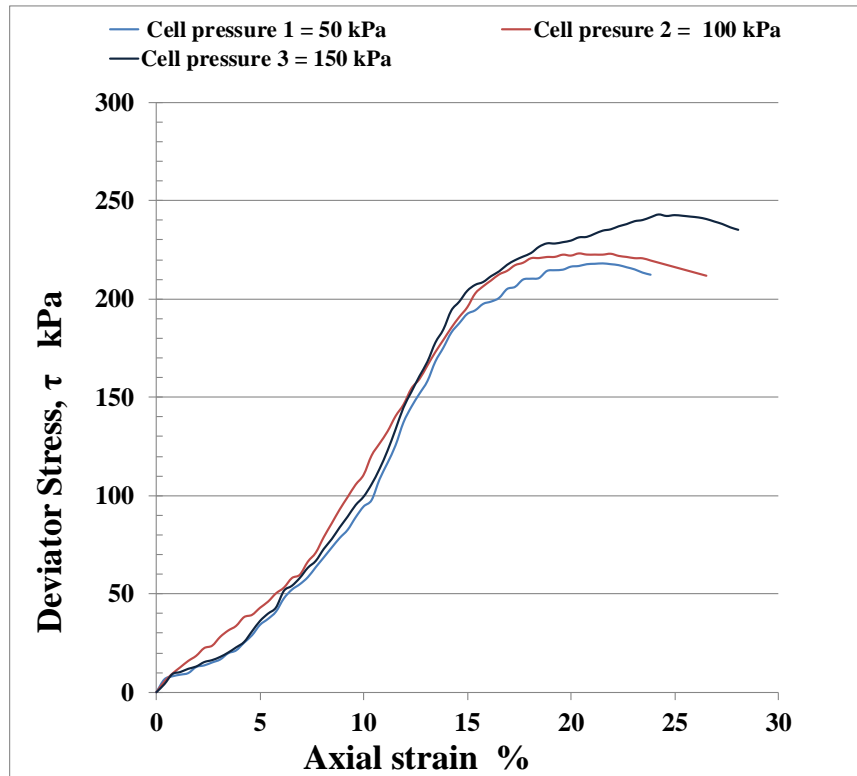
| | | | |
|--|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress ($\sigma_1 - \sigma_3$), (kPa) | 167.8 | 182.7 | 206.3 |
| Cohesion (kPa) | 63.1 | | |
| Angle of Friction ($^\circ$) | 9.2 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN32



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 AKURE.

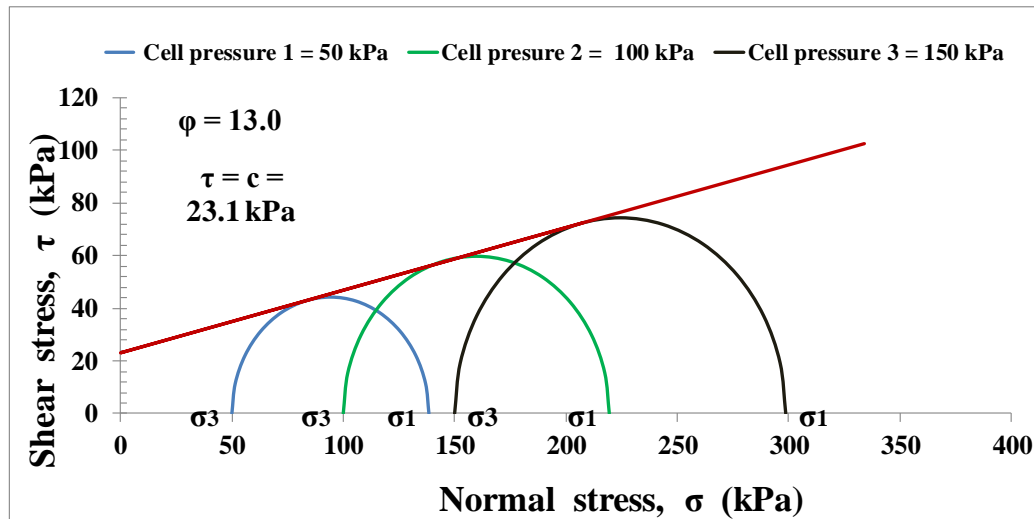
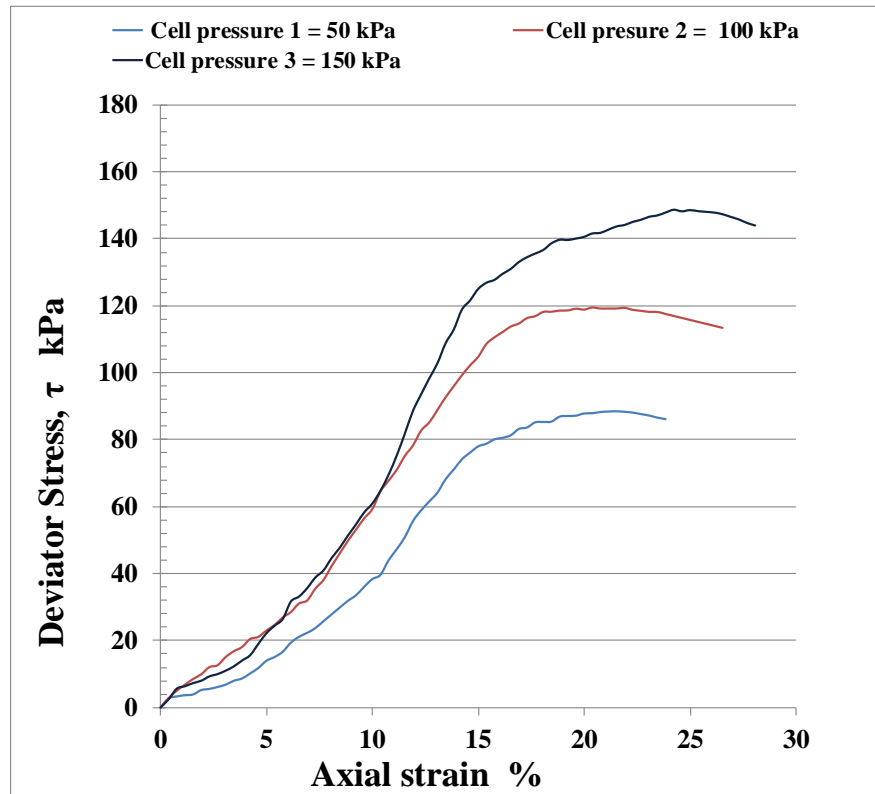
| | | | |
|--|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress ($\sigma_1 - \sigma_3$), (kPa) | 218.1 | 223.2 | 243.0 |
| Cohesion (kPa) | 92.0 | | |
| Angle of Friction ($^\circ$) | 6.3 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN34



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 AKURE.

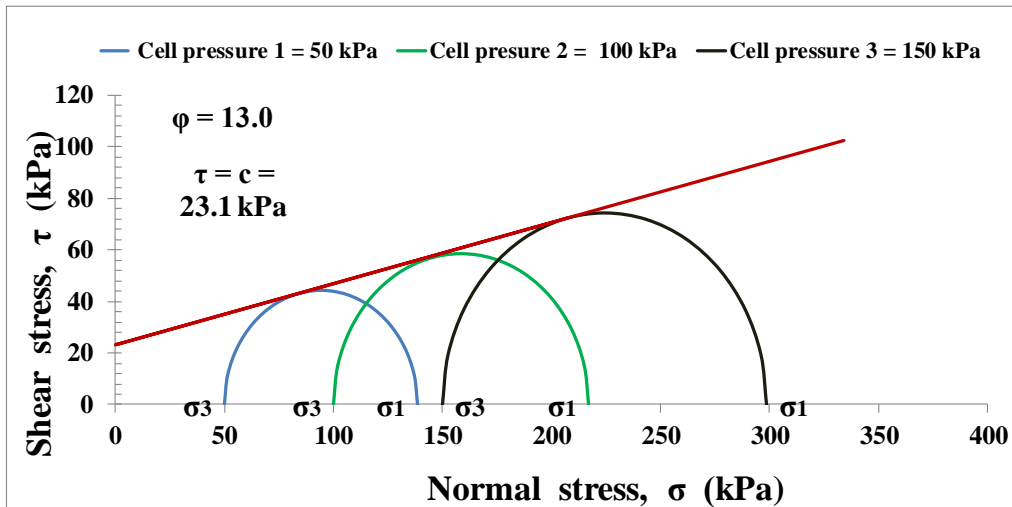
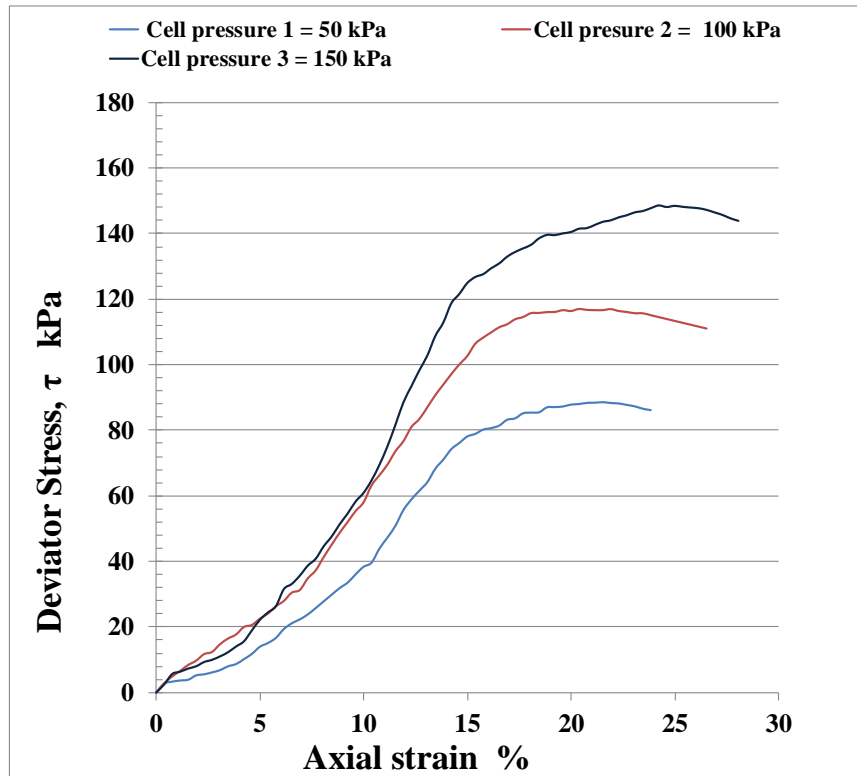
| | | | |
|---|------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 88.5 | 119.5 | 148.7 |
| Cohesion (kPa) | 23.1 | | |
| Angle of Friction ($^\circ$) | 13.0 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN37



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 AKURE.

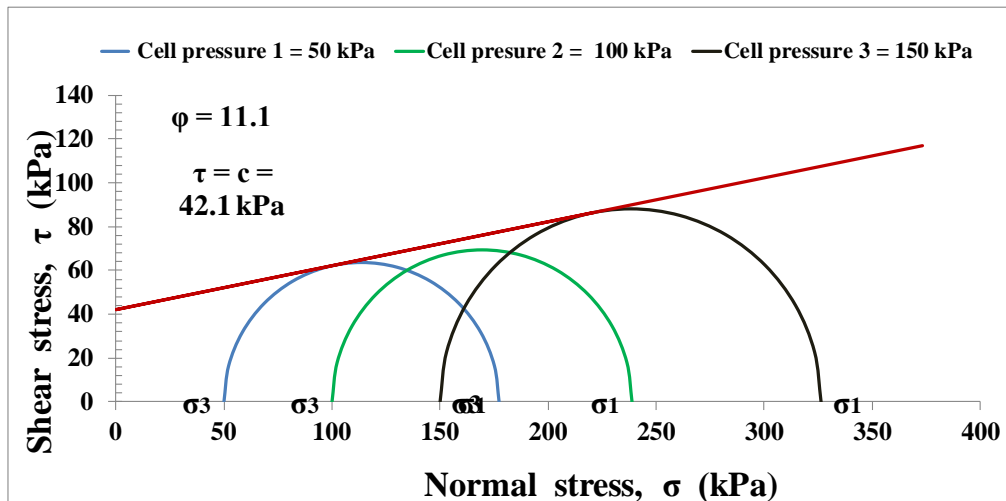
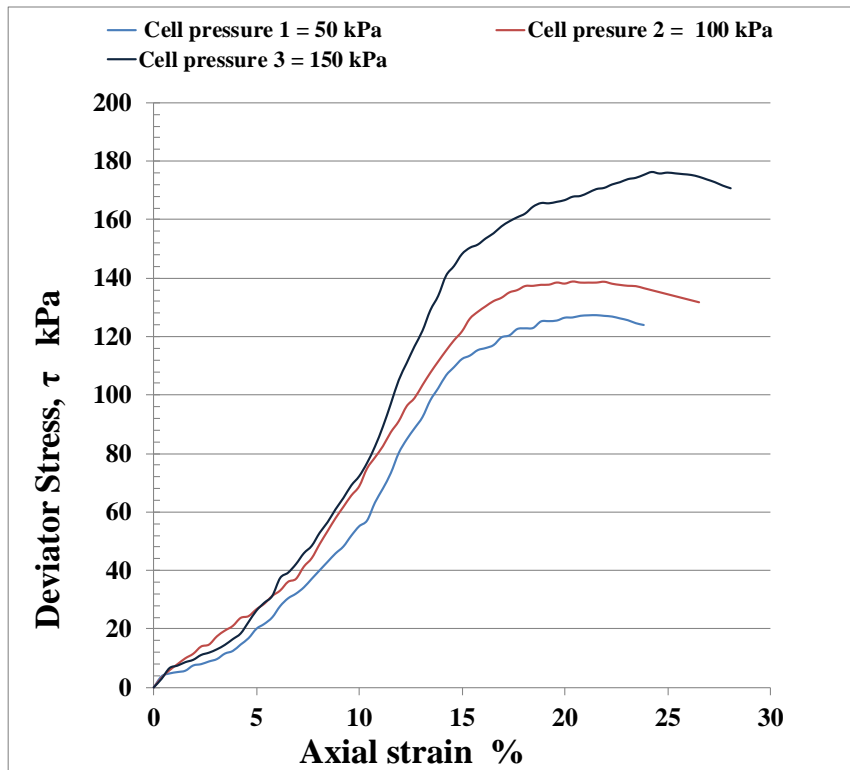
| | | | |
|--|------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress ($\sigma_1 - \sigma_3$), (kPa) | 88.6 | 117.0 | 148.6 |
| Cohesion (kPa) | 23.1 | | |
| Angle of Friction ($^\circ$) | 13.0 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN38



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 AKURE.

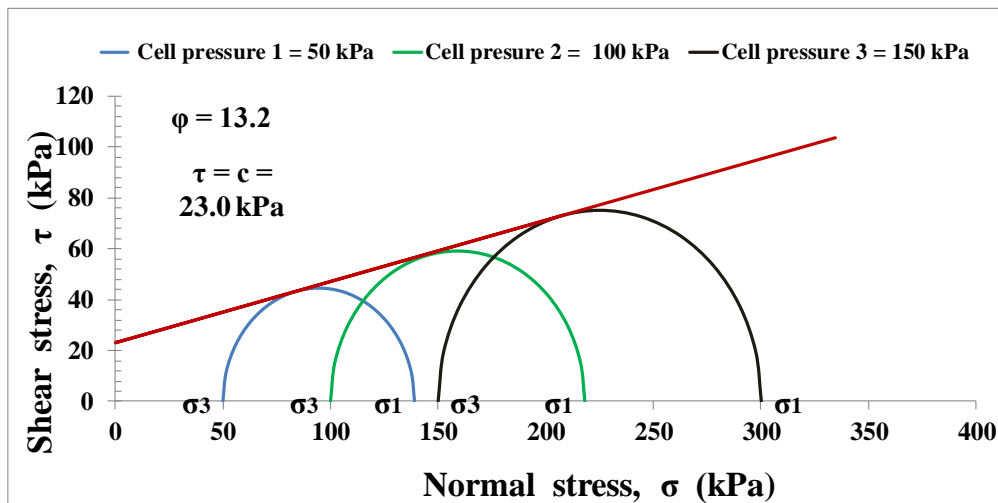
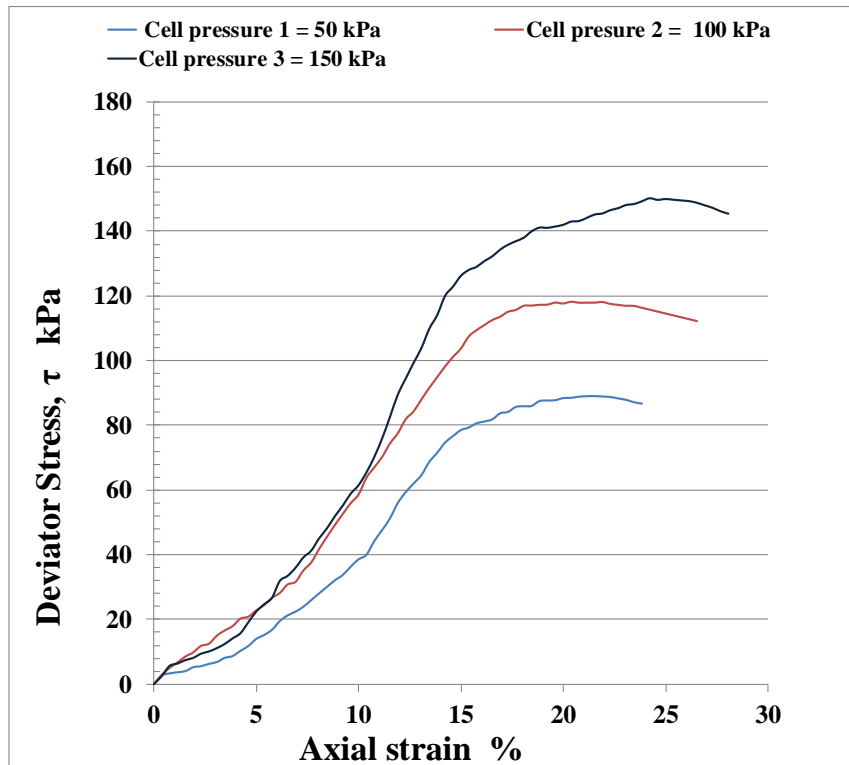
| | | | |
|---|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress $(\sigma_1 - \sigma_3)$, (kPa) | 127.3 | 138.8 | 176.3 |
| Cohesion (kPa) | 42.1 | | |
| Angle of Friction ($^\circ$) | 11.1 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN39



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 AKURE.

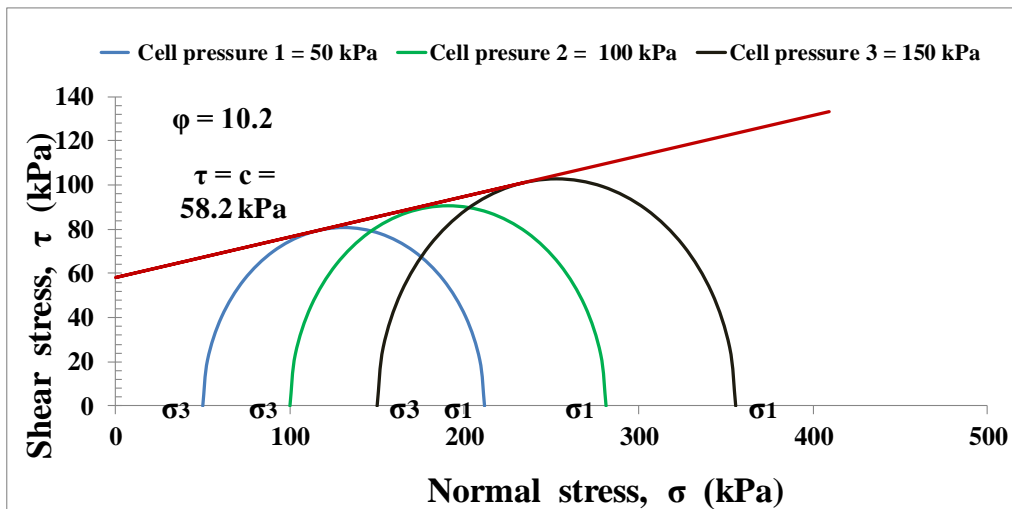
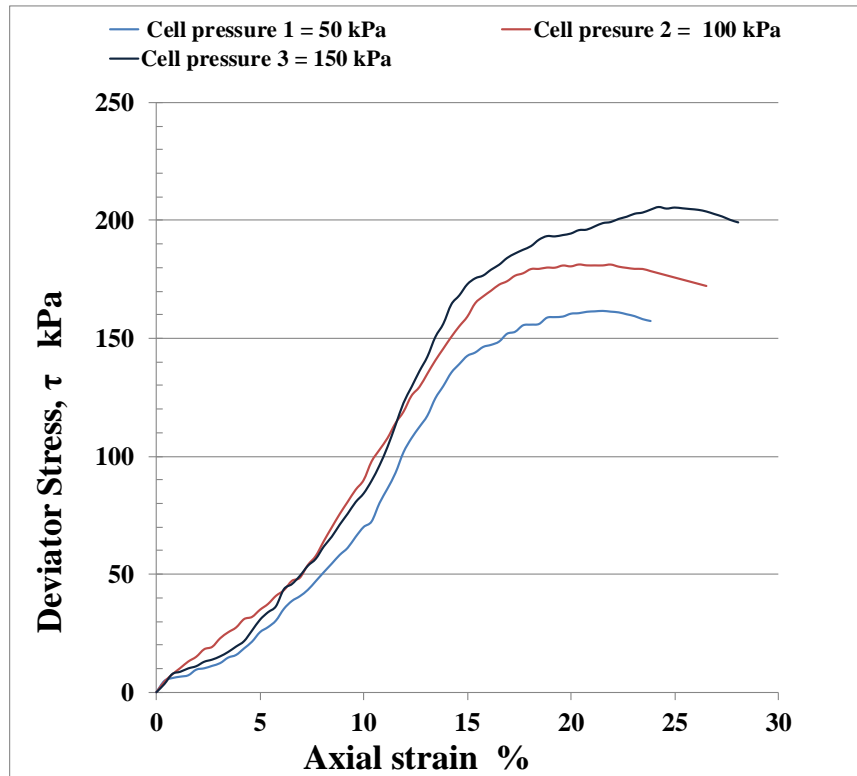
| | | | |
|--|------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress ($\sigma_1 - \sigma_3$), (kPa) | 89.0 | 118.2 | 150.2 |
| Cohesion (kPa) | 23.0 | | |
| Angle of Friction ($^\circ$) | 13.2 | | |

Quick Undrained Triaxial test

Project:

SAMPLE No.:

SUN40



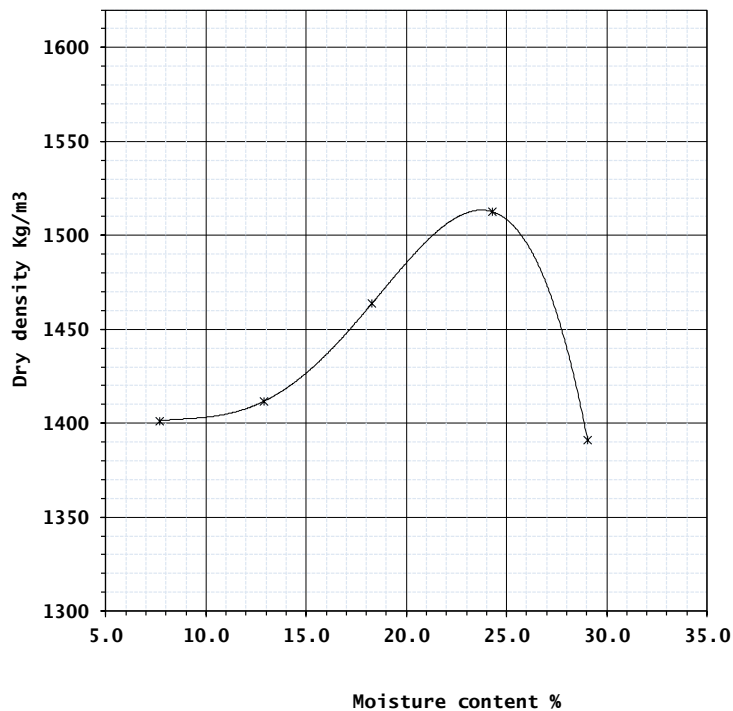
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 AKURE.

| | | | |
|--|-------|-------|-------|
| Cell Pressure σ_3 , (kPa) | 50 | 100 | 150 |
| Maximum Deviator Stress ($\sigma_1 - \sigma_3$), (kPa) | 161.6 | 181.3 | 205.7 |
| Cohesion (kPa) | 58.2 | | |
| Angle of Friction ($^\circ$) | 10.2 | | |

Appendix 7. Compaction

| Compaction Test | | | | | | | | | | |
|----------------------------------|--------|-----------------|-----------------|---------------|------|-------------------------|------|---------|------|------|
| Sample No. : | | SUN1 | | Borehole No.: | | | | Depth.: | | |
| Compaction Method: | | | | | | | | | | |
| Mould | | Hammer | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | | 3 | | |
| Height: | 11.643 | cm | weight: | 2.5 | kg | No. Of blows per layer: | | 25 | | |
| Volume: | 944 | cm ³ | | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 4 | |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | 1485 | |
| Mass of Mould+Compacted Soil (g) | | | 2910 | | 2990 | | 3120 | | 3260 | |
| Mass of Compacted Soil (g) | | | 1425 | | 1505 | | 1635 | | 1775 | |
| Wet Density (kg/m ³) | | | 1509 | | 1594 | | 1731 | | 1880 | |
| Mass of can (g) | 9.0 | 8.1 | 8.4 | 8.9 | 10.1 | 8.7 | 10.4 | 8.3 | 8.5 | 8.5 |
| Mass of can+wet soil (g) | 46.7 | 52.9 | 64.1 | 51.7 | 67.8 | 49.0 | 69.0 | 67.5 | 75.5 | 57.0 |
| Mass of can+dry soil (g) | 44.1 | 49.6 | 57.5 | 47.0 | 58.7 | 42.9 | 57.6 | 55.9 | 60.4 | 46.1 |
| Mass of moisture (g) | 2.6 | 3.3 | 6.6 | 4.7 | 9.1 | 6.1 | 11.4 | 11.6 | 15.1 | 10.9 |
| Mass of dry soil (g) | 35.1 | 41.5 | 49.1 | 38.1 | 48.6 | 34.2 | 47.2 | 47.6 | 51.9 | 37.6 |
| Moisture content, % | 7.4 | 8.0 | 13.4 | 12.3 | 18.7 | 17.8 | 24.2 | 24.4 | 29.1 | 29.0 |
| Average moisture content, % | | | 7.7 | | 12.9 | | 18.3 | | 24.3 | |
| Dry Density (kg/m ³) | | | 1401 | | 1412 | | 1464 | | 1513 | |

Compaction curve

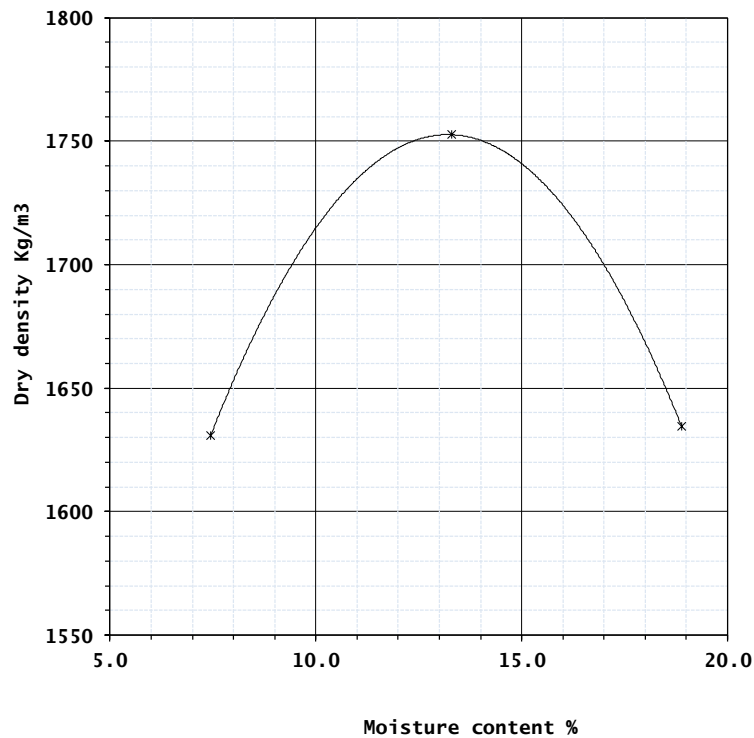


| SUN1 | | Units |
|------|------|-------------------|
| OMC | 24.3 | % |
| MDD | 1513 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | |
|----------------------------------|--------|-----------------|-----------------|--------|---------------|-------------------------|----------|---------|----------|
| Sample No. : | P1 | | SUN2 | | Borehole No.: | | | Depth.: | |
| Compaction Method: | | | | | | | | | |
| Mould | Hammer | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | | |
| Volume: | 944 | cm ³ | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 5 |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | |
| Mass of Mould+Compacted Soil (g) | | | 3140 | | 3360 | | 3320 | | |
| Mass of Compacted Soil (g) | | | 1655 | | 1875 | | 1835 | | |
| Wet Density (kg/m ³) | | | 1752 | | 1985 | | 1943 | | |
| Mass of can (g) | 9.0 | 8.6 | 9.0 | 8.1 | 9.6 | 8.1 | | | |
| Mass of can+wet soil (g) | 42.7 | 49.8 | 43.1 | 46.6 | 52.8 | 65.7 | | | |
| Mass of can+dry soil (g) | 40.4 | 46.9 | 39.0 | 42.2 | 45.9 | 56.6 | | | |
| Mass of moisture (g) | 2.3 | 2.9 | 4.1 | 4.4 | 6.9 | 9.1 | | | |
| Mass of dry soil (g) | 31.4 | 38.3 | 30.0 | 34.1 | 36.3 | 48.5 | | | |
| Moisture content,% | 7.3 | 7.6 | 13.7 | 12.9 | 19.0 | 18.8 | | | |
| Average moisture content,% | 7.4 | | 13.3 | | 18.9 | | | | |
| Dry Density (kg/m ³) | 1631 | | 1753 | | 1634 | | | | |

