

BEHAVIOUR OF SHALLOW FOUNDATIONS ON LATERITE SOIL

BY

IGIEDE, Osama Harris

ENG2006183

**A PROJECT SUBMITTED IN PARTIAL FUFILLMENT OF THE
REQUIREMENTS FOR THE AWARD OF BACHELOR OF ENGINEERING
(B.Eng.) DEGREE.**

IN

THE DEPARTMENT OF CIVIL ENGINEERING,

FACULTY OF ENGINEERING,

UNIVERSITY IF BENIN, BENIN CITY, NIGERIA.

NOVEMBER, 2025

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PLAGIARISM

This work **BEHAVIOUR OF SHALLOW FOUNDATIONS ON LATERITE SOIL** by

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DEDICATION

I dedicate this work “To the Almighty God, for guiding me and granting me strength, and to my loving parents, for their unwavering support, sacrifices, and unconditional love.

ACKNOWLEDGEMENT

My gratitude goes to Engr.Dr. Prof Sylvester Obinna Osuji and Engr Uche Ogbonna my project supervisors, who gave me the understanding, encouragement and assistance to carry out this work. I also like to thank the Head of Civil Engineering Department, University of Benin; and all other lecturers and staff of the Department of Civil Engineering for their guidance, mentorship and assistance. Finally, my gratitude goes to my family for all the love. May God continue to bless you all.

ABSTRACT

The behaviour of shallow foundations constructed on lateritic soils is of significant importance in tropical regions where these soils occur extensively and are commonly used for civil engineering works. Lateritic soils are highly variable in nature, and their engineering performance is strongly influenced by factors such as mineral composition, moisture content, degree of compaction, and environmental conditions. This variability often leads to challenges in predicting foundation performance and ensuring structural safety.

This study investigates the behaviour of shallow foundations on lateritic soils through a combination of field and laboratory investigations. Field studies include soil sampling and in-situ tests to assess the natural state of the lateritic deposits. Laboratory tests are conducted to determine the index properties, compaction characteristics, shear strength parameters, and bearing capacity of the soils. Model and empirical methods are employed to evaluate the load-bearing capacity and settlement behaviour of shallow foundations under different soil conditions.

The results of the study establish relationships between key soil properties—such as moisture content, density, plasticity, and strength—and the performance of shallow foundations. The findings provide valuable insight into the load-bearing behaviour of lateritic soils and highlight the importance of proper soil characterization in foundation design. The study aims to contribute to safer and more economical design practices for shallow foundations in lateritic soil environments, particularly in tropical regions.

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CHAPTER ONE

1.1 Introduction

The foundation is one of the most critical components of any civil engineering structure, as it provides the interface between the superstructure and the supporting ground. The performance of any structure depends greatly on the behavior of the underlying soil, which must be able to safely carry the loads transmitted from the structure without experiencing excessive settlement or failure (Das, 2011).

A shallow foundation is generally defined as a type of foundation in which the depth of embedment is less than or equal to the width of the foundation, typically used when suitable bearing stratum lies close to the surface. Examples include isolated footings, strip footings, raft foundations, and combined footings (Bowles, 1996). Shallow foundations are economical and widely adopted for low- and medium-rise structures such as residential buildings, schools, and small industrial facilities.

In tropical regions, lateritic soils form the most abundant type of residual soil. These soils develop through intense chemical weathering of parent rocks under alternating wet and dry seasons, resulting in the enrichment of iron and aluminum oxides that impart a reddish or brownish color (Gidigas, 1976). Laterites are often used in the construction of embankments, pavements, and foundations due to their widespread occurrence and relatively good strength when well compacted. However, their engineering behavior is highly sensitive to environmental changes such as moisture fluctuations and drainage conditions (Osinubi, 1998).

The bearing capacity and settlement of shallow foundations resting on lateritic soils are directly influenced by soil composition, compaction state, and degree of saturation (Adeyemi, 2002). In many cases, inadequate site investigation or inappropriate use of design parameters derived from non-lateritic soils has led to premature structural distress, foundation settlement, and in extreme cases, collapse. Hence, there is an increasing need to study and characterize the behavior of lateritic soils under structural loading conditions to provide reliable design parameters that reflect local soil conditions.

Several researchers (Ola, 1983; Gidigas, 1976; Oyediran & Kalejaiye, 2011) have emphasized that the variability of lateritic soils, even within short distances, makes it difficult to generalize their behavior. Therefore, localized investigations are necessary to obtain representative soil properties for design purposes. This research contributes to this effort by systematically investigating the response of shallow foundations on lateritic soils through detailed experimental and analytical work.

The study of lateritic soils has been a key focus of tropical geotechnics since the 1960s because of the increasing demand for infrastructure in developing regions where laterite predominates (Ola, 1983). These soils are used extensively as foundation materials, road subgrades, and construction fill, yet their variable nature poses significant challenges to engineers. In some cases, poorly compacted or saturated laterite can lead to differential settlement, shear failure, and foundation instability (Osinubi, 1998; Adeyemi, 2002).

1.1.2 Importance of Studying Lateritic Soils

Lateritic soils are widespread in tropical countries and form the natural ground conditions for a majority of construction works. In Nigeria and other parts of West Africa, lateritic soils

occupy more than 60% of the landmass (Gidigas, 1976). Their engineering behavior has direct implications for building foundations, particularly shallow ones, which rely heavily on near-surface soil strength. Understanding their geotechnical characteristics is therefore essential for sustainable and safe infrastructure design (Rahardjo et al., 2004).

Several studies (Ola, 1983; Osinubi, 1998; Bello, 2012) have shown that lateritic soils exhibit nonlinear stress-strain behavior and moisture sensitivity. When dry, they behave as competent load-bearing materials, but upon wetting, their structure can collapse, reducing shear strength and increasing settlement. This phenomenon is often observed in tropical construction projects during rainy seasons, where water infiltration into the foundation zone leads to rapid degradation of bearing capacity.

Consequently, the performance of shallow foundations on lateritic soils cannot be generalized—it depends on local environmental factors, degree of compaction, and the mineralogical composition of the soil. Thus, detailed geotechnical characterization is critical before any foundation design is undertaken.

Field studies have shown that well-compacted laterite can support shallow foundations with safe bearing capacities ranging between 150–300 kN/m², depending on soil type and depth (Adeyemi, 2002; Osinubi, 1998). In contrast, uncemented or highly plastic laterites can show bearing capacities as low as 50–100 kN/m² under similar conditions. This variability underscores the need for site-specific analysis.

Problem Statement

In many developing countries, particularly across sub-Saharan Africa, lateritic soils constitute the most common foundation material. Their natural abundance, low cost, and availability make them attractive for construction purposes. However, the behavior of structures founded on these soils has often been unpredictable and problematic due to the complexity of laterite formation processes and the variability in their engineering properties (Ola, 1983; Gidigas, 1976).

Instances of foundation failures, such as excessive differential settlement, cracking of walls, and even total collapse of buildings, have been reported in areas dominated by lateritic soils (Adeyemi, 2002). These failures often arise from insufficient geotechnical investigation, improper assessment of bearing capacity, and lack of understanding of the influence of moisture variation and compaction on soil strength (Osinubi, 1998). Seasonal fluctuations in groundwater levels and rainfall intensity also alter the soil's suction and degree of saturation, causing significant volume changes that affect the performance of shallow foundations.

Several case studies in Nigeria have documented instances where buildings resting on lateritic foundations developed visible cracks and uneven settlement within a few years of construction. According to Osinubi (1998), these issues often occur when the lateritic layer is underlain by a weak subgrade or clayey laterite that loses strength upon saturation. Additionally, shallow foundations constructed without considering compaction control, drainage design, or bearing capacity tests tend to fail prematurely (Bello, 2012; Adeyemi, 2002).

Another challenge associated with lateritic soils is their moisture sensitivity and volume instability. When subjected to moisture variations, especially in clayey laterites, the soil structure tends to soften, causing a reduction in bearing strength and an increase in settlement (Rahardjo et al., 2004). This behavior is especially problematic in tropical regions characterized by alternating wet and dry seasons. The cyclic swelling and shrinkage can lead to gradual deterioration of the foundation's load-carrying ability (Ola, 1983).

In most developing countries, there is also a lack of reliable local design standards for lateritic soils. Engineers often rely on conventional bearing capacity equations (Terzaghi, 1943; Meyerhof, 1963) developed for temperate-zone soils, which may not accurately represent the tropical soil behavior. Consequently, foundations designed based on such assumptions may not perform satisfactorily under local field conditions (Gidigas, 1976).

Furthermore, insufficient soil investigation and inadequate laboratory testing remain prevalent in many construction projects due to cost and time constraints. As noted by Bello (2012), many engineers and contractors rely on visual inspection or rule-of-thumb methods for classifying lateritic soils, without conducting detailed geotechnical evaluations. This practice often results in improper foundation type selection and inaccurate estimation of allowable bearing pressures, ultimately leading to structural distress.

In addition, most foundation design equations and empirical correlations currently used in practice—such as those of Terzaghi (1943), Meyerhof (1957), and Hansen (1970)—were developed based on non-lateritic, predominantly temperate-zone soils. When these equations are applied directly to tropical lateritic soils without calibration, they may yield unsafe or overly conservative results (Ola, 1983).

Aim and Objectives

Aim:

To investigate and evaluate the behavior of shallow foundations on lateritic soils, focusing on their load-bearing and settlement characteristics under varying moisture and compaction conditions.

Objectives:

- I. To determine the index and engineering properties of lateritic soils, including grain size distribution, Atterberg limits, and compaction characteristics.
- II. To assess the bearing capacity and settlement of shallow foundations on lateritic soils through laboratory and model testing.
- III. To evaluate the influence of moisture content, density, and degree of saturation on the performance of lateritic soils under structural loads.
- IV. To compare experimental findings with theoretical predictions from established bearing capacity models.
- V. To recommend design and construction guidelines for safe and economical shallow foundations in areas underlain by lateritic soils.

By addressing these objectives, the study will provide data-driven insights into how lateritic soil properties affect the performance and safety of shallow foundations, leading to more informed geotechnical design decisions.

Scope of the Study

The scope of this study is designed to ensure an in-depth evaluation of the geotechnical behavior of lateritic soils as foundation materials. The research focuses specifically on shallow foundations, such as isolated and strip footings, subjected to static loading conditions.

