**DETERMINING THE EFFECT OF PARTICLE SIZE DISTRIBUTION ON SHEAR BEHAVIOR OF SOIL**

# ABSTRACT

This study examines the effect of particle size distribution (PSD) on the shear behavior of Farin Gida soil, a lateritic soil found in Kaduna State, Nigeria. Utilizing particle size analysis and direct shear tests, the research aimed to establish the relationship between PSD metrics and shear strength parameters, including cohesion and internal friction angle. The results revealed that Farin Gida soil is well-graded, with a wide range of particle sizes that enhance interparticle friction and reduce void spaces, resulting in improved shear strength. Cohesion values ranged from 10 to 15 kPa, and internal friction angles varied between 32° and 35°, showing a strong correlation with PSD characteristics. Comparative analysis with existing studies highlighted consistency in the behavior of Farin Gida soil with other well-graded tropical soils in Nigeria, while also emphasizing its unique regional features. The findings demonstrated that optimizing PSD during soil preparation could significantly enhance mechanical properties, making Farin Gida soil suitable for applications such as foundation design and slope stabilization. This study contributes to the body of knowledge in geotechnical engineering by providing localized insights into the interplay between PSD and shear behavior, particularly in tropical soils. It underscores the importance of detailed soil characterization in ensuring the safety and efficiency of engineering designs. Recommendations include incorporating PSD analysis in geotechnical evaluations, standardizing testing protocols, and fostering capacity building in soil mechanics. These findings offer practical guidance for infrastructure development in Kaduna State and similar regions, where soil stability is critical for construction success.

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# CHAPTER ONE

# INTRODUCTION

## 1.1 Background to the Study

Soil behavior is a fundamental factor in geotechnical engineering, influencing the design and stability of infrastructure, including buildings, roads, and dams. Among the soil properties critical to engineering applications, shear strength is paramount as it determines a soil's resistance to deformation and failure under stress. Shear strength is profoundly affected by particle size distribution (PSD), a key parameter describing the range and proportion of particle sizes within a soil mass (Gee & Or, 2002). PSD directly impacts the soil's porosity, permeability, and mechanical stability, making it a crucial focus in the study of soil behavior.

Particle size distribution affects the contact points and frictional resistance between soil grains. Soils with a broader PSD often demonstrate higher shear strength due to better particle interlocking (Morgan, 1999). Conversely, uniformly graded soils, where particles are of similar size, may exhibit reduced shear strength as fewer inter-particle contacts develop. Gu et al. (2017) emphasized that PSD significantly influences the stiffness of granular soils, particularly at small strain levels. Their discrete element modeling highlighted the critical role of fine and coarse particle ratios in determining mechanical properties.

The unique geotechnical characteristics of Nigerian soils add another layer of complexity to understanding the influence of PSD. Nigeria's diverse geological zones encompass a wide variety of soil types, ranging from laterites in the tropical regions to sandy soils in arid areas. These soils often exhibit distinctive PSD profiles that are shaped by weathering, erosion, and sediment deposition processes (Raei et al., 2015). For instance, lateritic soils, abundant in iron and aluminum oxides, often feature a bimodal PSD that influences their compaction and shear strength characteristics. This makes studying the relationship between PSD and shear behavior particularly relevant for engineering applications in Nigeria.

The influence of PSD extends to critical engineering applications such as slope stability, foundation design, and earthworks. For example, particle size has been shown to affect the interface shear behavior between soil and reinforcement materials. Vangla and Gali (2016) investigated the role of sand particle size in geotextile applications, concluding that finer sands exhibited higher interface shear resistance due to greater contact area and friction. Similarly, Wang et al. (2016) explored the effects of particle size on coarse soil-geogrid interfaces, finding that larger particles tended to reduce post-cyclic shear strength, underscoring the need for careful consideration of PSD in soil-structure interactions.