Compaction curve

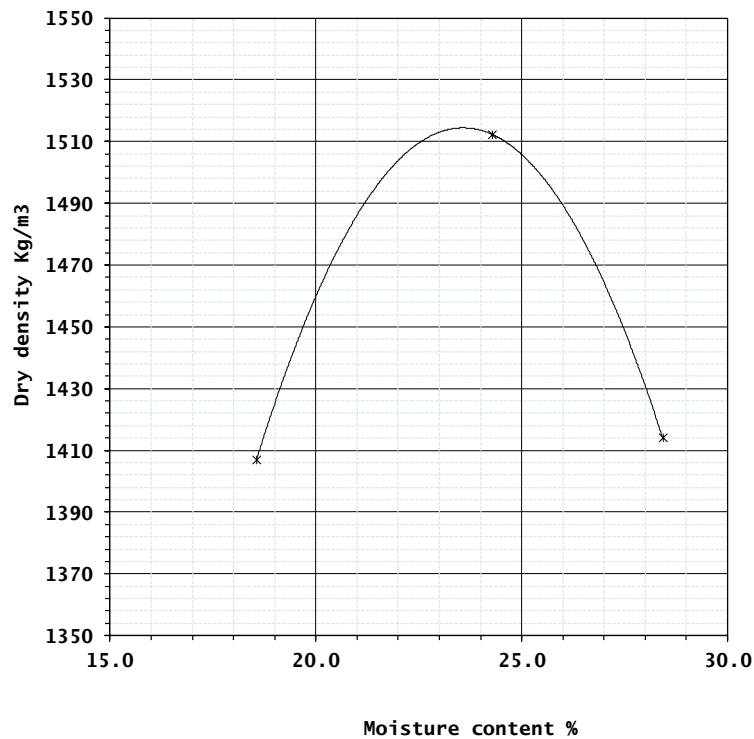


| SUN2 | | Units |
|------|------|-------------------|
| OMC | 13.3 | % |
| MDD | 1753 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | |
|----------------------------------|--------|-----------------|-----------------|-------|---------|-------------------------|----|--|---|--|
| Sample No. : P1 SUN3 | | Borehole No.: | | | Depth.: | | | | | |
| Compaction Method: | | | | | | | | | | |
| Mould | Hammer | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | | | |
| Height: | 11.643 | cm | weight: | 2.5 | kg | No. Of blows per layer: | 25 | | | |
| Volume: | 944 | cm ³ | | | | | | | | |
| Test number | 1 | | 2 | | 3 | | 4 | | 5 | |
| Mass of Mould (g) | 1485 | | 1485 | | 1485 | | | | | |
| Mass of Mould+Compacted Soil (g) | 3060 | | 3260 | | 3200 | | | | | |
| Mass of Compacted Soil (g) | 1575 | | 1775 | | 1715 | | | | | |
| Wet Density (kg/m ³) | 1668 | | 1880 | | 1816 | | | | | |
| Mass of can (g) | 8.9 | 8.2 | 6.3 | 7.3 | 7.9 | 33.5 | | | | |
| Mass of can+wet soil (g) | 49.9 | 61.1 | 38.1 | 45.6 | 51.1 | 99.5 | | | | |
| Mass of can+dry soil (g) | 43.5 | 52.8 | 31.9 | 38.1 | 41.6 | 84.8 | | | | |
| Mass of moisture (g) | 6.4 | 8.3 | 6.2 | 7.5 | 9.5 | 14.7 | | | | |
| Mass of dry soil (g) | 34.6 | 44.6 | 25.6 | 30.8 | 33.7 | 51.3 | | | | |
| Moisture content,% | 18.5 | 18.6 | 24.2 | 24.4 | 28.2 | 28.7 | | | | |
| Average moisture content,% | 18.6 | | 24.3 | | 28.4 | | | | | |
| Dry Density (kg/m ³) | 1407 | | 1512 | | 1414 | | | | | |

Compaction curve

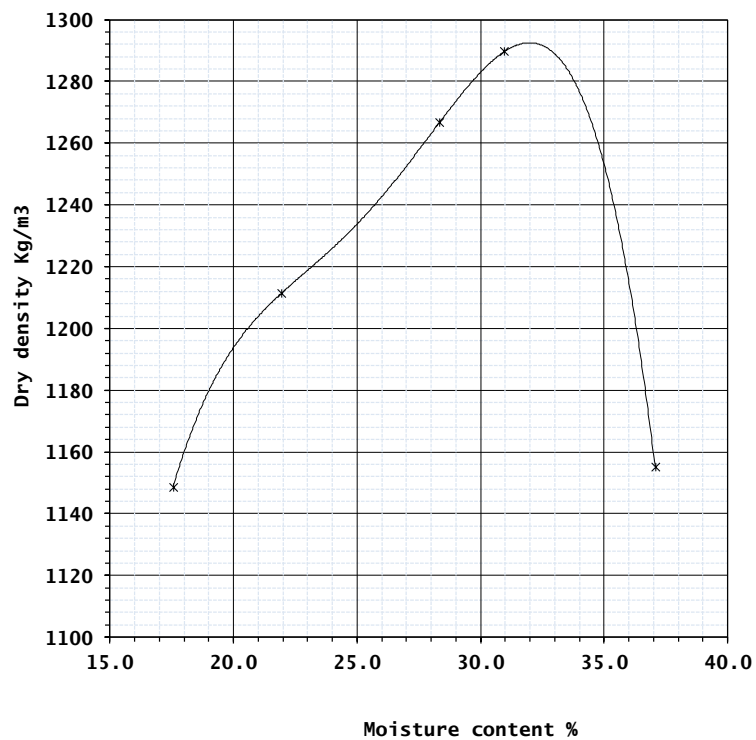


| SUN3 | | Units |
|------|------|-------------------|
| OMC | 23.5 | % |
| MDD | 1514 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | |
|----------------------------------|--|----------------------|-----------------|-----------------|------|-------|------|-------------------------|------|------|
| Sample No. : | | 5 | | Borehole No.: | | | | Depth.: | | |
| Compaction Method: | | West Africa Standard | | | | | | | | |
| Mould | | Hammer | | | | | | | | |
| Diameter: | | 10.16 | cm | height of drop: | | 30.55 | cm | No. Of layers: | | 3 |
| Height: | | 11.643 | cm | weight: | | 2.5 | kg | No. Of blows per layer: | | 25 |
| Volume: | | 944 | cm ³ | | | | | | | |
| Test number | | 1 | | 2 | | 3 | | 4 | | 5 |
| Mass of Mould (g) | | 1485 | | 1485 | | 1485 | | 1485 | | 1485 |
| Mass of Mould+Compacted Soil (g) | | 2700 | | 2760 | | 2880 | | 3020 | | 3080 |
| Mass of Compacted Soil (g) | | 1215 | | 1275 | | 1395 | | 1535 | | 1595 |
| Wet Density (kg/m ³) | | 1287 | | 1350 | | 1477 | | 1626 | | 1689 |
| Mass of can (g) | | 22.4 | 19.6 | 23.3 | 23.6 | 19.4 | 7.9 | 10.2 | 7.0 | 9.0 |
| Mass of can+wet soil (g) | | 61.4 | 56.8 | 62.9 | 67.8 | 58.9 | 50.1 | 55.2 | 45.3 | 29.3 |
| Mass of can+dry soil (g) | | 57.1 | 52.5 | 56.9 | 61.3 | 51.8 | 42.5 | 45.2 | 36.9 | 24.5 |
| Mass of moisture (g) | | 4.3 | 4.3 | 6.0 | 6.5 | 7.1 | 7.6 | 10.0 | 8.4 | 4.8 |
| Mass of dry soil (g) | | 34.7 | 32.9 | 33.6 | 37.7 | 32.4 | 34.6 | 35.0 | 29.9 | 15.5 |
| Moisture content,% | | 12.4 | 13.1 | 17.9 | 17.2 | 21.9 | 22.0 | 28.6 | 28.1 | 31.0 |
| Average moisture content,% | | | | 17.5 | | 21.9 | | 28.3 | | 31.0 |
| Dry Density (kg/m ³) | | | | 1149 | | 1211 | | 1267 | | 1290 |

Compaction curve

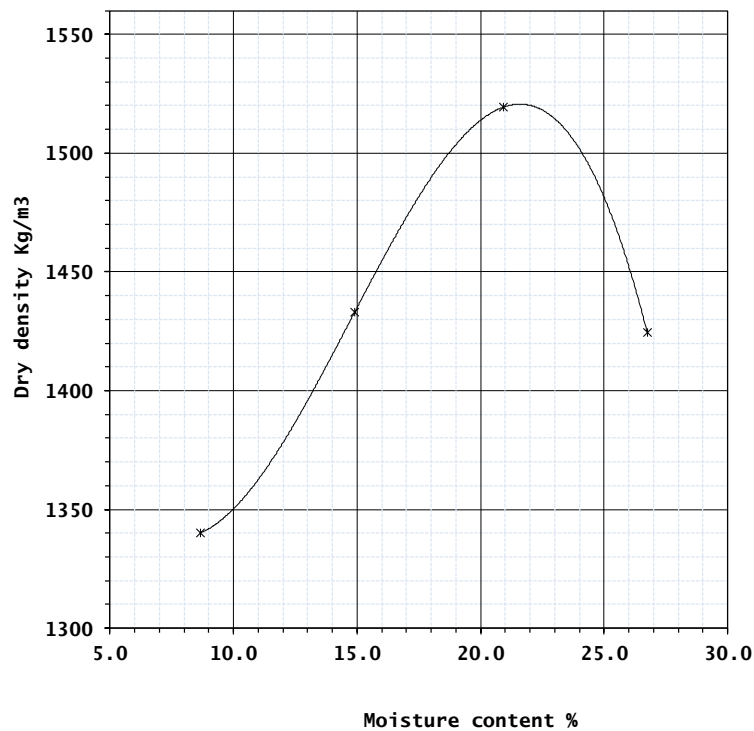


| 5 | | Units |
|-----|------|-------------------|
| OMC | 32.0 | % |
| MDD | 1292 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | |
|----------------------------------|--------|-----------------|-----------------|---------------|------|-------------------------|------|---------|---|--|
| Sample No. : | | 6 | | Borehole No.: | | | | Depth.: | | |
| Compaction Method: | | | | | | | | | | |
| Mould | | Hammer | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | | 3 | | |
| Height: | 11.643 | cm | weight: | 2.5 | kg | No. Of blows per layer: | | 25 | | |
| Volume: | 944 | cm ³ | | | | | | | | |
| Test number | 1 | | 2 | | 3 | | 4 | | 5 | |
| Mass of Mould (g) | 1485 | | 1485 | | 1485 | | 1485 | | | |
| Mass of Mould+Compacted Soil (g) | 2860 | | 3040 | | 3220 | | 3190 | | | |
| Mass of Compacted Soil (g) | 1375 | | 1555 | | 1735 | | 1705 | | | |
| Wet Density (kg/m ³) | 1456 | | 1647 | | 1837 | | 1805 | | | |
| Mass of can (g) | 6.0 | 6.0 | 6.3 | 6.3 | 10.6 | 10.6 | 10.4 | 10.4 | | |
| Mass of can+wet soil (g) | 86.4 | 86.4 | 83.4 | 83.4 | 86.9 | 86.9 | 63.0 | 63.0 | | |
| Mass of can+dry soil (g) | 80.0 | 80.0 | 73.4 | 73.4 | 73.7 | 73.7 | 51.9 | 51.9 | | |
| Mass of moisture (g) | 6.4 | 6.4 | 10.0 | 10.0 | 13.2 | 13.2 | 11.1 | 11.1 | | |
| Mass of dry soil (g) | 74.0 | 74.0 | 67.1 | 67.1 | 63.1 | 63.1 | 41.5 | 41.5 | | |
| Moisture content, % | 8.6 | 8.6 | 14.9 | 14.9 | 20.9 | 20.9 | 26.7 | 26.7 | | |
| Average moisture content, % | 8.6 | | 14.9 | | 20.9 | | 26.7 | | | |
| Dry Density (kg/m ³) | 1340 | | 1433 | | 1519 | | 1424 | | | |

Compaction curve



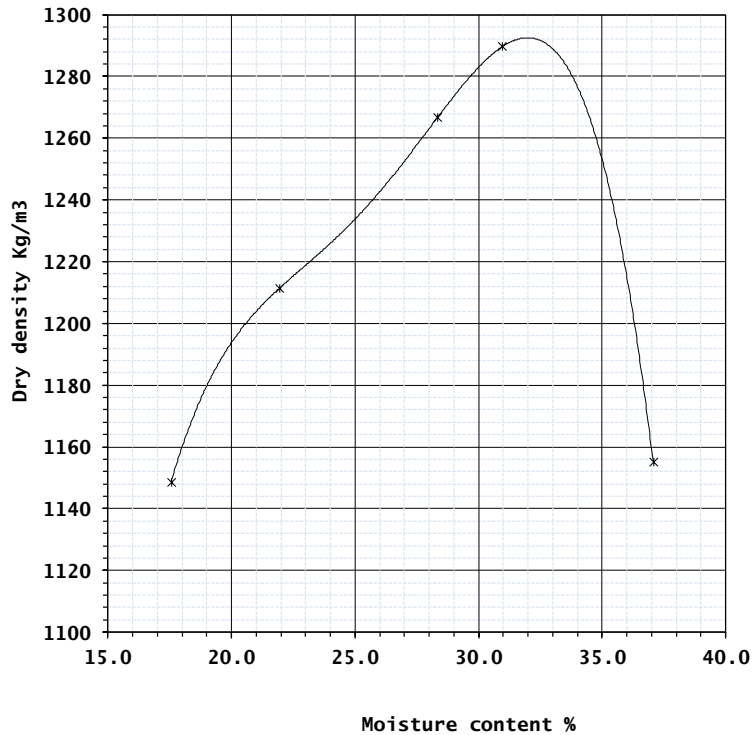
| 6 | | Units |
|-----|------|-------------------|
| OMC | 21.5 | % |
| MDD | 1520 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

Compaction Test

| | | | | | | | | | | | |
|----------------------------------|-----------|----------------------|----------------------|----------|------|-------------------------|----------------|----------|------|----------|--|
| Sample No. : | P1 | 5 | Borehole No.: | | | | Depth.: | | | | |
| Compaction Method: | | West Africa Standard | | | | | | | | | |
| Mould | Hammer | | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | | | | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | | | | |
| Volume: | 944 | cm ³ | | | | | | | | | |
| Test number | | | 1 | 2 | | 3 | | 4 | | 5 | |
| Mass of Mould (g) | | | 1485 | 1485 | | 1485 | | 1485 | | 1485 | |
| Mass of Mould+Compacted Soil (g) | | | 2700 | 2760 | | 2880 | | 3020 | | 3080 | |
| Mass of Compacted Soil (g) | | | 1215 | 1275 | | 1395 | | 1535 | | 1595 | |
| Wet Density (kg/m ³) | | | 1287 | 1350 | | 1477 | | 1626 | | 1689 | |
| Mass of can (g) | 22.4 | 19.6 | 23.3 | 23.6 | 19.4 | 7.9 | 10.2 | 7.0 | 9.0 | 9.0 | |
| Mass of can+wet soil (g) | 61.4 | 56.8 | 62.9 | 67.8 | 58.9 | 50.1 | 55.2 | 45.3 | 29.3 | 29.3 | |
| Mass of can+dry soil (g) | 57.1 | 52.5 | 56.9 | 61.3 | 51.8 | 42.5 | 45.2 | 36.9 | 24.5 | 24.5 | |
| Mass of moisture (g) | 4.3 | 4.3 | 6.0 | 6.5 | 7.1 | 7.6 | 10.0 | 8.4 | 4.8 | 4.8 | |
| Mass of dry soil (g) | 34.7 | 32.9 | 33.6 | 37.7 | 32.4 | 34.6 | 35.0 | 29.9 | 15.5 | 15.5 | |
| Moisture content,% | 12.4 | 13.1 | 17.9 | 17.2 | 21.9 | 22.0 | 28.6 | 28.1 | 31.0 | 31.0 | |
| Average moisture content,% | | | 17.5 | | 21.9 | | 28.3 | | 31.0 | | |
| Dry Density (kg/m ³) | | | 1149 | | 1211 | | 1267 | | 1290 | | |

Compaction curve

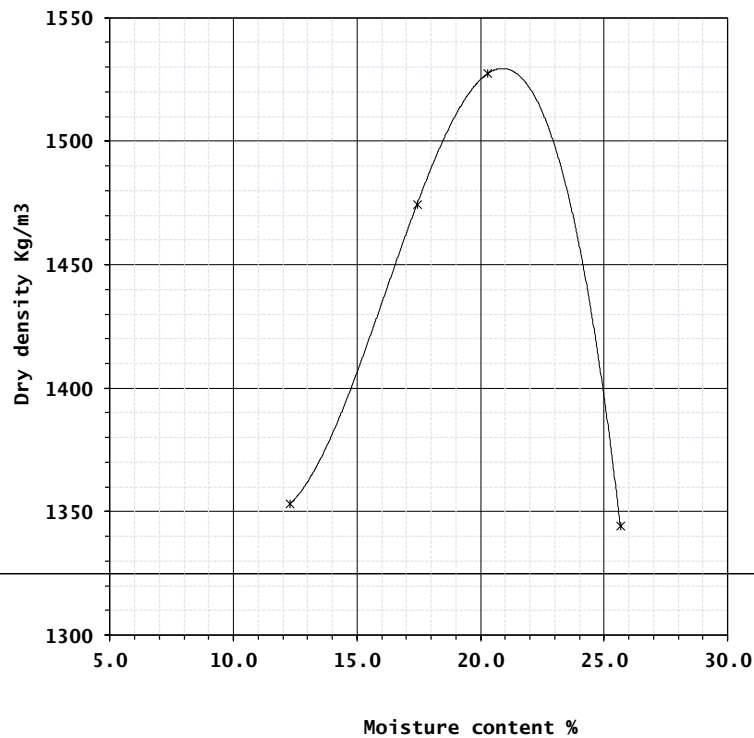


| | | |
|-----|----------|-------------------|
| | 5 | Units |
| OMC | 32.0 | % |
| MDD | 1292 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | |
|----------------------------------|--------|-----------------|-----------------|--------|------|-------------------------|---------|------|--|
| Sample No. : | Pt | 7 | Borehole No.: | | | | Depth.: | | |
| Compaction Method: | | | | | | | | | |
| Mould | Hammer | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | | |
| Volume: | 944 | cm ³ | | | | | | | |
| Test number | | | 1 | 2 | | 3 | 4 | | |
| Mass of Mould (g) | | | 1485 | 1485 | | 1485 | 1485 | | |
| Mass of Mould+Compacted Soil (g) | | | 2920 | 3120 | | 3220 | 3080 | | |
| Mass of Compacted Soil (g) | | | 1435 | 1635 | | 1735 | 1595 | | |
| Wet Density (kg/m ³) | | | 1520 | 1731 | | 1837 | 1689 | | |
| Mass of can (g) | 35.6 | 24.9 | 8.9 | 8.9 | 26.2 | 8.2 | 32.5 | 28.2 | |
| Mass of can+wet soil (g) | 76.0 | 89.1 | 39.9 | 39.9 | 59.5 | 38.3 | 95.7 | 65.7 | |
| Mass of can+dry soil (g) | 71.5 | 82.2 | 35.3 | 35.3 | 53.8 | 33.3 | 82.7 | 58.1 | |
| Mass of moisture (g) | 4.5 | 6.9 | 4.6 | 4.6 | 5.7 | 5.0 | 13.0 | 7.6 | |
| Mass of dry soil (g) | 35.9 | 57.3 | 26.4 | 26.4 | 27.6 | 25.1 | 50.2 | 29.9 | |
| Moisture content,% | 12.5 | 12.0 | 17.4 | 17.4 | 20.7 | 19.9 | 25.9 | 25.4 | |
| Average moisture content,% | 12.3 | | 17.4 | | 20.3 | | 25.7 | | |
| Dry Density (kg/m ³) | 1353 | | 1474 | | 1527 | | 1344 | | |

Compaction curve

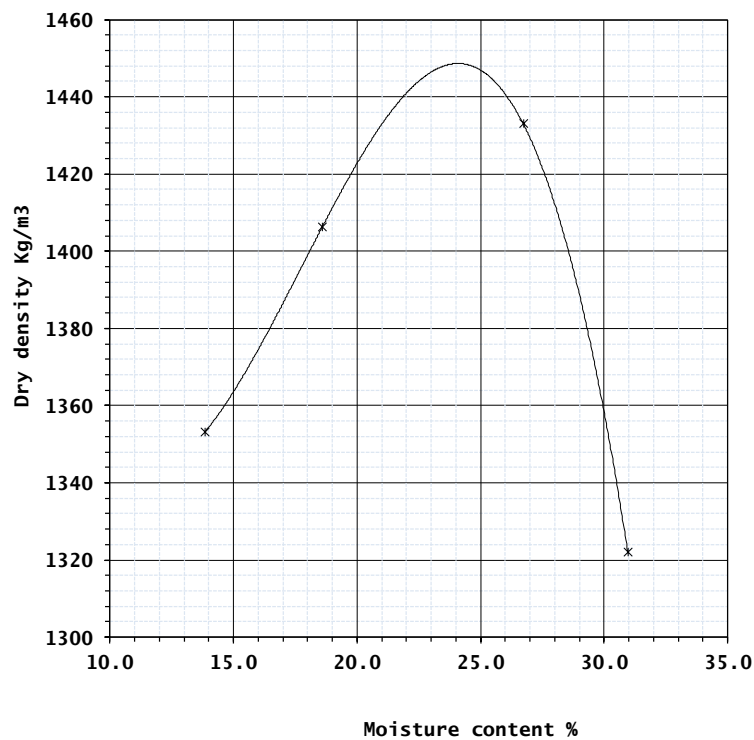


| 7 | | Units |
|-----|------|-------------------|
| OMC | 21.0 | % |
| MDD | 1530 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | | | |
|----------------------------------|--------|-----------------|-----------------|---------------|------|-------------------------|-------|---------|------|------|---|--|
| Sample No. : | | SUN | | Borehole No.: | | | | Depth.: | | | | |
| Compaction Method: | | | | | | | | | | | | |
| Mould | | Hammer | | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | | | | | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | | | | | |
| Volume: | 944 | cm ³ | | | | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 4 | | 5 | |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | 1485 | | | |
| Mass of Mould+Compacted Soil (g) | | | 2940 | | 3060 | | 3200 | | 3120 | | | |
| Mass of Compacted Soil (g) | | | 1455 | | 1575 | | 1715 | | 1635 | | | |
| Wet Density (kg/m ³) | | | 1541 | | 1668 | | 1816 | | 1731 | | | |
| Mass of can (g) | | | 19.5 | 25.1 | 19.4 | 25.5 | 51.3 | 23.5 | 19.1 | 23.0 | | |
| Mass of can+wet soil (g) | | | 55.0 | 56.3 | 61.3 | 75.6 | 113.7 | 86.3 | 97.2 | 66.9 | | |
| Mass of can+dry soil (g) | | | 50.8 | 52.4 | 54.2 | 68.4 | 100.5 | 73.1 | 78.6 | 56.6 | | |
| Mass of moisture (g) | | | 4.2 | 3.9 | 7.1 | 7.2 | 13.2 | 13.2 | 18.6 | 10.3 | | |
| Mass of dry soil (g) | | | 31.3 | 27.3 | 34.8 | 42.9 | 49.2 | 49.6 | 59.5 | 33.6 | | |
| Moisture content,% | | | 13.4 | 14.3 | 20.4 | 16.8 | 26.8 | 26.6 | 31.3 | 30.7 | | |
| Average moisture content,% | | | 13.9 | | 18.6 | | 26.7 | | 31.0 | | | |
| Dry Density (kg/m ³) | | | 1353 | | 1406 | | 1433 | | 1322 | | | |

Compaction curve

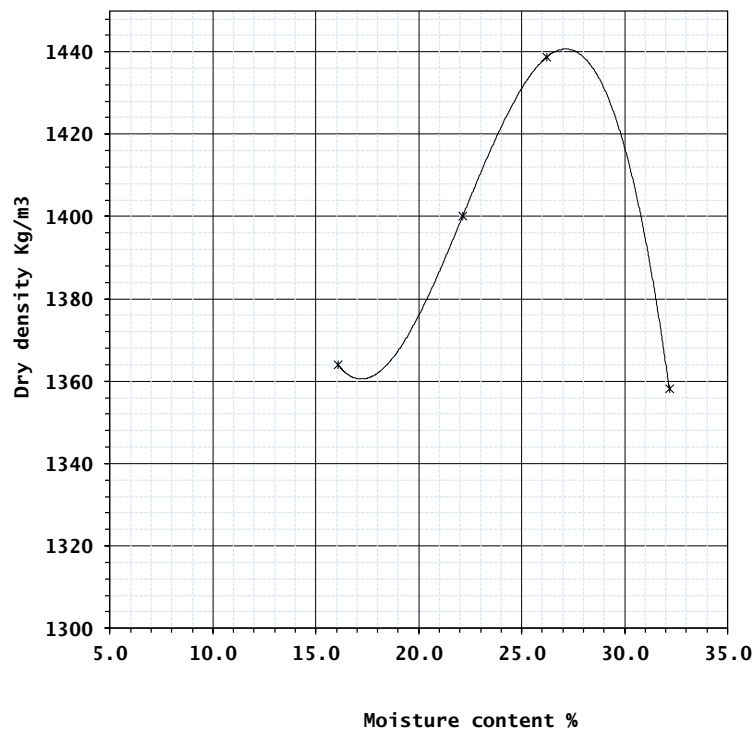


| SUN | | Units |
|-----|------|-------------------|
| OMC | 24.0 | % |
| MDD | 1449 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | |
|----------------------------------|--|----------------------|-----------------|-----------------|------|-------|------|-------------------------|------|----|
| Sample No. : | | 11 | | Borehole No.: | | | | Depth.: | | |
| Compaction Method: | | West Africa Standard | | | | | | | | |
| Mould | | Hammer | | | | | | | | |
| Diameter: | | 10.16 | cm | height of drop: | | 30.55 | cm | No. Of layers: | | 3 |
| Height: | | 11.643 | cm | weight: | | 2.5 | kg | No. Of blows per layer: | | 25 |
| Volume: | | 944 | cm ³ | | | | | | | |
| Test number | | 1 | | 2 | | 3 | | 4 | | |
| Mass of Mould (g) | | 1485 | | 1485 | | 1485 | | 1485 | | |
| Mass of Mould+Compacted Soil (g) | | 2980 | | 3100 | | 3200 | | 3180 | | |
| Mass of Compacted Soil (g) | | 1495 | | 1615 | | 1715 | | 1695 | | |
| Wet Density (kg/m ³) | | 1583 | | 1710 | | 1816 | | 1795 | | |
| Mass of can (g) | | 8.7 | 6.9 | 8.2 | 10.4 | 6.3 | 7.2 | 8.3 | 8.6 | |
| Mass of can+wet soil (g) | | 51.8 | 54.9 | 43.0 | 43.3 | 46.7 | 86.2 | 73.4 | 49.7 | |
| Mass of can+dry soil (g) | | 45.8 | 48.3 | 37.4 | 36.7 | 38.2 | 70.0 | 57.4 | 39.8 | |
| Mass of moisture (g) | | 6.0 | 6.6 | 5.6 | 6.6 | 8.5 | 16.2 | 16.0 | 9.9 | |
| Mass of dry soil (g) | | 37.1 | 41.4 | 29.2 | 26.3 | 31.9 | 62.8 | 49.1 | 31.2 | |
| Moisture content, % | | 16.2 | 15.9 | 19.2 | 25.1 | 26.6 | 25.8 | 32.6 | 31.7 | |
| Average moisture content, % | | 16.1 | | 22.1 | | 26.2 | | 32.2 | | |
| Dry Density (kg/m ³) | | 1364 | | 1400 | | 1439 | | 1358 | | |

Compaction curve

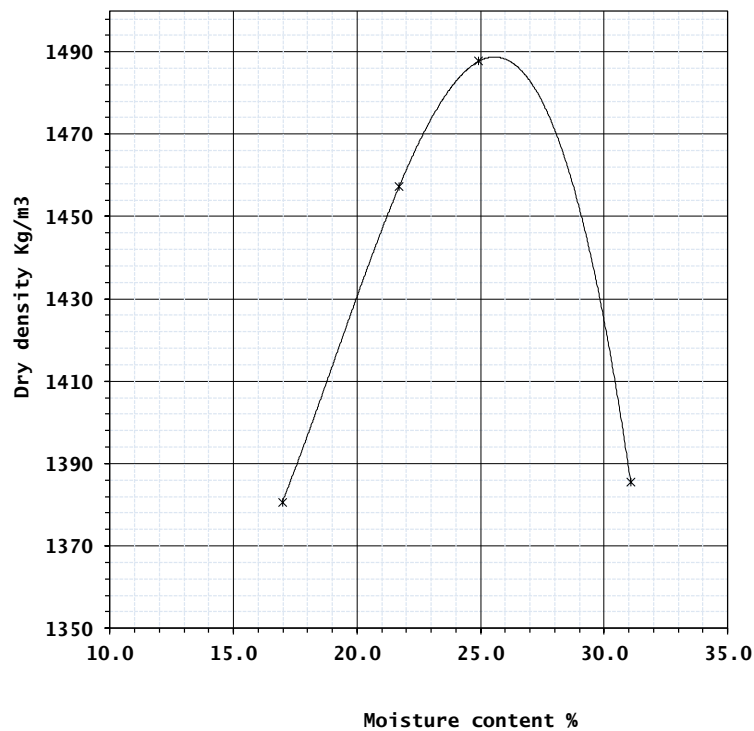


| 11 | | Units |
|-----|------|-------------------|
| OMC | 27.0 | % |
| MDD | 1440 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | |
|----------------------------------|--------|----------------------|-----------------|-------|------|-------------------------|------|---------|--|---|
| Sample No. : | P1 | SUN12 | | | | Borehole No.: | | Depth.: | | |
| Compaction Method: | | West Africa Standard | | | | | | | | |
| Mould | Hammer | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | | 3 | | |
| Height: | 11.643 | cm | weight: | 2.5 | kg | No. Of blows per layer: | | 25 | | |
| Volume: | 944 | cm ³ | | | | | | | | |
| Test number | | | 1 | 2 | | 3 | | 4 | | 5 |
| Mass of Mould (g) | | | 1485 | 1485 | | 1485 | | 1485 | | |
| Mass of Mould+Compacted Soil (g) | | | 3010 | 3160 | | 3240 | | 3200 | | |
| Mass of Compacted Soil (g) | | | 1525 | 1675 | | 1755 | | 1715 | | |
| Wet Density (kg/m ³) | | | 1615 | 1774 | | 1858 | | 1816 | | |
| Mass of can (g) | 10.3 | 8.2 | 8.3 | 7.0 | 9.6 | 9.4 | 8.5 | 6.9 | | |
| Mass of can+wet soil (g) | 52.3 | 57.2 | 57.8 | 76.3 | 79.7 | 51.4 | 86.7 | 74.5 | | |
| Mass of can+dry soil (g) | 46.2 | 50.1 | 49.0 | 63.9 | 65.1 | 43.4 | 67.9 | 58.7 | | |
| Mass of moisture (g) | 6.1 | 7.1 | 8.8 | 12.4 | 14.6 | 8.0 | 18.8 | 15.8 | | |
| Mass of dry soil (g) | 35.9 | 41.9 | 40.7 | 56.9 | 55.5 | 34.0 | 59.4 | 51.8 | | |
| Moisture content,% | 17.0 | 16.9 | 21.6 | 21.8 | 26.3 | 23.5 | 31.6 | 30.5 | | |
| Average moisture content,% | 17.0 | | 21.7 | | 24.9 | | 31.1 | | | |
| Dry Density (kg/m ³) | 1381 | | 1457 | | 1488 | | 1385 | | | |