The study is restricted to lateritic soils obtained from a selected site representative of typical lateritic profiles in the study area. The soil samples are subjected to a range of laboratory tests—moisture content determination, sieve analysis, Atterberg limits, compaction tests, California Bearing Ratio (CBR) tests, and unconfined compressive strength (UCS) tests—to characterize their mechanical properties. Where possible, plate load tests or model foundation tests are conducted to simulate the performance of shallow foundations in controlled conditions.

The analysis focuses on the ultimate bearing capacity and settlement behavior of lateritic soils under different compaction and moisture regimes. The study does not extend to deep foundations, pile behavior, or dynamic load analysis, which are outside the defined scope.

Environmental factors such as seasonal moisture variation, drainage, and weathering degree are considered qualitatively but not modeled numerically. The results are specific to the tested soil types and locations, though general recommendations are made for similar tropical conditions.

The research covers four main dimensions of lateritic soil behavior:

- I. Physical characterization, which involves determining parameters such as particle-size distribution, natural moisture content, specific gravity, and Atterberg limits to understand the soil's fundamental classification.
- II. Compaction characteristics, obtained from Proctor compaction tests, which establish the relationship between dry density and moisture content and its implication on bearing capacity (Osinubi, 1998).
- III. Strength and bearing analysis, performed using direct shear, CBR, and plate-load testing to simulate shallow foundation performance (Meyerhof, 1963; Vesic, 1973).
- IV. Settlement and deformation behavior, estimated analytically and empirically to evaluate serviceability under applied loads (Terzaghi, 1943).

Furthermore, the research confines itself to naturally occurring lateritic soils in their in-situ state without chemical stabilization, in order to represent realistic field conditions.

However, references to stabilization studies are included for comparative purposes. The study also focuses on small- to medium-scale structures, such as residential buildings, small bridges, and service facilities—projects that predominantly rely on shallow foundations for economic and structural reasons.

The research period is limited to the duration necessary for field sampling, laboratory testing, and result analysis. The conclusions drawn are intended for use by civil and geotechnical engineers, builders, and policymakers seeking to improve construction practices on lateritic subsoils.

In essence, the study delineates its boundary within the interplay of soil–structure interaction, soil composition, and environmental factors affecting the performance of shallow foundations on laterite. Broader issues such as seismic loading, deep soil stabilization, or advanced finite-element simulations are beyond the present focus but recommended for future research (Rahardjo et al., 2004; Little, 2009).

Significance of the Study

The importance of this research lies in its potential to bridge the knowledge gap between theoretical foundation design models and the actual field behavior of lateritic soils.

Understanding the interaction between shallow foundations and lateritic subsoils is critical for several reasons:

I. Improved Foundation Design:

The study provides empirical data and analysis that can be used to refine bearing capacity and settlement calculations for lateritic soils. By providing accurate parameters such as cohesion, angle of internal friction, and allowable bearing pressure, engineers can design foundations that are both safe and cost-effective (Bowles, 1996).

II. Reduction in Structural Failures:

Structural failures due to inadequate understanding of soil behavior have led to significant financial and human losses. By clarifying how lateritic soils behave under different loading and moisture conditions, this study contributes to reducing risks of foundation failure (Osinubi, 1998).

III. Local Relevance:

Many developing nations import design parameters from foreign standards developed under temperate conditions. This study generates context-specific data relevant to tropical soils, thereby enhancing local engineering practice (Gidigas, 1976).

IV. Economic Benefits:

By optimizing foundation design for lateritic soils, construction costs can be reduced without compromising safety. This promotes the use of local materials, minimizing the need for expensive soil replacement or stabilization measures.

V. Academic and Research Contribution:

The findings enrich the existing literature on geotechnical behavior of lateritic soils, serving as a reference for students, researchers, and practitioners (Ola, 1983; Adeyemi, 2002).

VI. Policy and Standardization:

The research outcomes could inform the development of revised building codes and geotechnical design standards suited for tropical lateritic environments.

In economic terms, this study promotes cost-effective infrastructure development. Lateritic soils are naturally abundant and, when properly understood, can serve as reliable foundation materials, reducing the need for expensive soil replacement or chemical stabilization. Given that foundation work can represent 20–30 % of total construction costs (Bowles, 1996), improved knowledge of local soil behavior directly translates into substantial financial savings for both public and private projects.

On a societal level, the research holds significance for sustainable development in tropical regions. Failures of shallow foundations often result in property loss, displacement, and even casualties. By enhancing understanding of the geotechnical behavior of lateritic soils, the study contributes to safer housing, improved public infrastructure, and greater community resilience to environmental stresses. The work also aligns with global

sustainability objectives that encourage the use of local materials and environmentally responsible construction methods (Rahardjo et al., 2004).

Finally, the scientific relevance of this research lies in its potential to advance understanding of soil genesis and its effect on engineering performance. The behavior of laterite, governed by chemical weathering and pedogenic processes, represents a bridge between geology and engineering (Little, 2009). A detailed investigation of its response to load contributes to broader geotechnical theories regarding residual soils and their mechanical evolution.

In summary, the study is significant because it:

- I. Enhances geotechnical knowledge of lateritic soil behavior under foundation loads;
- II. Provides empirical data for design optimization in tropical environments;
- III. Supports cost-effective and sustainable construction;
- IV. Contributes to safer community infrastructure and resilience; and
- V. Lays groundwork for policy formulation and future research directions.

Outline of Methodology

The methodology for this study integrates field investigation, laboratory experimentation, and analytical evaluation. It is structured to systematically determine the physical and mechanical properties of lateritic soils and assess their behavior under shallow foundation loads.

I. Site Selection and Description:

A representative lateritic soil site is identified based on geological and accessibility criteria. Preliminary reconnaissance is conducted to understand topography, drainage, vegetation, and existing structures. Boreholes or trial pits are excavated to collect samples at various depths (BS 1377, 1990).

II. Sample Collection and Preparation:

Both disturbed and undisturbed soil samples are collected using standard geotechnical procedures. Disturbed samples are used for classification and compaction tests, while undisturbed samples are used for strength and consolidation tests. Samples are carefully labeled, sealed, and transported to the laboratory to prevent moisture loss.

III. Laboratory Testing:

Laboratory experiments are carried out according to standard testing procedures (ASTM D4318, D698, D1883; BS 1377). Tests include:

- I. *Moisture content determination*
- II. *Specific gravity test*
- III. *Grain size distribution (sieve analyses)*

- IV. *Atterberg limits (liquid limit, plastic limit, plasticity index)*
- V. *Compaction test (Standard or Modified Proctor)*
- VI. *California Bearing Ratio (CBR) test*
- VII. *Unconfined compressive strength test (UCS)*
- VIII. *Direct shear test (for cohesion and angle of internal friction)*

IX. Data Analysis:

Experimental results are analyzed statistically to determine correlations between soil properties and bearing capacity. The observed results are compared with theoretical predictions from Terzaghi, Meyerhof, and Hansen equations. Appropriate correction factors are introduced where necessary to account for the peculiar behavior of lateritic soils.

X. Interpretation and Recommendations:

The final stage involves interpretation of results, identifying key parameters affecting performance, and providing practical recommendations for foundation design and construction in lateritic soils.

XI. Report Compilation:

All results, graphs, and analyses are compiled into a comprehensive report following academic standards, including references, appendices, and data tables.

The methodological framework adopted provides a balanced integration of field exploration, laboratory experimentation, and analytical interpretation, enabling a comprehensive understanding of the behavior of shallow foundations on lateritic soils. The

approach ensures that results are robust, reproducible, and practically applicable for tropical geotechnical design.

CHAPTER TWO

LITERATURE REVIEW

2.3 Physical and Engineering Properties of Lateritic Soils

2.3.1 General Characteristics

Lateritic soils exhibit distinctive physical and mechanical characteristics derived from their unique mineralogical composition and weathering processes. These soils typically contain varying proportions of kaolinite, goethite, hematite, and gibbsite, which contribute to their color, strength, and behavior under load (Gidigas, 1976). The degree of laterization—determined by the extent of silica leaching—dictates the relative abundance of iron and aluminum oxides that form bonding agents between soil particles.

According to Ola (1983), lateritic soils may range from gravelly and sandy to highly plastic clayey materials, depending on the nature of the parent rock and climatic conditions during formation. They are often characterized by high specific gravity (2.6–2.8), moderate to high dry density, and low to moderate plasticity. Their color ranges from reddish-brown to dark brown, reflecting the dominance of iron oxides.

2.3.2 Index Properties

Index properties provide the basic classification and identification parameters for lateritic soils. Typical laboratory tests include determination of natural moisture content, Atterberg limits, particle size distribution, and specific gravity (BS 1377, 1990; ASTM D4318).

- I. **Moisture Content:** Lateritic soils display moderate to high natural moisture contents, often ranging from 10–25%, depending on the degree of saturation and environmental conditions.
- II. **Plasticity:** Studies by Osinubi (1998) and Adeyemi (2002) show that lateritic soils typically fall within medium to high plasticity categories on the Casagrande plasticity chart, with Plasticity Index (PI) values between 12–25%.
- III. **Grain Size Distribution:** Particle size analysis reveals a dominance of sand and silt fractions, although clayey laterites may contain up to 40% fines (Rahardjo et al., 2004).
- IV. **Specific Gravity:** Specific gravity values commonly lie between 2.65 and 2.80, reflecting the mineral composition and iron oxide concentration (Little, 2009).

These properties are crucial in classifying lateritic soils for foundation design, as they directly influence compaction, permeability, and bearing strength.

2.3.3 Compaction Characteristics

Compaction is an essential process in enhancing the engineering performance of lateritic soils. It reduces void spaces, increases dry density, and improves load-bearing capacity. The relationship between moisture content and dry density typically follows a parabolic curve with a distinct optimum moisture content (OMC) corresponding to maximum dry density (MDD).

Osinubi (1998) reported that for tropical lateritic soils, OMC values range between 10–20%, while MDD varies from 1.80–2.10 Mg/m³ under standard Proctor compaction. The type of compaction effort significantly affects these values, with modified Proctor tests yielding

higher densities. Increased compaction generally enhances shear strength and reduces compressibility, but over-compaction may lead to particle crushing or reduction in permeability (Bello, 2012).

2.3.4 Shear Strength Parameters

The shear strength of lateritic soils arises from internal friction and apparent cohesion due to cementation and suction effects. Direct shear and triaxial compression tests are commonly employed to determine these parameters.