In addition to engineering implications, PSD plays a crucial role in soil erosion and environmental sustainability. Raei et al. (2015) compared the initial motion of soil aggregates with sand particles of varying sizes, demonstrating that larger aggregates are more resistant to erosion forces. This finding is particularly pertinent to regions like Nigeria, where soil erosion is a prevalent environmental challenge. Understanding how PSD influences soil stability can inform erosion control measures and sustainable land management practices.

The dynamic interaction between PSD and shear behavior is further influenced by factors such as moisture content, particle shape, and loading conditions. Jiang et al. (2016) highlighted the impact of shear speed on granular materials, showing that higher shear speeds can exacerbate frictional instability, especially in soils with poorly graded PSD. This underscores the complexity of soil behavior under varying loading scenarios, which are common in real-world applications.

While extensive research has been conducted globally on PSD and soil mechanics, there is a paucity of studies specifically addressing Nigerian soils. This research gap is significant, considering the critical role of soil in Nigeria’s rapidly growing infrastructure sector. Stefanow and Dudziński (2021) emphasized that state-of-the-art methods for determining soil shear strength must be adapted to regional contexts, considering local soil characteristics and engineering needs. This study aims to bridge this gap by investigating the effect of PSD on the shear behavior of Nigerian soils, providing insights that can enhance geotechnical design and construction practices.

## 1.2 Statement of the Research Problem

The relationship between particle size distribution and soil shear behavior is well-established in the field of geotechnical engineering. However, the application of these principles to the specific context of Nigerian soils remains underexplored. This knowledge gap poses challenges for engineers and researchers attempting to predict and optimize soil performance for infrastructure development in Nigeria's diverse geotechnical landscape. Despite the availability of sophisticated soil analysis techniques, such as those outlined by Loveland and Whalley (2000), their use in analyzing Nigerian soils has been limited, often resulting in suboptimal design and increased project costs.

One of the primary challenges lies in the variability of Nigerian soils, which are shaped by diverse climatic, geological, and anthropogenic factors. For instance, lateritic soils, prevalent in southern Nigeria, differ significantly in composition and PSD from the sandy soils of the northern regions. The lack of a comprehensive understanding of how these variations in PSD influence shear behavior undermines the reliability of geotechnical designs, particularly for critical structures such as dams, bridges, and retaining walls (Gu et al., 2017).

Another issue is the lack of standardization in soil testing practices across Nigeria. While global studies, such as those by Wang et al. (2016), have emphasized the importance of controlled laboratory conditions for assessing soil properties, such rigor is often lacking in local contexts. This can lead to discrepancies in test results, making it difficult to establish consistent correlations between PSD and shear strength. Furthermore, environmental factors such as erosion and land degradation, which are widespread in Nigeria, exacerbate the variability in soil properties, adding to the complexity of predicting shear behavior (Raei et al., 2015).

The limited integration of regional data into geotechnical modeling tools further compounds the problem. Many existing models are based on studies conducted in temperate regions, which may not accurately reflect the behavior of tropical soils like those in Nigeria. This disconnect highlights the need for localized research to provide data-driven insights and practical recommendations for the engineering community.

In light of these challenges, this study seeks to address the critical gap in understanding the effect of particle size distribution on the shear behavior of Nigerian soils. By employing advanced soil analysis techniques and focusing on regional soil types, the research aims to contribute to the development of more reliable and efficient geotechnical practices tailored to Nigeria's unique conditions.

## 1.3 Objectives of the Study

The primary objective of this study is to investigate the effect of particle size distribution (PSD) on the shear behavior of Farin Gida soil in Kaduna State, Nigeria. The specific objectives are:

1. To analyze the particle size distribution of Farin Gida soil using standard laboratory methods.
2. To evaluate the shear strength parameters of Farin Gida soil under varying PSD conditions.
3. To establish the relationship between PSD and shear behavior for Farin Gida soil.
4. To compare the findings with existing studies on similar soils in Nigeria and other regions.
5. To provide recommendations for geotechnical design and construction practices in areas with similar soil characteristics.