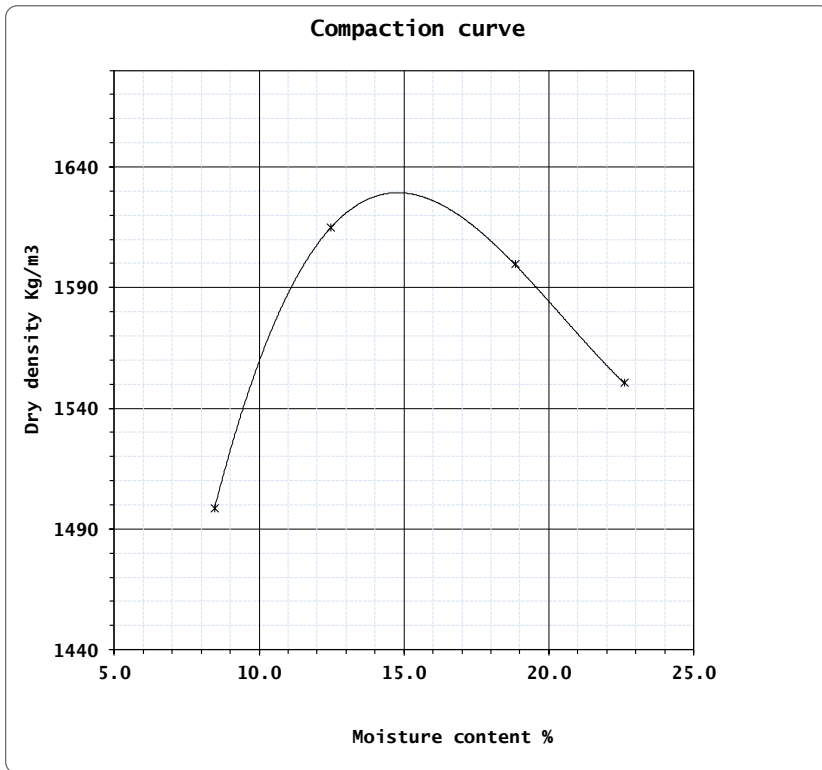
Compaction curve



| SUN12 | | Units |
|-------|------|-------------------|
| OMC | 25.5 | % |
| MDD | 1488 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | |
|----------------------------------|--------|----------------------|-----------------|--------|----------|-------------------------|----------|---------|----------|--|
| Sample No. : P1 | | SUN13 | | | | Borehole No.: | | Depth.: | | |
| Compaction Method: | | West Africa Standard | | | | | | | | |
| Mould | Hammer | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | | | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | | | |
| Volume: | 944 | cm ³ | | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 4 | |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | 1485 | |
| Mass of Mould+Compacted Soil (g) | | | 3020 | | 3200 | | 3280 | | 3280 | |
| Mass of Compacted Soil (g) | | | 1535 | | 1715 | | 1795 | | 1795 | |
| Wet Density (kg/m ³) | | | 1625 | | 1816 | | 1901 | | 1901 | |
| Mass of can (g) | 32.4 | 10.2 | 23.3 | 23.3 | 10.0 | 10.0 | 8.3 | 8.3 | | |
| Mass of can+wet soil (g) | 93.9 | 62.6 | 63.9 | 63.9 | 60.5 | 60.5 | 59.3 | 59.3 | | |
| Mass of can+dry soil (g) | 89.0 | 58.6 | 59.4 | 59.4 | 52.5 | 52.5 | 49.9 | 49.9 | | |
| Mass of moisture (g) | 4.9 | 4.0 | 4.5 | 4.5 | 8.0 | 8.0 | 9.4 | 9.4 | | |
| Mass of dry soil (g) | 56.6 | 48.4 | 36.1 | 36.1 | 42.5 | 42.5 | 41.6 | 41.6 | | |
| Moisture content,% | 8.7 | 8.3 | 12.5 | 12.5 | 18.8 | 18.8 | 22.6 | 22.6 | | |
| Average moisture content,% | 8.5 | | 12.5 | | 18.8 | | 22.6 | | | |
| Dry Density (kg/m ³) | 1499 | | 1615 | | 1600 | | 1550 | | | |



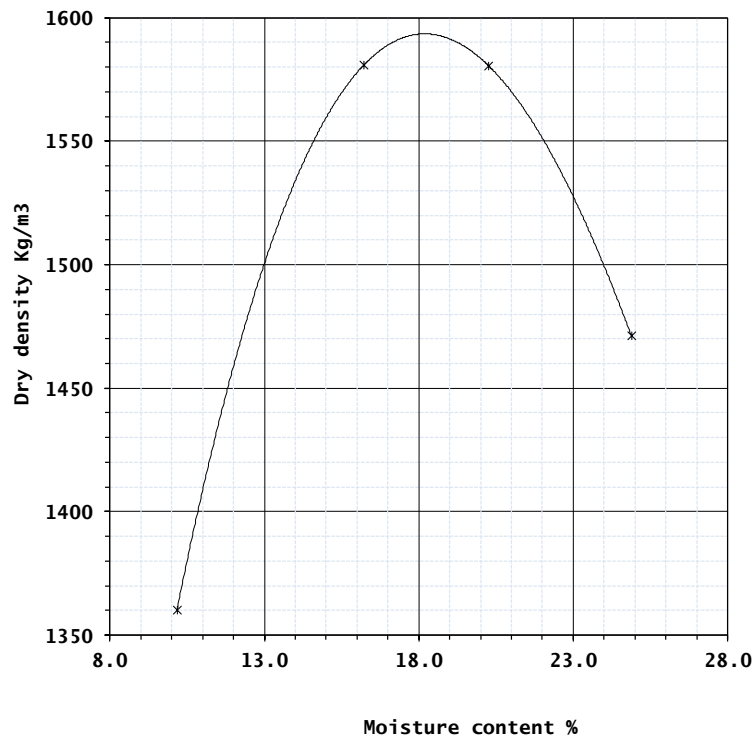
| SUN13 | | Units |
|-------|------|-------------------|
| OMC | 14.5 | % |
| MDD | 1630 | kg/m ³ |

OMC = Optimum moisture content

MDD = Maximum dry density

| Compaction Test | | | | | | | | | | |
|----------------------------------|--------|----------------------|-----------------|-------|------|-------------------------|------|---------|--|---|
| Sample No. : | P1 | SUN14 | | | | Borehole No.: | | Depth.: | | |
| Compaction Method: | | West Africa Standard | | | | | | | | |
| Mould | Hammer | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | | 3 | | |
| Height: | 11.643 | cm | weight: | 2.5 | kg | No. Of blows per layer: | | 25 | | |
| Volume: | 944 | cm ³ | | | | | | | | |
| Test number | | | 1 | 2 | | 3 | | 4 | | 5 |
| Mass of Mould (g) | | | 1485 | 1485 | | 1485 | | 1485 | | |
| Mass of Mould+Compacted Soil (g) | | | 2900 | 3220 | | 3280 | | 3220 | | |
| Mass of Compacted Soil (g) | | | 1415 | 1735 | | 1795 | | 1735 | | |
| Wet Density (kg/m ³) | | | 1498 | 1837 | | 1901 | | 1837 | | |
| Mass of can (g) | 8.0 | 6.2 | 7.1 | 7.1 | 8.5 | 8.5 | 9.4 | 9.0 | | |
| Mass of can+wet soil (g) | 47.7 | 46.7 | 49.3 | 32.1 | 54.2 | 54.2 | 89.9 | 60.2 | | |
| Mass of can+dry soil (g) | 44.0 | 43.0 | 43.6 | 28.5 | 46.5 | 46.5 | 73.7 | 50.1 | | |
| Mass of moisture (g) | 3.7 | 3.7 | 5.7 | 3.6 | 7.7 | 7.7 | 16.2 | 10.1 | | |
| Mass of dry soil (g) | 36.0 | 36.8 | 36.5 | 21.4 | 38.0 | 38.0 | 64.3 | 41.1 | | |
| Moisture content,% | 10.3 | 10.1 | 15.6 | 16.8 | 20.3 | 20.3 | 25.2 | 24.6 | | |
| Average moisture content,% | 10.2 | | 16.2 | | 20.3 | | 24.9 | | | |
| Dry Density (kg/m ³) | 1360 | | 1581 | | 1580 | | 1471 | | | |

Compaction curve

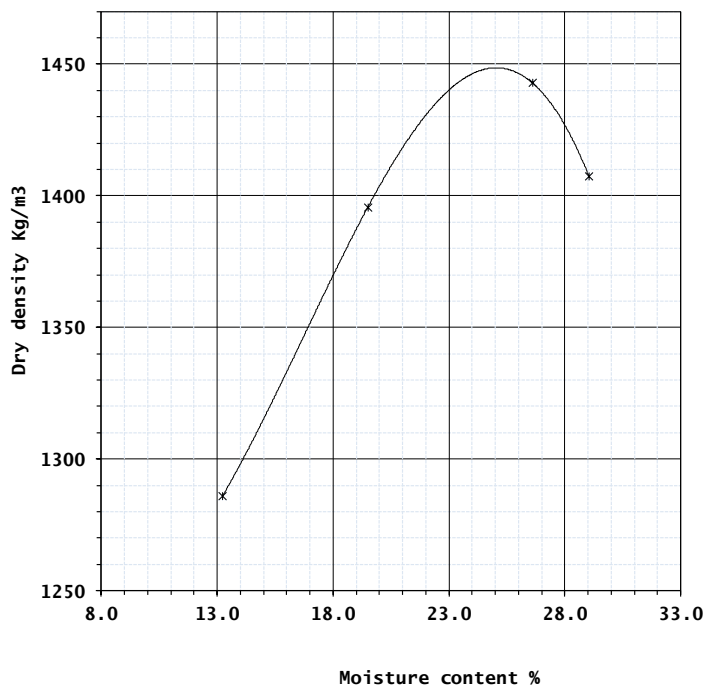


| SUN14 | | Units |
|-------|------|-------------------|
| OMC | 18.0 | % |
| MDD | 1592 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | | | |
|----------------------------------|--------|----------------------|-----------------|---------------|-------|-------------------------|-------|---------|-------|-------|---|--|
| Sample No. : | | 16 | | Borehole No.: | | | | Depth.: | | | | |
| Compaction Method: | | West Africa Standard | | | | | | | | | | |
| Mould | | Hammer | | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | | | | | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | | | | | |
| Volume: | 944 | cm ³ | | | | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 4 | | 5 | |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | 1485 | | | |
| Mass of Mould+Compacted Soil (g) | | | 2860 | | 3060 | | 3210 | | 3200 | | | |
| Mass of Compacted Soil (g) | | | 1375 | | 1575 | | 1725 | | 1715 | | | |
| Wet Density (kg/m ³) | | | 1456 | | 1668 | | 1827 | | 1816 | | | |
| Mass of can (g) | | | 42.1 | 42.1 | 29.3 | 29.3 | 34.1 | 34.1 | 9.0 | 9.0 | | |
| Mass of can+wet soil (g) | | | 98.6 | 98.6 | 115.1 | 115.1 | 111.7 | 111.7 | 117.4 | 117.4 | | |
| Mass of can+dry soil (g) | | | 92.0 | 92.0 | 101.1 | 101.1 | 95.4 | 95.4 | 93.0 | 93.0 | | |
| Mass of moisture (g) | | | 6.6 | 6.6 | 14.0 | 14.0 | 16.3 | 16.3 | 24.4 | 24.4 | | |
| Mass of dry soil (g) | | | 49.9 | 49.9 | 71.8 | 71.8 | 61.3 | 61.3 | 84.0 | 84.0 | | |
| Moisture content,% | | | 13.2 | 13.2 | 19.5 | 19.5 | 26.6 | 26.6 | 29.0 | 29.0 | | |
| Average moisture content,% | | | 13.2 | | 19.5 | | 26.6 | | 29.0 | | | |
| Dry Density (kg/m ³) | | | 1286 | | 1396 | | 1443 | | 1407 | | | |

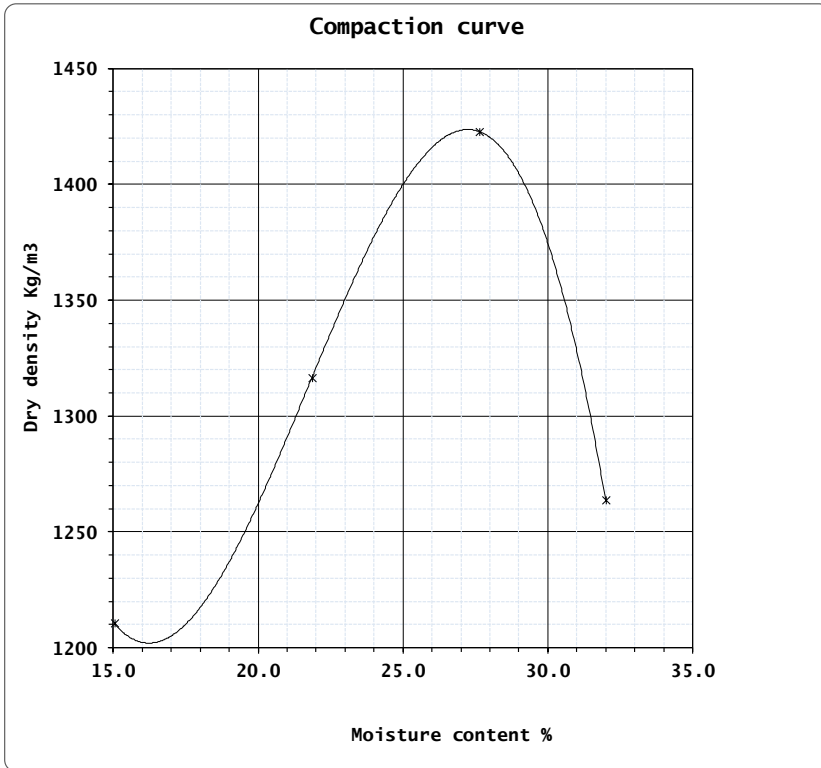
Compaction curve



| 16 | | Units |
|-----|------|-------------------|
| OMC | 25.0 | % |
| MDD | 1449 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | |
|----------------------------------|--------|----------------------|-----------------|-------|----------|-------------------------|----------|---------|----------|--|
| Sample No. : P1 | | SUN17 | | | | Borehole No.: | | Depth.: | | |
| Compaction Method: | | West Africa Standard | | | | | | | | |
| Mould | Hammer | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | | 3 | | |
| Height: | 11.643 | cm | weight: | 2.5 | kg | No. Of blows per layer: | | 25 | | |
| Volume: | 944 | cm ³ | | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 4 | |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | 1485 | |
| Mass of Mould+Compacted Soil (g) | | | 2800 | | 3000 | | 3200 | | 3060 | |
| Mass of Compacted Soil (g) | | | 1315 | | 1515 | | 1715 | | 1575 | |
| Wet Density (kg/m ³) | | | 1392 | | 1604 | | 1816 | | 1668 | |
| Mass of can (g) | 8.8 | 8.8 | 13.6 | 13.6 | 7.1 | 7.1 | 5.9 | 5.9 | | |
| Mass of can+wet soil (g) | 70.0 | 70.0 | 105.6 | 105.6 | 72.2 | 72.2 | 74.8 | 74.8 | | |
| Mass of can+dry soil (g) | 62.0 | 62.0 | 89.1 | 89.1 | 58.1 | 58.1 | 58.1 | 58.1 | | |
| Mass of moisture (g) | 8.0 | 8.0 | 16.5 | 16.5 | 14.1 | 14.1 | 16.7 | 16.7 | | |
| Mass of dry soil (g) | 53.2 | 53.2 | 75.5 | 75.5 | 51.0 | 51.0 | 52.2 | 52.2 | | |
| Moisture content,% | 15.0 | 15.0 | 21.9 | 21.9 | 27.6 | 27.6 | 32.0 | 32.0 | | |
| Average moisture content,% | 15.0 | | 21.9 | | 27.6 | | 32.0 | | | |
| Dry Density (kg/m ³) | 1210 | | 1317 | | 1423 | | 1264 | | | |



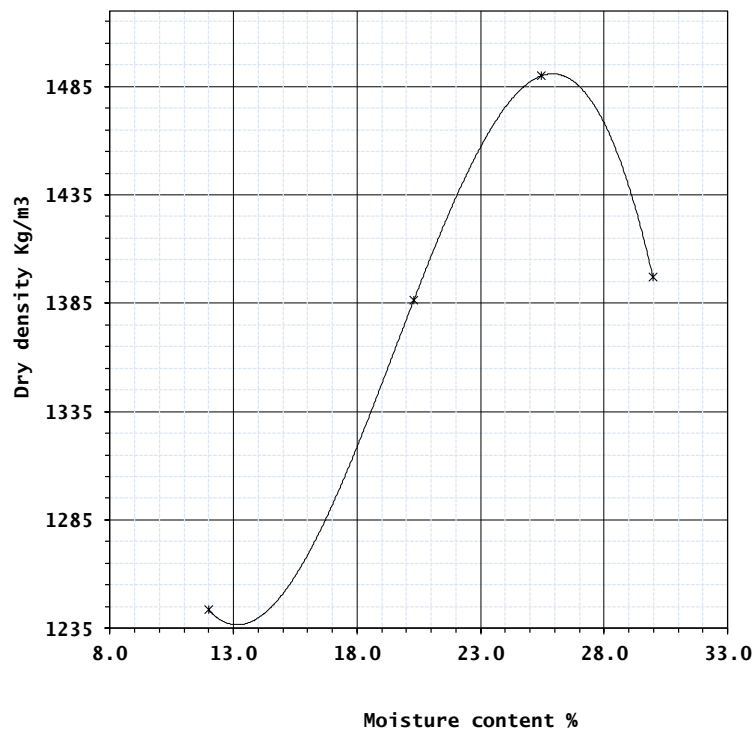
| SUN17 | | Units |
|-------|------|-------------------|
| OMC | 27.3 | % |
| MDD | 1423 | kg/m ³ |

OMC = Optimum moisture content

MDD = Maximum dry density

| Compaction Test | | | | | | | | | | |
|----------------------------------|--------|----------------------|-----------------|-------|------|-------------------------|------|---------|-------|-------|
| Sample No. : | P1 | SUN18 | | | | Borehole No.: | | Depth.: | | |
| Compaction Method: | | West Africa Standard | | | | | | | | |
| Mould | Hammer | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | | 3 | | |
| Height: | 11.643 | cm | weight: | 2.5 | kg | No. Of blows per layer: | | 25 | | |
| Volume: | 944 | cm ³ | | | | | | | | |
| Test number | | | 1 | 2 | | 3 | | 4 | | 5 |
| Mass of Mould (g) | | | 1485 | 1485 | | 1485 | | 1485 | | |
| Mass of Mould+Compacted Soil (g) | | | 2800 | 3060 | | 3250 | | 3200 | | |
| Mass of Compacted Soil (g) | | | 1315 | 1575 | | 1765 | | 1715 | | |
| Wet Density (kg/m ³) | | | 1392 | 1668 | | 1869 | | 1816 | | |
| Mass of can (g) | | | 39.1 | 39.1 | 39.8 | 39.8 | 40.5 | 40.5 | 57.9 | 57.9 |
| Mass of can+wet soil (g) | | | 123.2 | 123.2 | 88.4 | 88.4 | 96.7 | 96.7 | 152.0 | 152.0 |
| Mass of can+dry soil (g) | | | 114.2 | 114.2 | 80.2 | 80.2 | 85.3 | 85.3 | 130.3 | 130.3 |
| Mass of moisture (g) | | | 9.0 | 9.0 | 8.2 | 8.2 | 11.4 | 11.4 | 21.7 | 21.7 |
| Mass of dry soil (g) | | | 75.1 | 75.1 | 40.4 | 40.4 | 44.8 | 44.8 | 72.4 | 72.4 |
| Moisture content,% | | | 12.0 | 12.0 | 20.3 | 20.3 | 25.4 | 25.4 | 30.0 | 30.0 |
| Average moisture content,% | | | 12.0 | | 20.3 | | 25.4 | | 30.0 | |
| Dry Density (kg/m ³) | | | 1243 | | 1386 | | 1490 | | 1397 | |

Compaction curve

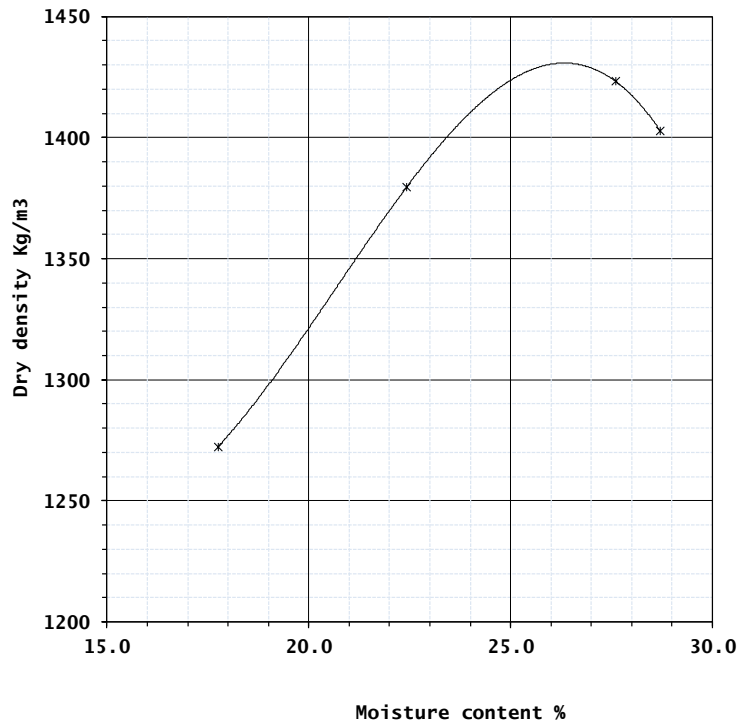


| SUN18 | | Units |
|-------|------|-------------------|
| OMC | 26.0 | % |
| MDD | 1490 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | | | |
|----------------------------------|--------|----------------------|-----------------|---------------|------|-------------------------|------|---------|------|------|------|--|
| Sample No. : | | SUN19 | | Borehole No.: | | | | Depth.: | | | | |
| Compaction Method: | | West Africa Standard | | | | | | | | | | |
| Mould | | Hammer | | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | | 3 | | | | |
| Height: | 11.643 | cm | weight: | 2.5 | kg | No. Of blows per layer: | | 25 | | | | |
| Volume: | 944 | cm ³ | | | | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 4 | | | |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | 1485 | | 1485 | |
| Mass of Mould+Compacted Soil (g) | | | 2740 | | 2900 | | 3080 | | 3200 | | 3190 | |
| Mass of Compacted Soil (g) | | | 1255 | | 1415 | | 1595 | | 1715 | | 1705 | |
| Wet Density (kg/m ³) | | | 1329 | | 1498 | | 1689 | | 1816 | | 1805 | |
| Mass of can (g) | 9.8 | 23.1 | 6.2 | 8.4 | 24.3 | 24.3 | 10.2 | 23.3 | 10.2 | 23.3 | | |
| Mass of can+wet soil (g) | 54.5 | 60.8 | 37.9 | 45.7 | 64.7 | 64.7 | 76.3 | 81.6 | 77.0 | 82.0 | | |
| Mass of can+dry soil (g) | 49.7 | 56.4 | 33.1 | 40.1 | 57.3 | 57.3 | 62.0 | 69.0 | 62.0 | 69.0 | | |
| Mass of moisture (g) | 4.8 | 4.4 | 4.8 | 5.6 | 7.4 | 7.4 | 14.3 | 12.6 | 15.0 | 13.0 | | |
| Mass of dry soil (g) | 39.9 | 33.3 | 26.9 | 31.7 | 33.0 | 33.0 | 51.8 | 45.7 | 51.8 | 45.7 | | |
| Moisture content,% | 12.0 | 13.2 | 17.8 | 17.7 | 22.4 | 22.4 | 27.6 | 27.6 | 29.0 | 28.4 | | |
| Average moisture content,% | | | 17.8 | | 22.4 | | 27.6 | | 28.7 | | | |
| Dry Density (kg/m ³) | | | 1272 | | 1380 | | 1423 | | 1403 | | | |

Compaction curve

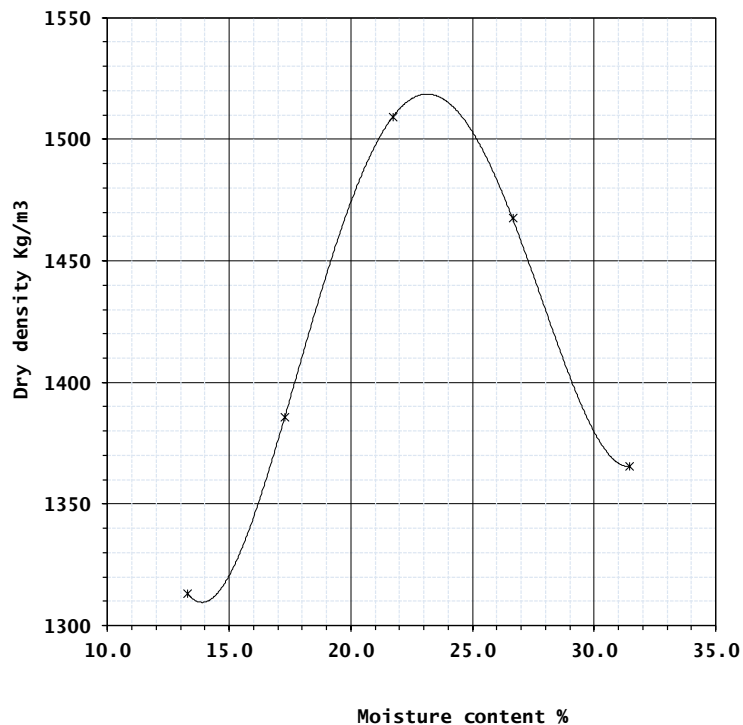


| SUN19 | | Units |
|-------|------|-------------------|
| OMC | 26.5 | % |
| MDD | 1430 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | | | |
|----------------------------------|----------------|----------------------|-----------------|---------------|------|-------------------------|------|------|------|---------|------|--|
| Sample No. : | P ^t | 20 | | Borehole No.: | | | | | | Depth.: | | |
| Compaction Method: | | West Africa Standard | | | | | | | | | | |
| Mould | | Hammer | | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | | 3 | | | | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | | 25 | | | | |
| Volume: | 944 | cm ³ | | | | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 4 | | 5 | |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | 1485 | | 1485 | |
| Mass of Mould+Compacted Soil (g) | | | 2890 | | 3020 | | 3220 | | 3240 | | 3180 | |
| Mass of Compacted Soil (g) | | | 1405 | | 1535 | | 1735 | | 1755 | | 1695 | |
| Wet Density (kg/m ³) | | | 1488 | | 1625 | | 1837 | | 1858 | | 1795 | |
| Mass of can (g) | 8.4 | 9.1 | 25.1 | 8.9 | 6.9 | 7.9 | 7.8 | 10.2 | 23.0 | 23.3 | | |
| Mass of can+wet soil (g) | 60.5 | 69.4 | 75.9 | 61.3 | 49.2 | 71.9 | 74.3 | 64.6 | 90.5 | 90.4 | | |
| Mass of can+dry soil (g) | 54.5 | 62.2 | 68.2 | 53.8 | 41.7 | 60.4 | 60.5 | 53.0 | 74.2 | 74.5 | | |
| Mass of moisture (g) | 6.0 | 7.2 | 7.7 | 7.5 | 7.5 | 11.5 | 13.8 | 11.6 | 16.3 | 15.9 | | |
| Mass of dry soil (g) | 46.1 | 53.1 | 43.1 | 44.9 | 34.8 | 52.5 | 52.7 | 42.8 | 51.2 | 51.2 | | |
| Moisture content,% | 13.0 | 13.6 | 17.9 | 16.7 | 21.6 | 21.9 | 26.2 | 27.1 | 31.8 | 31.1 | | |
| Average moisture content,% | | | 13.3 | | 17.3 | | 21.7 | | 26.6 | | 31.4 | |
| Dry Density (kg/m ³) | | | 1313 | | 1386 | | 1509 | | 1467 | | 1366 | |

Compaction curve



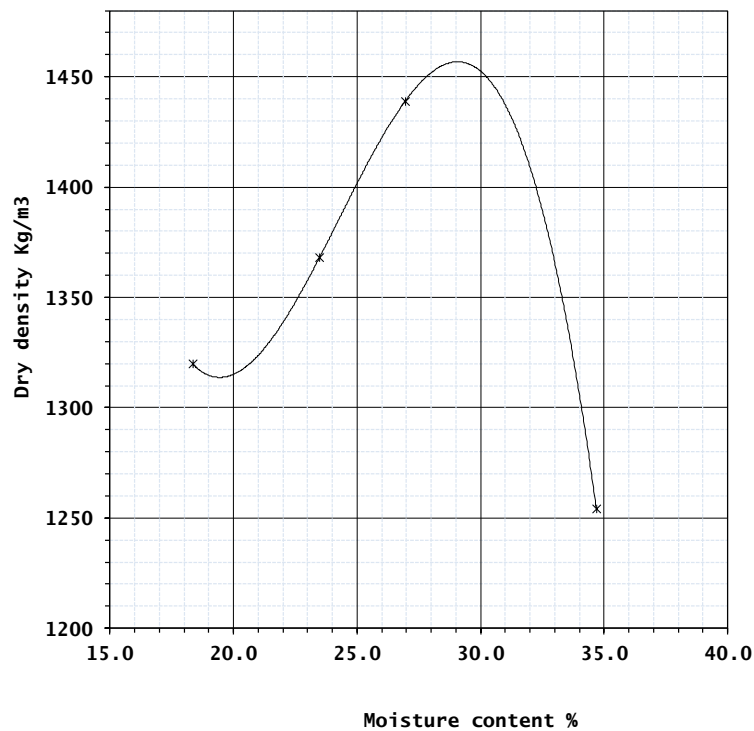
| 20 | | Units |
|-----|------|-------------------|
| OMC | 23.3 | % |
| MDD | 1521 | kg/m ³ |

OMC = Optimum moisture content

MDD = Maximum dry density

| Compaction Test | | | | | | | | | | | |
|----------------------------------|--|----------------------|-----------------|-----------------|------|-------|-------|-------------------------|------|------|------|
| Sample No. : | | SUN21 | | Borehole No.: | | | | Depth.: | | | |
| Compaction Method: | | West Africa Standard | | | | | | | | | |
| Mould | | Hammer | | | | | | | | | |
| Diameter: | | 10.16 | cm | height of drop: | | 30.55 | cm | No. Of layers: | | 3 | |
| Height: | | 11.643 | cm | weight: | | 2.5 | kg | No. Of blows per layer: | | 25 | |
| Volume: | | 944 | cm ³ | | | | | | | | |
| Test number | | | | 1 | | 2 | | 3 | | 4 | |
| Mass of Mould (g) | | 1485 | | 1485 | | 1485 | | 1485 | | 1485 | |
| Mass of Mould+Compacted Soil (g) | | 2900 | | 2960 | | 3080 | | 3210 | | 3080 | |
| Mass of Compacted Soil (g) | | 1415 | | 1475 | | 1595 | | 1725 | | 1595 | |
| Wet Density (kg/m ³) | | 1498 | | 1562 | | 1689 | | 1827 | | 1689 | |
| Mass of can (g) | | 23.4 | 6.7 | 6.7 | 26.0 | 50.8 | 52.3 | 26.0 | 11.4 | 10.5 | 9.0 |
| Mass of can+wet soil (g) | | 74.9 | 61.3 | 40.0 | 83.9 | 120.2 | 112.3 | 86.0 | 34.4 | 58.0 | 71.2 |
| Mass of can+dry soil (g) | | 68.8 | 54.9 | 34.8 | 75.0 | 107.0 | 100.9 | 72.8 | 29.7 | 45.6 | 55.4 |
| Mass of moisture (g) | | 6.1 | 6.4 | 5.2 | 8.9 | 13.2 | 11.4 | 13.2 | 4.7 | 12.4 | 15.8 |
| Mass of dry soil (g) | | 45.4 | 48.2 | 28.1 | 49.0 | 56.2 | 48.6 | 46.8 | 18.3 | 35.1 | 46.4 |
| Moisture content, % | | 13.4 | 13.3 | 18.5 | 18.2 | 23.5 | 23.5 | 28.2 | 25.7 | 35.3 | 34.1 |
| Average moisture content, % | | | | 18.3 | | 23.5 | | 26.9 | | 34.7 | |
| Dry Density (kg/m ³) | | | | 1320 | | 1368 | | 1439 | | 1254 | |