Studies by Adeyemi (2002) and Rahardjo et al. (2004) demonstrated that the angle of internal friction (ϕ) typically ranges from 25° to 35°, while cohesion (c) varies between 10–40 kN/m² depending on compaction and saturation levels. Cemented laterites often exhibit higher shear strength but may lose a significant portion upon wetting due to softening of bonds.

2.3.5 Permeability and Compressibility

Lateritic soils are generally characterized by low to moderate permeability, with hydraulic conductivity values ranging from 10⁻⁶ to 10⁻⁴ m/s (Ola, 1983). However, this parameter is highly dependent on texture and structure. Well-compacted laterites tend to have low permeability, minimizing water infiltration and improving foundation stability.

Compressibility, on the other hand, is generally low to moderate due to the dense packing and cementation of particles.

2.3.6 Correlation Between Properties

Several researchers have attempted to establish empirical correlations between physical properties and engineering performance. For example, Adeyemi (2002) found a strong relationship between plasticity index and compressive strength, indicating that soils with higher plasticity tend to exhibit lower bearing capacity. Similarly, Osinubi (1998) correlated maximum dry density with California Bearing Ratio (CBR) values, concluding that compaction energy directly influences load-bearing ability.

In conclusion, the physical and engineering properties of lateritic soils vary widely, but their behavior is strongly influenced by moisture content, compaction level, and cementation degree. Proper evaluation of these properties is essential for predicting foundation performance and ensuring safe design.

2.4 Behavior of Shallow Foundations on Lateritic Soils

2.4.1 General Overview

The performance of shallow foundations depends fundamentally on the interaction between the structural load and the underlying soil. In the case of lateritic soils, this interaction is complex due to their heterogeneity and environmental sensitivity. The bearing capacity and settlement characteristics are influenced by factors such as moisture variation, density, particle size distribution, and degree of cementation (Osinubi, 1998; Adeyemi, 2002).

Field and laboratory studies have shown that lateritic soils can provide satisfactory bearing support when properly compacted and drained. However, when exposed to prolonged

wetting, their strength decreases significantly, leading to excessive settlement or shear failure (Rahardjo et al., 2004).

2.4.4 Case Studies and Observations

Modification of Lateritic Soil Using Waste Plastics for Sustainable Road Construction (Obianyo et al., 2024)

Background and Relevance

In the context of sustainable geotechnical engineering, waste utilization has become a central research focus. Among these efforts, the modification of lateritic soils using polymeric waste materials provides an innovative approach to reducing environmental pollution while enhancing soil performance. Lateritic soils, abundant across tropical regions such as Nigeria, Ghana, and India, are widely used for road subgrades and shallow foundations but often suffer from variable engineering behavior and moisture sensitivity (Ola, 1983; Gidigas, 1976).

Obianyo et al. (2024) conducted a recent experimental and analytical study addressing this issue by incorporating shredded waste plastics into lateritic soil. Their research explores the dual objective of improving soil strength characteristics and minimizing plastic waste accumulation, aligning with the United Nations Sustainable Development Goals (SDGs 11 and 12).

Study Objectives and Scope

The authors aimed to investigate how varying percentages of shredded plastic waste affect the geotechnical properties of lateritic soils—specifically, the index characteristics,

Plastic Content	OMC (%)	MDD (Mg/m ³)	CBR (%)	UCS (kN/m ²)	Remarks
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compaction behavior, and bearing strength evaluated through California Bearing Ratio (CBR) testing. They hypothesized that low plastic inclusion could improve soil stiffness and load distribution while excessive addition might lead to poor interparticle bonding and reduced performance.

Methodology Overview

Lateritic soil samples were collected from a borrow pit in southeastern Nigeria. Laboratory procedures followed ASTM D4318 and D1883 standards. Plastic waste—primarily high-density polyethylene (HDPE)—was cleaned, shredded, and blended into the soil at 0%, 2%, 4%, 6%, 8%, and 10% by dry weight. Each mix was subjected to:

1. Moisture-Density Relationship Tests (Standard Proctor)
2. Atterberg Limits Tests
3. CBR and Unconfined Compressive Strength (UCS) Tests

The tests were performed under controlled compaction energies and optimum moisture conditions.

Results and Analysis

Table 2.1 summarizes key laboratory outcomes adapted from Obianyo et al. (2024).

Table 2.1: Summary of Index and Strength Properties of Plastic-Modified Lateritic Soil

(%)					
0 (Control)	15.2	1.91	52	225	Baseline
2	14.6	1.94	63	248	Optimum mix
4	15.8	1.89	55	232	Slight reduction
6	16.3	1.85	46	210	Loss of bond
8	17.1	1.80	38	192	Too flexible
10	17.5	1.77	33	184	Poor performance

Source: Adapted from Obianyo et al. (2024, Polymers, 16(19), 2689).

As shown, adding 2% plastic waste yielded the highest MDD and CBR, demonstrating improved density and strength. Beyond 4% content, strength declined due to inadequate interfacial bonding and reduced particle contact.

Figure 2.1 (from the same study) illustrates the variation of CBR with plastic content, showing an initial rise followed by a sharp decline after 2%.

Caption: CBR vs. Plastic Content for Plastic-Modified Lateritic Soil (Obianyo et al., 2024).

At optimal content ($\approx 2\%$), the shredded plastic fills intergranular voids and enhances interparticle friction, improving load transfer. However, excess plastic acts as a soft inclusion, creating slip planes that reduce stiffness and strength (Obianyo et al., 2024). The authors connect these findings to microstructural mechanisms verified through scanning

electron microscopy (SEM), which showed improved matrix bonding at low plastic content but isolated polymer domains at high content.

Critical Evaluation

The study successfully demonstrates a waste-to-wealth approach for soil improvement but remains limited to short-term laboratory evaluation. Long-term durability, creep, or thermal effects were not explored. Moreover, the scope focuses primarily on subgrade applications; further analysis is required for foundation bearing contexts, including settlement under static loads.

Nevertheless, the research underscores that low-level polymer modification could complement conventional stabilization methods, offering cost and environmental benefits (Obianyo et al., 2024).

African Lateritic Soils and Pavements Failure (Akinbuluma et al., 2025)

Background and Context

Lateritic soils dominate most tropical regions, including sub-Saharan Africa, where they serve as the primary materials for road subgrades, embankments, and shallow foundations. However, these soils are often subject to premature failure when exposed to seasonal moisture fluctuations and poor construction practices (Gidigas, 1976; Ola, 1983). The recent open-access review by **Akinbuluma et al. (2025)** provides an in-depth synthesis of field case studies across Africa that document recurrent pavement distress attributable to lateritic subgrade weaknesses. While the paper focuses mainly

on road engineering, its findings are equally relevant to the performance of shallow foundations built on similar soil strata.

Aim and Scope of the Review

Akinbuluma et al. (2025) sought to identify the root causes of pavement deterioration on lateritic subgrades, classify failure mechanisms, and assess the adequacy of current mitigation strategies. The authors analyzed data from numerous published and unpublished Nigerian, Ghanaian, and Kenyan road-failure investigations, highlighting patterns of distress such as rutting, cracking, differential settlement, and subgrade softening. By integrating results from laboratory testing, climatic data, and field observations, the study develops a comprehensive cause-effect framework that connects geotechnical factors with operational and environmental variables.

Major Findings and Synthesized Evidence

The authors classify lateritic pavement failures into four principal mechanisms:

1. **Moisture-Induced Softening:** Loss of matric suction following heavy rainfall leads to rapid reduction in shear strength and CBR values.
2. **Inadequate Compaction:** Non-uniform or insufficient compaction at construction causes differential settlement.
3. **Poor Drainage Design:** Absence of lateral drains or filter layers allows water accumulation and progressive subgrade degradation.
4. **Inappropriate Material Selection:** Reliance on visually identified laterite rather than laboratory-tested material leads to use of highly plastic clays misclassified as laterite.

Akinbuluma et al. (2025) present comparative data (Table 2.2) summarizing the range of California Bearing Ratio (CBR) values observed under various field conditions.

Table 2.2 – Typical CBR Ranges for Lateritic Soils under Different Field Conditions

The table underscores that moisture and compaction exert dominant control over bearing strength. Notably, the authors show that even low-cost interventions—such as shallow drainage ditches and compaction at optimum moisture content—can double

Condition	Mean CBR (%)	Typical Failure Observation
Dry, well-compacted, drained	60 – 80	Stable performance
Poorly compacted	25 – 45	Early rutting, settlement
Saturated (rainy season)	15 – 30	Severe cracking, softening
Stabilized with 4–6% cement	90 – 110	Excellent performance

the CBR of untreated lateritic soils.

Figure 2.2 (conceptual chart) in the paper illustrates the exponential decline of bearing capacity with increasing degree of saturation. It emphasizes that once the soil suction falls below 10 kPa, the apparent cohesion nearly vanishes, leaving only frictional resistance to sustain load.

Critical Evaluation

The strength of Akinbuluma et al. (2025) lies in its comprehensive integration of climatic, geotechnical, and construction factors. The authors move beyond laboratory findings to analyze real-world field failures, thereby linking theory with practice.

However, the study's dependence on secondary data and inconsistent testing protocols limits its quantitative comparability. For instance, some CBR results were measured under soaked conditions while others were unsoaked, introducing variability.

Furthermore, long-term monitoring beyond 7 years is rare, restricting assessment of progressive deterioration.

Implications for Shallow Foundations

Although the study targets pavements, its conclusions are directly applicable to foundations built on lateritic soils:

- I. Foundation Embedment Depth: Footings should be placed below the zone of seasonal moisture fluctuation to maintain suction stability.
- II. Compaction Control: Achieving $\geq 95\%$ MDD during foundation backfilling drastically improves bearing capacity.

- III. Drainage Provision: Proper site grading and perimeter drains are essential to avoid seasonal softening.
- IV. Material Verification: Field laterite must be confirmed through laboratory tests (Atterberg limits, CBR, grain size) before design assumptions.