## 1.4 Research Questions

This study seeks to answer the following research questions:

1. What is the particle size distribution profile of Farin Gida soil in Kaduna State?
2. How do variations in PSD influence the shear strength parameters of Farin Gida soil?
3. What is the nature of the relationship between PSD and the shear behavior of this soil?
4. How do the results for Farin Gida soil compare to findings from other studies on Nigerian soils?
5. What geotechnical recommendations can be derived from the study's findings?

## 1.5 Significance of the Study

This study holds significant implications for both academic research and practical applications:

**Academic Contribution**  
The research addresses a critical gap in understanding the geotechnical properties of Farin Gida soil, a representative soil type in Kaduna State. It builds on the limited body of work on Nigerian soils, providing data that can inform future studies and refine existing models of soil behavior under varying PSD conditions.

**Practical Relevance**  
For geotechnical engineers, the study provides valuable insights into the relationship between PSD and shear behavior, which are crucial for designing stable and cost-effective structures in Kaduna State and similar regions. Specifically, the findings can guide decisions on foundation design, slope stability, and earthworks, minimizing the risk of structural failure due to soil instability.

**Policy and Environmental Implications**  
The study’s results can also inform land use planning and soil conservation strategies, particularly in areas prone to erosion. By understanding how PSD impacts shear strength, policymakers can develop targeted interventions to mitigate land degradation in Kaduna State.

## 1.6 Scope and Limitations of the Study

**Scope**  
This study focuses exclusively on the Farin Gida soil in Kaduna State, examining its PSD and shear behavior through laboratory experiments. The research emphasizes geotechnical applications, particularly in the context of construction and infrastructure development.

**Limitations**

The study is confined to the Farin Gida soil, and its findings may not be directly applicable to other soil types in Nigeria.

Laboratory conditions may not fully replicate field conditions, which could introduce variability in results when applied to real-world scenarios.

The research does not account for the long-term effects of environmental changes, such as climate variations and erosion, on PSD and shear behavior.

## 1.7 Definition of Key Terms

**Particle Size Distribution (PSD):** A measurement of the range and proportion of different particle sizes in a soil sample, typically expressed as a cumulative percentage.

**Shear Strength:** The resistance of soil to deformation or failure under applied shear stress, influenced by factors such as cohesion and friction.

**Farin Gida Soil:** A specific soil type found in Farin Gida, Kaduna State, characterized by its unique geotechnical properties.

**Geotechnical Engineering:** A branch of civil engineering concerned with the behavior of earth materials and their application in construction.

**Soil Stability:** The ability of soil to resist deformation and maintain structural integrity under stress.

**Lateritic Soil:** A type of soil rich in iron and aluminum oxides, commonly found in tropical regions, including parts of Nigeria.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1. Introduction

Understanding the relationship between particle size distribution (PSD) and the shear behavior of soil is pivotal in geotechnical engineering. PSD plays a critical role in influencing various soil properties, including permeability, compressibility, and strength, all of which are crucial for the stability of foundations, embankments, and other civil structures. Shear behavior, defined by the soil's ability to resist deformation under applied stress, is particularly affected by the gradation and arrangement of soil particles.

Previous studies have emphasized the significance of PSD in determining soil shear strength, highlighting factors such as particle size, shape, and angularity. For instance, well-graded soils, with a broader range of particle sizes, tend to exhibit higher shear resistance due to improved interlocking. Conversely, uniformly graded soils often experience reduced shear strength due to limited particle interaction.

This research seeks to explore the nuanced effects of PSD on shear behavior, synthesizing experimental findings and theoretical frameworks to enhance our understanding. By analyzing factors such as grain size distribution, fines content, and particle breakage, this study aims to contribute to the predictive modeling of soil behavior. These insights are vital for optimizing geotechnical designs, ensuring safety, and mitigating the risk of soil failure in engineering applications.

## 2.2. Theoretical Framework

The theoretical framework for this study focuses on the interplay between particle size distribution (PSD) and the shear behavior of soils, integrating fundamental principles of soil mechanics and empirical findings. PSD, defined by the gradation of particle sizes within a soil sample, significantly influences mechanical properties such as shear strength, compressibility, and stiffness. This section explores key theoretical concepts, experimental observations, and the role of PSD parameters in shaping the shear response of soils.