Compaction curve

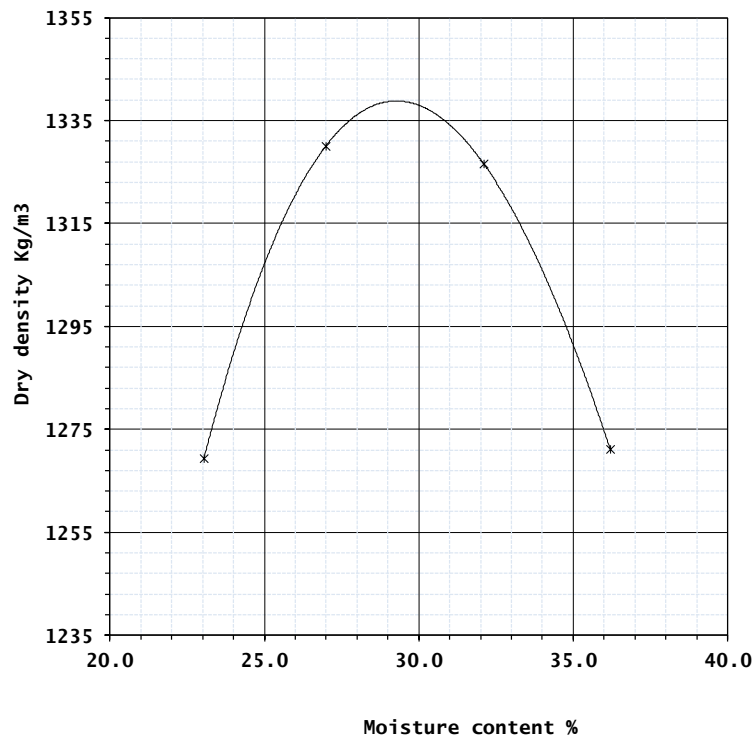


| SUN21 | | Units |
|-------|------|-------------------|
| OMC | 29.0 | % |
| MDD | 1455 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | | |
|----------------------------------|--|----------------------|-----------------|-----------------|------|-------|---------|-------------------------|-------|----|--|
| Sample No. : | | SUN22 | | Borehole No.: | | | Depth.: | | | | |
| Compaction Method: | | West Africa Standard | | | | | | | | | |
| Mould | | Hammer | | | | | | | | | |
| Diameter: | | 10.16 | cm | height of drop: | | 30.55 | cm | No. Of layers: | | 3 | |
| Height: | | 11.643 | cm | weight: | | 2.5 | kg | No. Of blows per layer: | | 25 | |
| Volume: | | 944 | cm ³ | | | | | | | | |
| Test number | | 1 | | 2 | | 3 | | 4 | | 5 | |
| Mass of Mould (g) | | 1485 | | 1485 | | 1485 | | 1485 | | | |
| Mass of Mould+Compacted Soil (g) | | 2960 | | 3080 | | 3140 | | 3120 | | | |
| Mass of Compacted Soil (g) | | 1475 | | 1595 | | 1655 | | 1635 | | | |
| Wet Density (kg/m ³) | | 1562 | | 1689 | | 1752 | | 1731 | | | |
| Mass of can (g) | | 23.5 | 25.1 | 51.2 | 19.5 | 25.4 | 23.3 | 23.4 | 23.4 | | |
| Mass of can+wet soil (g) | | 68.9 | 64.6 | 110.3 | 56.5 | 102.3 | 78.0 | 128.0 | 128.0 | | |
| Mass of can+dry soil (g) | | 60.4 | 57.2 | 97.8 | 48.6 | 83.9 | 64.5 | 100.2 | 100.2 | | |
| Mass of moisture (g) | | 8.5 | 7.4 | 12.5 | 7.9 | 18.4 | 13.5 | 27.8 | 27.8 | | |
| Mass of dry soil (g) | | 36.9 | 32.1 | 46.6 | 29.1 | 58.5 | 41.2 | 76.8 | 76.8 | | |
| Moisture content,% | | 23.0 | 23.1 | 26.8 | 27.1 | 31.5 | 32.8 | 36.2 | 36.2 | | |
| Average moisture content,% | | 23.0 | | 27.0 | | 32.1 | | 36.2 | | | |
| Dry Density (kg/m ³) | | 1269 | | 1330 | | 1327 | | 1271 | | | |

Compaction curve

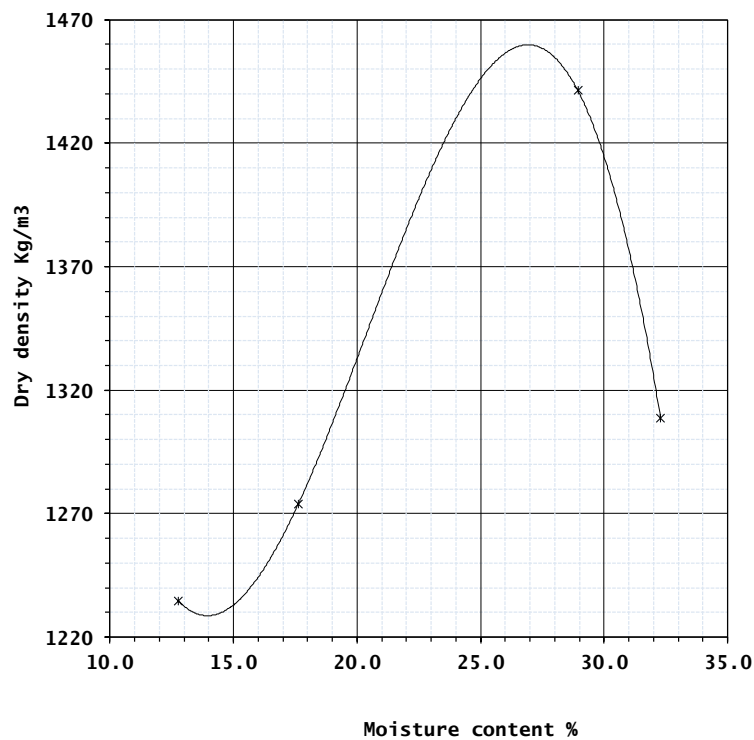


| SUN22 | | Units |
|-------|------|-------------------|
| OMC | 29.5 | % |
| MDD | 1339 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | |
|----------------------------------|--------|----------------------|-----------------|---------------|------|-------------------------|---------|-------|---|
| Sample No. : | | SUN23 | | Borehole No.: | | | Depth.: | | |
| Compaction Method: | | West Africa Standard | | | | | | | |
| Mould | | Hammer | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | | |
| Volume: | 944 | cm ³ | | | | | | | |
| Test number | 1 | | 2 | | 3 | | 4 | | 5 |
| Mass of Mould (g) | 1485 | | 1485 | | 1485 | | 1485 | | |
| Mass of Mould+Compacted Soil (g) | 2800 | | 2900 | | 3240 | | 3120 | | |
| Mass of Compacted Soil (g) | 1315 | | 1415 | | 1755 | | 1635 | | |
| Wet Density (kg/m ³) | 1392 | | 1498 | | 1858 | | 1731 | | |
| Mass of can (g) | 6.1 | 6.1 | 9.8 | 9.8 | 11.5 | 11.5 | 11.9 | 11.9 | |
| Mass of can+wet soil (g) | 96.2 | 96.2 | 63.2 | 63.2 | 72.1 | 72.1 | 100.0 | 100.0 | |
| Mass of can+dry soil (g) | 86.0 | 86.0 | 55.2 | 55.2 | 58.5 | 58.5 | 78.5 | 78.5 | |
| Mass of moisture (g) | 10.2 | 10.2 | 8.0 | 8.0 | 13.6 | 13.6 | 21.5 | 21.5 | |
| Mass of dry soil (g) | 79.9 | 79.9 | 45.4 | 45.4 | 47.0 | 47.0 | 66.6 | 66.6 | |
| Moisture content, % | 12.8 | 12.8 | 17.6 | 17.6 | 28.9 | 28.9 | 32.3 | 32.3 | |
| Average moisture content, % | 12.8 | | 17.6 | | 28.9 | | 32.3 | | |
| Dry Density (kg/m ³) | 1235 | | 1274 | | 1441 | | 1309 | | |

Compaction curve

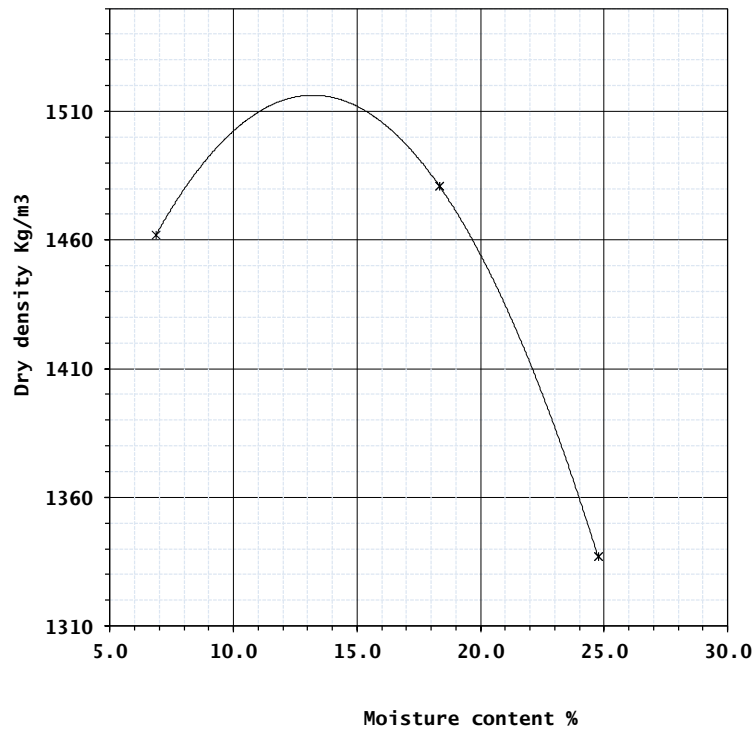


| SUN23 | | Units |
|-------|------|-------------------|
| OMC | 27.0 | % |
| MDD | 1460 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| | | | | | | | | | | | | |
|----------------------------------|-----------|----------------------|----------------------|--------|----------|-------------------------|----------------|------|----------|-------|----------|--|
| Sample No. : | 24 | | Borehole No.: | | | | Depth.: | | | | | |
| Compaction Method: | | West Africa Standard | | | | | | | | | | |
| Mould | | Hammer | | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | | | | | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | | | | | |
| Volume: | 944 | cm ³ | | | | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 4 | | 5 | |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | 1485 | | 1485 | |
| Mass of Mould+Compacted Soil (g) | | | 2960 | | 3140 | | 3060 | | 3140 | | 3060 | |
| Mass of Compacted Soil (g) | | | 1475 | | 1655 | | 1575 | | 1655 | | 1575 | |
| Wet Density (kg/m ³) | | | 1562 | | 1752 | | 1668 | | 1752 | | 1668 | |
| Mass of can (g) | 9.7 | 9.7 | 6.6 | 6.6 | 25.7 | 25.7 | 6.6 | 6.6 | 25.7 | 25.7 | | |
| Mass of can+wet soil (g) | 56.5 | 56.5 | 55.0 | 55.0 | 128.5 | 128.5 | 55.0 | 55.0 | 128.5 | 128.5 | | |
| Mass of can+dry soil (g) | 53.5 | 53.5 | 47.5 | 47.5 | 108.1 | 108.1 | 47.5 | 47.5 | 108.1 | 108.1 | | |
| Mass of moisture (g) | 3.0 | 3.0 | 7.5 | 7.5 | 20.4 | 20.4 | 7.5 | 7.5 | 20.4 | 20.4 | | |
| Mass of dry soil (g) | 43.8 | 43.8 | 40.9 | 40.9 | 82.4 | 82.4 | 40.9 | 40.9 | 82.4 | 82.4 | | |
| Moisture content,% | 6.8 | 6.8 | 18.3 | 18.3 | 24.8 | 24.8 | 18.3 | 18.3 | 24.8 | 24.8 | | |
| Average moisture content,% | 6.8 | | 18.3 | | 24.8 | | 18.3 | | 24.8 | | | |
| Dry Density (kg/m ³) | 1462 | | 1481 | | 1337 | | 1481 | | 1337 | | | |

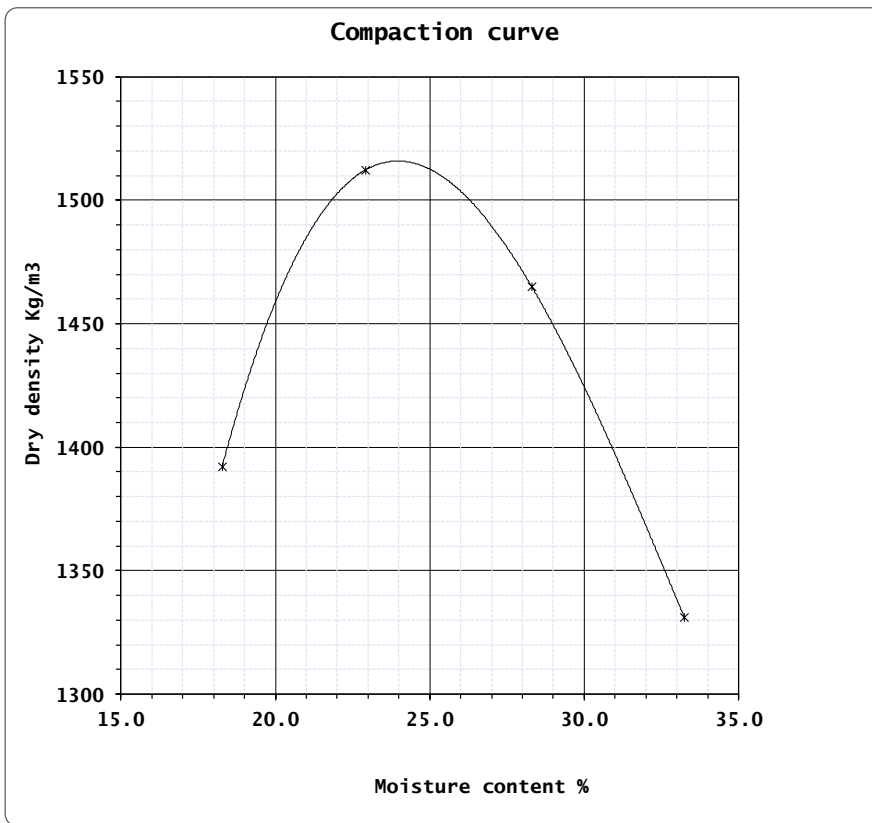
Compaction curve



| | | |
|-----|------|-------------------|
| | 24 | Units |
| OMC | 13.0 | % |
| MDD | 1512 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | |
|----------------------------------|--------|----------------------|-----------------|---------------|------|-------------------------|------|---------|------|--|
| Sample No. : | | 26 | | Borehole No.: | | | | Depth.: | | |
| Compaction Method: | | West Africa Standard | | | | | | | | |
| Mould | | Hammer | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | | | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | | | |
| Volume: | 944 | cm ³ | | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 4 | |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | 1485 | |
| Mass of Mould+Compacted Soil (g) | | | 3040 | | 3240 | | 3260 | | 3160 | |
| Mass of Compacted Soil (g) | | | 1555 | | 1755 | | 1775 | | 1675 | |
| Wet Density (kg/m ³) | | | 1647 | | 1858 | | 1880 | | 1774 | |
| Mass of can (g) | 19.3 | 19.3 | 23.6 | 26.0 | 19.1 | 23.3 | 22.7 | 22.7 | | |
| Mass of can+wet soil (g) | 63.3 | 63.3 | 55.7 | 58.3 | 79.9 | 108.6 | 68.8 | 68.8 | | |
| Mass of can+dry soil (g) | 56.5 | 56.5 | 49.7 | 52.3 | 66.4 | 89.9 | 57.3 | 57.3 | | |
| Mass of moisture (g) | 6.8 | 6.8 | 6.0 | 6.0 | 13.5 | 18.7 | 11.5 | 11.5 | | |
| Mass of dry soil (g) | 37.2 | 37.2 | 26.1 | 26.3 | 47.3 | 66.6 | 34.6 | 34.6 | | |
| Moisture content,% | 18.3 | 18.3 | 23.0 | 22.8 | 28.5 | 28.1 | 33.2 | 33.2 | | |
| Average moisture content,% | 18.3 | | 22.9 | | 28.3 | | 33.2 | | | |
| Dry Density (kg/m ³) | 1392 | | 1512 | | 1465 | | 1331 | | | |



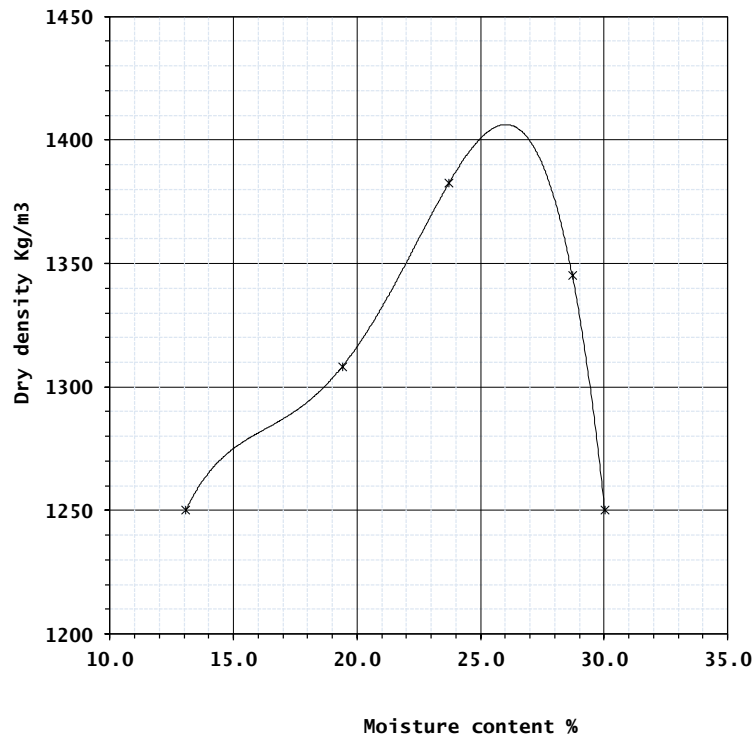
| 26 | | Units |
|-----|------|-------------------|
| OMC | 24.0 | % |
| MDD | 1515 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

Compaction Test

| | | | | | | | | | | | |
|----------------------------------|----------------------|-----------------|----------------------|----------|------|-------------------------|----------|------|----------|------|--|
| Sample No. : | 30 | | Borehole No.: | | | Depth.: | | | | | |
| Compaction Method: | West Africa Standard | | | | | | | | | | |
| Mould | Hammer | | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | | | | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | | | | |
| Volume: | 944 | cm ³ | | | | | | | | | |
| Test number | | | 1 | 2 | | 3 | 4 | | 5 | | |
| Mass of Mould (g) | | | 1485 | 1485 | | 1485 | 1485 | | 1485 | | |
| Mass of Mould+Compacted Soil (g) | | | 2820 | 2960 | | 3100 | 3120 | | 3020 | | |
| Mass of Compacted Soil (g) | | | 1335 | 1475 | | 1615 | 1635 | | 1535 | | |
| Wet Density (kg/m ³) | | | 1414 | 1562 | | 1710 | 1731 | | 1626 | | |
| Mass of can (g) | 7.9 | 7.8 | 8.9 | 6.9 | 9.0 | 8.0 | 8.3 | 9.0 | 8.2 | 8.2 | |
| Mass of can+wet soil (g) | 53.6 | 48.3 | 38.4 | 36.5 | 55.7 | 52.6 | 72.5 | 65.7 | 50.2 | 50.2 | |
| Mass of can+dry soil (g) | 48.8 | 43.2 | 33.6 | 31.7 | 46.7 | 44.1 | 57.9 | 53.3 | 40.5 | 40.5 | |
| Mass of moisture (g) | 4.8 | 5.1 | 4.8 | 4.8 | 9.0 | 8.5 | 14.6 | 12.4 | 9.7 | 9.7 | |
| Mass of dry soil (g) | 40.9 | 35.4 | 24.7 | 24.8 | 37.7 | 36.1 | 49.6 | 44.3 | 32.3 | 32.3 | |
| Moisture content,% | 11.7 | 14.4 | 19.4 | 19.4 | 23.9 | 23.5 | 29.4 | 28.0 | 30.0 | 30.0 | |
| Average moisture content,% | 13.1 | | 19.4 | | 23.7 | | 28.7 | | 30.0 | | |
| Dry Density (kg/m ³) | 1250 | | 1308 | | 1382 | | 1345 | | 1250 | | |

Compaction curve

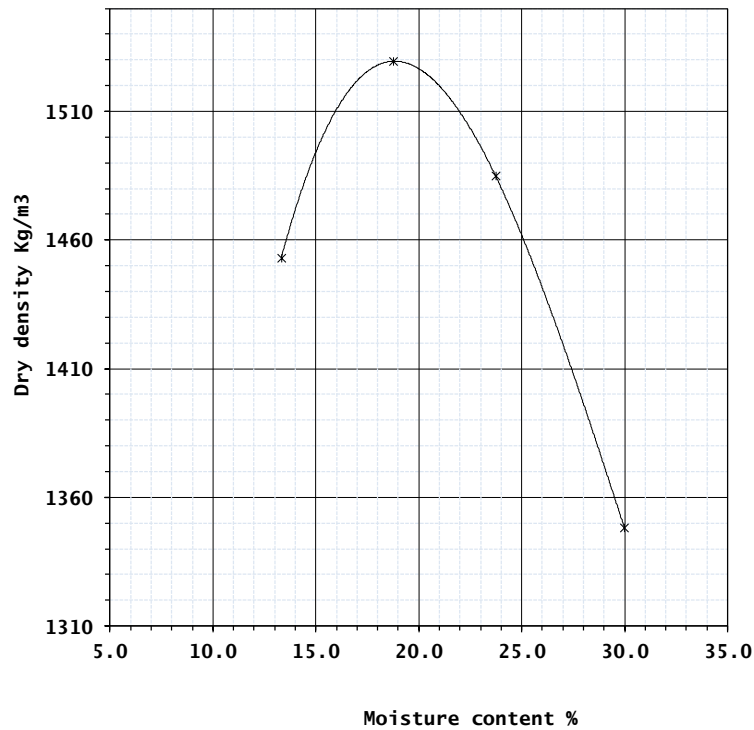


| | | |
|-----|------|-------------------|
| 30 | | Units |
| OMC | 26.0 | % |
| MDD | 1405 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| | | | | | | | | |
|----------------------------------|----------------------|-----------------|----------------------|----------|----------------|-------------------------|----------|------|
| Sample No. : | 29 | | Borehole No.: | | Depth.: | | | |
| Compaction Method: | West Africa Standard | | | | | | | |
| Mould | Hammer | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | |
| Volume: | 944 | cm ³ | | | | | | |
| Test number | | | 1 | 2 | 3 | 4 | 5 | |
| Mass of Mould (g) | | | 1485 | 1485 | 1485 | 1485 | | |
| Mass of Mould+Compacted Soil (g) | | | 3040 | 3200 | 3220 | 3140 | | |
| Mass of Compacted Soil (g) | | | 1555 | 1715 | 1735 | 1655 | | |
| Wet Density (kg/m ³) | | | 1647 | 1816 | 1837 | 1752 | | |
| Mass of can (g) | 10.8 | 11.8 | 7.9 | 7.9 | 9.9 | 9.9 | 9.3 | 8.8 |
| Mass of can+wet soil (g) | 33.7 | 33.2 | 58.6 | 58.6 | 49.0 | 49.0 | 64.6 | 63.6 |
| Mass of can+dry soil (g) | 31.1 | 30.6 | 50.6 | 50.6 | 41.5 | 41.5 | 51.6 | 51.2 |
| Mass of moisture (g) | 2.6 | 2.6 | 8.0 | 8.0 | 7.5 | 7.5 | 13.0 | 12.4 |
| Mass of dry soil (g) | 20.3 | 18.8 | 42.7 | 42.7 | 31.6 | 31.6 | 42.3 | 42.4 |
| Moisture content,% | 12.8 | 13.8 | 18.7 | 18.7 | 23.7 | 23.7 | 30.7 | 29.2 |
| Average moisture content,% | 13.3 | | 18.7 | | 23.7 | | 30.0 | |
| Dry Density (kg/m ³) | 1453 | | 1529 | | 1485 | | 1348 | |

Compaction curve

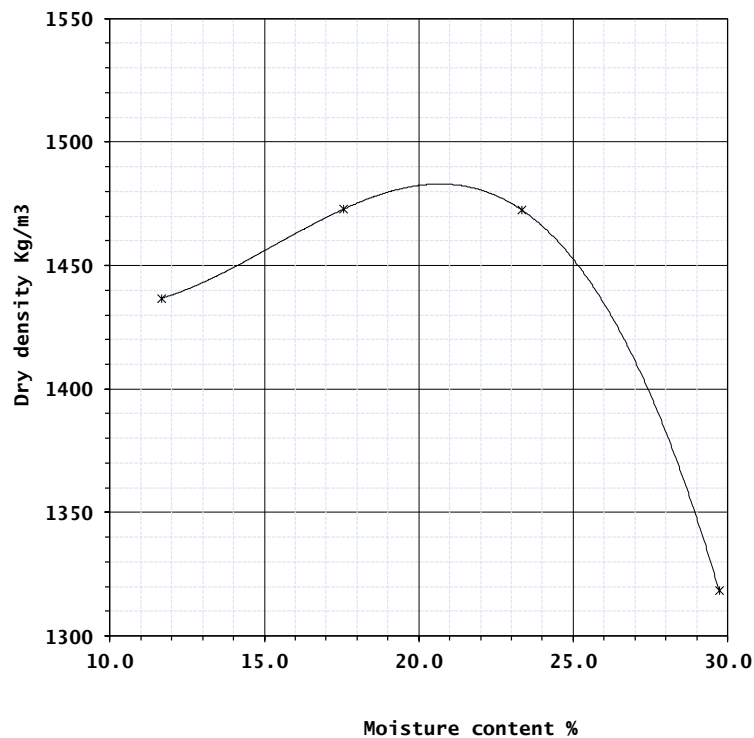


| | | |
|-----|------|-------------------|
| | 29 | Units |
| OMC | 23.7 | % |
| MDD | 1529 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| | | | | | | | | |
|----------------------------------|----------------------|-----------------|----------------------|----------|----------|-------------------------|------|------|
| Sample No. : | SUN28 | | Borehole No.: | | | Depth.: | | |
| Compaction Method: | West Africa Standard | | | | | | | |
| Mould | Hammer | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | |
| Volume: | 944 | cm ³ | | | | | | |
| Test number | | | 1 | 2 | 3 | 4 | | |
| Mass of Mould (g) | | | 1485 | 1485 | 1485 | 1485 | | |
| Mass of Mould+Compacted Soil (g) | | | 3000 | 3120 | 3200 | 3100 | | |
| Mass of Compacted Soil (g) | | | 1515 | 1635 | 1715 | 1615 | | |
| Wet Density (kg/m ³) | | | 1604 | 1731 | 1816 | 1710 | | |
| Mass of can (g) | 32.5 | 5.9 | 50.8 | 52.2 | 50.7 | 19.5 | 25.0 | 25.4 |
| Mass of can+wet soil (g) | 62.5 | 25.8 | 84.4 | 88.9 | 89.2 | 56.6 | 80.8 | 76.0 |
| Mass of can+dry soil (g) | 59.4 | 23.7 | 79.4 | 83.4 | 81.9 | 49.6 | 67.8 | 64.6 |
| Mass of moisture (g) | 3.1 | 2.1 | 5.0 | 5.5 | 7.3 | 7.0 | 13.0 | 11.4 |
| Mass of dry soil (g) | 26.9 | 17.8 | 28.6 | 31.2 | 31.2 | 30.1 | 42.8 | 39.2 |
| Moisture content,% | 11.5 | 11.8 | 17.5 | 17.6 | 23.4 | 23.3 | 30.4 | 29.1 |
| Average moisture content,% | 11.7 | | 17.6 | | 23.3 | | 29.7 | |
| Dry Density (kg/m ³) | 1437 | | 1473 | | 1473 | | 1318 | |

Compaction curve

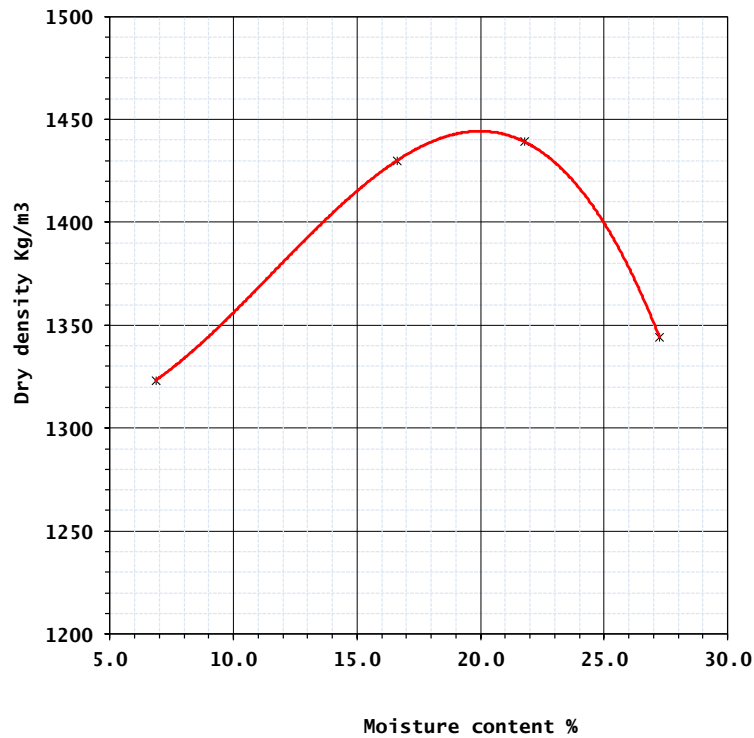


| SUN28 | | Units |
|-------|------|-------------------|
| OMC | 21.0 | % |
| MDD | 1483 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| | | | | | | | | |
|----------------------------------|----------------------|-----------------|----------------------|----------|----------------|-------------------------|----------|-------|
| Sample No. : | SUN31 | | Borehole No.: | | Depth.: | | | |
| Compaction Method: | West Africa Standard | | | | | | | |
| Mould | Hammer | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | |
| Volume: | 944 | cm ³ | | | | | | |
| Test number | | | 1 | 2 | 3 | 4 | 5 | |
| Mass of Mould (g) | | | 1485 | 1485 | 1485 | 1485 | | |
| Mass of Mould+Compacted Soil (g) | | | 2820 | 3060 | 3140 | 3100 | | |
| Mass of Compacted Soil (g) | | | 1335 | 1575 | 1655 | 1615 | 0 | |
| Wet Density (kg/m ³) | | | 1414 | 1668 | 1752 | 1710 | 0 | |
| Mass of can (g) | 6.6 | 6.6 | 50.9 | 50.9 | 22.4 | 22.4 | 32.4 | 32.4 |
| Mass of can+wet soil (g) | 64.4 | 64.4 | 96.5 | 96.5 | 88.4 | 88.4 | 125.8 | 125.8 |
| Mass of can+dry soil (g) | 60.7 | 60.7 | 90.0 | 90.0 | 76.6 | 76.6 | 105.8 | 105.8 |
| Mass of moisture (g) | 3.7 | 3.7 | 6.5 | 6.5 | 11.8 | 11.8 | 20.0 | 20.0 |
| Mass of dry soil (g) | 54.1 | 54.1 | 39.1 | 39.1 | 54.2 | 54.2 | 73.4 | 73.4 |
| Moisture content,% | 6.8 | 6.8 | 16.6 | 16.6 | 21.8 | 21.8 | 27.2 | 27.2 |
| Average moisture content,% | 6.8 | | 16.6 | | 21.8 | | 27.2 | |
| Dry Density (kg/m ³) | 1323 | | 1430 | | 1439 | | 1344 | |