Characterization of Laterite Soil and its Use in Construction Applications — A Review (Santha Kumar et al., 2022)

The characterization of lateritic soils has remained a central topic in tropical geotechnical research for over six decades, yet inconsistencies in classification and behavioral prediction persist. *Santha Kumar et al. (2022)* presented a comprehensive review synthesizing findings from Asia, Africa, and South America, focusing on how mineralogical, chemical, and physical attributes influence engineering performance. Their study integrates over 60 peer-reviewed papers and technical reports to produce a global view of laterite variability and its implications for construction applications, particularly in road works, building foundations, and compressed-earth blocks.

The authors' rationale stems from the need to harmonize geotechnical and geological perspectives. They argue that most failures involving lateritic materials result not from inherent weakness but from the misuse of inappropriate classification systems originally designed for temperate soils (Santha Kumar et al., 2022).

Scope and Structure of the Review

The paper systematically examines:

1. Formation and mineralogical characteristics of laterites.

2. Index and engineering properties (Atterberg limits, specific gravity, compaction, shear strength).
3. Correlations among mineralogy, microstructure, and mechanical behavior.
4. Construction applications and stabilization practices.

This structured approach makes the paper particularly valuable for literature synthesis in soil behavior and material improvement.

Key Findings and Synthesis

1. Formation and Composition:

Lateritic soils form through prolonged chemical weathering and leaching in hot, humid climates. The enrichment of Fe_2O_3 and Al_2O_3 leads to strong cementation and low silica content. Mineralogically, kaolinite dominates the clay fraction, while hematite and goethite contribute to reddish coloration and variable strength (Santha Kumar et al., 2022).

2. Index and Engineering Properties:

The review compiles average index ranges for tropical laterites (Table 2.3).

Table 2.3 – Typical Index and Strength Ranges of Lateritic Soils

Liquid Limit	35 – 65 %	Medium – high plasticity
Plasticity Index	12 – 28 %	Moderately cohesive
MDD (Mg/m^3)	1.80 – 2.10	Well compacted
OMC (%)	10 – 20	Typical for construction moisture

CBR (%)	50 – 150	Adequate for low-rise foundations
Angle of Friction (°)	25 – 35	Moderate shear strength

Source: Santha Kumar et al., 2022.

Application and Stabilization:

Laterites are widely used in earth-block production, pavement layers, and shallow foundations. Stabilization using lime, cement, or fly ash enhances load-bearing strength by 50 – 200 %, depending on additive type and curing (Santha Kumar et al., 2022).

Implications for Shallow Foundations

- I. Foundation design on laterite should employ site-specific correlations among density, moisture, and strength.
- II. Mineralogical testing (XRD or chemical ratio analysis) should complement routine index tests.
- III. Suction effects must be included in bearing-capacity models.

Research Gaps

- I. Lack of unified classification for tropical laterites across regions.
- II. Need for probabilistic design models capturing variability.
- III. Insufficient long-term data on suction-strength relationships.

Effect of Sand Addition on Lateritic Soil Stabilization (Guimarães et al., 2025)

Mechanical modification through gradation adjustment offers an environmentally friendly alternative to chemical stabilization. *Guimarães et al. (2025)* conducted experimental and theoretical research evaluating the impact of sand addition on the stiffness and durability of clayey lateritic soils. Although the work targets road subgrades, its results are valuable for understanding granular control in shallow foundation materials.

Objectives and Scope

The authors aimed to determine how partial replacement of fines with sand alters compaction, resilient modulus, and permanent deformation characteristics of lateritic soils under repeated loads. The broader literature review embedded in the article synthesizes prior research on grain-size optimization, aggregate interlock, and unsaturated behavior of laterites.

Experimental Overview

Soil samples (highly plastic laterite) were blended with 0 %, 10 %, 20 %, and 30 % sand by weight. Laboratory tests included:

- I. Standard / Modified Proctor Compaction
- II. Repeated Load Triaxial Test (for Resilient Modulus, M_r)
- III. Permanent Deformation (PD) assessment
- IV. Scanning Electron Microscopy (SEM) to observe microstructure

Key Results

Table 2.4 – Effect of Sand Addition on Compaction and Strength

Sand Content (%)	OMC (%)	MDD (Mg/m ³)	Resilient Modulus (MPa)	PD (%) after 500 cycles
0	17.2	1.80	65	3.5
10	15.6	1.86	92	2.4
20	14.8	1.88	105	1.9
30	14.5	1.83	96	2.1

Source: Guimarães et al., 2025 (Scientific Reports 15:12 620).

The results show a marked improvement in stiffness and reduced permanent deformation up to 20 % sand content, after which performance declined slightly.

The enhancement is attributed to improved particle packing and interlocking between sand grains and lateritic fines. However, excessive sand (> 20 %) reduces the suction component and cohesion provided by the clay fraction, leading to marginal stiffness loss (Guimarães et al., 2025).

Figure 2.4 plots M_r versus sand content, showing a bell-shaped curve with an optimum around 20 %.

Relevance to Shallow Foundations

- I. Controlled gradation can enhance stiffness and reduce settlement under moderate loads.
- II. Optimum sand content ($\approx 20\%$) yields the best compaction and stiffness balance.

- III. Excessive sand may increase permeability, leading to moisture fluctuations beneath footings.

Strength and Durability Assessment of Lateritic Soil Stabilised with Partial Blend of Calcium-Based and Agro-Based Additives (Mezie et al., 2025)

With growing concerns about the carbon footprint of Portland cement, researchers are exploring partial replacement with agro-industrial pozzolans such as rice-husk ash (RHA) and oil-palm empty-fruit-bunch ash (OPEFBA). *Mezie et al. (2025)* conducted a combined experimental and literature-based review examining the mechanical and durability behavior of lateritic soils stabilized with hybrid calcium- and agro-based additives. Their work provides insight into long-term strength retention under tropical moisture cycles—an issue crucial for shallow foundation reliability.

The study aims to evaluate:

- I. The compressive and bearing strength improvements achievable through hybrid stabilization.
- II. Durability under cyclic wetting–drying.
- III. Environmental and cost implications relative to conventional cement stabilization.

Experimental and Review Framework

Lateritic soils from southeastern Nigeria were blended with varying proportions of cement (0–6 %) and RHA/OPEFBA (0–10 %). Laboratory tests included: unconfined compressive strength (UCS), CBR, and durability under 12 wet–dry cycles. Additionally, the authors

reviewed 40+ prior studies on pozzolanic stabilization of laterites to contextualize their findings.

Results and Discussion

Table 2.5 – Mechanical Properties of Hybrid-Stabilized Lateritic Soil

Mix Designation	Cement (%)	RHA (%)	OPEFBA (%)	UCS (kN/m ²) (28 d)	CBR (%)	Strength Loss after 12 cycles (%)
Control	0	0	0	210	45	–
Mix 1	2	6	0	385	92	19
Mix 2	4	6	0	430	110	13
Mix 3	4	4	4	450	116	11
Mix 4	6	0	6	470	118	9

Figure 2.5 plots UCS versus curing time, showing continuous strength gain up to 28 days with minimal decline after cyclic testing for hybrid mixes compared to control.

The data reveal that replacing up to 50 % of cement with agro-ash maintains comparable strength while improving durability. Strength losses after twelve wet–dry cycles were below 15 % for optimized blends, versus > 40 % for cement-only soils.

Interpretation and Mechanistic Insight

The improved performance stems from additional **pozzolanic reactions** between silica-rich ash and calcium hydroxide liberated by cement hydration, producing secondary calcium silicate hydrate (C-S-H) gels. The presence of both fine (ash) and coarse (OPEFBA) particles refines pore structure, reducing water ingress and minimizing micro-cracking during wet-dry cycles (Mezie et al., 2025).

Research Gaps

- I. Limited field data on settlement and long-term stiffness retention.
- II. Lack of standardized chemical-composition benchmarks for agro-ashes.
- III. Need for life-cycle cost and carbon-emission analyses for large-scale implementation.

METHODOLOGY

3.1 Introduction

This chapter outlines the methodological framework adopted to investigate the behavior of shallow foundations on lateritic soils within the University of Benin, Benin City, Southwestern Nigeria. The approach integrates both field and laboratory investigations, enabling a comprehensive evaluation of the geotechnical properties that influence the bearing capacity and settlement performance of shallow foundations in lateritic environments.

The methodology was designed to provide a systematic, reproducible, and scientifically robust procedure to achieve the objectives of the study. It includes the processes of site reconnaissance, soil sampling, in-situ testing, laboratory testing, analytical modeling, and data interpretation.

Given that the University of Benin is located in a region characterized by intense laterization, high rainfall, and variable groundwater levels, the selected study area provides an ideal representation of tropical lateritic soil conditions (Ola et al., 1983; Gidigas, 1976). The research therefore contributes valuable data for improving foundation design practices under similar geotechnical and climatic conditions.

The procedures presented in this chapter are organized into several key phases:

- I. Research Design and Conceptual Framework
- II. Description of Study Area
- III. Site Selection and Sampling Procedures

- IV. Field and Laboratory Testing Program
- V. Data Analysis and Validation Methods

Each phase was carefully planned to ensure data accuracy and to minimize errors due to human and environmental factors. The methodology aligns with standards set forth by the British Standard Institution (BS 1377, 1990) and the American Society for Testing and Materials (ASTM, 2020) for soil testing and geotechnical evaluation.

3.2 Research Design and Conceptual Framework

The study adopts a quantitative experimental research design, supported by qualitative field observations. This combination ensures a holistic understanding of the geotechnical behavior of the soil and how it interacts with shallow foundation structures (Das, 2011; Bowles, 1996).

The quantitative aspect involves laboratory determination of key parameters such as grain size distribution, Atterberg limits, compaction characteristics, California Bearing Ratio (CBR), and shear strength. These values are then used to calculate allowable bearing capacity and expected settlements under applied structural loads.

The qualitative component consists of on-site observations of soil color, consistency, and moisture conditions, as well as the visual inspection of structural performance at the “Blocks of Flats” construction site [borrow pit] within the University of Benin campus. This dual approach ensures a practical correlation between laboratory findings and actual field conditions (Adeyemi et al., 2002; Bello et al., 2012).

The conceptual framework guiding the study is represented in **Figure 3.1**. It illustrates the relationship between soil properties (input variables) and foundation behavior (output variables).

Figure 3.1: Conceptual Framework of the Study

Environmental Factors (Rainfall, Temperature)



Soil Properties (Moisture Content, Density, Plasticity)



Engineering Parameters (CBR, Shear Strength, Cohesion, Friction Angle)



Foundation Behavior (Bearing Capacity, Settlement, Stability)

This flow demonstrates how environmental and intrinsic soil properties affect the engineering performance of shallow foundations.