**2.2.1. Particle Size Distribution: Definition and Importance**

Particle size distribution refers to the proportion of soil particles of various sizes within a given sample. It is typically characterized by gradation curves, which plot cumulative particle size against percentage finer (Gee & Or, 2002). Important indices such as the coefficient of uniformity (Cu) and the coefficient of curvature (Cc) provide insights into the soil's gradation and its implications for mechanical properties (Loveland & Whalley, 2000).

The significance of PSD in geotechnical engineering lies in its ability to dictate interparticle interactions, packing density, and void ratios. Well-graded soils, characterized by a wide range of particle sizes, tend to achieve higher densities and lower void ratios, enhancing shear resistance. Conversely, uniformly graded soils with similar-sized particles exhibit lower shear strength due to limited interlocking (Li, 2013).

**2.3. Shear Behavior of Soils**

Shear behavior describes the resistance of soil to deformation or failure under applied shear stress. This property is pivotal in geotechnical engineering, as it directly affects the stability of slopes, retaining structures, and foundations. Soil shear behavior is governed by a combination of intrinsic properties, such as particle size distribution (PSD), particle shape, and interparticle interactions, as well as external conditions, including stress levels and boundary constraints (Li, 2013). This section explores the factors influencing shear behavior, mechanisms underlying soil response to shear stress, and experimental findings that shed light on these phenomena.

**2.3.1. Mechanisms Governing Shear Behavior in Soils**

The shear behavior of soils is primarily dictated by the interlocking of particles, frictional resistance, and the degree of cohesion.

**2.3.1.1. Frictional Resistance**

Frictional resistance is the primary contributor to the shear strength of granular soils. It arises from surface roughness and interparticle contact forces. Studies by Santamarina and Cho (2004) revealed that particle angularity enhances frictional resistance, making angular soils more shear-resistant compared to rounded soils.

**2.3.1.2. Particle Interlocking**

The degree of interlocking among soil particles affects the soil’s ability to resist deformation. Well-graded soils, due to their varied particle sizes, achieve better interlocking and higher shear resistance (Kim & Ha, 2014). Conversely, uniformly graded soils lack sufficient interlocking, making them more prone to shear failure (Wang et al., 2013).

**2.3.1.3. Cohesion and Adhesion**

Cohesive soils exhibit shear resistance due to attractive forces between particles. The presence of clay minerals introduces plasticity and cohesion, which play a significant role in determining shear strength under low-stress conditions (Rezvani, Nabizadeh, & Tutunchian, 2021).

**2.3.2. Influence of Particle Size Distribution on Shear Behavior**

PSD is a critical determinant of shear behavior, as it influences void ratios, packing density, and stress transmission within the soil matrix.

**2.3.2.1. Well-Graded vs. Uniformly Graded Soils**

Well-graded soils demonstrate higher shear resistance due to reduced void ratios and enhanced interparticle forces. Li (2013) found that soils with broader PSD ranges resist deformation more effectively under shear loading. On the other hand, uniformly graded soils exhibit lower shear resistance owing to poor packing and higher void ratios.

**2.3.2.2. Role of Fines**

The inclusion of fines (particles smaller than 75 microns) significantly impacts shear behavior. Santamarina and Cho (2004) observed that moderate fines content enhances soil density and shear strength, while excessive fines lead to pore pressure buildup, reducing stability during shear loading.

**2.3.2.3. Particle Breakage**

The extent of particle breakage under shear stress depends on particle size, shape, and mineral composition. Liu et al. (2020) reported that coarse-grained soils with larger particles are more prone to breakage, which can diminish shear strength over time.

**2.3.3. Stress-Strain Behavior Under Shear Loading**

Soils exhibit distinct stress-strain responses based on their composition and stress conditions.