Compaction curve

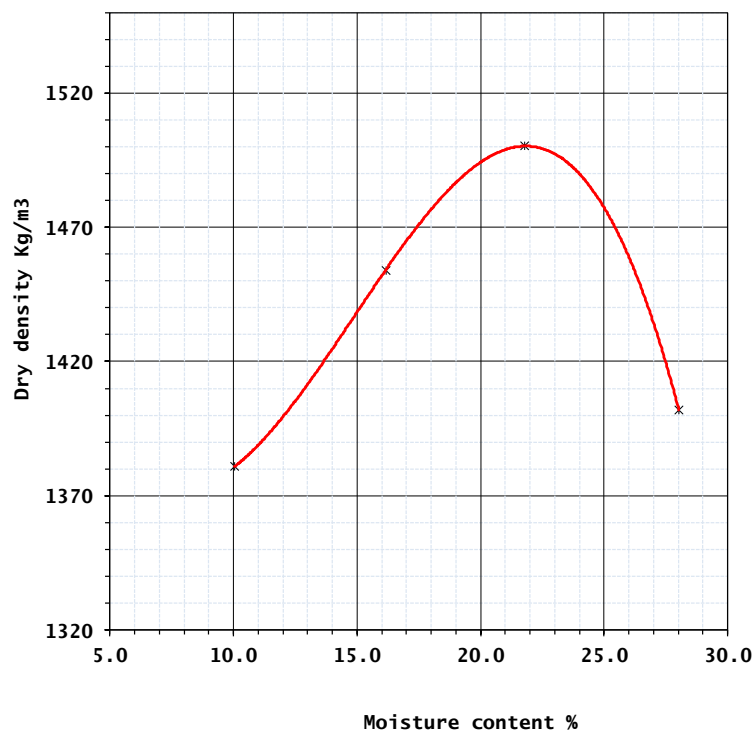


| SUN31 | | Units |
|-------|------|-------------------|
| OMC | 20.0 | % |
| MDD | 1445 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| | | | | | | | | | | | |
|----------------------------------|-----------|----------------------|----------------------|--------|----------|-------------------------|----------------|------|----------|-------|----------|
| Sample No. : | P1 | SUN32 | Borehole No.: | | | | Depth.: | | | | |
| Compaction Method: | | West Africa Standard | | | | | | | | | |
| Mould | Hammer | | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | | | | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | | | | |
| Volume: | 944 | cm ³ | | | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 4 | | 5 |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | 1485 | | |
| Mass of Mould+Compacted Soil (g) | | | 2920 | | 3080 | | 3210 | | 3180 | | |
| Mass of Compacted Soil (g) | | | 1435 | | 1595 | | 1725 | | 1695 | | 0 |
| Wet Density (kg/m ³) | | | 1520 | | 1689 | | 1827 | | 1795 | | 0 |
| Mass of can (g) | | | 8.2 | 8.2 | 6.1 | 6.1 | 8.5 | 8.5 | 23.1 | 23.1 | |
| Mass of can+wet soil (g) | | | 60.8 | 60.8 | 62.9 | 62.9 | 66.7 | 66.7 | 100.3 | 100.3 | |
| Mass of can+dry soil (g) | | | 56.0 | 56.0 | 55.0 | 55.0 | 56.3 | 56.3 | 83.4 | 83.4 | |
| Mass of moisture (g) | | | 4.8 | 4.8 | 7.9 | 7.9 | 10.4 | 10.4 | 16.9 | 16.9 | |
| Mass of dry soil (g) | | | 47.8 | 47.8 | 48.9 | 48.9 | 47.8 | 47.8 | 60.3 | 60.3 | |
| Moisture content,% | | | 10.0 | 10.0 | 16.2 | 16.2 | 21.8 | 21.8 | 28.0 | 28.0 | |
| Average moisture content,% | | | 10.0 | | 16.2 | | 21.8 | | 28.0 | | |
| Dry Density (kg/m ³) | | | 1381 | | 1454 | | 1500 | | 1402 | | |

Compaction curve

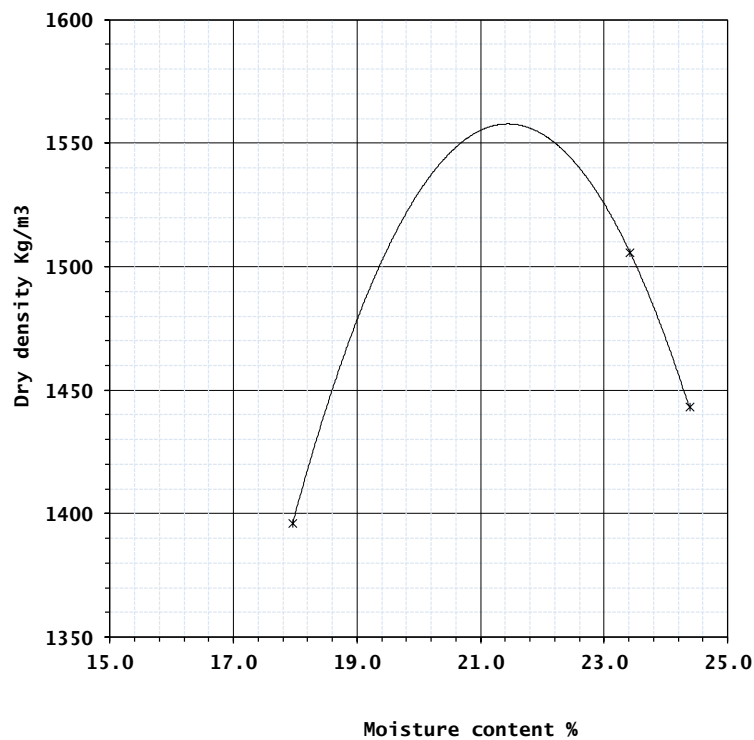


| SUN32 | | Units |
|-------|------|-------------------|
| OMC | 22.0 | % |
| MDD | 1500 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | | | |
|----------------------------------|--------|-----------------|-----------------|---------------|-------|-------------------------|------|---------|-------|-------|------|--|
| Sample No. : | | SUN34 | | Borehole No.: | | | | Depth.: | | | | |
| Compaction Method: | | | | | | | | | | | | |
| Mould | | Hammer | | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | | 3 | | | | |
| Height: | 11.643 | cm | weight: | 2.5 | kg | No. Of blows per layer: | | 25 | | | | |
| Volume: | 944 | cm ³ | | | | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 4 | | 5 | |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | 1485 | | 1485 | |
| Mass of Mould+Compacted Soil (g) | | | 2890 | | 2890 | | 3040 | | 3240 | | 3180 | |
| Mass of Compacted Soil (g) | | | 1405 | | 1405 | | 1555 | | 1755 | | 1695 | |
| Wet Density (kg/m ³) | | | 1488 | | 1488 | | 1647 | | 1858 | | 1795 | |
| Mass of can (g) | 12.3 | 12.3 | 12.3 | 12.3 | 6.4 | 6.4 | 7.3 | 7.3 | 6.6 | 6.6 | | |
| Mass of can+wet soil (g) | 70.3 | 70.3 | 70.3 | 70.3 | 101.0 | 101.0 | 87.4 | 87.4 | 121.8 | 121.8 | | |
| Mass of can+dry soil (g) | 64.0 | 64.0 | 64.0 | 64.0 | 86.6 | 86.6 | 72.2 | 72.2 | 95.2 | 95.2 | | |
| Mass of moisture (g) | 6.3 | 6.3 | 6.3 | 6.3 | 14.4 | 14.4 | 15.2 | 15.2 | 26.6 | 26.6 | | |
| Mass of dry soil (g) | 51.7 | 51.7 | 51.7 | 51.7 | 80.2 | 80.2 | 64.9 | 64.9 | 88.6 | 88.6 | | |
| Moisture content, % | 12.2 | 12.2 | 12.2 | 12.2 | 18.0 | 18.0 | 23.4 | 23.4 | 30.0 | 30.0 | | |
| Average moisture content, % | | | | | 18.0 | | 23.4 | | 24.4 | | | |
| Dry Density (kg/m ³) | | | | | 1396 | | 1506 | | 1443 | | | |

Compaction curve

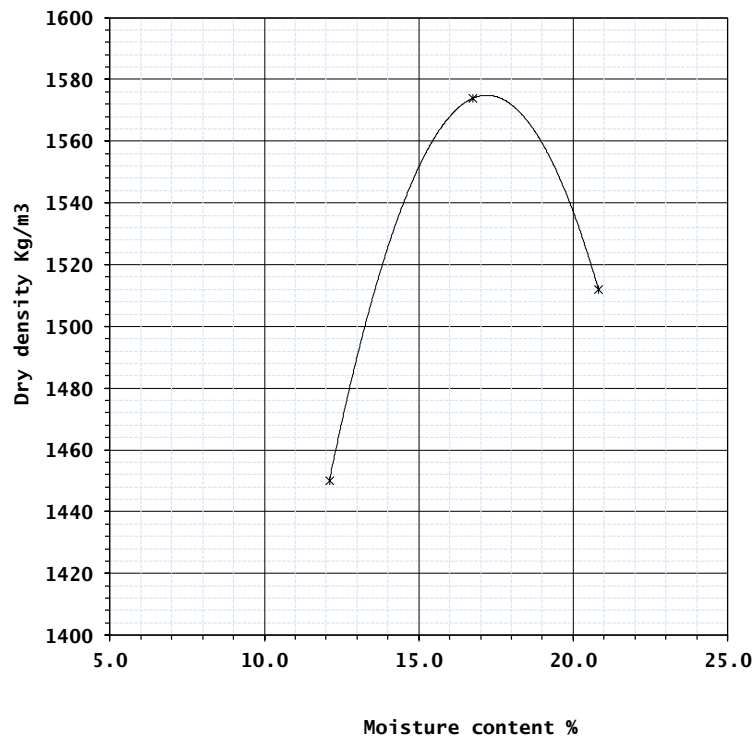


| SUN34 | | Units |
|-------|------|-------------------|
| OMC | 22.0 | % |
| MDD | 1558 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | |
|----------------------------------|--------|-----------------|-----------------|---------------|------|-------------------------|------|---------|---|--|
| Sample No. : | | SUN35 | | Borehole No.: | | | | Depth.: | | |
| Compaction Method: | | | | | | | | | | |
| Mould | | Hammer | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | | 3 | | |
| Height: | 11.643 | cm | weight: | 2.5 | kg | No. Of blows per layer: | | 25 | | |
| Volume: | 944 | cm ³ | | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 5 | |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | | |
| Mass of Mould+Compacted Soil (g) | | | 3020 | | 3220 | | 3210 | | | |
| Mass of Compacted Soil (g) | | | 1535 | | 1735 | | 1725 | | | |
| Wet Density (kg/m ³) | | | 1625 | | 1837 | | 1827 | | | |
| Mass of can (g) | | | 51.5 | 51.5 | 7.8 | 7.8 | 7.9 | 7.9 | | |
| Mass of can+wet soil (g) | | | 135.8 | 135.8 | 65.7 | 65.7 | 87.4 | 87.4 | | |
| Mass of can+dry soil (g) | | | 126.7 | 126.7 | 57.4 | 57.4 | 73.7 | 73.7 | | |
| Mass of moisture (g) | | | 9.1 | 9.1 | 8.3 | 8.3 | 13.7 | 13.7 | | |
| Mass of dry soil (g) | | | 75.2 | 75.2 | 49.6 | 49.6 | 65.8 | 65.8 | | |
| Moisture content,% | | | 12.1 | 12.1 | 16.7 | 16.7 | 20.8 | 20.8 | | |
| Average moisture content,% | | | 12.1 | | 16.7 | | 20.8 | | | |
| Dry Density (kg/m ³) | | | 1450 | | 1574 | | 1512 | | | |

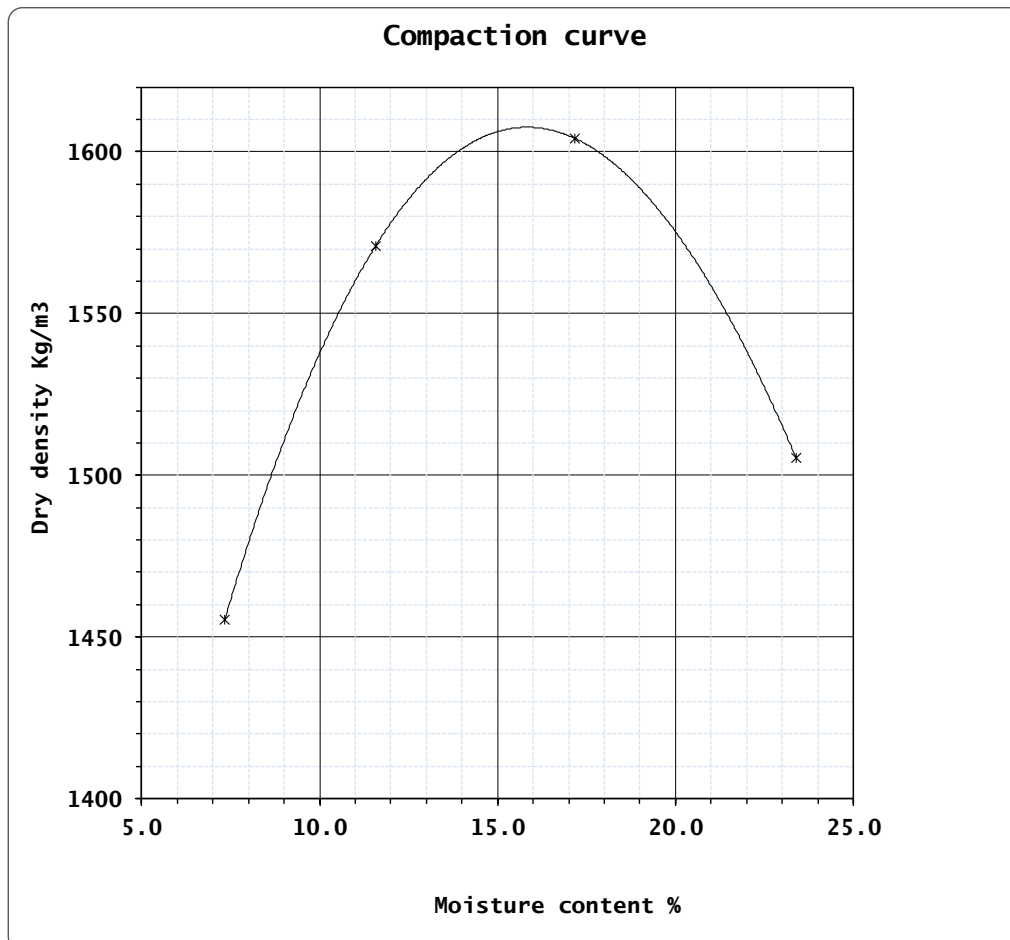
Compaction curve



| SUN35 | | Units |
|-------|------|-------------------|
| OMC | 17.5 | % |
| MDD | 1579 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | |
|----------------------------------|--------|-----------------|-----------------|-------|------|-------------------------|------|---------|------|--|
| Sample No. : | | SUN36 | | | | Borehole No.: | | Depth.: | | |
| Compaction Method: | | | | | | | | | | |
| Mould | | Hammer | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | | 3 | | |
| Height: | 11.643 | cm | weight: | 2.5 | kg | No. Of blows per layer: | | 25 | | |
| Volume: | 944 | cm ³ | | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 4 | |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | 1486 | |
| Mass of Mould+Compacted Soil (g) | | | 2960 | | 3140 | | 3260 | | 3240 | |
| Mass of Compacted Soil (g) | | | 1475 | | 1655 | | 1775 | | 1754 | |
| Wet Density (kg/m ³) | | | 1562 | | 1752 | | 1880 | | 1857 | |
| Mass of can (g) | 23.6 | 23.6 | 7.8 | 7.8 | 6.8 | 6.8 | 8.7 | 8.7 | | |
| Mass of can+wet soil (g) | 105.6 | 105.6 | 67.6 | 67.6 | 88.7 | 88.7 | 89.4 | 89.4 | | |
| Mass of can+dry soil (g) | 100.0 | 100.0 | 61.4 | 61.4 | 76.7 | 76.7 | 74.1 | 74.1 | | |
| Mass of moisture (g) | 5.6 | 5.6 | 6.2 | 6.2 | 12.0 | 12.0 | 15.3 | 15.3 | | |
| Mass of dry soil (g) | 76.4 | 76.4 | 53.6 | 53.6 | 69.9 | 69.9 | 65.4 | 65.4 | | |
| Moisture content,% | 7.3 | 7.3 | 11.6 | 11.6 | 17.2 | 17.2 | 23.4 | 23.4 | | |
| Average moisture content,% | 7.3 | | 11.6 | | 17.2 | | 23.4 | | | |
| Dry Density (kg/m ³) | 1455 | | 1571 | | 1604 | | 1505 | | | |

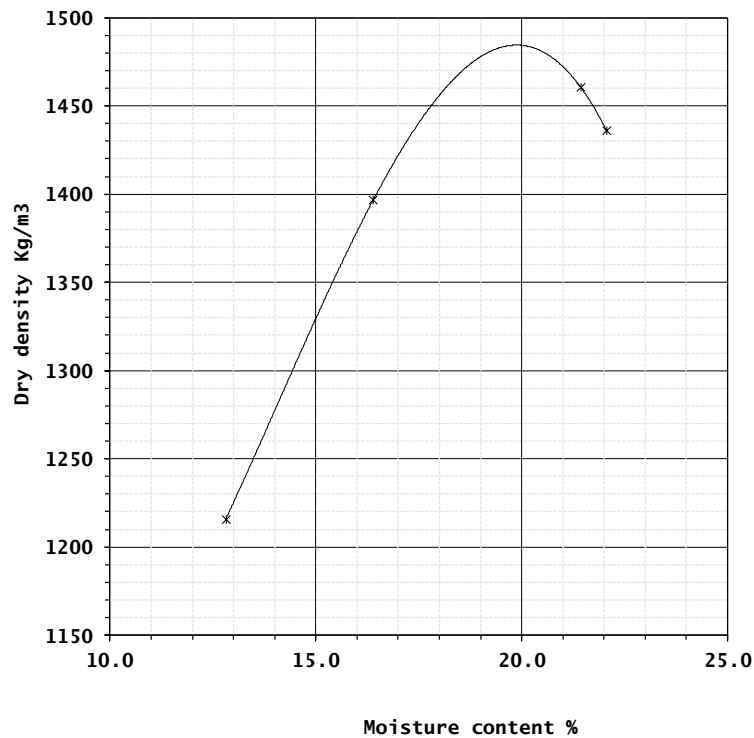


| SUN36 | | Units |
|-------|------|-------------------|
| OMC | 16.0 | % |
| MDD | 1608 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | |
|----------------------------------|--------|-----------------|-----------------|---------------|------|-------------------------|-------|---------|---|
| Sample No. : | | SUN37 | | Borehole No.: | | | | Depth.: | |
| Compaction Method: | | | | | | | | | |
| Mould | | Hammer | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | | |
| Volume: | 944 | cm ³ | | | | | | | |
| Test number | 1 | | 2 | | 3 | | 4 | | 5 |
| Mass of Mould (g) | 1485 | | 1485 | | 1485 | | 1485 | | |
| Mass of Mould+Compacted Soil (g) | 2780 | | 3020 | | 3160 | | 3140 | | |
| Mass of Compacted Soil (g) | 1295 | | 1535 | | 1675 | | 1655 | | |
| Wet Density (kg/m ³) | 1371 | | 1625 | | 1774 | | 1752 | | |
| Mass of can (g) | 8.1 | 8.1 | 7.4 | 7.4 | 7.3 | 7.3 | 8.2 | 8.2 | |
| Mass of can+wet soil (g) | 76.8 | 76.8 | 70.6 | 70.6 | 94.0 | 94.0 | 110.0 | 110.0 | |
| Mass of can+dry soil (g) | 69.0 | 69.0 | 61.7 | 61.7 | 78.7 | 78.7 | 91.6 | 91.6 | |
| Mass of moisture (g) | 7.8 | 7.8 | 8.9 | 8.9 | 15.3 | 15.3 | 18.4 | 18.4 | |
| Mass of dry soil (g) | 60.9 | 60.9 | 54.3 | 54.3 | 71.4 | 71.4 | 83.4 | 83.4 | |
| Moisture content,% | 12.8 | 12.8 | 16.4 | 16.4 | 21.4 | 21.4 | 22.1 | 22.1 | |
| Average moisture content,% | 12.8 | | 16.4 | | 21.4 | | 22.1 | | |
| Dry Density (kg/m ³) | 1216 | | 1397 | | 1461 | | 1436 | | |

Compaction curve

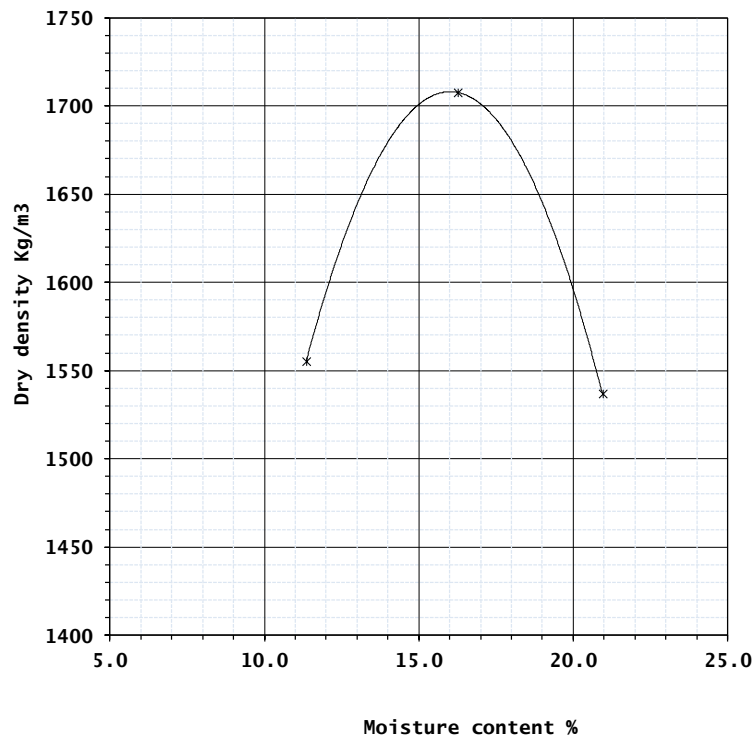


| SUN37 | | Units |
|-------|------|-------------------|
| OMC | 20.0 | % |
| MDD | 1482 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | |
|----------------------------------|--------|-----------------|-----------------|---------------|-------|-------------------------|-------|---------|---|
| Sample No. : | | 38 | | Borehole No.: | | | | Depth.: | |
| Compaction Method: | | | | | | | | | |
| Mould | | Hammer | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | 3 | | |
| Height: | 11.643 | cm | weight: | 2.5 kg | | No. Of blows per layer: | 25 | | |
| Volume: | 944 | cm ³ | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 5 |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | |
| Mass of Mould+Compacted Soil (g) | | | 3120 | | 3360 | | 3240 | | |
| Mass of Compacted Soil (g) | | | 1635 | | 1875 | | 1755 | | |
| Wet Density (kg/m ³) | | | 1731 | | 1985 | | 1858 | | |
| Mass of can (g) | | | 7.4 | 7.4 | 23.8 | 23.8 | 7.9 | 7.9 | |
| Mass of can+wet soil (g) | | | 70.2 | 70.2 | 113.1 | 113.1 | 110.1 | 110.1 | |
| Mass of can+dry soil (g) | | | 63.8 | 63.8 | 100.6 | 100.6 | 92.4 | 92.4 | |
| Mass of moisture (g) | | | 6.4 | 6.4 | 12.5 | 12.5 | 17.7 | 17.7 | |
| Mass of dry soil (g) | | | 56.4 | 56.4 | 76.8 | 76.8 | 84.5 | 84.5 | |
| Moisture content,% | | | 11.3 | 11.3 | 16.3 | 16.3 | 20.9 | 20.9 | |
| Average moisture content,% | | | 11.3 | | 16.3 | | 20.9 | | |
| Dry Density (kg/m ³) | | | 1555 | | 1708 | | 1537 | | |

Compaction curve

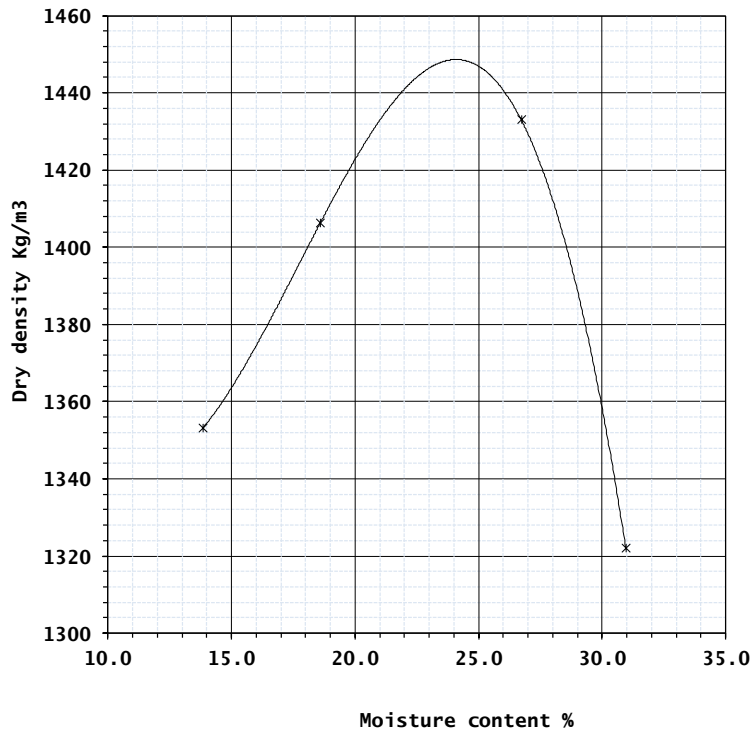


| 38 | | Units |
|-----|------|-------------------|
| OMC | 17.5 | % |
| MDD | 1579 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

| Compaction Test | | | | | | | | | | | |
|----------------------------------|--------|-----------------|-----------------|---------------|-------|-------------------------|------|---------|------|--|---|
| Sample No. : | | SUN40 | | Borehole No.: | | | | Depth.: | | | |
| Compaction Method: | | | | | | | | | | | |
| Mould | | Hammer | | | | | | | | | |
| Diameter: | 10.16 | cm | height of drop: | 30.55 | cm | No. Of layers: | | 3 | | | |
| Height: | 11.643 | cm | weight: | 2.5 | kg | No. Of blows per layer: | | 25 | | | |
| Volume: | 944 | cm ³ | | | | | | | | | |
| Test number | | | 1 | | 2 | | 3 | | 4 | | 5 |
| Mass of Mould (g) | | | 1485 | | 1485 | | 1485 | | 1485 | | |
| Mass of Mould+Compacted Soil (g) | | | 2940 | | 3060 | | 3200 | | 3120 | | |
| Mass of Compacted Soil (g) | | | 1455 | | 1575 | | 1715 | | 1635 | | |
| Wet Density (kg/m ³) | | | 1541 | | 1668 | | 1816 | | 1731 | | |
| Mass of can (g) | 19.5 | 25.1 | 19.4 | 25.5 | 51.3 | 23.5 | 19.1 | 23.0 | | | |
| Mass of can+wet soil (g) | 55.0 | 56.3 | 61.3 | 75.6 | 113.7 | 86.3 | 97.2 | 66.9 | | | |
| Mass of can+dry soil (g) | 50.8 | 52.4 | 54.2 | 68.4 | 100.5 | 73.1 | 78.6 | 56.6 | | | |
| Mass of moisture (g) | 4.2 | 3.9 | 7.1 | 7.2 | 13.2 | 13.2 | 18.6 | 10.3 | | | |
| Mass of dry soil (g) | 31.3 | 27.3 | 34.8 | 42.9 | 49.2 | 49.6 | 59.5 | 33.6 | | | |
| Moisture content,% | 13.4 | 14.3 | 20.4 | 16.8 | 26.8 | 26.6 | 31.3 | 30.7 | | | |
| Average moisture content,% | | | 13.9 | | 18.6 | | 26.7 | | 31.0 | | |
| Dry Density (kg/m ³) | | | 1353 | | 1406 | | 1433 | | 1322 | | |

Compaction curve



| SUN40 | | Units |
|-------|------|-------------------|
| OMC | 24.0 | % |
| MDD | 1449 | kg/m ³ |

OMC = Optimum moisture content
MDD = Maximum dry density

Appendix 8. Coefficient of permeability

| COEFFICIENT OF PERMEABILITY (Falling Head) | | | | | | | | | | | |
|---|--------------------|--------------------|------|-----------------------------------|------------------------------------|-----------------------|----------|-----------------------|--------------------|------------------------|-------|
| Project: | | | | Sample No.: | | | | SUN1 | | | |
| Soil Description : | | | | | | | | | | | |
| Tested by: | | | | Date : | | | | 11/18/2023 | | | |
| Sample Dimensions: | | Diam. 6.2 cm; | | Area,A | | 30.20 cm ² | | Vol. | | 120.81 cm ³ | |
| | | | | Ht.L | | 4.0 cm | | | | | |
| Standpipe = | | Burette (50 ml) | | Diam. 1.06 cm | | Area,a | | 0.883 cm ² | | | |
| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
| 1 | 83.4 | 82.6 | 1080 | | 0.71 | 26 | 1 | 83.4 | 82.6 | 1080 | 26 |
| 2 | 82.6 | 82.3 | 486 | | 0.26 | 26 | 2 | 82.6 | 82.3 | 486 | 26 |
| 3 | 82.3 | 81.9 | 520 | | 0.35 | 26 | 3 | 82.3 | 81.9 | 520 | 26 |
| 4 | 81.9 | 81.4 | 660 | | 0.44 | 26 | 4 | 81.9 | 81.4 | 660 | 26 |
| Average | | | | | | | | 82.55 | 82.05 | 686.5 | 26 |
| <div style="display: flex; justify-content: space-between; margin-bottom: 10px;"> $\alpha = \eta_T / \eta_{20} =$ 0.8642 </div> <div style="display: flex; justify-content: space-between; margin-bottom: 10px;"> $k_T = (aL/At) \ln (h_1/h_2) =$ 1.03E-06 = 0.0000010347 cm/s </div> <div style="display: flex; justify-content: space-between;"> $k_{20} = \alpha k_T =$ 8.94E-07 = 0.0000008942 cm/s </div> | | | | | | | | | | | |
| Degree of Permeability: <u>Very low</u> (Soil testing for Engineerers by T. William Lambe, 1951) | | | | | | | | | | | |