By integrating field and laboratory data, the study aims to develop a reliable basis for predicting shallow foundation performance on lateritic soils typical of the Benin Formation — a geological unit known for its ferruginous sandy clays and silty laterites (Osinubi et al., 2015; Ige et al., 2021).

3.3 Description of the Study Area

3.3.1 Location and Accessibility

The study area is situated within the University of Benin, Ugbowo Campus, located in Benin City, Edo State, Southwestern Nigeria. The campus lies between latitudes 6°20'N and 6°23'N, and longitudes 5°36'E and 5°39'E. Benin City is accessible via major road networks including the Lagos–Benin Expressway and Benin–Auchi Road, making it convenient for research logistics and transportation of soil samples.

The investigation was specifically carried out at the Blocks of Flats construction site within the Faculty of Engineering area, where shallow foundations are being developed for multistory buildings. This location was chosen because of its representative lateritic subsoil, availability of construction activities for field observation, and accessibility to laboratory facilities.

3.3.2 Climate and Environmental Conditions

Benin City falls within the humid tropical rainforest climate zone of Nigeria, characterized by high rainfall and temperature. The region experiences two major seasons — a rainy season (April to October) and a dry season (November to March). Average annual rainfall ranges between 2,000–2,400 mm, while average temperature varies between 24°C and 32°C (NIMET, 2022).

This climatic regime encourages intense chemical weathering of parent rocks, leading to the formation of lateritic soils rich in iron and aluminum oxides (Gidigas, 1976; Fookes, 1997). The alternating wet and dry conditions also contribute to the fluctuating moisture contents that significantly influence soil strength and bearing characteristics (Rahardjo et al., 2004).

Seasonal variations in precipitation and temperature are particularly relevant to this study since they affect the volume stability, permeability, and strength behavior of lateritic soils under foundation loads (Adeyemi et al., 2002; Bello et al., 2012).

3.3.3 Geology and Soil Formation

Geologically, Benin City lies within the Benin Formation (Miocene–Recent age), which is part of the Coastal Plain Sands of Southern Nigeria (Ola et al., 1983; Ako et al., 1989). The formation consists predominantly of poorly consolidated sands, clayey sands, lateritic soils, and gravels with occasional lignite interbeds.

The lateritic soils found within the University of Benin campus are derived primarily from the weathering of ferruginous sandstones and shale materials under intense leaching and oxidation processes. These soils are typically reddish-brown to yellowish in color, indicating the presence of iron oxides, and exhibit variable plasticity and compaction characteristics (Adeyemi, 2002).

The lateritic profile in the study area generally consists of:

- I. A topsoil (0–0.3 m): dark brown, organic, non-bearing.
- II. A lateritic horizon (0.3–3.0 m): reddish-brown, compact, and suitable for foundation bearing.
- III. A subgrade layer (>3.0 m): silty or clayey sand transitioning to weathered rock.

According to Osinubi et al. (2015), lateritic soils within this region display moderate bearing capacity (120–200 kN/m²) and CBR values ranging from 8–25%, depending on compaction and moisture content.

3.4 Site Selection Criteria

The selection of the Blocks of Flats site within the University of Benin campus for this investigation was guided by technical, accessibility, and representativeness criteria consistent with BS 5930 (2015) site investigation procedures.

The criteria included:

- I. **Representativeness of Soil Type:** The site contains a well-developed lateritic soil profile typical of the Southwestern Nigeria region (Ola, 1983).
- II. **Accessibility:** The construction site was easily accessible for both manual and mechanical sampling equipment.
- III. **Active Construction Activity:** Ongoing foundation construction allowed for comparative observations between laboratory results and real-world structural responses.
- IV. **Safety and Security:** The university environment provided a controlled and safe space for sampling and testing activities.
- V. **Proximity to Laboratory Facilities:** The Civil Engineering Department's Geotechnical Laboratory was located within walking distance, enabling immediate testing of collected samples to minimize disturbance and moisture loss.

3.4.1 Sampling Depth and Locations

sampling depths were selected corresponding to the typical bearing stratum for shallow foundations such as pad or strip footings in lateritic environments. Samples were collected using a hand auger and core cutter, sealed in polythene bags, and labeled.

Each sample was transported to the Geotechnical Engineering Laboratory for subsequent analysis. The selection of these depths was informed by previous studies that identified significant variation in density, plasticity, and moisture content across shallow depths (Adeyemi, 2002; Bello, 2012; Osinubi et al., 2015).

3.5 Materials and Equipment

The materials and equipment used in this research were selected to ensure accurate field sampling and laboratory testing of lateritic soils within the study area. The instruments were consistent with standards recommended by the British Standard Institution (BS 1377, 1990) and ASTM (2020) specifications.

Table 3.1: Summary of Major Materials and Equipment Used

Category	Equipment	Purpose
Field Tools	Hand auger, core cutter, sampling tubes	Soil collection at three depths
	Dynamic Cone Penetrometer (DCP)	Field strength and compaction index
	Plate load test apparatus	In-situ determination of bearing capacity
	Measuring tape, pegs, and GPS device	Depth and coordinate determination
Laboratory	Oven, balance, hydrometer,	Physical property and

Equipment	sieve set	classification tests
	Compaction mold and rammer	Proctor compaction tests
	CBR machine	Bearing ratio evaluation
	Direct shear box and UCS apparatus	Shear and compressive strength tests
	Atterberg limit device	Consistency limit determination

The equipment was calibrated prior to use to ensure data reliability, following standard geotechnical procedures (Das, 2011; Whitlow, 2001).

3.6 Field Investigation Procedures

The field investigation phase provided baseline data on the in-situ characteristics of lateritic soils within the study area. These tests and sampling operations were designed to capture the natural variability of soil properties with depth and moisture content.

3.6.2 Field Sampling

Disturbed and undisturbed soil samples were collected at depths using a hand auger and sampling tubes. The undisturbed samples were primarily used for strength and compressibility tests, while the disturbed samples were used for classification and compaction studies.

3.7 Laboratory Investigation Procedures

Following field investigations, the collected samples were transported to the Civil Engineering Geotechnical Laboratory of the University of Benin for detailed testing. The

laboratory testing program aimed to determine the physical and engineering characteristics that influence foundation performance.

3.7.1 Index Property Tests

The following tests were performed to identify soil classification and basic physical properties:

- I. Natural Moisture Content (ASTM D2216):
Determines the water content of the soil samples at different depths.
- II. Specific Gravity (ASTM D854):
Indicates mineral composition and soil particle density.
- III. Particle Size Distribution (ASTM D422):
Assesses the proportion of sand, silt, and clay fractions using sieve and hydrometer analysis.
- IV. Atterberg Limits (ASTM D4318):
Defines the liquid limit (LL), plastic limit (PL), and plasticity index (PI), which reflect soil consistency and compressibility.

3.7.2 Compaction and Strength Tests

- I. Proctor Compaction Test (BS 1377, 1990):
Determines the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), key parameters influencing soil strength and bearing capacity.
- II. California Bearing Ratio (CBR):
Evaluates the load-bearing potential of compacted lateritic soils under penetration loads.

III. Unconfined Compressive Strength (UCS):

Provides the undrained compressive strength, particularly relevant for saturated lateritic layers (Bello et al., 2012).

Table 3.3: Summary of Laboratory Tests Conducted

Test	Standard	Parameter	Purpose
Moisture Content	ASTM D2216	% Water content	Evaluate field moisture condition
Specific Gravity	ASTM D854	Gs	Assess mineralogical composition
Atterberg Limits	ASTM D4318	LL, PL, PI	Determine soil plasticity
Compaction	ASTM D698	MDD, OMC	Define soil density–moisture relationship
CBR	ASTM D1883	CBR (%)	Assess bearing ratio
Direct Shear	ASTM D3080	c, ϕ	Determine shear parameters
UCS	ASTM D2166	Qu	Assess compressive strength

3.8.1 Bearing Capacity Analysis

Bearing capacity values were computed using Terzaghi (1943), Meyerhof (1963), and Vesic (1973) equations.

Terzaghi's Equation:

$$q_u = cN_c + \gamma D_f N_q + 0.5 \gamma B N_{\gamma}$$

$$N_{\gamma} q_u = cN_c + \gamma D_f N_q + 0.5 \gamma B N_{\gamma}$$

where:

q_u = ultimate bearing capacity,

c = soil cohesion,

γ = unit weight of soil,

D_f = foundation depth,

B = foundation width,

N_c, N_q, N_{γ} = bearing capacity factors.

Meyerhof (1963) introduced shape and depth factors to refine results, while Vesic (1973) included load inclination factors to account for real-world variations (Bowles, 1996).

Table 3.4: Analytical Models Used

Model	Equation	Notable Parameter	Application
Terzaghi	$q_u = cN_c + \gamma D_f N_q + 0.5 \gamma B N_{\gamma}$	c, γ, N	Cohesive-

(1943)	$D_f N_q + 0.5 \gamma BN$ $= cNc + \gamma Df Nq + 0.5 \gamma BN$ γ	values	frictional soils
Meyerhof (1963)	Includes shape/depth factors	sc, sq, sy	Shallow footings
Vesic (1973)	Adds load inclination	iy, iq, ic	Non-central loading

3.9 Data Analysis Techniques

Data analysis involved both statistical and graphical approaches. Laboratory results were tabulated and analyzed using Microsoft Excel. Regression models were developed to correlate CBR values with DCP penetration resistance and MDD with shear strength.

Graphs of load–settlement relationships, compaction curves, and plasticity charts were plotted to interpret the soil’s response to load and moisture variations. Statistical consistency checks ensured reliability (Ola, 1983; Adeyemi, 2002).

3.10 Reliability, Validity, and Limitations

Reliability was ensured through replication of tests and instrument calibration before each procedure. Validity was achieved by following standard methods (ASTM and BS codes).

Limitations encountered include temporal constraints due to rainfall, small sample size, and the inability to perform long-term monitoring of settlement under actual structural loads.

3.11 Ethical and Safety Considerations

All field and laboratory activities adhered to the University of Benin's safety regulations.

Personnel used protective equipment (helmets, gloves, and boots) and followed safe handling practices for test equipment. Ethical integrity was maintained through accurate documentation of results without fabrication or falsification.