**2.3.3.1. Elastic and Plastic Deformations**

Under low stress, soils exhibit elastic deformation, characterized by recoverable strain. With increasing stress, plastic deformation occurs, leading to permanent changes in soil structure. Wang et al. (2022) highlighted that PSD plays a crucial role in determining the transition from elastic to plastic behavior.

**2.3.3.2. Peak and Residual Shear Strength**

The peak shear strength of soils occurs at maximum stress, followed by a reduction to residual strength due to particle rearrangement. Kalasin, Khamchan, and Aoddej (2023) emphasized that well-graded soils maintain higher residual strength compared to uniformly graded soils, where particle disintegration leads to strength loss.

**2.3.4. Factors Affecting Shear Behavior**

Several intrinsic and external factors influence shear behavior, including particle morphology, moisture content, and loading conditions.

**2.3.4.1. Particle Morphology**

Particle shape and surface roughness significantly affect interparticle friction and shear resistance. Santamarina and Cho (2004) demonstrated that angular particles provide better interlocking and frictional resistance than rounded particles.

**2.3.4.2. Moisture Content**

The presence of water alters the effective stress in soil and influences shear behavior. Rezvani, Nabizadeh, and Tutunchian (2021) found that unsaturated soils exhibit higher shear strength due to capillary forces, while fully saturated soils are prone to reduced strength due to pore pressure buildup.

**2.3.4.3. Loading Rate and Stress History**

The rate of loading and the stress history of a soil sample impact its shear response. Jiang et al. (2016) observed that faster loading rates result in higher shear strength, while soils with prolonged stress exposure exhibit strain hardening and reduced shear resistance.

**2.3.5. Interface Shear Behavior**

Shear behavior at soil-structure interfaces is critical for the stability of foundations and retaining structures.

**2.3.5.1. Soil-Structure Interaction**

The interaction between soil and structural elements depends on the relative roughness and PSD of the soil. Wang et al. (2016) demonstrated that soils with coarser particles exhibit higher shear resistance at interfaces due to increased friction and interlocking.

**2.3.5.2. Role of Geosynthetics**

The inclusion of geosynthetics enhances shear behavior by reinforcing the soil structure. Kim and Ha (2014) highlighted that geogrid-reinforced soils with optimal PSD exhibit superior shear resistance due to improved confinement and reduced deformation.

**2.3.6. Experimental Insights on Shear Behavior**

Laboratory experiments provide valuable insights into soil shear behavior under controlled conditions.

**2.3.6.1. Direct Shear Test**

The direct shear test is commonly used to evaluate shear strength parameters, including cohesion and angle of internal friction. Kalasin, Khamchan, and Aoddej (2023) utilized this test to investigate the effects of PSD on shear behavior, highlighting the superior performance of well-graded soils.

**2.3.6.2. Triaxial Shear Test**

The triaxial shear test provides a comprehensive understanding of soil behavior under isotropic and anisotropic loading. Rezvani, Nabizadeh, and Tutunchian (2021) employed this test to analyze particle breakage and its impact on shear strength in calcareous soils.

**2.3.6.3. Discrete Element Modeling**

Numerical simulations, such as discrete element modeling (DEM), have been instrumental in understanding micromechanical interactions during shear loading. Morgan (1999) used DEM to explore the influence of PSD and interparticle friction on the macroscopic shear response of granular soils.

**2.3.7. Applications and Implications**

Understanding shear behavior is critical for various geotechnical applications, including slope stability, foundation design, and seismic risk assessment.

**2.3.7.1. Slope Stability**

The stability of slopes depends on the shear strength of the underlying soil. Well-graded soils provide better stability due to their higher resistance to shear deformation (Li, 2013).

**2.3.7.2. Foundation Design**

Foundation performance is influenced by the shear behavior of underlying soils. Soils with optimal PSD and high shear strength ensure better load distribution and reduced settlement (Wang et al., 2019).

**2.4.7.3. Earthquake Engineering**

The shear response of soils under cyclic loading is critical for seismic risk assessment. Sharifi, Sharifipour, and Rizvandy (2020) emphasized the role of PSD in determining the dynamic shear modulus and damping properties of granular soils.