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN2
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023
 Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 82.7 | 79.9 | 7176 | | 2.47 | 28 | 1 | 82.7 | 79.9 | 7176 | 28 |
| 2 | 82.7 | 79.9 | 7176 | | 2.47 | 28 | 2 | 82.7 | 79.9 | 7176 | 28 |
| 3 | 82.7 | 79.9 | 7176 | | 2.47 | 28 | 3 | 82.7 | 79.9 | 7176 | 28 |
| 4 | 82.7 | 79.9 | 7176 | | 2.47 | 28 | 4 | 82.7 | 79.9 | 7176 | 28 |
| Average | | | | | | | | 82.7 | 79.9 | 7176 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 5.61E-07 = 0.0000005612 \text{ cm/s}$

$k_{20} = \alpha k_T = 4.65E-07 = 0.0000004651 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN9
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023
 Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm
 Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 84.8 | 82.9 | 4612 | | 1.68 | 28 | 1 | 84.8 | 82.9 | 4612 | 28 |
| 2 | 82.9 | 81 | 4612 | | 1.68 | 28 | 2 | 82.9 | 81 | 4612 | 28 |
| 3 | 81 | 79.1 | 4612 | | 1.68 | 28 | 3 | 81 | 79.1 | 4612 | 28 |
| 4 | 79.1-77.2 | 75 | 4612 | | #VALUE! | 28 | 4 | 79.1-77.2 | 75 | 4612 | 28 |
| Average | | | | | | | | 82.9 | 79.5 | 4612 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 1.06E-06 = 0.0000010617 \text{ cm/s}$

$k_{20} = \alpha k_T = 8.80E-07 = 0.0000008798 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project:

Sample No.: SUN3

Soil Description :

Tested by:

Date : 11/18/2023

Sample Dimensions: Diam. 6.2 cm;

Area,A 30.20 cm²

Vol. 120.81 cm³

Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 84.8 | 83.7 | 9935 | | 0.97 | 28 | 1 | 84.8 | 83.7 | 9935 | 28 |
| 2 | 84.8 | 83.7 | 9935 | | 0.97 | 28 | 2 | 84.8 | 83.7 | 9935 | 28 |
| 3 | 84.8 | 83.7 | 9935 | | 0.97 | 28 | 3 | 84.8 | 83.7 | 9935 | 28 |
| 4 | 84.8 | 83.7 | 9935 | | 0.97 | 28 | 4 | 84.8 | 83.7 | 9935 | 28 |
| Average | | | | | | | | 84.8 | 83.7 | 9935 | 28 |

$$\alpha = \eta_T / \eta_{20} = 0.8287$$

$$k_T = (aL/At) \ln (h_1/h_2) = 1.54E-07 = 0.0000001537 \text{ cm/s}$$

$$k_{20} = \alpha k_T = 1.27E-07 = 0.0000001273 \text{ cm/s}$$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN11
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023
 Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm
 Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 83.5 | 82.5 | 5515 | | 0.88 | 28 | 1 | 83.5 | 82.5 | 5515 | 28 |
| 2 | 82.5 | 81.5 | 7315 | | 0.88 | 28 | 2 | 82.5 | 81.5 | 7315 | 28 |
| 3 | 81.5 | 80.5 | 7125 | | 0.88 | 28 | 3 | 81.5 | 80.5 | 7125 | 28 |
| 4 | 81.5 | 80.5 | 7125 | | 0.88 | 28 | 4 | 81.5 | 80.5 | 7125 | 28 |
| Average | | | | | | | | 82.25 | 81.25 | 6770 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 2.11E-07 = 0.0000002113 \text{ cm/s}$

$k_{20} = \alpha k_T = 1.75E-07 = 0.0000001751 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN5

Soil Description :

Tested by: _____ Date : 11/18/2023

Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²

Vol. 120.81 cm³

Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 84.5 | 79.5 | 1860 | | 4.41 | 28 | 1 | 84.5 | 79.5 | 1860 | 28 |
| 2 | 79.5 | 74.5 | 1860 | | 4.41 | 28 | 2 | 79.5 | 74.5 | 1860 | 28 |
| 3 | 74.5 | 69.5 | 1860 | | 4.41 | 28 | 3 | 74.5 | 69.5 | 1860 | 28 |
| 4 | 74.5 | 69.5 | 1860 | | 4.41 | 28 | 4 | 74.5 | 69.5 | 1860 | 28 |
| Average | | | | | | | | 78.25 | 73.25 | 1860 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 4.15E-06 = 0.0000041507 \text{ cm/s}$

$k_{20} = \alpha k_T = 3.44E-06 = 0.0000034396 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN6
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023

Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 84.5 | 83.3 | 1800 | | 1.06 | 26 | 1 | 84.5 | 83.3 | 1800 | 26 |
| 2 | 83.3 | 82.3 | 1800 | | 0.88 | 26 | 2 | 83.3 | 82.3 | 1800 | 26 |
| 3 | 84.5 | 83.3 | 1800 | | 1.06 | 26 | 3 | 84.5 | 83.3 | 1800 | 26 |
| 4 | 83.3 | 82.3 | 1800 | | 0.88 | 26 | 4 | 83.3 | 82.3 | 1800 | 26 |
| Average | | | | | | | | 83.9 | 82.8 | 1800 | 26 |

$\alpha = \eta_T / \eta_{20} = 0.8642$

$k_T = (aL/At) \ln (h_1/h_2) = 8.57E-07 = 0.0000008573 \text{ cm/s}$

$k_{20} = \alpha k_T = 7.41E-07 = 0.0000007409 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN11

Soil Description :

Tested by: _____ Date : 11/18/2023

Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²

Vol. 120.81 cm³

Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 84.4 | 83.3 | 1895 | | 0.97 | 28 | 1 | 84.4 | 83.3 | 1895 | 28 |
| 2 | 84.4 | 83.3 | 1895 | | 0.97 | 28 | 2 | 84.4 | 83.3 | 1895 | 28 |
| 3 | 84.4 | 83.3 | 1895 | | 0.97 | 28 | 3 | 84.4 | 83.3 | 1895 | 28 |
| 4 | 84.4 | 83.3 | 1895 | | 0.97 | 28 | 4 | 84.4 | 83.3 | 1895 | 28 |
| Average | | | | | | | | 84.4 | 83.3 | 1895 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 8.09E-07 = 0.0000008094 \text{ cm/s}$

$k_{20} = \alpha k_T = 6.71E-07 = 0.0000006708 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: Sample No.: SUN7
 Soil Description :
 Tested by: Date : 11/18/2023
 Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
Vol. 120.81 cm³
Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 84.5 | 83.4 | 1800 | | 0.97 | 28 | 1 | 84.5 | 83.4 | 1800 | 28 |
| 2 | 83.4 | 82.5 | 1800 | | 0.79 | 28 | 2 | 83.4 | 82.5 | 1800 | 28 |
| 3 | 82.5 | 81.3 | 1920 | | 1.06 | 28 | 3 | 82.5 | 81.3 | 1920 | 28 |
| 4 | 84.3 | 83.4 | 1800 | | 0.79 | 28 | 4 | 84.3 | 83.4 | 1800 | 28 |
| Average | | | | | | | | 83.675 | 82.65 | 1830 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 7.87E-07 = 0.0000007875 \text{ cm/s}$

$k_{20} = \alpha k_T = 6.53E-07 = 0.0000006526 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN2
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023
 Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 80.3 | 79.5 | 6068 | | 0.71 | 26 | 1 | 80.3 | 79.5 | 6068 | 26 |
| 2 | 80.3 | 79.5 | 6068 | | 0.71 | 26 | 2 | 80.3 | 79.5 | 6068 | 26 |
| 3 | 80.3 | 79.5 | 6068 | | 0.71 | 26 | 3 | 80.3 | 79.5 | 6068 | 26 |
| 4 | 80.3 | 79.5 | 6068 | | 0.71 | 26 | 4 | 80.3 | 79.5 | 6068 | 26 |
| | | | | | | | Average | 80.3 | 79.5 | 6068 | 26 |

$\alpha = \eta_T / \eta_{20} = 0.8642$

$k_T = (aL/At) \ln (h_1/h_2) = 1.93E-07 = 0.0000001929 \text{ cm/s}$

$k_{20} = \alpha k_T = 1.67E-07 = 0.0000001667 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN16
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023
 Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 83.4 | 82.6 | 8956 | | 0.71 | 28 | 1 | 83.4 | 82.6 | 8956 | 28 |
| 2 | 83.4 | 82.6 | 8956 | | 0.71 | 28 | 2 | 83.4 | 82.6 | 8956 | 28 |
| 3 | 83.4 | 82.6 | 8956 | | 0.71 | 28 | 3 | 83.4 | 82.6 | 8956 | 28 |
| 4 | 83.4 | 82.6 | 8956 | | 0.71 | 28 | 4 | 83.4 | 82.6 | 8956 | 28 |
| Average | | | | | | | | 83.4 | 82.6 | 8956 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 1.26E-07 = 0.0000001258 \text{ cm/s}$

$k_{20} = \alpha k_T = 1.04E-07 = 0.0000001043 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: **20**

Soil Description : _____

Tested by: _____ Date : 11/18/2023

Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²

Vol. 120.81 cm³

Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 82.4 | 81.7 | 6786 | | 0.62 | 28 | 1 | 82.4 | 81.7 | 6786 | 28 |
| 2 | 81.7 | 81.3 | 7690 | | 0.35 | 28 | 2 | 81.7 | 81.3 | 7690 | 28 |
| 3 | 81.7 | 81.3 | 7690 | | 0.35 | 28 | 3 | 81.7 | 81.3 | 7690 | 28 |
| 4 | 81.7 | 81.3 | 7690 | | 0.35 | 28 | 4 | 81.7 | 81.3 | 7690 | 28 |
| Average | | | | | | | | 81.875 | 81.4 | 7464 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 9.11E-08 = 0.0000000911 \text{ cm/s}$

$k_{20} = \alpha k_T = 7.55E-08 = 0.0000000755 \text{ cm/s}$

Degree of Permeability: Practically impermeable (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN15
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023
 Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm
 Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 81.3 | 79.5 | 2809 | | 1.59 | 28 | 1 | 81.3 | 79.5 | 2809 | 28 |
| 2 | 81.3 | 79.5 | 2809 | | 1.59 | 28 | 2 | 81.3 | 79.5 | 2809 | 28 |
| 3 | 81.3 | 79.5 | 2809 | | 1.59 | 28 | 3 | 81.3 | 79.5 | 2809 | 28 |
| 4 | 81.3 | 79.5 | 2809 | | 1.59 | 28 | 4 | 81.3 | 79.5 | 2809 | 28 |
| Average | | | | | | | | 81.3 | 79.5 | 2809 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 9.32E-07 = 0.0000009319 \text{ cm/s}$

$k_{20} = \alpha k_T = 7.72E-07 = 0.0000007723 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN19

Soil Description : _____

Tested by: _____ Date : 11/18/2023

Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²

Vol. 120.81 cm³

Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 81.6 | 80.8 | 7865 | | 0.71 | 28 | 1 | 81.6 | 80.8 | 7865 | 28 |
| 2 | 81.6 | 80.8 | 7865 | | 0.71 | 28 | 2 | 81.6 | 80.8 | 7865 | 28 |
| 3 | 81.6 | 80.8 | 7865 | | 0.71 | 28 | 3 | 81.6 | 80.8 | 7865 | 28 |
| 4 | 81.6 | 80.8 | 7865 | | 0.71 | 28 | 4 | 81.6 | 80.8 | 7865 | 28 |
| Average | | | | | | | | 81.6 | 80.8 | 7865 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 1.46E-07 = 0.0000001465 \text{ cm/s}$

$k_{20} = \alpha k_T = 1.21E-07 = 0.0000001214 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: 14
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023

Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm
 Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|-------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|-------|-------|
| 1 | 78.6 | 73.1 | 87852 | | 4.86 | 28 | 1 | 78.6 | 73.1 | 87852 | 28 |
| 2 | 78.6 | 73.1 | 87852 | | 4.86 | 28 | 2 | 78.6 | 73.1 | 87852 | 28 |
| 3 | 78.6 | 73.1 | 87852 | | 4.86 | 28 | 3 | 78.6 | 73.1 | 87852 | 28 |
| 4 | 78.6 | 73.1 | 87852 | | 4.86 | 28 | 4 | 78.6 | 73.1 | 87852 | 28 |
| Average | | | | | | | | 78.6 | 73.1 | 87852 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 9.65E-08 = 0.0000000965 \text{ cm/s}$

$k_{20} = \alpha k_T = 8.00E-08 = 0.0000000800 \text{ cm/s}$

Degree of Permeability: Practically impermeable (Soil testing for Engineers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN12
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023
 Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²
 Ht.L 4.0 cm

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 65.4 | 64.7 | 4733 | | 0.62 | 28 | 1 | 65.4 | 64.7 | 4733 | 28 |
| 2 | 65.4 | 64.7 | 4733 | | 0.62 | 28 | 2 | 65.4 | 64.7 | 4733 | 28 |
| 3 | 65.4 | 64.7 | 4733 | | 0.62 | 28 | 3 | 65.4 | 64.7 | 4733 | 28 |
| 4 | 65.4 | 64.7 | 4733 | | 0.62 | 28 | 4 | 65.4 | 64.7 | 4733 | 28 |

| | | | | | | | | | | |
|---------|--|--|--|--|--|--|------|------|------|----|
| Average | | | | | | | 65.4 | 64.7 | 4733 | 28 |
|---------|--|--|--|--|--|--|------|------|------|----|

$\alpha = \eta_T / \eta_{20} = 0.8287$ Temperature = 28 °C

$k_T = (aL/At) \ln (h_1/h_2) = 2.66E-07 = 0.0000002658 \text{ cm/s}$

$k_{20} = \alpha k_T = 2.20E-07 = 0.0000002203 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: 13

Soil Description : _____

Tested by: _____ Date : 11/18/2023

Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|-------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|-------|-------|
| 1 | 84.5 | 79.5 | 85301 | | 4.41 | 26 | 1 | 84.5 | 79.5 | 85301 | 26 |
| 2 | 84.5 | 79.5 | 85301 | | 4.41 | 26 | 2 | 84.5 | 79.5 | 85301 | 26 |
| 3 | 84.5 | 79.5 | 85301 | | 4.41 | 26 | 3 | 84.5 | 79.5 | 85301 | 26 |
| 4 | 84.5 | 79.5 | 85301 | | 4.41 | 26 | 4 | 84.5 | 79.5 | 85301 | 26 |
| Average | | | | | | | | 84.5 | 79.5 | 85301 | 26 |

$\alpha = \eta_T / \eta_{20} = 0.8642$

$k_T = (aL/At) \ln (h_1/h_2) = 8.36E-08 = 0.0000000836 \text{ cm/s}$

$k_{20} = \alpha k_T = 7.23E-08 = 0.0000000723 \text{ cm/s}$

Degree of Permeability: Practically impermeable (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: 10
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023
 Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm
 Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|-------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|-------|-------|
| 1 | 84.4 | 67.8 | 59452 | | 14.65 | 28 | 1 | 84.4 | 67.8 | 59452 | 28 |
| 2 | 84.4 | 67.8 | 59452 | | 14.65 | 28 | 2 | 84.4 | 67.8 | 59452 | 28 |
| 3 | 84.4 | 67.8 | 59452 | | 14.65 | 28 | 3 | 84.4 | 67.8 | 59452 | 28 |
| 4 | 84.4 | 67.8 | 59452 | | 14.65 | 28 | 4 | 84.4 | 67.8 | 59452 | 28 |
| | | | | | | | Average | 84.4 | 67.8 | 59452 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 4.31E-07 = 0.0000004307 \text{ cm/s}$

$k_{20} = \alpha k_T = 3.57E-07 = 0.0000003569 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project:

Sample No.: SUN12

Soil Description :

Tested by:

Date : 11/18/2023

Sample Dimensions: Diam. 6.2 cm;

Area,A 30.20 cm²

Vol. 120.81 cm³

Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|-------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|-------|-------|
| 1 | 82.2 | 80.1 | 15076 | | 1.85 | 28 | 1 | 82.2 | 80.1 | 15076 | 28 |
| 2 | 82.2 | 80.1 | 15076 | | 1.85 | 28 | 2 | 82.2 | 80.1 | 15076 | 28 |
| 3 | 80.1 | 79.3 | 7800 | | 0.71 | 28 | 3 | 80.1 | 79.3 | 7800 | 28 |
| 4 | 80.1 | 70.3 | 7800 | | 8.65 | 28 | 4 | 80.1 | 70.3 | 7800 | 28 |
| | | | | | | | Average | 81.15 | 77.45 | 11438 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 4.77E-07 = 0.0000004770 \text{ cm/s}$

$k_{20} = \alpha k_T = 3.95E-07 = 0.0000003953 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN10
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023
 Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm
 Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|-------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|-------|-------|
| 1 | 83.5 | 78.5 | 53183 | | 4.41 | 28 | 1 | 83.5 | 78.5 | 53183 | 28 |
| 2 | 83.5 | 78.5 | 53183 | | 4.41 | 28 | 2 | 83.5 | 78.5 | 53183 | 28 |
| 3 | 83.5 | 78.5 | 53183 | | 4.41 | 28 | 3 | 83.5 | 78.5 | 53183 | 28 |
| 4 | 83.5 | 78.5 | 53183 | | 4.41 | 28 | 4 | 83.5 | 78.5 | 53183 | 28 |
| Average | | | | | | | | 83.5 | 78.5 | 53183 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$ Temperature = 28 °C

$kT = (aL/At) \ln (h_1/h_2) = 1.36E-07 = 0.0000001357 \text{ cm/s}$

$k_{20} = \alpha k_T = 1.12E-07 = 0.0000001125 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN17
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023
 Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 63.4 | 52.7 | 6068 | | 9.45 | 26 | 1 | 63.4 | 52.7 | 6068 | 26 |
| 2 | 63.4 | 52.7 | 6068 | | 9.45 | 26 | 2 | 63.4 | 52.7 | 6068 | 26 |
| 3 | 63.4 | 52.7 | 6068 | | 9.45 | 26 | 3 | 63.4 | 52.7 | 6068 | 26 |
| 4 | 63.4 | 52.7 | 6068 | | 9.45 | 26 | 4 | 63.4 | 52.7 | 6068 | 26 |
| Average | | | | | | | | 63.4 | 52.7 | 6068 | 26 |

$\alpha = \eta_T / \eta_{20} = 0.8642$

$k_T = (aL/At) \ln (h_1/h_2) = 3.56E-06 = 0.0000035617 \text{ cm/s}$

$k_{20} = \alpha k_T = 3.08E-06 = 0.0000030782 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project:

Sample No.: 22

Soil Description :

Tested by:

Date : 11/18/2023

Sample Dimensions: Diam. 6.2 cm;

Area,A 30.20 cm²

Vol. 120.81 cm³

Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 77.5 | 75.4 | 4250 | | 1.85 | 28 | 1 | 77.5 | 75.4 | 4250 | 28 |
| 2 | 77.5 | 75.4 | 4250 | | 1.85 | 28 | 2 | 77.5 | 75.4 | 4250 | 28 |
| 3 | 77.5 | 75.4 | 4250 | | 1.85 | 28 | 3 | 77.5 | 75.4 | 4250 | 28 |
| 4 | 77.5 | 75.4 | 4250 | | 1.85 | 28 | 4 | 77.5 | 75.4 | 4250 | 28 |
| Average | | | | | | | | 77.5 | 75.4 | 4250 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 7.56E-07 = 0.0000007557 \text{ cm/s}$

$k_{20} = \alpha k_T = 6.26E-07 = 0.0000006263 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: 18
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023
 Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm
 Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 81.7 | 81.2 | 6222 | | 0.44 | 28 | 1 | 81.7 | 81.2 | 6222 | 28 |
| 2 | 81.7 | 81.2 | 6222 | | 0.44 | 28 | 2 | 81.7 | 81.2 | 6222 | 28 |
| 3 | 81.7 | 81.2 | 6222 | | 0.44 | 28 | 3 | 81.7 | 81.2 | 6222 | 28 |
| 4 | 81.7 | 81.2 | 6222 | | 0.44 | 28 | 4 | 81.7 | 81.2 | 6222 | 28 |
| Average | | | | | | | | 81.7 | 81.2 | 6222 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 1.15E-07 = 0.0000001154 \text{ cm/s}$

$k_{20} = \alpha k_T = 9.56E-08 = 0.0000000956 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

| | | |
|--|-------------|------------------------|
| Project: | Sample No.: | SUN23 |
| Soil Description : | Date : | 11/18/2023 |
| Tested by: | Area,A | 30.20 cm ² |
| Sample Dimensions: Diam. 6.2 cm; | Vol. | 120.81 cm ³ |
| | Ht.L | 4.0 cm |
| Standpipe = Burette (50 ml) Diam. 1.06 cm | Area,a | 0.883 cm ² |

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 84.5 | 77.1 | 1165 | | 6.53 | 28 | 1 | 84.5 | 77.1 | 1165 | 28 |
| 2 | 77.1 | 71.5 | 2154 | | 4.94 | 28 | 2 | 77.1 | 71.5 | 2154 | 28 |
| 3 | 71.5 | 64.5 | 3540 | | 6.18 | 28 | 3 | 71.5 | 64.5 | 3540 | 28 |
| 4 | 81.3 | 79.5 | 1165 | | 1.59 | 28 | 4 | 81.3 | 79.5 | 1165 | 28 |
| Average | | | | | | | | 78.6 | 73.15 | 2006 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 4.19E-06 = 0.0000041883 \text{ cm/s}$

$k_{20} = \alpha k_T = 3.47E-06 = 0.0000034708 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN24
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023
 Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm

Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 80.5 | 73.7 | 364 | | 6.00 | 28 | 1 | 80.5 | 73.7 | 364 | 28 |
| 2 | 80.5 | 73.7 | 364 | | 6.00 | 28 | 2 | 80.5 | 73.7 | 364 | 28 |
| 3 | 80.5 | 73.7 | 364 | | 6.00 | 28 | 3 | 80.5 | 73.7 | 364 | 28 |
| 4 | 80.5 | 73.7 | 364 | | 6.00 | 28 | 4 | 80.5 | 73.7 | 364 | 28 |
| Average | | | | | | | | 80.5 | 73.7 | 364 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 2.83E-05 = 0.0000283481 \text{ cm/s}$

$k_{20} = \alpha k_T = 2.35E-05 = 0.0000234917 \text{ cm/s}$

Degree of Permeability: Low (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

| | | |
|--------------------|-----------------|------------------------|
| Project: | Sample No.: | SUN25 |
| Soil Description : | | |
| Tested by: | Date : | 11/18/2023 |
| Sample Dimensions: | Diam. | 6.2 cm; |
| | Area,A | 30.20 cm ² |
| | Vol. | 120.81 cm ³ |
| | Ht.L | 4.0 cm |
| Standpipe = | Burette (50 ml) | Diam. |
| | | 1.06 cm |
| | Area,a | 0.883 cm ² |

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|-------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|-------|-------|
| 1 | 84.5 | 81.9 | 11465 | | 2.30 | 26 | 1 | 84.5 | 81.9 | 11465 | 26 |
| 2 | 84.5 | 81.9 | 11465 | | 2.30 | 26 | 2 | 84.5 | 81.9 | 11465 | 26 |
| 3 | 84.5 | 81.9 | 11465 | | 2.30 | 26 | 3 | 84.5 | 81.9 | 11465 | 26 |
| 4 | 84.5 | 81.9 | 11465 | | 2.30 | 26 | 4 | 84.5 | 81.9 | 11465 | 26 |
| Average | | | | | | | | 84.5 | 81.9 | 11465 | 26 |

$\alpha = \eta_T / \eta_{20} = 0.8642$

$k_T = (aL/At) \ln (h_1/h_2) = 3.19E-07 = 0.0000003187 \text{ cm/s}$

$k_{20} = \alpha k_T = 2.75E-07 = 0.0000002754 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN26
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023

Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm
 Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|-------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|-------|-------|
| 1 | 83.2 | 82.4 | 12087 | | 0.71 | 28 | 1 | 83.2 | 82.4 | 12087 | 28 |
| 2 | 83.2 | 82.4 | 12087 | | 0.71 | 28 | 2 | 83.2 | 82.4 | 12087 | 28 |
| 3 | 83.2 | 82.4 | 12087 | | 0.71 | 28 | 3 | 83.2 | 82.4 | 12087 | 28 |
| 4 | 83.2 | 82.4 | 12087 | | 0.71 | 28 | 4 | 83.2 | 82.4 | 12087 | 28 |
| | | | | | | | Average | 83.2 | 82.4 | 12087 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$

$k_T = (aL/At) \ln (h_1/h_2) = 9.35E-08 = 0.0000000935 \text{ cm/s}$

$k_{20} = \alpha k_T = 7.75E-08 = 0.0000000775 \text{ cm/s}$

Degree of Permeability: Practically impermeable (Soil testing for Engineerers by T. William Lambe, 1951)

COEFFICIENT OF PERMEABILITY (Falling Head)

Project: _____ Sample No.: SUN27
 Soil Description : _____
 Tested by: _____ Date : 11/18/2023

Sample Dimensions: Diam. 6.2 cm; Area,A 30.20 cm²
 Vol. 120.81 cm³
 Ht.L 4.0 cm
 Standpipe = Burette (50 ml) Diam. 1.06 cm Area,a 0.883 cm²

| Test no. | h ₁ ,cm | h ₂ ,cm | t, s | Q _{in} , cm ³ | Q _{out} , cm ⁴ | T, °C | Test no. | h ₁ ,cm | h ₂ ,cm | t, s | T, °C |
|----------|--------------------|--------------------|------|-----------------------------------|------------------------------------|-------|----------|--------------------|--------------------|------|-------|
| 1 | 84.5 | 76.5 | 9428 | | 7.06 | 28 | 1 | 84.5 | 76.5 | 9428 | 28 |
| 2 | 84.5 | 76.5 | 9428 | | 7.06 | 28 | 2 | 84.5 | 76.5 | 9428 | 28 |
| 3 | 84.5 | 76.5 | 9428 | | 7.06 | 28 | 3 | 84.5 | 76.5 | 9428 | 28 |
| 4 | 84.5 | 76.5 | 9428 | | 7.06 | 28 | 4 | 84.5 | 76.5 | 9428 | 28 |
| Average | | | | | | | | 84.5 | 76.5 | 9428 | 28 |

$\alpha = \eta_T / \eta_{20} = 0.8287$ Temperature = 28 °C

$k_T = (aL/At) \ln (h_1/h_2) = 1.23E-06 = 0.0000012334 \text{ cm/s}$

$k_{20} = \alpha k_T = 1.02E-06 = 0.0000010221 \text{ cm/s}$

Degree of Permeability: Very low (Soil testing for Engineerers by T. William Lambe, 1951)