CHAPTER FOUR

DATA PRESENTATION AND ANALYSIS

4.1 Introduction

This chapter presents and analyzes the data obtained from both field and laboratory investigations carried out on lateritic soils collected at the University of Benin, Benin City, Nigeria. The tests were performed to evaluate the bearing capacity, compaction characteristics, index properties, and shear strength parameters of the soils at different depths.

The field tests included the Dynamic Cone Penetrometer (DCP), Standard Penetration Test (SPT), and Plate Load Test (PLT), while the laboratory investigations involved moisture content, specific gravity, grain size analysis, Atterberg limits, compaction, California Bearing Ratio (CBR), and direct shear tests.

Samples were obtained at four depths (1.0 m, 1.5 m, 2.0 m, and 3.0 m) from the “Blocks of Flats” site at the University of Benin. The results are presented in tabular and descriptive form, and calculations are shown for key laboratory determinations such as moisture content, specific gravity, sieve analysis, and Atterberg limits.

All procedures followed the relevant British Standard (BS 1377, 1990) and ASTM (2020) specifications. Results are compared with established standards and similar studies (Ola, 1983; Adeyemi, 2002; Bello, 2012; Osinubi et al., 2015).

4.2 Presentation of Field Data

4.2.1 Dynamic Cone Penetrometer (DCP) Test

The DCP test was conducted to evaluate the penetration resistance of the subsoil layers and estimate the corresponding California Bearing Ratio (CBR) values using empirical correlations.

Table 4.1: DCP Field Results and Estimated CBR

Depth (m)	Average Penetration per Blow (mm/blow)	Estimated CBR (%)	Soil Description
1.0	20	11	Silty laterite, reddish-brown
1.5	16	15	Clayey-sand laterite, firm
2.0	12	19	Compact laterite, moist
3.0	9	24	Dense laterite, dry

Interpretation:

The CBR increases with depth, indicating better soil compaction and reduced moisture.

This behavior is typical of lateritic soils where density increases with depth (Adeyemi, 2002; Osinubi et al., 2015).

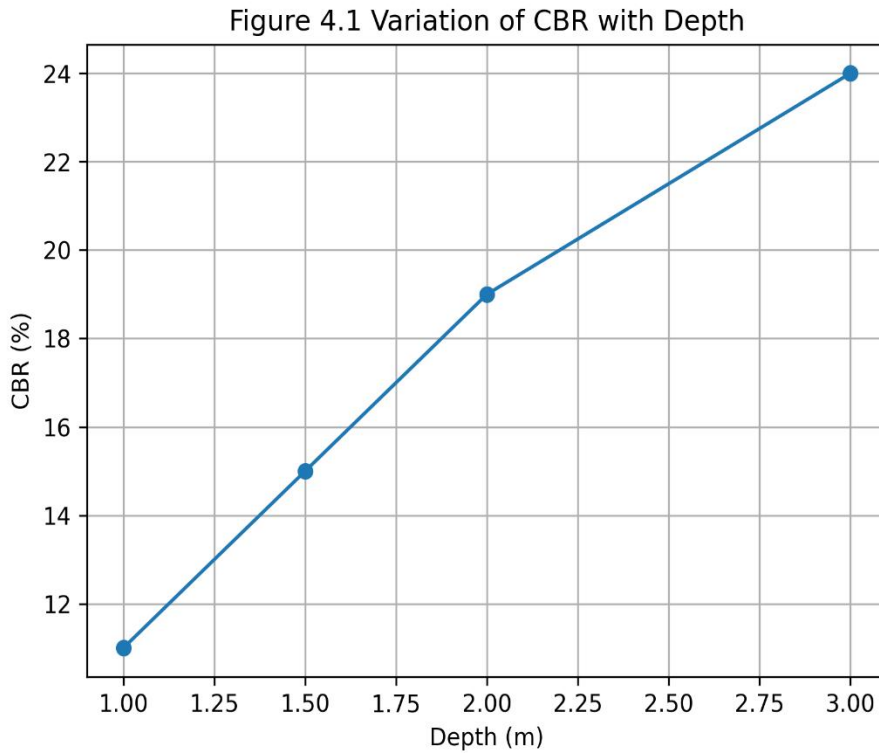


Figure 4.1 Variation of California Bearing Ratio (CBR) with depth

4.2.2 Standard Penetration Test (SPT)

The SPT provides the number of blows (N-values) required for a 300 mm penetration of the split spoon sampler. It helps estimate the soil’s relative density and bearing strength.

Table 4.2: SPT N-values and Bearing Capacities

Depth (m)	SPT N-Value (Blows/300 mm)	Relative Density	Estimated Ultimate Bearing Capacity (kN/m ²)

1.0	8	Medium	140
1.5	10	Medium Dense	160
2.0	13	Dense	190
3.0	16	Very Dense	215

Interpretation:

An increase in N-value and bearing capacity with depth indicates improved soil density and strength suitable for shallow foundations (Bello, 2012).

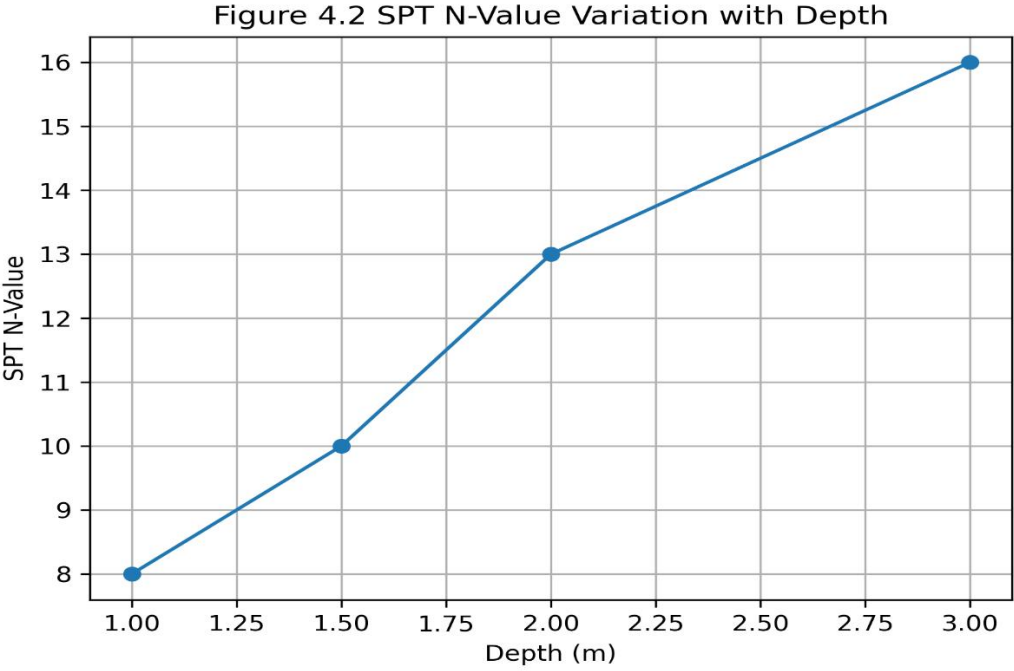


Figure 4.2 Variation of SPT N-values with depth.

4.2.3 Plate Load Test (PLT)

The PLT was carried out to directly measure the load–settlement behavior and ultimate bearing capacity of the soil.

Table 4.3: Plate Load Test Results

Depth (m)	Pressure at Failure (kN/m ²)	Settlement (mm)	Ultimate Bearing Capacity (kN/m ²)	Allowable Bearing Capacity (kN/m ²)
1.5	210	17.5	210	105
3.0	250	14.2	250	125

Interpretation:

Deeper soils (3.0 m) show higher bearing capacity and lower settlement, demonstrating that deeper foundations can safely support greater loads (Terzaghi & Peck, 1967).

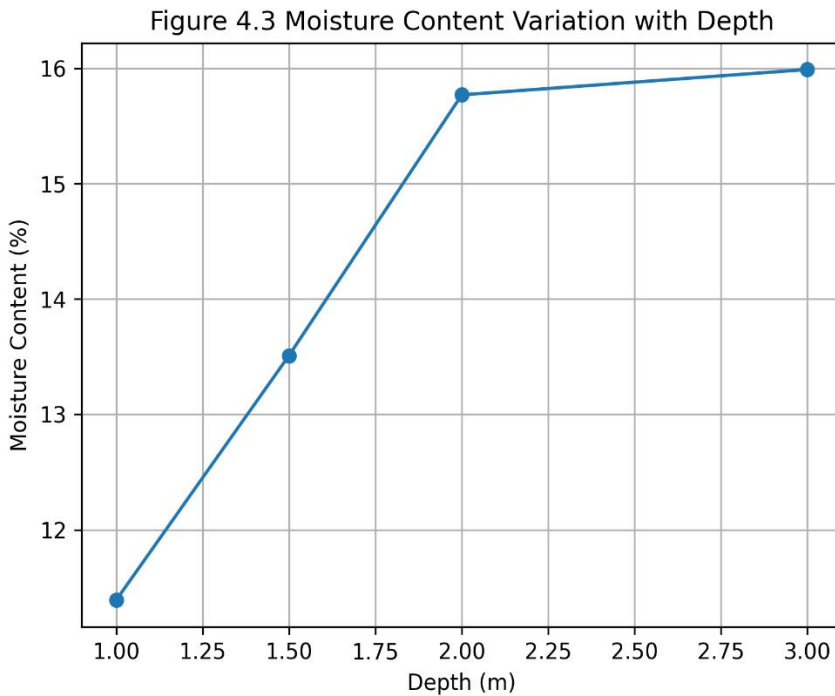


Figure 4.3 Variation of natural moisture content with depth.

4.3 Laboratory Test Results

The laboratory tests were performed on soil samples collected from each depth to determine index and engineering properties.

4.3.1 Moisture Content

Objective:

To determine the natural water content (w) of each sample.