## 2.4. Effect of Particle Size Distribution on Shear Behavior

Particle size distribution (PSD) is a fundamental property of soil that significantly impacts its shear behavior. It governs soil packing, interparticle forces, stress distribution, and mechanical performance under loading. This section explores the interplay between PSD and shear behavior, including its influence on packing density, stress transfer, interparticle friction, and critical state parameters, as evidenced by experimental and numerical studies.

**2.4.1. Overview of PSD and Its Relevance**

PSD represents the proportion of different particle sizes in a soil sample. Well-graded soils, containing a wide range of particle sizes, typically exhibit higher shear strength due to enhanced packing and interlocking. Conversely, uniformly graded soils, composed of particles of nearly identical size, tend to have higher void ratios and lower shear resistance (Li, 2013). PSD is therefore essential for understanding the stress-strain response of soils during shear.

**2.4.2. Influence of PSD on Packing Density**

The arrangement of particles in a soil matrix, defined by its packing density, plays a crucial role in determining shear behavior.

**2.4.2.1. Well-Graded vs. Uniformly Graded Soils**

Well-graded soils achieve denser packing and lower void ratios due to the filling of voids by smaller particles. This leads to a more stable soil structure under shear loading. Kalasin, Khamchan, and Aoddej (2023) found that soils with broader PSD ranges resisted deformation better during direct shear tests, compared to uniformly graded soils, which exhibited higher compressibility and lower shear strength.

**2.4.2.2. Compaction and Void Ratios**

The compactness of a soil influences its shear strength. Dense soils with optimized PSD require higher energy for particle displacement, thus offering greater resistance. Liu et al. (2020) highlighted that soils with well-distributed particle sizes achieve lower void ratios, which enhances interparticle contact and friction, contributing to higher shear resistance.

**2.4.3. Stress Transfer and Interparticle Forces**

PSD influences the distribution of stresses within the soil matrix and the interactions between particles during shear loading.

**2.4.3.1. Contact Networks**

A broad PSD range promotes the formation of stable contact networks, where larger particles serve as load-bearing elements, while smaller particles provide support by filling voids. This configuration enhances the shear strength of the soil (Rezvani, Nabizadeh, & Tutunchian, 2021).

**2.4.3.2. Stress Transmission**

Soils with a narrow PSD exhibit concentrated stress at particle contacts, increasing the likelihood of particle crushing under high loads. Wang et al. (2022) demonstrated that well-graded soils distribute stress more evenly across the matrix, reducing the risk of localized failure.

**2.4.4. Influence of PSD on Interparticle Friction and Interlocking**

The frictional resistance and degree of interlocking between particles are critical determinants of shear strength.

**2.4.4.1. Role of Particle Size Variability**

Well-graded soils exhibit higher interlocking due to the presence of particles of varying sizes. This arrangement minimizes the movement of particles under shear stress, increasing the soil's ability to resist deformation (Li, 2013). Conversely, uniformly graded soils with limited size variation lack sufficient interlocking, leading to lower shear strength.

**2.4.4.2. Angularity and Roughness**

While PSD plays a primary role, particle angularity and surface roughness also contribute to shear resistance. Santamarina and Cho (2004) observed that angular particles with rough surfaces exhibit higher frictional resistance, which complements the stabilizing effects of a well-graded PSD.

## 2.5. PSD and Critical State Shear Strength

Critical state shear strength describes the condition where soil deformation occurs at constant volume and shear stress.

**2.5.5.1. Influence of PSD on Critical State Parameters**

The critical state behavior of soils depends on PSD, as it affects the density and arrangement of particles at failure. Vangla and Latha (2015) demonstrated that soils with broader PSD ranges achieve higher critical state friction angles, reflecting greater shear resistance at equilibrium.