Appendix 9. Batch equilibrium test Data

Appendix 9.1. Sorption data

| Sample codes | Cr(ppm) | | | | | | | | | | | |
|--------------|--------------|-------------|------|--------|-------|------|------|--------|-----------|-------|-----------|-------------------------|
| | Initial Conc | Supernatant | 1/Ce | Log Ce | ln Ce | qe | 1/qe | log qe | % removal | Slope | Intercept | regression |
| Sun30 | 50 | 6.83 | 0.15 | 0.83 | 1.92 | 0.39 | 2.59 | 0.41 | 86.35 | 15.46 | 0.37 | y = 13.32x + 0.4012 |
| | 100 | 20.71 | 0.05 | 1.32 | 3.03 | 0.74 | 1.35 | 0.13 | 79.29 | | | R ² = 0.9543 |
| | 150 | 30.24 | 0.03 | 1.48 | 3.41 | 1.15 | 0.87 | -0.06 | 79.84 | | | |
| | 200 | 35.10 | 0.03 | 1.55 | 3.56 | 1.63 | 0.61 | -0.21 | 82.45 | | | |
| Sun33 | 50 | 7.71 | 0.13 | 0.89 | 2.04 | 0.37 | 2.69 | 0.43 | 84.58 | 17.87 | 0.41 | y = 15.09x + 0.444 |
| | 100 | 25.60 | 0.04 | 1.41 | 3.24 | 0.69 | 1.44 | 0.16 | 74.40 | | | R ² = 0.9202 |
| | 150 | 31.91 | 0.03 | 1.50 | 3.46 | 1.13 | 0.89 | -0.05 | 78.73 | | | |
| | 200 | 39.58 | 0.03 | 1.60 | 3.68 | 1.55 | 0.64 | -0.19 | 80.21 | | | |
| Sun02 | 50 | 11.66 | 0.09 | 1.07 | 2.46 | 0.34 | 2.92 | 0.47 | 76.68 | 34.38 | -0.02 | y = 32.019x - 0.1276 |
| | 100 | 24.16 | 0.04 | 1.38 | 3.18 | 0.72 | 1.40 | 0.15 | 75.84 | | | R ² = 0.9991 |
| | 150 | 39.12 | 0.03 | 1.59 | 3.67 | 1.13 | 0.88 | -0.05 | 73.92 | | | |
| | 200 | 49.91 | 0.02 | 1.70 | 3.91 | 1.55 | 0.64 | -0.19 | 75.04 | | | |
| Sun25 | 50 | 12.03 | 0.08 | 1.08 | 2.49 | 0.33 | 2.99 | 0.48 | 75.93 | 35.32 | 0.10 | y = 29.953x + 0.1876 |
| | 100 | 30.52 | 0.03 | 1.48 | 3.42 | 0.64 | 1.55 | 0.19 | 69.48 | | | R ² = 0.9566 |
| | 150 | 37.16 | 0.03 | 1.57 | 3.62 | 1.08 | 0.93 | -0.03 | 75.23 | | | |
| | 200 | 50.01 | 0.02 | 1.70 | 3.91 | 1.45 | 0.69 | -0.16 | 74.99 | | | |
| Sun4 | 50 | 3.14 | 0.32 | 0.50 | 1.14 | 0.42 | 2.36 | 0.37 | 93.72 | 5.20 | 0.74 | y = 4.5238x + 0.7182 |
| | 100 | 18.61 | 0.05 | 1.27 | 2.92 | 0.76 | 1.31 | 0.12 | 81.39 | | | R ² = 0.9178 |
| | 150 | 28.21 | 0.04 | 1.45 | 3.34 | 1.17 | 0.86 | -0.07 | 81.19 | | | |
| | 200 | 43.29 | 0.02 | 1.64 | 3.77 | 1.53 | 0.65 | -0.19 | 78.36 | | | |
| Sun14 | 50 | 2.07 | 0.48 | 0.32 | 0.73 | 0.43 | 2.33 | 0.37 | 95.86 | 3.20 | 0.81 | y = 2.7589x + 0.775 |
| | 100 | 16.61 | 0.06 | 1.22 | 2.81 | 0.78 | 1.28 | 0.11 | 83.39 | | | R ² = 0.9177 |
| | 150 | 26.81 | 0.04 | 1.43 | 3.29 | 1.17 | 0.85 | -0.07 | 82.12 | | | |
| | 200 | 48.40 | 0.02 | 1.68 | 3.88 | 1.47 | 0.68 | -0.17 | 75.80 | | | |
| Sun38 | 50 | 12.96 | 0.08 | 1.11 | 2.56 | 0.33 | 3.00 | 0.48 | 74.07 | 4.20 | 2.77 | y = 6.4773x + 2.27 |
| | 100 | 78.07 | 0.01 | 1.89 | 4.36 | 0.17 | 5.88 | 0.77 | 21.93 | | | R ² = 0.0182 |
| | 150 | 85.87 | 0.01 | 1.93 | 4.45 | 0.60 | 1.67 | 0.22 | 42.75 | | | |
| | 200 | 98.36 | 0.01 | 1.99 | 4.59 | 0.99 | 1.01 | 0.00 | 50.82 | | | |
| Sun40 | 50 | 12.80 | 0.08 | 1.11 | 2.55 | 0.33 | 3.06 | 0.49 | 74.40 | 16.79 | 1.82 | y = 15.041x + 1.5624 |
| | 100 | 68.39 | 0.01 | 1.83 | 4.23 | 0.26 | 3.89 | 0.59 | 31.61 | | | R ² = 0.2004 |
| | 150 | 71.43 | 0.01 | 1.85 | 4.27 | 0.74 | 1.36 | 0.13 | 52.38 | | | |
| | 200 | 88.89 | 0.01 | 1.95 | 4.49 | 1.07 | 0.93 | -0.03 | 55.55 | | | |
| Sun32 | 50 | 7.81 | 0.13 | 0.89 | 2.06 | 0.37 | 2.71 | 0.43 | 84.38 | 17.28 | 0.48 | y = 14.486x + 0.4961 |
| | 100 | 18.20 | 0.05 | 1.26 | 2.90 | 0.75 | 1.33 | 0.13 | 81.80 | | | R ² = 0.9913 |
| | 150 | 42.17 | 0.02 | 1.62 | 3.74 | 1.00 | 1.00 | 0.00 | 71.89 | | | |
| | 200 | 58.56 | 0.02 | 1.77 | 4.07 | 1.37 | 0.73 | -0.14 | 70.72 | | | |
| Sun35 | 50 | 6.15 | 0.16 | 0.79 | 1.82 | 0.39 | 2.59 | 0.41 | 87.69 | 11.71 | 0.73 | y = 9.8704x + 0.7122 |
| | 100 | 26.12 | 0.04 | 1.42 | 3.26 | 0.68 | 1.47 | 0.17 | 73.88 | | | R ² = 0.9286 |
| | 150 | 40.10 | 0.02 | 1.60 | 3.69 | 1.03 | 0.97 | -0.01 | 73.26 | | | |
| | 200 | 57.84 | 0.02 | 1.76 | 4.06 | 1.37 | 0.73 | -0.14 | 71.08 | | | |

| Cd (ppm) | | | | | | | | | | | | |
|--------------|--------------|-------------|------|--------|-------|-------|------|--------|-----------|-------|-----------|-------------------------|
| Sample codes | Initial Conc | Supernatant | 1/Ce | Log Ce | ln Ce | qe | 1/qe | log qe | % removal | Slope | Intercept | regression |
| Sun30 | 50 | 8.92 | 0.11 | 0.95 | 2.19 | 2.26 | 0.44 | -0.35 | 82.17 | 0.45 | 0.53 | y = 20.291x + 0.1805 |
| | 100 | 20.98 | 0.05 | 1.32 | 3.04 | 1.27 | 0.79 | -0.10 | 79.02 | | | R ² = 0.9897 |
| | 150 | 28.41 | 0.04 | 1.45 | 3.35 | 4.58 | 0.22 | -0.66 | 81.06 | | | |
| | 200 | 42.52 | 0.02 | 1.63 | 3.75 | 1.74 | 0.58 | -0.24 | 78.74 | | | |
| Sun33 | 50 | 7.07 | 0.14 | 0.85 | 1.96 | 2.26 | 0.44 | -0.35 | 85.86 | 2.41 | 0.21 | y = 14.68x + 0.2703 |
| | 100 | 17.13 | 0.06 | 1.23 | 2.84 | 1.30 | 0.77 | -0.11 | 82.87 | | | R ² = 0.995 |
| | 150 | 25.53 | 0.04 | 1.41 | 3.24 | 6.24 | 0.16 | -0.80 | 82.98 | | | |
| | 200 | 39.42 | 0.03 | 1.60 | 3.67 | 11.30 | 0.09 | -1.05 | 80.29 | | | |
| Sun02 | 50 | 6.73 | 0.15 | 0.83 | 1.91 | 1.59 | 0.63 | -0.20 | 86.53 | 0.64 | 0.55 | y = 13.995x + 0.2202 |
| | 100 | 14.27 | 0.07 | 1.15 | 2.66 | 1.29 | 0.78 | -0.11 | 85.73 | | | R ² = 0.9989 |
| | 150 | 24.24 | 0.04 | 1.38 | 3.19 | 4.97 | 0.20 | -0.70 | 83.84 | | | |
| | 200 | 37.64 | 0.03 | 1.58 | 3.63 | 1.28 | 0.78 | -0.11 | 81.18 | | | |
| Sun25 | 50 | 9.47 | 0.11 | 0.98 | 2.25 | 1.51 | 0.66 | -0.18 | 81.06 | 4.46 | 0.25 | y = 22.015x + 0.1624 |
| | 100 | 23.76 | 0.04 | 1.38 | 3.17 | 1.29 | 0.77 | -0.11 | 76.24 | | | R ² = 0.9598 |
| | 150 | 26.68 | 0.04 | 1.43 | 3.28 | 3.13 | 0.32 | -0.50 | 82.22 | | | |
| | 200 | 43.78 | 0.02 | 1.64 | 3.78 | 5.61 | 0.18 | -0.75 | 78.11 | | | |
| Sun4 | 50 | 5.91 | 0.17 | 0.77 | 1.78 | 1.55 | 0.64 | -0.19 | 88.19 | 1.07 | 0.42 | |
| | 100 | 13.63 | 0.07 | 1.13 | 2.61 | 2.00 | 0.50 | -0.30 | 86.37 | | | y = 11.135x + 0.3675 |
| | 150 | 24.02 | 0.04 | 1.38 | 3.18 | 5.80 | 0.17 | -0.76 | 83.99 | | | R ² = 0.997 |
| | 200 | 47.06 | 0.02 | 1.67 | 3.85 | 1.43 | 0.70 | -0.16 | 76.47 | | | |
| Sun14 | 50 | 7.32 | 0.14 | 0.86 | 1.99 | 5.77 | 0.17 | -0.76 | 85.35 | 0.45 | 0.23 | |
| | 100 | 21.52 | 0.05 | 1.33 | 3.07 | 4.70 | 0.21 | -0.67 | 78.48 | | | |
| | 150 | 28.47 | 0.04 | 1.45 | 3.35 | 8.59 | 0.12 | -0.93 | 81.02 | | | y = 14.466x + 0.401 |
| | 200 | 44.60 | 0.02 | 1.65 | 3.80 | 3.42 | 0.29 | -0.53 | 77.70 | | | R ² = 0.9681 |
| Sun38 | 50 | 11.21 | 0.09 | 1.05 | 2.42 | 3.66 | 0.27 | -0.56 | 77.59 | 5.26 | 0.73 | |
| | 100 | 28.88 | 0.03 | 1.46 | 3.36 | 1.22 | 0.82 | -0.09 | 71.12 | | | |
| | 150 | 32.29 | 0.03 | 1.51 | 3.47 | 6.76 | 0.15 | -0.83 | 78.47 | | | |
| | 200 | 46.40 | 0.02 | 1.67 | 3.84 | 1.29 | 0.77 | -0.11 | 76.80 | | | y = 27.495x + 0.1587 |
| Sun40 | 50 | 13.98 | 0.07 | 1.15 | 2.64 | 1.31 | 0.76 | -0.12 | 72.04 | 10.30 | 0.06 | R ² = 0.9447 |
| | 100 | 35.09 | 0.03 | 1.55 | 3.56 | 1.86 | 0.54 | -0.27 | 64.91 | | | |
| | 150 | 47.60 | 0.02 | 1.68 | 3.86 | 4.39 | 0.23 | -0.64 | 68.27 | | | |
| | 200 | 65.86 | 0.02 | 1.82 | 4.19 | 7.88 | 0.13 | -0.90 | 67.07 | | | |
| Sun32 | 50 | 9.11 | 0.11 | 0.96 | 2.21 | 2.89 | 0.35 | -0.46 | 81.77 | 0.50 | 0.26 | y = 34.995x + 0.3178 |
| | 100 | 20.88 | 0.05 | 1.32 | 3.04 | 4.07 | 0.25 | -0.61 | 79.12 | | | R ² = 0.9719 |
| | 150 | 33.45 | 0.03 | 1.52 | 3.51 | 6.74 | 0.15 | -0.83 | 77.70 | | | |
| | 200 | 56.94 | 0.02 | 1.76 | 4.04 | 2.46 | 0.41 | -0.39 | 71.53 | | | |
| Sun35 | 50 | 11.83 | 0.08 | 1.07 | 2.47 | 2.29 | 0.44 | -0.36 | 76.33 | 3.66 | 0.12 | y = 19.276x + 0.3284 |
| | 100 | 29.57 | 0.03 | 1.47 | 3.39 | 4.36 | 0.23 | -0.64 | 70.43 | | | R ² = 0.9982 |
| | 150 | 43.08 | 0.02 | 1.63 | 3.76 | 5.22 | 0.19 | -0.72 | 71.28 | | | |
| | 200 | 63.35 | 0.02 | 1.80 | 4.15 | 4.94 | 0.20 | -0.69 | 68.32 | | | |

| Cu (ppm) | | | | | | | | | | | | |
|--------------|--------------|-------------|------|--------|-------|------|------|--------|-----------|-------|-----------|-------------------------|
| Sample codes | Initial Conc | Supernatant | 1/Ce | Log Ce | ln Ce | qe | 1/qe | log qe | % removal | Slope | Intercept | regression |
| Sun30 | 50 | 8.22 | 0.12 | 0.91 | 2.11 | 0.36 | 2.75 | 0.44 | 83.57 | 15.78 | 0.87 | R ² = 0.8318 |
| | 100 | 38.62 | 0.03 | 1.59 | 3.65 | 0.59 | 1.70 | 0.23 | 61.38 | | | y = 12.724x + 0.8863 |
| | 150 | 53.18 | 0.02 | 1.73 | 3.97 | 0.92 | 1.09 | 0.04 | 64.55 | | | |
| | 200 | 72.36 | 0.01 | 1.86 | 4.28 | 1.27 | 0.79 | -0.10 | 63.82 | | | |
| Sun33 | 50 | 9.67 | 0.10 | 0.99 | 2.27 | 0.35 | 2.88 | 0.46 | 80.65 | 16.90 | 1.19 | y = 13.625x + 1.1211 |
| | 100 | 49.03 | 0.02 | 1.69 | 3.89 | 0.47 | 2.12 | 0.33 | 50.97 | | | R ² = 0.6927 |
| | 150 | 66.03 | 0.02 | 1.82 | 4.19 | 0.76 | 1.32 | 0.12 | 55.98 | | | |
| | 200 | 88.70 | 0.01 | 1.95 | 4.49 | 1.04 | 0.96 | -0.02 | 55.65 | | | |
| Sun02 | 50 | 12.89 | 0.08 | 1.11 | 2.56 | 0.32 | 3.10 | 0.49 | 74.23 | 34.26 | 0.48 | y = 28.521x + 0.521 |
| | 100 | 34.71 | 0.03 | 1.54 | 3.55 | 0.62 | 1.62 | 0.21 | 65.29 | | | R ² = 0.9773 |
| | 150 | 51.48 | 0.02 | 1.71 | 3.94 | 0.90 | 1.12 | 0.05 | 65.68 | | | |
| | 200 | 76.10 | 0.01 | 1.88 | 4.33 | 1.20 | 0.83 | -0.08 | 61.95 | | | |
| Sun25 | 50 | 13.27 | 0.08 | 1.12 | 2.59 | 0.33 | 3.07 | 0.49 | 73.47 | 29.45 | 0.91 | y = 24.918x + 0.9091 |
| | 100 | 48.02 | 0.02 | 1.68 | 3.87 | 0.49 | 2.05 | 0.31 | 51.98 | | | R ² = 0.8131 |
| | 150 | 67.25 | 0.01 | 1.83 | 4.21 | 0.78 | 1.28 | 0.11 | 55.17 | | | |
| | 200 | 82.58 | 0.01 | 1.92 | 4.41 | 1.13 | 0.89 | -0.05 | 58.71 | | | |
| Sun4 | 50 | 6.35 | 0.16 | 0.80 | 1.85 | 0.35 | 2.89 | 0.46 | 87.29 | 13.60 | 0.79 | |
| | 100 | 32.27 | 0.03 | 1.51 | 3.47 | 0.62 | 1.62 | 0.21 | 67.73 | | | y = 9.6777x + 0.8017 |
| | 150 | 42.50 | 0.02 | 1.63 | 3.75 | 0.99 | 1.01 | 0.01 | 71.67 | | | R ² = 0.8578 |
| | 200 | 60.89 | 0.02 | 1.78 | 4.11 | 1.37 | 0.73 | -0.14 | 69.55 | | | |
| Sun14 | 50 | 5.04 | 0.20 | 0.70 | 1.62 | 0.31 | 3.24 | 0.51 | 89.91 | 11.47 | 1.00 | y = 6.699x + 0.9212 |
| | 100 | 34.89 | 0.03 | 1.54 | 3.55 | 0.52 | 1.91 | 0.28 | 65.11 | | | R ² = 0.7801 |
| | 150 | 49.48 | 0.02 | 1.69 | 3.90 | 0.85 | 1.18 | 0.07 | 67.01 | | | |
| | 200 | 57.58 | 0.02 | 1.76 | 4.05 | 1.39 | 0.72 | -0.14 | 71.21 | | | |
| Sun38 | 50 | 10.93 | 0.09 | 1.04 | 2.39 | 0.36 | 2.76 | 0.44 | 78.14 | 16.21 | 1.34 | y = 14.529x + 1.2857 |
| | 100 | 56.47 | 0.02 | 1.75 | 4.03 | 0.40 | 2.50 | 0.40 | 43.53 | | | R ² = 0.5364 |
| | 150 | 67.76 | 0.01 | 1.83 | 4.22 | 0.80 | 1.26 | 0.10 | 54.83 | | | |
| | 200 | 101.40 | 0.01 | 2.01 | 4.62 | 0.98 | 1.02 | 0.01 | 49.30 | | | |
| Sun40 | 50 | 11.91 | 0.08 | 1.08 | 2.48 | 0.36 | 2.81 | 0.45 | 76.18 | 21.78 | 1.05 | y = 20.085x + 0.9998 |
| | 100 | 48.32 | 0.02 | 1.68 | 3.88 | 0.48 | 2.08 | 0.32 | 51.68 | | | R ² = 0.7749 |
| | 150 | 66.78 | 0.01 | 1.82 | 4.20 | 0.80 | 1.26 | 0.10 | 55.48 | | | |
| | 200 | 85.59 | 0.01 | 1.93 | 4.45 | 1.10 | 0.91 | -0.04 | 57.21 | | | |
| Sun32 | 50 | 8.54 | 0.12 | 0.93 | 2.14 | 0.35 | 2.85 | 0.46 | 82.93 | 18.74 | 0.70 | y = 14.742x + 0.7242 |
| | 100 | 30.93 | 0.03 | 1.49 | 3.43 | 0.63 | 1.58 | 0.20 | 69.07 | | | R ² = 0.9457 |
| | 150 | 46.69 | 0.02 | 1.67 | 3.84 | 0.97 | 1.03 | 0.01 | 68.87 | | | |
| | 200 | 73.35 | 0.01 | 1.87 | 4.30 | 1.25 | 0.80 | -0.10 | 63.33 | | | |
| Sun35 | 50 | 6.79 | 0.15 | 0.83 | 1.92 | 0.37 | 2.67 | 0.43 | 86.42 | 10.06 | 1.23 | y = 8.1486x + 1.1486 |
| | 100 | 46.33 | 0.02 | 1.67 | 3.84 | 0.48 | 2.10 | 0.32 | 53.67 | | | R ² = 0.6417 |
| | 150 | 66.07 | 0.02 | 1.82 | 4.19 | 0.78 | 1.28 | 0.11 | 55.95 | | | |
| | 200 | 79.18 | 0.01 | 1.90 | 4.37 | 1.18 | 0.85 | -0.07 | 60.41 | | | |

| Mn (ppm) | | | | | | | | | | | | |
|--------------|--------------|-------------|------|--------|-------|------|------|--------|-----------|-------|-----------|------------------------|
| Sample codes | Initial Conc | Supernatant | 1/Ce | Log Ce | ln Ce | qe | 1/qe | log qe | % removal | Slope | Intercept | regression |
| Sun30 | 50 | 10.20 | 0.10 | 1.01 | 2.32 | 0.35 | 2.84 | 0.45 | 79.61 | 24.43 | 0.48 | $y = 40.804x + 0.8914$ |
| | 100 | 29.55 | 0.03 | 1.47 | 3.39 | 0.67 | 1.48 | 0.17 | 70.45 | | | $R^2 = 0.7719$ |
| | 150 | 44.42 | 0.02 | 1.65 | 3.79 | 1.02 | 0.98 | -0.01 | 70.39 | | | |
| | 200 | 65.93 | 0.02 | 1.82 | 4.19 | 1.33 | 0.75 | -0.13 | 67.04 | | | |
| Sun33 | 50 | 8.84 | 0.11 | 0.95 | 2.18 | 0.35 | 2.82 | 0.45 | 82.32 | 22.40 | 0.30 | |
| | 100 | 22.03 | 0.05 | 1.34 | 3.09 | 0.73 | 1.37 | 0.14 | 77.97 | | | $y = 18.477x + 0.3613$ |
| | 150 | 35.11 | 0.03 | 1.55 | 3.56 | 1.08 | 0.92 | -0.03 | 76.60 | | | $R^2 = 0.9949$ |
| | 200 | 51.73 | 0.02 | 1.71 | 3.95 | 1.42 | 0.71 | -0.15 | 74.14 | | | |
| Sun02 | 50 | 12.83 | 0.08 | 1.11 | 2.55 | 0.26 | 3.92 | 0.59 | 74.35 | 48.48 | 0.23 | |
| | 100 | 31.46 | 0.03 | 1.50 | 3.45 | 0.45 | 2.22 | 0.35 | 68.54 | | | $y = 30.724x + 0.3304$ |
| | 150 | 46.11 | 0.02 | 1.66 | 3.83 | 0.90 | 1.11 | 0.05 | 69.26 | | | $R^2 = 0.9859$ |
| | 200 | 63.48 | 0.02 | 1.80 | 4.15 | 1.21 | 0.82 | -0.08 | 68.26 | | | |
| Sun25 | 50 | 14.19 | 0.07 | 1.15 | 2.65 | 0.27 | 3.76 | 0.57 | 71.61 | 45.95 | 0.58 | |
| | 100 | 43.15 | 0.02 | 1.64 | 3.76 | 0.51 | 1.96 | 0.29 | 56.85 | | | $y = 30.169x + 0.728$ |
| | 150 | 63.20 | 0.02 | 1.80 | 4.15 | 0.80 | 1.26 | 0.10 | 57.87 | | | $R^2 = 0.9246$ |
| | 200 | 84.61 | 0.01 | 1.93 | 4.44 | 1.10 | 0.91 | -0.04 | 57.70 | | | |
| Sun4 | 50 | 10.73 | 0.09 | 1.03 | 2.37 | 0.33 | 3.00 | 0.48 | 78.55 | 26.33 | 0.55 | |
| | 100 | 28.56 | 0.04 | 1.46 | 3.35 | 0.67 | 1.49 | 0.17 | 71.44 | | | $y = 20.931x + 0.6114$ |
| | 150 | 52.40 | 0.02 | 1.72 | 3.96 | 0.92 | 1.09 | 0.04 | 65.07 | | | $R^2 = 0.9965$ |
| | 200 | 78.73 | 0.01 | 1.90 | 4.37 | 1.20 | 0.83 | -0.08 | 60.64 | | | |
| Sun14 | 50 | 13.34 | 0.07 | 1.13 | 2.59 | 0.21 | 4.79 | 0.68 | 73.33 | 55.36 | 0.71 | |
| | 100 | 54.01 | 0.02 | 1.73 | 3.99 | 0.36 | 2.74 | 0.44 | 45.99 | | | $y = 24.115x + 0.9756$ |
| | 150 | 60.66 | 0.02 | 1.78 | 4.11 | 0.80 | 1.25 | 0.10 | 59.56 | | | $R^2 = 0.6497$ |
| | 200 | 80.15 | 0.01 | 1.90 | 4.38 | 1.17 | 0.85 | -0.07 | 59.93 | | | |
| Sun38 | 50 | 7.52 | 0.13 | 0.88 | 2.02 | 0.40 | 2.48 | 0.39 | 84.96 | 14.10 | 0.65 | |
| | 100 | 25.97 | 0.04 | 1.41 | 3.26 | 0.71 | 1.41 | 0.15 | 74.03 | | | $y = 13.117x + 0.6465$ |
| | 150 | 42.59 | 0.02 | 1.63 | 3.75 | 1.05 | 0.95 | -0.02 | 71.61 | | | $R^2 = 0.9613$ |
| | 200 | 61.32 | 0.02 | 1.79 | 4.12 | 1.38 | 0.72 | -0.14 | 69.34 | | | |
| Sun40 | 50 | 8.53 | 0.12 | 0.93 | 2.14 | 0.39 | 2.57 | 0.41 | 82.94 | 16.63 | 0.65 | |
| | 100 | 28.76 | 0.03 | 1.46 | 3.36 | 0.68 | 1.47 | 0.17 | 71.24 | | | $y = 15.359x + 0.6467$ |
| | 150 | 41.96 | 0.02 | 1.62 | 3.74 | 1.05 | 0.95 | -0.02 | 72.03 | | | $R^2 = 0.9584$ |
| | 200 | 69.71 | 0.01 | 1.84 | 4.24 | 1.26 | 0.80 | -0.10 | 65.15 | | | |
| Sun32 | 50 | 7.83 | 0.13 | 0.89 | 2.06 | 0.38 | 2.65 | 0.42 | 84.34 | 17.03 | 0.51 | |
| | 100 | 23.66 | 0.04 | 1.37 | 3.16 | 0.72 | 1.39 | 0.14 | 76.34 | | | $y = 14.617x + 0.5358$ |
| | 150 | 36.60 | 0.03 | 1.56 | 3.60 | 1.09 | 0.92 | -0.04 | 75.60 | | | $R^2 = 0.98$ |
| | 200 | 59.26 | 0.02 | 1.77 | 4.08 | 1.39 | 0.72 | -0.14 | 70.37 | | | |
| Sun35 | 50 | 17.74 | 0.06 | 1.25 | 2.88 | 0.18 | 5.55 | 0.74 | 64.51 | 87.46 | 0.80 | |
| | 100 | 56.32 | 0.02 | 1.75 | 4.03 | 0.26 | 3.81 | 0.58 | 43.68 | | | $y = 40.804x + 0.8914$ |
| | 150 | 72.83 | 0.01 | 1.86 | 4.29 | 0.68 | 1.48 | 0.17 | 51.45 | | | $R^2 = 0.7719$ |
| | 200 | 90.67 | 0.01 | 1.96 | 4.51 | 0.98 | 1.02 | 0.01 | 54.67 | | | |

| Pb (ppm) | | | | | | | | | | | | |
|--------------|--------------|-------------|------|--------|-------|------|------|--------|-------|-------|-----------|-------------------------|
| Sample codes | Initial Conc | Supernatant | 1/Ce | Log Ce | ln Ce | qe | 1/qe | log qe | remov | Slope | Intercept | regression |
| Sun30 | 50 | 7.04 | 0.14 | 0.85 | 1.95 | 0.37 | 2.74 | 0.44 | 85.91 | 18.14 | 0.14 | y = 14.583x + 0.2603 |
| | 100 | 16.34 | 0.06 | 1.21 | 2.79 | 0.82 | 1.22 | 0.09 | 83.66 | | | R ² = 0.9953 |
| | 150 | 24.03 | 0.04 | 1.38 | 3.18 | 1.19 | 0.84 | -0.08 | 83.98 | | | |
| | 200 | 42.62 | 0.02 | 1.63 | 3.75 | 1.57 | 0.64 | -0.20 | 78.69 | | | |
| Sun33 | 50 | 6.40 | 0.16 | 0.81 | 1.86 | 0.35 | 2.84 | 0.45 | 87.20 | 17.11 | 0.18 | y = 12.94x + 0.2964 |
| | 100 | 16.94 | 0.06 | 1.23 | 2.83 | 0.80 | 1.26 | 0.10 | 83.06 | | | R ² = 0.9831 |
| | 150 | 22.79 | 0.04 | 1.36 | 3.13 | 1.13 | 0.88 | -0.05 | 84.81 | | | |
| | 200 | 36.44 | 0.03 | 1.56 | 3.60 | 1.57 | 0.64 | -0.19 | 81.78 | | | |
| Sun02 | 50 | 5.52 | 0.18 | 0.74 | 1.71 | 0.36 | 2.78 | 0.44 | 88.96 | 14.06 | 0.23 | y = 10.742x + 0.3231 |
| | 100 | 14.03 | 0.07 | 1.15 | 2.64 | 0.83 | 1.20 | 0.08 | 85.97 | | | R ² = 0.9929 |
| | 150 | 23.83 | 0.04 | 1.38 | 3.17 | 1.08 | 0.92 | -0.03 | 84.11 | | | |
| | 200 | 31.38 | 0.03 | 1.50 | 3.45 | 1.65 | 0.60 | -0.22 | 84.31 | | | |
| Sun25 | 50 | 5.00 | 0.20 | 0.70 | 1.61 | 0.40 | 2.51 | 0.40 | 90.00 | 10.11 | 0.52 | y = 8.6055x + 0.5307 |
| | 100 | 16.62 | 0.06 | 1.22 | 2.81 | 0.79 | 1.26 | 0.10 | 83.38 | | | R ² = 0.9735 |
| | 150 | 29.51 | 0.03 | 1.47 | 3.38 | 1.13 | 0.88 | -0.05 | 80.33 | | | |
| | 200 | 39.21 | 0.03 | 1.59 | 3.67 | 1.55 | 0.64 | -0.19 | 80.39 | | | |
| Sun4 | 50 | 7.38 | 0.14 | 0.87 | 2.00 | 0.32 | 3.14 | 0.50 | 85.24 | 22.77 | 0.08 | y = 15.658x + 0.2545 |
| | 100 | 18.45 | 0.05 | 1.27 | 2.91 | 0.73 | 1.38 | 0.14 | 81.55 | | | R ² = 0.9874 |
| | 150 | 27.34 | 0.04 | 1.44 | 3.31 | 1.05 | 0.95 | -0.02 | 81.77 | | | |
| | 200 | 35.86 | 0.03 | 1.55 | 3.58 | 1.61 | 0.62 | -0.21 | 82.07 | | | |
| Sun14 | 50 | 10.55 | 0.09 | 1.02 | 2.36 | 0.17 | 5.80 | 0.76 | 78.91 | 72.24 | -1.04 | y = 25.406x + 0.1664 |
| | 100 | 26.89 | 0.04 | 1.43 | 3.29 | 0.56 | 1.78 | 0.25 | 73.11 | | | R ² = 0.9575 |
| | 150 | 32.98 | 0.03 | 1.52 | 3.50 | 0.95 | 1.06 | 0.02 | 78.02 | | | |
| | 200 | 42.30 | 0.02 | 1.63 | 3.74 | 1.53 | 0.65 | -0.19 | 78.85 | | | |
| Sun38 | 50 | 6.84 | 0.15 | 0.83 | 1.92 | 0.41 | 2.45 | 0.39 | 86.32 | 15.78 | 0.14 | y = 14.807x + 0.1592 |
| | 100 | 14.83 | 0.07 | 1.17 | 2.70 | 0.83 | 1.21 | 0.08 | 85.17 | | | R ² = 0.9983 |
| | 150 | 24.44 | 0.04 | 1.39 | 3.20 | 1.18 | 0.85 | -0.07 | 83.70 | | | |
| | 200 | 31.25 | 0.03 | 1.49 | 3.44 | 1.68 | 0.59 | -0.23 | 84.37 | | | |
| Sun40 | 50 | 8.44 | 0.12 | 0.93 | 2.13 | 0.39 | 2.58 | 0.41 | 83.12 | 19.00 | 0.34 | y = 17.525x + 0.3484 |
| | 100 | 20.63 | 0.05 | 1.31 | 3.03 | 0.76 | 1.31 | 0.12 | 79.37 | | | R ² = 0.9959 |
| | 150 | 34.65 | 0.03 | 1.54 | 3.55 | 1.08 | 0.93 | -0.03 | 76.90 | | | |
| | 200 | 47.94 | 0.02 | 1.68 | 3.87 | 1.49 | 0.67 | -0.17 | 76.03 | | | |
| Sun32 | 50 | 7.05 | 0.14 | 0.85 | 1.95 | 0.36 | 2.80 | 0.45 | 85.89 | 17.37 | 0.37 | y = 13.688x + 0.4203 |
| | 100 | 20.32 | 0.05 | 1.31 | 3.01 | 0.72 | 1.39 | 0.14 | 79.68 | | | R ² = 0.9785 |
| | 150 | 30.26 | 0.03 | 1.48 | 3.41 | 1.07 | 0.94 | -0.03 | 79.83 | | | |
| | 200 | 43.96 | 0.02 | 1.64 | 3.78 | 1.55 | 0.65 | -0.19 | 78.02 | | | |
| Sun35 | 50 | 16.12 | 0.06 | 1.21 | 2.78 | 0.25 | 4.02 | 0.60 | 67.76 | 71.90 | 0.44 | y = 49.563x - 0.1305 |
| | 100 | 31.47 | 0.03 | 1.50 | 3.45 | 0.54 | 1.87 | 0.27 | 68.53 | | | R ² = 0.9965 |
| | 150 | 43.15 | 0.02 | 1.64 | 3.76 | 0.86 | 1.16 | 0.07 | 71.23 | | | |
| | 200 | 62.21 | 0.02 | 1.79 | 4.13 | 1.33 | 0.75 | -0.12 | 68.89 | | | |