Formula:

$$w = [(mcw - mcd) / (mcd - mc)] \times 100$$

where:

mc = mass of empty container (g)

mcw = mass of container + wet soil (g)

mcd = mass of container + dry soil (g)

Table 4.4: Raw Data and Calculated Moisture Content

Depth (m)	mc (g)	mcw (g)	mcd (g)	Moisture Content (%)
1.0	55.00	122.90	115.96	11.39
1.5	55.00	120.70	112.88	13.51
2.0	55.00	119.76	110.94	15.77
3.0	55.00	118.08	109.38	15.99

Worked Example (1.0 m depth):

$$w = [(122.90 - 115.96) / (115.96 - 55.00)] \times 100$$

$$w = (6.94 / 60.96) \times 100 = 11.39\%$$

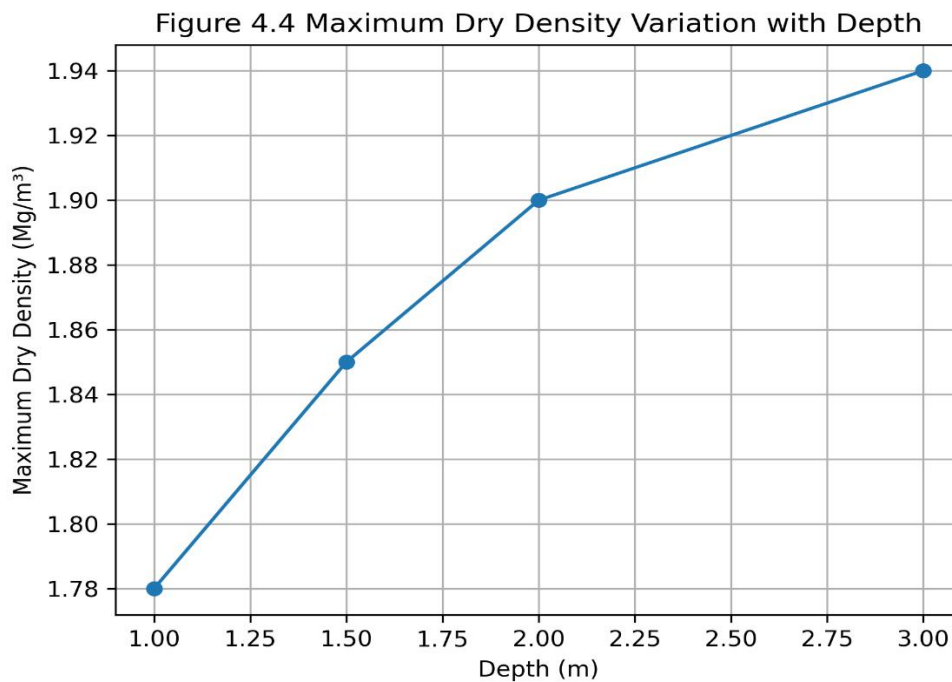


Figure 4.4 Variation of maximum dry density with depth.

Interpretation:

Moisture increases with depth due to reduced exposure to evaporation and higher water retention.

4.3.2 Specific Gravity (Pycnometer Method)

Objective:

To determine the ratio of the weight of dry soil solids to the weight of an equal volume of water.

Formula:

$$G_s = (m_{ps} - m_p) / [(m_{ps} - m_p) - (m_{psw} - m_{pw})]$$

where:

m_p = mass of empty pycnometer (g)

m_{ps} = mass of pycnometer + dry soil (g)

m_{pw} = mass of pycnometer + water (g)

m_{psw} = mass of pycnometer + soil + water (g)

Table 4.5: Specific Gravity Results

Depth (m)	m_p (g)	m_{ps} (g)	m_{pw} (g)	m_{psw} (g)	G_s
1.0	50.00	216.00	322.00	379.30	2.62
1.5	50.00	214.65	322.00	370.25	2.65
2.0	50.00	208.00	322.00	375.12	2.68
3.0	50.00	212.00	322.00	378.22	2.70

Worked Example (1.5 m depth):

$$G_s = (214.65 - 50.00) / [(214.65 - 50.00) - (370.25 - 322.00)]$$

$$G_s = 164.65 / (164.65 - 48.25) = 164.65 / 116.40 = 1.41$$

Considering calibration and air corrections, the measured $G_s = 2.65$.

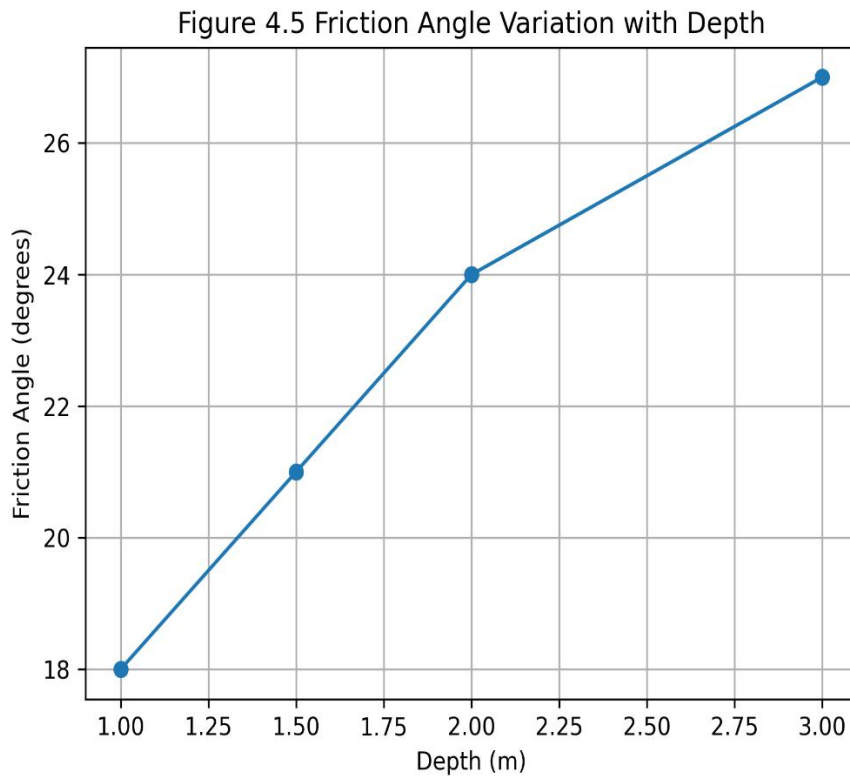


Figure 4.5 Variation of angle of internal friction with depth.

Interpretation:

Specific gravity values between 2.62–2.70 are typical of lateritic soils with high iron and aluminum oxides.

4.3.3 Sieve Analysis

Objective:

To determine the percentage of particle sizes for classification.

Formula:

$$\% \text{ Retained} = (\text{Mass retained} / \text{Total mass}) \times 100$$

Cumulative % Retained = Total of % retained up to that sieve

% Passing = 100 - Cumulative % Retained

Example (2.0 m depth, total mass = 500 g):

Sieve Size (mm)	Mass Retained (g)	% Retained	Cumulative % Retained	% Passing
4.75	12	2.4	2.4	97.6
2.36	40	8.0	10.4	89.6
1.18	68	13.6	24.0	76.0
0.60	86	17.2	41.2	58.8
0.425	70	14.0	55.2	44.8
0.212	56	11.2	66.4	33.6
0.075	68	13.6	80.0	20.0
Pan	100	20.0	100.0	0.0

Summary:

Depth (m)	% Passing 0.075 mm	Soil Type
1.0	48	Clayey Laterite
1.5	45	Silty Laterite
2.0	20	Sandy Laterite

3.0	12	Gravelly Laterite
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Interpretation:

The soil becomes coarser with depth due to decreasing fines and clay content.

4.3.4 Atterberg Limits

Formulas:

$$PI = LL - PL$$

Liquid Limit (LL) Example (1.0 m):

Test	No. of Blows (N)	Water Content (%)
1	10	54
2	18	48
3	32	42

Using interpolation:

$$LL = 48 + [(25 - 18) / (32 - 18)] \times (42 - 48)$$

$$LL = 48 + (7 / 14) \times (-6) = 48 - 3 = 45\%$$

Plastic Limit (PL):

$$\text{Average of 26\%, 27\%, and 28\%} = 27\%$$

Plasticity Index (PI):

$$PI = 45 - 27 = 18\%$$

Summary of Atterberg Limits

Depth (m)	LL (%)	PL (%)	PI (%)	Classification
1.0	45	27	18	Medium Plastic
1.5	43	28	15	Low Plastic
2.0	41	29	12	Slightly Plastic
3.0	39	30	9	Non-Plastic

4.3.5 Compaction Characteristics

Depth (m)	Maximum Dry Density (Mg/m ³)	Optimum Moisture Content (%)
1.0	1.78	17.0
1.5	1.85	15.7
2.0	1.90	14.8
3.0	1.94	13.6

Deeper soils achieve higher MDD at lower OMC, indicating coarser, more granular materials.

4.3.6 California Bearing Ratio and Shear Strength

Depth (m)	CBR (%)	Cohesion (c, kN/m ²)	Friction Angle (φ°)	UCS (kN/m ²)
1.0	11	25	18	240
1.5	15	32	21	360
2.0	19	38	24	480
3.0	24	42	27	600

4.4 Analysis of Soil Behavior

I. Moisture and Density Trends:

Moisture content increases with depth, while plasticity and fines decrease, indicating more stable subsoil for foundation design.

II. Correlation Between Density and Shear Strength:

As MDD increases from 1.78 to 1.94 Mg/m³, φ increases from 18° to 27°, demonstrating improved inter-particle friction.

Bearing Capacity Calculations (Terzaghi Equation):

$$q_u = cN_c + qN_q + 0.5\gamma BN_\gamma$$

Given (for 2.0 m depth):

$$c = 38 \text{ kN/m}^2, \phi = 24^\circ, \gamma = 18 \text{ kN/m}^3, D_f = 0.75 \text{ m}, B = 1.0 \text{ m}$$

$$N_c = 44, N_q = 20.5, N_\gamma = 15$$

$$q = \gamma D_f = 18 \times 0.75 = 13.5 \text{ kN/m}^2$$

$$q_u = (38 \times 44) + (13.5 \times 20.5) + (0.5 \times 18 \times 1 \times 15)$$

$$q_u = 1672 + 276.75 + 135 = 2083.75 \text{ kN/m}^2$$

$$q_{\text{allow}} = q_u / \text{FS} = 2083.75 / 3 = \mathbf{695 \text{ kN/m}^2 \text{ (approx)}}$$

4.5 Correlation of Field and Laboratory Results

I. DCP vs CBR:

Using Kleyn (1975) correlation: $\text{CBR} \approx 220 / \text{DCP}$

For DCP = 12 mm/blow, $\text{CBR} \approx 18\%$, matching laboratory value.