Appendix 9.2. Desorption data

| Cd (ppm) | | | | | | | | | | |
|----------|---------|------|----------|----------|----------|-----------|------|------|------|-------|
| | residue | soil | retained | adsorbed | desorbed | %desorbed | qret | qads | qdes | Ce |
| SUN30 | 1.95 | 0.06 | 1.89 | 41.08 | 39.20 | 95.41 | 0.02 | 0.41 | 0.39 | 8.92 |
| | 0.77 | 0.06 | 0.71 | 79.02 | 78.32 | 99.11 | 0.01 | 0.79 | 0.78 | 20.98 |
| | 2.24 | 0.06 | 2.17 | 121.59 | 119.42 | 98.21 | 0.02 | 1.22 | 1.19 | 28.41 |
| | 0.67 | 0.06 | 0.60 | 157.48 | 156.87 | 99.62 | 0.01 | 1.57 | 1.57 | 42.52 |
| SUN33 | 1.99 | 0.04 | 1.95 | 42.93 | 40.98 | 95.45 | 0.02 | 0.43 | 0.41 | 7.07 |
| | 0.79 | 0.04 | 0.75 | 82.87 | 82.12 | 99.09 | 0.01 | 0.83 | 0.82 | 17.13 |
| | 3.05 | 0.04 | 3.01 | 124.47 | 121.46 | 97.58 | 0.03 | 1.24 | 1.21 | 25.53 |
| | 4.34 | 0.04 | 4.31 | 160.58 | 156.28 | 97.32 | 0.04 | 1.61 | 1.56 | 39.42 |
| SUN02 | 1.38 | 0.05 | 1.33 | 43.27 | 41.93 | 96.92 | 0.01 | 0.43 | 0.42 | 6.73 |
| | 0.32 | 0.05 | 0.27 | 85.73 | 85.45 | 99.68 | 0.00 | 0.86 | 0.85 | 14.27 |
| | 2.43 | 0.05 | 2.38 | 125.76 | 123.38 | 98.11 | 0.02 | 1.26 | 1.23 | 24.24 |
| | 0.49 | 0.05 | 0.45 | 162.36 | 161.91 | 99.73 | 0.00 | 1.62 | 1.62 | 37.64 |
| SUN25 | 1.31 | 0.06 | 1.25 | 40.53 | 39.28 | 96.92 | 0.01 | 0.41 | 0.39 | 9.47 |
| | 0.62 | 0.06 | 0.56 | 76.24 | 75.68 | 99.26 | 0.01 | 0.76 | 0.76 | 23.76 |
| | 1.53 | 0.06 | 1.47 | 123.32 | 121.85 | 98.81 | 0.01 | 1.23 | 1.22 | 26.68 |
| | 2.16 | 0.06 | 2.10 | 156.22 | 154.13 | 98.66 | 0.02 | 1.56 | 1.54 | 43.78 |
| SUN04 | 2.24 | 0.01 | 2.22 | 44.09 | 41.87 | 94.96 | 0.02 | 0.44 | 0.42 | 5.91 |
| | 1.21 | 0.01 | 1.20 | 86.37 | 85.17 | 98.61 | 0.01 | 0.86 | 0.85 | 13.63 |
| | 2.83 | 0.01 | 2.82 | 125.98 | 123.16 | 97.76 | 0.03 | 1.26 | 1.23 | 24.02 |
| | 0.55 | 0.01 | 0.54 | 152.94 | 152.40 | 99.65 | 0.01 | 1.53 | 1.52 | 47.06 |
| SUN14 | 4.99 | 0.05 | 4.94 | 42.68 | 37.74 | 88.42 | 0.05 | 0.43 | 0.38 | 7.32 |
| | 2.84 | 0.05 | 2.79 | 78.48 | 75.69 | 96.44 | 0.03 | 0.78 | 0.76 | 21.52 |
| | 4.19 | 0.05 | 4.14 | 121.53 | 117.39 | 96.59 | 0.04 | 1.22 | 1.17 | 28.47 |
| | 1.31 | 0.05 | 1.27 | 155.40 | 154.14 | 99.19 | 0.01 | 1.55 | 1.54 | 44.60 |
| SUN38 | 0.86 | 0.03 | 0.83 | 38.79 | 37.96 | 97.86 | 0.01 | 0.39 | 0.38 | 11.21 |
| | 0.74 | 0.03 | 0.71 | 71.12 | 70.41 | 99.00 | 0.01 | 0.71 | 0.70 | 28.88 |
| | 3.30 | 0.03 | 3.27 | 117.71 | 114.44 | 97.22 | 0.03 | 1.18 | 1.14 | 32.29 |
| | 0.50 | 0.03 | 0.46 | 153.60 | 153.13 | 99.70 | 0.00 | 1.54 | 1.53 | 46.40 |
| SUN40 | 1.14 | 0.06 | 1.07 | 36.02 | 34.95 | 97.03 | 0.01 | 0.36 | 0.35 | 13.98 |
| | 1.13 | 0.06 | 1.06 | 64.91 | 63.85 | 98.37 | 0.01 | 0.65 | 0.64 | 35.09 |
| | 2.14 | 0.06 | 2.08 | 102.40 | 100.32 | 97.97 | 0.02 | 1.02 | 1.00 | 47.60 |
| | 3.03 | 0.06 | 2.97 | 134.14 | 131.17 | 97.79 | 0.03 | 1.34 | 1.31 | 65.86 |
| SUN35 | 2.50 | 0.01 | 2.49 | 40.89 | 38.39 | 93.91 | 0.02 | 0.41 | 0.38 | 9.11 |
| | 2.46 | 0.01 | 2.45 | 79.12 | 76.67 | 96.90 | 0.02 | 0.79 | 0.77 | 20.88 |
| | 3.29 | 0.01 | 3.28 | 116.55 | 113.27 | 97.19 | 0.03 | 1.17 | 1.13 | 33.45 |
| | 0.95 | 0.01 | 0.94 | 143.06 | 142.12 | 99.35 | 0.01 | 1.43 | 1.42 | 56.94 |
| SUN32 | 1.99 | 0.02 | 1.97 | 38.17 | 36.20 | 94.84 | 0.02 | 0.38 | 0.36 | 11.83 |
| | 2.64 | 0.02 | 2.62 | 70.43 | 67.81 | 96.28 | 0.03 | 0.70 | 0.68 | 29.57 |
| | 2.55 | 0.02 | 2.53 | 106.92 | 104.39 | 97.63 | 0.03 | 1.07 | 1.04 | 43.08 |
| | 1.90 | 0.02 | 1.88 | 136.65 | 134.77 | 98.62 | 0.02 | 1.37 | 1.35 | 63.35 |

| Cr (ppm) | | | | | | | | | | |
|----------|---------|------|----------|----------|----------|-------|------|------|------|-------|
| | residue | soil | retained | adsorbed | desorbed | %des | qret | qads | qdes | Ce |
| SUN30 | 5.33 | 0.77 | 4.55 | 43.17 | 38.62 | 89.46 | 0.05 | 0.43 | 0.39 | 6.83 |
| | 6.12 | 0.77 | 5.35 | 79.29 | 73.94 | 93.25 | 0.05 | 0.79 | 0.74 | 20.71 |
| | 5.27 | 0.77 | 4.49 | 119.76 | 115.27 | 96.25 | 0.04 | 1.20 | 1.15 | 30.24 |
| | 2.64 | 0.77 | 1.87 | 164.90 | 163.03 | 98.87 | 0.02 | 1.65 | 1.63 | 35.10 |
| SUN33 | 5.51 | 0.46 | 5.06 | 42.29 | 37.23 | 88.04 | 0.05 | 0.42 | 0.37 | 7.71 |
| | 5.54 | 0.46 | 5.09 | 74.40 | 69.31 | 93.16 | 0.05 | 0.74 | 0.69 | 25.60 |
| | 5.82 | 0.46 | 5.36 | 118.09 | 112.73 | 95.46 | 0.05 | 1.18 | 1.13 | 31.91 |
| | 5.66 | 0.46 | 5.21 | 160.42 | 155.22 | 96.75 | 0.05 | 1.60 | 1.55 | 39.58 |
| SUN02 | 5.09 | 0.95 | 4.14 | 38.34 | 34.19 | 89.19 | 0.04 | 0.38 | 0.34 | 11.66 |
| | 6.31 | 0.95 | 5.36 | 76.94 | 71.57 | 93.03 | 0.05 | 0.77 | 0.72 | 23.06 |
| | 5.50 | 0.95 | 4.56 | 117.88 | 113.32 | 96.13 | 0.05 | 1.18 | 1.13 | 32.12 |
| | 4.17 | 0.95 | 3.22 | 158.29 | 155.07 | 97.97 | 0.03 | 1.58 | 1.55 | 41.71 |
| SUN25 | 5.02 | 0.47 | 4.55 | 37.97 | 33.42 | 88.01 | 0.05 | 0.38 | 0.33 | 12.03 |
| | 5.55 | 0.47 | 5.08 | 69.48 | 64.40 | 92.69 | 0.05 | 0.69 | 0.64 | 30.52 |
| | 5.27 | 0.47 | 4.80 | 112.84 | 108.04 | 95.74 | 0.05 | 1.13 | 1.08 | 37.16 |
| | 5.26 | 0.47 | 4.80 | 149.99 | 145.19 | 96.80 | 0.05 | 1.50 | 1.45 | 50.01 |
| SUN04 | 5.37 | 0.81 | 4.56 | 46.86 | 42.30 | 90.26 | 0.05 | 0.47 | 0.42 | 3.14 |
| | 5.72 | 0.81 | 4.91 | 81.39 | 76.47 | 93.96 | 0.05 | 0.81 | 0.76 | 18.61 |
| | 5.97 | 0.81 | 5.16 | 121.79 | 116.63 | 95.77 | 0.05 | 1.22 | 1.17 | 28.21 |
| | 4.33 | 0.81 | 3.52 | 156.71 | 153.19 | 97.75 | 0.04 | 1.57 | 1.53 | 43.29 |
| SUN14 | 5.79 | 0.87 | 4.93 | 47.93 | 43.00 | 89.72 | 0.05 | 0.48 | 0.43 | 2.07 |
| | 6.35 | 0.87 | 5.48 | 83.39 | 77.91 | 93.43 | 0.05 | 0.83 | 0.78 | 16.61 |
| | 6.78 | 0.87 | 5.92 | 123.19 | 117.27 | 95.20 | 0.06 | 1.23 | 1.17 | 26.81 |
| | 5.20 | 0.87 | 4.33 | 151.60 | 147.28 | 97.15 | 0.04 | 1.52 | 1.47 | 48.40 |
| SUN38 | 4.12 | 0.39 | 3.72 | 37.04 | 33.31 | 89.95 | 0.04 | 0.37 | 0.33 | 12.96 |
| | 5.32 | 0.39 | 4.93 | 21.93 | 17.00 | 77.53 | 0.05 | 0.22 | 0.17 | 78.07 |
| | 4.69 | 0.39 | 4.29 | 64.13 | 59.84 | 93.31 | 0.04 | 0.64 | 0.60 | 85.87 |
| | 2.54 | 0.39 | 2.15 | 101.64 | 99.49 | 97.88 | 0.02 | 1.02 | 0.99 | 98.36 |
| SUN40 | 4.91 | 0.35 | 4.56 | 37.20 | 32.64 | 87.75 | 0.05 | 0.37 | 0.33 | 12.80 |
| | 6.27 | 0.35 | 5.92 | 31.61 | 25.69 | 81.27 | 0.06 | 0.32 | 0.26 | 68.39 |
| | 5.36 | 0.35 | 5.01 | 78.57 | 73.57 | 93.63 | 0.05 | 0.79 | 0.74 | 71.43 |
| | 3.96 | 0.35 | 3.61 | 111.11 | 107.50 | 96.75 | 0.04 | 1.11 | 1.07 | 88.89 |
| SUN35 | 5.58 | 0.22 | 5.36 | 42.19 | 36.83 | 87.30 | 0.05 | 0.42 | 0.37 | 7.81 |
| | 7.03 | 0.22 | 6.81 | 81.80 | 74.99 | 91.67 | 0.07 | 0.82 | 0.75 | 18.20 |
| | 7.71 | 0.22 | 7.49 | 107.83 | 100.34 | 93.05 | 0.07 | 1.08 | 1.00 | 42.17 |
| | 4.54 | 0.22 | 4.32 | 141.44 | 137.11 | 96.94 | 0.04 | 1.41 | 1.37 | 58.56 |
| SUN32 | 5.49 | 0.20 | 5.29 | 43.85 | 38.56 | 87.95 | 0.05 | 0.44 | 0.39 | 6.15 |
| | 5.96 | 0.20 | 5.76 | 73.88 | 68.12 | 92.20 | 0.06 | 0.74 | 0.68 | 26.12 |
| | 7.10 | 0.20 | 6.90 | 109.90 | 102.99 | 93.72 | 0.07 | 1.10 | 1.03 | 40.10 |
| | 5.65 | 0.20 | 5.45 | 142.16 | 136.71 | 96.17 | 0.05 | 1.42 | 1.37 | 57.84 |

| Cu (ppm) | | | | | | | | | | |
|----------|---------|------|----------|----------|----------|-------|------|------|------|--------|
| | residue | soil | retained | adsorbed | desorbed | %des | qret | qads | qdes | Ce |
| SUN30 | 5.55 | 0.17 | 5.38 | 41.78 | 36.41 | 87.13 | 0.05 | 0.36 | 0.42 | 8.22 |
| | 2.64 | 0.17 | 2.48 | 61.38 | 58.90 | 95.96 | 0.02 | 0.59 | 0.61 | 38.62 |
| | 4.89 | 0.17 | 4.72 | 96.82 | 92.10 | 95.12 | 0.05 | 0.92 | 0.97 | 53.18 |
| | 1.26 | 0.17 | 1.09 | 127.64 | 126.54 | 99.14 | 0.01 | 1.27 | 1.28 | 72.36 |
| SUN33 | 5.78 | 0.19 | 5.60 | 40.33 | 34.73 | 86.12 | 0.06 | 0.35 | 0.40 | 9.67 |
| | 4.06 | 0.19 | 3.87 | 50.97 | 47.10 | 92.40 | 0.04 | 0.47 | 0.51 | 49.03 |
| | 8.13 | 0.19 | 7.94 | 83.97 | 76.03 | 90.54 | 0.08 | 0.76 | 0.84 | 66.03 |
| | 7.66 | 0.19 | 7.47 | 111.30 | 103.82 | 93.29 | 0.07 | 1.04 | 1.11 | 88.70 |
| SUN02 | 5.22 | 0.35 | 4.87 | 37.11 | 32.24 | 86.87 | 0.05 | 0.32 | 0.37 | 12.89 |
| | 3.93 | 0.35 | 3.58 | 65.29 | 61.71 | 94.51 | 0.04 | 0.62 | 0.65 | 34.71 |
| | 9.37 | 0.35 | 9.02 | 98.52 | 89.50 | 90.85 | 0.09 | 0.90 | 0.99 | 51.48 |
| | 4.38 | 0.35 | 4.03 | 123.90 | 119.87 | 96.75 | 0.04 | 1.20 | 1.24 | 76.10 |
| SUN25 | 4.28 | 0.17 | 4.11 | 36.73 | 32.62 | 88.81 | 0.04 | 0.33 | 0.37 | 13.27 |
| | 3.29 | 0.17 | 3.12 | 51.98 | 48.86 | 93.99 | 0.03 | 0.49 | 0.52 | 48.02 |
| | 5.01 | 0.17 | 4.84 | 82.75 | 77.91 | 94.15 | 0.05 | 0.78 | 0.83 | 67.25 |
| | 4.99 | 0.17 | 4.81 | 117.42 | 112.61 | 95.90 | 0.05 | 1.13 | 1.17 | 82.58 |
| SUN04 | 9.29 | 0.25 | 9.04 | 43.65 | 34.61 | 79.29 | 0.09 | 0.35 | 0.44 | 6.35 |
| | 6.15 | 0.25 | 5.90 | 67.73 | 61.83 | 91.29 | 0.06 | 0.62 | 0.68 | 32.27 |
| | 9.21 | 0.25 | 8.96 | 107.50 | 98.54 | 91.66 | 0.09 | 0.99 | 1.08 | 42.50 |
| | 2.38 | 0.25 | 2.13 | 139.11 | 136.98 | 98.47 | 0.02 | 1.37 | 1.39 | 60.89 |
| SUN14 | 14.37 | 0.25 | 14.12 | 44.96 | 30.83 | 68.58 | 0.14 | 0.31 | 0.45 | 5.04 |
| | 12.87 | 0.25 | 12.63 | 65.11 | 52.48 | 80.61 | 0.13 | 0.52 | 0.65 | 34.89 |
| | 16.13 | 0.25 | 15.89 | 100.52 | 84.63 | 84.19 | 0.16 | 0.85 | 1.01 | 49.48 |
| | 3.49 | 0.25 | 3.24 | 142.42 | 139.18 | 97.72 | 0.03 | 1.39 | 1.42 | 57.58 |
| SUN38 | 3.02 | 0.18 | 2.84 | 39.07 | 36.23 | 92.74 | 0.03 | 0.36 | 0.39 | 10.93 |
| | 3.70 | 0.18 | 3.52 | 43.53 | 40.01 | 91.92 | 0.04 | 0.40 | 0.44 | 56.47 |
| | 2.75 | 0.18 | 2.56 | 82.24 | 79.68 | 96.88 | 0.03 | 0.80 | 0.82 | 67.76 |
| | 0.73 | 0.18 | 0.55 | 98.60 | 98.06 | 99.45 | 0.01 | 0.98 | 0.99 | 101.40 |
| SUN40 | 2.61 | 0.11 | 2.51 | 38.09 | 35.58 | 93.42 | 0.03 | 0.36 | 0.38 | 11.91 |
| | 3.81 | 0.11 | 3.70 | 51.68 | 47.98 | 92.83 | 0.04 | 0.48 | 0.52 | 48.32 |
| | 3.71 | 0.11 | 3.61 | 83.22 | 79.61 | 95.67 | 0.04 | 0.80 | 0.83 | 66.78 |
| | 4.27 | 0.11 | 4.16 | 114.41 | 110.25 | 96.36 | 0.04 | 1.10 | 1.14 | 85.59 |
| SUN35 | 6.48 | 0.09 | 6.39 | 41.46 | 35.07 | 84.58 | 0.06 | 0.35 | 0.41 | 8.54 |
| | 5.71 | 0.09 | 5.63 | 69.07 | 63.45 | 91.85 | 0.06 | 0.63 | 0.69 | 30.93 |
| | 6.49 | 0.09 | 6.40 | 103.31 | 96.91 | 93.81 | 0.06 | 0.97 | 1.03 | 46.69 |
| | 1.43 | 0.09 | 1.34 | 126.65 | 125.31 | 98.94 | 0.01 | 1.25 | 1.27 | 73.35 |
| SUN32 | 5.89 | 0.14 | 5.75 | 43.21 | 37.46 | 86.70 | 0.06 | 0.37 | 0.43 | 6.79 |
| | 6.13 | 0.14 | 5.99 | 53.67 | 47.68 | 88.84 | 0.06 | 0.48 | 0.54 | 46.33 |
| | 5.92 | 0.14 | 5.78 | 83.93 | 78.15 | 93.11 | 0.06 | 0.78 | 0.84 | 66.07 |
| | 2.97 | 0.14 | 2.82 | 120.82 | 118.00 | 97.66 | 0.03 | 1.18 | 1.21 | 79.18 |

| Pb (ppm) | | | | | | | | | | |
|----------|---------|------|----------|----------|----------|-------|------|------|------|-------|
| | residue | soil | retained | adsorbed | desorbed | %des | qret | qads | qdes | Ce |
| SUN30 | 6.58 | 0.17 | 6.41 | 42.96 | 36.54 | 85.08 | 0.06 | 0.43 | 0.37 | 7.04 |
| | 1.66 | 0.17 | 1.49 | 83.66 | 82.16 | 98.22 | 0.01 | 0.84 | 0.82 | 16.34 |
| | 7.24 | 0.17 | 7.07 | 125.97 | 118.90 | 94.39 | 0.07 | 1.26 | 1.19 | 24.03 |
| | 0.71 | 0.17 | 0.54 | 157.38 | 156.84 | 99.65 | 0.01 | 1.57 | 1.57 | 42.62 |
| SUN33 | 8.56 | 0.14 | 8.42 | 43.60 | 35.18 | 80.68 | 0.08 | 0.44 | 0.35 | 6.40 |
| | 3.56 | 0.14 | 3.42 | 83.06 | 79.64 | 95.88 | 0.03 | 0.83 | 0.80 | 16.94 |
| | 14.30 | 0.14 | 14.16 | 127.21 | 113.06 | 88.87 | 0.14 | 1.27 | 1.13 | 22.79 |
| | 7.17 | 0.14 | 7.03 | 163.56 | 156.52 | 95.70 | 0.07 | 1.64 | 1.57 | 36.44 |
| SUN02 | 8.73 | 0.25 | 8.48 | 44.48 | 36.00 | 80.93 | 0.08 | 0.44 | 0.36 | 5.52 |
| | 2.81 | 0.25 | 2.56 | 85.97 | 83.41 | 97.02 | 0.03 | 0.86 | 0.83 | 14.03 |
| | 18.13 | 0.25 | 17.88 | 126.17 | 108.28 | 85.83 | 0.18 | 1.26 | 1.08 | 23.83 |
| | 3.47 | 0.25 | 3.22 | 168.62 | 165.40 | 98.09 | 0.03 | 1.69 | 1.65 | 31.38 |
| SUN25 | 5.37 | 0.17 | 5.20 | 45.00 | 39.80 | 88.45 | 0.05 | 0.45 | 0.40 | 5.00 |
| | 4.33 | 0.17 | 4.15 | 83.38 | 79.23 | 95.02 | 0.04 | 0.83 | 0.79 | 16.62 |
| | 7.36 | 0.17 | 7.19 | 120.49 | 113.30 | 94.03 | 0.07 | 1.20 | 1.13 | 29.51 |
| | 5.53 | 0.17 | 5.36 | 160.79 | 155.43 | 96.67 | 0.05 | 1.61 | 1.55 | 39.21 |
| SUN04 | 10.96 | 0.19 | 10.77 | 42.62 | 31.85 | 74.72 | 0.11 | 0.43 | 0.32 | 7.38 |
| | 9.05 | 0.19 | 8.86 | 81.55 | 72.69 | 89.13 | 0.09 | 0.82 | 0.73 | 18.45 |
| | 17.47 | 0.19 | 17.29 | 122.66 | 105.37 | 85.91 | 0.17 | 1.23 | 1.05 | 27.34 |
| | 3.65 | 0.19 | 3.47 | 164.14 | 160.67 | 97.89 | 0.03 | 1.64 | 1.61 | 35.86 |
| SUN14 | 22.32 | 0.11 | 22.21 | 39.45 | 17.25 | 43.72 | 0.22 | 0.39 | 0.17 | 10.55 |
| | 17.07 | 0.11 | 16.96 | 73.11 | 56.16 | 76.80 | 0.17 | 0.73 | 0.56 | 26.89 |
| | 22.56 | 0.11 | 22.45 | 117.02 | 94.57 | 80.82 | 0.22 | 1.17 | 0.95 | 32.98 |
| | 4.35 | 0.11 | 4.24 | 157.70 | 153.47 | 97.31 | 0.04 | 1.58 | 1.53 | 42.30 |
| SUN38 | 2.42 | 0.13 | 2.29 | 43.16 | 40.87 | 94.69 | 0.02 | 0.43 | 0.41 | 6.84 |
| | 2.34 | 0.13 | 2.21 | 85.17 | 82.96 | 97.41 | 0.02 | 0.85 | 0.83 | 14.83 |
| | 7.93 | 0.13 | 7.80 | 125.56 | 117.76 | 93.79 | 0.08 | 1.26 | 1.18 | 24.44 |
| | 0.68 | 0.13 | 0.55 | 168.75 | 168.20 | 99.67 | 0.01 | 1.69 | 1.68 | 31.25 |
| SUN40 | 2.83 | 0.09 | 2.75 | 41.56 | 38.81 | 93.39 | 0.03 | 0.42 | 0.39 | 8.44 |
| | 3.23 | 0.09 | 3.15 | 79.37 | 76.23 | 96.03 | 0.03 | 0.79 | 0.76 | 20.63 |
| | 7.59 | 0.09 | 7.50 | 115.35 | 107.85 | 93.50 | 0.08 | 1.15 | 1.08 | 34.65 |
| | 2.81 | 0.09 | 2.72 | 152.06 | 149.34 | 98.21 | 0.03 | 1.52 | 1.49 | 47.94 |
| SUN35 | 7.29 | 0.10 | 7.20 | 42.95 | 35.75 | 83.25 | 0.07 | 0.43 | 0.36 | 7.05 |
| | 7.58 | 0.10 | 7.48 | 79.68 | 72.20 | 90.61 | 0.07 | 0.80 | 0.72 | 20.32 |
| | 13.16 | 0.10 | 13.07 | 119.74 | 106.68 | 89.09 | 0.13 | 1.20 | 1.07 | 30.26 |
| | 1.38 | 0.10 | 1.28 | 156.04 | 154.77 | 99.18 | 0.01 | 1.56 | 1.55 | 43.96 |
| SUN32 | 9.12 | 0.11 | 9.02 | 33.88 | 24.86 | 73.39 | 0.09 | 0.34 | 0.25 | 16.12 |
| | 15.09 | 0.11 | 14.99 | 68.53 | 53.54 | 78.13 | 0.15 | 0.69 | 0.54 | 31.47 |
| | 21.01 | 0.11 | 20.91 | 106.85 | 85.94 | 80.43 | 0.21 | 1.07 | 0.86 | 43.15 |
| | 5.21 | 0.11 | 5.11 | 137.79 | 132.68 | 96.29 | 0.05 | 1.38 | 1.33 | 62.21 |

| Mn (ppm) | | | | | | | | | | |
|----------|---------|------|----------|----------|----------|-------|------|------|------|-------|
| | residue | soil | retained | adsorbed | desorbed | %des | qret | qads | qdes | Ce |
| SUN30 | 5.13 | 0.57 | 4.56 | 39.80 | 35.25 | 88.56 | 0.05 | 0.40 | 0.35 | 10.20 |
| | 3.68 | 0.57 | 3.10 | 70.45 | 67.35 | 95.60 | 0.03 | 0.70 | 0.67 | 29.55 |
| | 4.38 | 0.57 | 3.81 | 105.58 | 101.78 | 96.39 | 0.04 | 1.06 | 1.02 | 44.42 |
| | 1.16 | 0.57 | 0.59 | 134.07 | 133.48 | 99.56 | 0.01 | 1.34 | 1.33 | 65.93 |
| SUN33 | 6.56 | 0.88 | 5.69 | 41.16 | 35.47 | 86.18 | 0.06 | 0.41 | 0.35 | 8.84 |
| | 5.90 | 0.88 | 5.03 | 77.97 | 72.94 | 93.55 | 0.05 | 0.78 | 0.73 | 22.03 |
| | 7.60 | 0.88 | 6.72 | 114.89 | 108.17 | 94.15 | 0.07 | 1.15 | 1.08 | 35.11 |
| | 7.55 | 0.88 | 6.68 | 148.27 | 141.60 | 95.50 | 0.07 | 1.48 | 1.42 | 51.73 |
| SUN02 | 12.37 | 0.74 | 11.63 | 37.17 | 25.54 | 68.71 | 0.12 | 0.37 | 0.26 | 12.83 |
| | 24.31 | 0.74 | 23.57 | 68.54 | 44.97 | 65.61 | 0.24 | 0.69 | 0.45 | 31.46 |
| | 14.51 | 0.74 | 13.78 | 103.89 | 90.12 | 86.74 | 0.14 | 1.04 | 0.90 | 46.11 |
| | 15.89 | 0.74 | 15.16 | 136.52 | 121.36 | 88.90 | 0.15 | 1.37 | 1.21 | 63.48 |
| SUN25 | 11.06 | 1.87 | 9.19 | 35.81 | 26.62 | 74.33 | 0.09 | 0.36 | 0.27 | 14.19 |
| | 7.82 | 1.87 | 5.95 | 56.85 | 50.90 | 89.53 | 0.06 | 0.57 | 0.51 | 43.15 |
| | 9.01 | 1.87 | 7.14 | 86.80 | 79.66 | 91.77 | 0.07 | 0.87 | 0.80 | 63.20 |
| | 7.37 | 1.87 | 5.49 | 115.39 | 109.90 | 95.24 | 0.05 | 1.15 | 1.10 | 84.61 |
| SUN04 | 6.82 | 0.92 | 5.90 | 39.27 | 33.37 | 84.98 | 0.06 | 0.39 | 0.33 | 10.73 |
| | 5.03 | 0.92 | 4.12 | 71.44 | 67.33 | 94.24 | 0.04 | 0.71 | 0.67 | 28.56 |
| | 6.99 | 0.92 | 6.08 | 97.60 | 91.52 | 93.78 | 0.06 | 0.98 | 0.92 | 52.40 |
| | 2.43 | 0.92 | 1.51 | 121.27 | 119.76 | 98.75 | 0.02 | 1.21 | 1.20 | 78.73 |
| SUN14 | 17.24 | 1.44 | 15.80 | 36.66 | 20.87 | 56.92 | 0.16 | 0.37 | 0.21 | 13.34 |
| | 10.95 | 1.44 | 9.50 | 45.99 | 36.49 | 79.34 | 0.10 | 0.46 | 0.36 | 54.01 |
| | 10.69 | 1.44 | 9.25 | 89.34 | 80.09 | 89.65 | 0.09 | 0.89 | 0.80 | 60.66 |
| | 3.91 | 1.44 | 2.46 | 119.85 | 117.39 | 97.95 | 0.02 | 1.20 | 1.17 | 80.15 |
| SUN38 | 2.33 | 0.16 | 2.18 | 42.48 | 40.30 | 94.88 | 0.02 | 0.42 | 0.40 | 7.52 |
| | 3.17 | 0.16 | 3.02 | 74.03 | 71.01 | 95.93 | 0.03 | 0.74 | 0.71 | 25.97 |
| | 2.41 | 0.16 | 2.25 | 107.41 | 105.16 | 97.91 | 0.02 | 1.07 | 1.05 | 42.59 |
| | 0.62 | 0.16 | 0.47 | 138.68 | 138.22 | 99.66 | 0.00 | 1.39 | 1.38 | 61.32 |
| SUN40 | 2.66 | 0.13 | 2.53 | 41.47 | 38.94 | 93.90 | 0.03 | 0.41 | 0.39 | 8.53 |
| | 3.11 | 0.13 | 2.98 | 71.24 | 68.26 | 95.81 | 0.03 | 0.71 | 0.68 | 28.76 |
| | 3.22 | 0.13 | 3.09 | 108.04 | 104.95 | 97.14 | 0.03 | 1.08 | 1.05 | 41.96 |
| | 4.89 | 0.13 | 4.76 | 130.29 | 125.53 | 96.35 | 0.05 | 1.30 | 1.26 | 69.71 |
| SUN35 | 4.56 | 0.12 | 4.43 | 42.17 | 37.74 | 89.49 | 0.04 | 0.42 | 0.38 | 7.83 |
| | 4.37 | 0.12 | 4.25 | 76.34 | 72.10 | 94.44 | 0.04 | 0.76 | 0.72 | 23.66 |
| | 4.92 | 0.12 | 4.80 | 113.40 | 108.61 | 95.77 | 0.05 | 1.13 | 1.09 | 36.60 |
| | 1.60 | 0.12 | 1.48 | 140.74 | 139.27 | 98.95 | 0.01 | 1.41 | 1.39 | 59.26 |
| SUN32 | 17.05 | 2.81 | 14.23 | 32.26 | 18.02 | 55.88 | 0.14 | 0.32 | 0.18 | 17.74 |
| | 20.25 | 2.81 | 17.44 | 43.68 | 26.24 | 60.07 | 0.17 | 0.44 | 0.26 | 56.32 |
| | 12.46 | 2.81 | 9.65 | 77.17 | 67.52 | 87.49 | 0.10 | 0.77 | 0.68 | 72.83 |