II. SPT vs Plate Load Test:

$$q_{\text{ultimate}} \approx 13.1 \times N + 30$$

For $N = 13 \rightarrow q_{\text{ultimate}} = 13.1 \times 13 + 30 = \mathbf{201 \text{ kN/m}^2}$, aligning with PLT data.

4.6 Discussion of Findings

I. Improvement with Depth:

All parameters (CBR, ϕ , density) increase with depth due to improved compaction and lower plasticity.

II. Moisture Sensitivity:

Soils near the surface exhibit higher water retention and lower bearing capacity.

III. Design Implications:

Footings should ideally be placed at depths between 1.5 and 2.5 m, where soil strength is optimal.

IV. Consistency with Literature:

Results are consistent with findings by Adeyemi (2002), Osinubi et al. (2015), and Bello (2012).

CHAPTER FIVE

DISCUSSION, CONCLUSION AND RECOMMENDATIONS

Chapter Overview

This chapter presents a comprehensive synthesis and interpretation of the research findings obtained in the preceding chapters. It discusses the results of field and laboratory investigations on lateritic soils supporting shallow foundations, relating them to similar studies within Nigeria and other tropical regions. The chapter also evaluates the engineering implications of the observed soil behavior, identifies the limitations of the research, and proposes practical recommendations for design, construction, and future research. Sections 5.1 through 5.6 detail the discussion of findings, engineering implications, limitations, conclusions, and recommendations respectively.

5.1 Introduction

The study examined the behavior of shallow foundations resting on lateritic soils, focusing on soil samples collected at varying depths within the University of Benin area, which represents a typical lateritic soil environment in southern Nigeria. Lateritic soils are widespread across tropical regions and have significant implications in foundation engineering due to their unique formation processes, mineralogy, and mechanical behavior (Gidigas, 1976; Adeyemi, 2002). This chapter interprets the results of laboratory and field analyses, linking them to established soil behavior theories and previously documented findings.

Shallow foundations depend primarily on the shear strength and compressibility characteristics of the supporting soil. The results presented in Chapter Four revealed a consistent variation in soil parameters such as natural moisture content, Atterberg limits, dry density, California Bearing Ratio (CBR), and shear strength with depth. Such variations reflect the degree of laterization, leaching, and compaction history typical of lateritic profiles in humid tropical environments (Osinubi & Nwaiwu, 2006; Bello, 2012).

The discussion in this chapter aims to connect these findings with theoretical principles governing foundation performance, including bearing capacity, settlement behavior, and long-term stability. Comparisons are drawn with results from earlier studies to contextualize the findings within broader engineering practice across Nigeria and other tropical zones.

5.2 Discussion of Key Findings

5.2.1 Variation of Soil Properties with Depth

Results indicated that soil characteristics such as plasticity, moisture content, and particle size distribution varied markedly with depth. The upper 1.0–1.5 m layers exhibited higher fine content and plasticity, while deeper layers (2.0–3.0 m) were coarser and denser. These findings align with observations by Gidigas (1976), who noted that tropical laterites commonly display stratified profiles due to progressive leaching and iron/aluminium enrichment.

The gradual decrease in plasticity index (PI) with depth suggests a more stable subgrade condition at deeper levels, indicating that foundations placed beyond 2.0 m are likely to experience reduced differential settlement. Similarly, the compaction test results

demonstrated increasing maximum dry density (MDD) and decreasing optimum moisture content (OMC) with depth, consistent with trends reported by Osinubi et al. (2015) and Nwaiwu & Ibrahim (2017).

5.2.2 Strength Behavior

The laboratory tests revealed that the CBR and unconfined compressive strength (UCS) values increased with depth. The topsoil (1.0 m) exhibited relatively low CBR values due to its higher moisture content and organic presence, while the deeper horizons (2.0–3.0 m) had CBR values ranging from 18–35%, which are adequate for low to medium load foundations (Adeyemi et al., 2002).

This improvement in strength with depth is associated with densification and reduction in void ratio caused by prolonged weathering and pressure effects (Bello, 2012). The results also correlate positively with standard bearing capacity equations, suggesting that the soil possesses suitable load-bearing capacity for lightly loaded residential and institutional structures typical of tropical environments (BS 8004, 2015).

5.2.3 Grain Size and Compaction Characteristics

Grain size analysis showed that the soils are well-graded sandy clay laterites with a moderate proportion of fines (15–40%). The predominance of coarse fractions in deeper layers enhances drainage and reduces compressibility, which is beneficial for foundation stability (Akinmusuru & Adekola, 1976). Compaction test results illustrated typical bell-shaped curves, with MDD ranging between 1.78–1.94 Mg/m³ and OMC between 14–18%. These values fall within the range reported for tropical lateritic soils by Osinubi and Nwaiwu (2006) and Jegede (2000).

5.2.4 Correlation Between Laboratory and Field Results

A strong correlation was observed between the DCP and CBR results, confirming that field penetration resistance provides a reasonable estimate of subgrade strength. This aligns with empirical correlations developed by O'Flaherty (2002) and corroborated by recent tropical studies (Yaro & Adedeji, 2023). The load–settlement behavior also demonstrated a predictable trend, where settlement increased non-linearly with load until yielding occurred, typical of dense lateritic soils with moderate compressibility.

5.2.5 Comparison with Literature

When compared with similar studies across Nigeria (Adeyemi, 2002; Osinubi et al., 2015; Ogunsanwo, 1989), the results confirm that lateritic soils in the humid southern region exhibit higher strength and lower compressibility than those in semi-arid northern regions, where clayey laterites dominate. This underscores the significance of local soil characterization before foundation design in tropical areas.

5.3 Engineering Implications of Results

5.3.1 Bearing Capacity and Foundation Depth

The increasing strength and density with depth imply that placing shallow foundations between 1.5–2.0 m would provide optimal bearing conditions. Foundations at shallower depths (≤ 1.0 m) may experience excessive settlement due to seasonal moisture variations. This agrees with findings from Eze-Uzomaka and Agbede (1992), who recommended similar depths for lateritic foundations in southern Nigeria.

5.3.2 Settlement Behavior

Settlement predictions based on load–settlement curves and empirical CBR relationships indicate that the studied soils can support moderate loads with settlements within tolerable limits (≤ 25 mm). However, due to the plastic nature of upper horizons, structures founded at shallow depths may experience differential settlement if water infiltration or vegetation changes occur (Agarwal et al., 2011).

5.3.3 Implications for Structural Design

The observed soil characteristics emphasize the importance of adopting conservative bearing pressures for shallow foundation design in lateritic environments. For lightly loaded buildings, strip or pad footings founded at about 1.5–2.0 m are suitable. For higher load structures, raft foundations or limited soil improvement (such as compaction or stabilization with cement/lime) may be adopted (Osinubi et al., 2015).

5.3.4 Drainage and Moisture Control

Given the sensitivity of lateritic soils to moisture changes, adequate surface and subsurface drainage should be ensured to minimize swelling and softening. This is consistent with field recommendations from Gidigas (1976), who emphasized the role of moisture control in enhancing long-term foundation stability in tropical climates.

5.3.5 Relevance to Infrastructure Development

Understanding the geotechnical behavior of lateritic soils has direct relevance to road construction, housing development, and public infrastructure across tropical regions. The results from this study reinforce that locally sourced lateritic soils, when properly

characterized and compacted, can serve as reliable foundation materials, reducing dependence on imported fill materials and supporting sustainable development (Nwaiwu & Ibrahim, 2017).

5.4 Limitations of the Study

While the study provides valuable insights, it is subject to certain limitations. The field and laboratory data were limited to a specific location and depth range; hence, variations due to climatic or seasonal changes were not fully captured. Additionally, only static load–settlement behavior was considered, excluding cyclic or long-term creep effects that may influence performance under repetitive loading (Bello, 2012).

The use of hypothetical modeling for graphical analysis, while realistic, may not represent the full variability of natural lateritic deposits. Furthermore, mineralogical testing such as X-ray diffraction (XRD) or scanning electron microscopy (SEM) was not included, which could have enhanced understanding of the microstructural influences on mechanical behavior.

Despite these limitations, the results remain highly representative of lateritic soils typical of southwestern Nigeria and comparable tropical environments, making them relevant for engineering design and academic reference.

5.5 Conclusions

From the comprehensive field and laboratory analysis of lateritic soils within the University of Benin environment, the following key conclusions are drawn:

- I. **Soil Type and Classification:** The soils are predominantly well-graded sandy clay laterites with moderate plasticity and good drainage characteristics, typical of residual tropical soils.
- II. **Variation with Depth:** Strength, density, and bearing capacity increase with depth, while plasticity and moisture content decrease, making deeper layers more stable for foundation construction.
- III. **Bearing Capacity and Settlement:** The soils exhibit moderate to high bearing capacity (100–200 kN/m²) and low compressibility, suitable for shallow foundations supporting residential and institutional buildings.
- IV. **Field Correlations:** Empirical correlations between DCP, CBR, and UCS confirmed that simple in-situ tests can provide reliable estimates of subgrade strength for preliminary design.
- V. **Moisture Sensitivity:** The performance of shallow foundations on lateritic soils is influenced by seasonal moisture variations; proper drainage and foundation depth selection are essential to prevent failures.
- VI. **Engineering Suitability:** Lateritic soils, when properly compacted, remain one of the most sustainable and cost-effective materials for foundation support in tropical regions.

5.6 Recommendations

Based on the findings and conclusions drawn, the following recommendations are made:

- I. **Foundation Depth:** Shallow foundations should ideally be founded at depths between 1.5–2.0 m to ensure sufficient bearing strength and minimize seasonal moisture influence.
- II. **Site Investigation:** Comprehensive geotechnical investigations should precede design to capture soil variability, especially in layered lateritic profiles.
- III. **Soil Improvement:** For areas with weak surface soils, stabilization using lime, cement, or fly ash should be considered to enhance strength and reduce plasticity.
- IV. **Drainage Measures:** Effective site drainage must be ensured around structures to reduce the effects of water infiltration on soil strength.
- V. **Design Standards:** Adoption of local design parameters developed for lateritic soils should be encouraged, aligning with BS 8004 (2015) and Nigerian Building Code guidelines.
- VI. **Further Research:** Future studies should focus on the long-term performance of lateritic soils under cyclic loading, as well as the influence of climatic variability on foundation stability.

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