**2.5.5.2. Role of Fines in Critical State Behavior**

The presence of fines alters critical state parameters. Moderate fines content enhances shear resistance by reducing void ratios and increasing packing density. However, excessive fines lead to pore pressure buildup, reducing shear strength and increasing susceptibility to failure under saturated conditions (Santamarina & Cho, 2004).

## 2.6. Particle Breakage and Shear Behavior

Particle breakage, a common phenomenon in coarse-grained soils under high stress, is influenced by PSD and impacts shear behavior.

**2.6.6.1. Breakage Potential in Well-Graded Soils**

Well-graded soils are less prone to particle breakage due to the effective distribution of stresses. Rezvani, Nabizadeh, and Tutunchian (2021) observed that soils with a balanced PSD experience minimal particle crushing, maintaining their shear strength over time.

**2.6.6.2. Impact of Uniform Grading on Breakage**

Uniformly graded soils, with their higher stress concentrations, are more susceptible to particle breakage. This results in a reduction in particle size and shear strength during prolonged loading (Morgan, 1999).

## 2.7. Experimental Evidence on PSD and Shear Behavior

Laboratory experiments and numerical simulations have provided valuable insights into the relationship between PSD and shear strength.

**2.7.1. Direct Shear Test Results**

Direct shear tests on soils with varying PSD ranges reveal that well-graded soils consistently exhibit higher shear resistance. Kalasin, Khamchan, and Aoddej (2023) reported that the peak shear strength of well-graded soils was significantly higher than that of uniformly graded counterparts under identical conditions.

**2.7.2. Triaxial Compression Test Findings**

Triaxial compression tests highlight the role of PSD in governing soil deformation under isotropic and anisotropic loading. Rezvani, Nabizadeh, and Tutunchian (2021) found that well-graded soils exhibited lower strain at failure, reflecting better resistance to deformation.

**2.7.3. Numerical Modeling Insights**

Numerical simulations using discrete element modeling (DEM) have demonstrated the micromechanical interactions influenced by PSD. Morgan (1999) used DEM to illustrate how stress transmission and contact forces are optimized in soils with broad PSD ranges, contributing to higher shear strength.

## 2.8.Analytical and Experimental Methods

To explore the influence of particle size distribution (PSD) on shear behavior, both analytical and experimental methods have been developed and widely utilized. These approaches provide valuable insights into the fundamental mechanics of soils under shear loading and offer practical applications in geotechnical engineering.

**1. Analytical Methods**

Analytical methods for studying the effect of PSD on shear behavior often involve theoretical models that predict the mechanical behavior of granular materials based on particle interaction. One widely used model is the Mohr-Coulomb criterion, which estimates shear strength based on the frictional resistance between soil particles. However, these traditional models typically simplify the complexities of particle size distribution, neglecting variations in interparticle forces that arise from different PSDs (Wang et al., 2019).

More advanced analytical techniques, such as the use of continuum mechanics and micromechanical models, can incorporate particle-scale interactions, providing a better representation of shear behavior in soils with complex PSDs. Santamarina and Cho (2004) discussed the application of micromechanical models to understand the role of particle size, shape, and distribution in determining the overall soil strength, using effective stress principles.

Discrete Element Method (DEM) simulations are increasingly used to model the mechanical behavior of soils. DEM models simulate the motion and interaction of individual particles in a granular assembly, providing a detailed analysis of how PSD influences shear strength. Gu, Lu, and Qian (2017) applied DEM to investigate the role of PSD in the small-strain stiffness of granular soils, observing how variations in particle size affect shear force transmission and stress distribution at the particle level.

**2. Experimental Methods**

Experimental approaches provide direct insights into the shear behavior of soils with different PSDs. One of the most commonly used laboratory tests is the direct shear test, which measures the shear strength of soil samples by applying horizontal force until failure. This method has been employed extensively by Kalasin, Khamchan, and Aoddej (2023) to study the impact of PSD on shear strength, demonstrating that well-graded soils resist shear failure better than poorly graded soils.

Another crucial experimental technique is the triaxial compression test, which allows for a more comprehensive understanding of soil behavior under both isotropic and anisotropic stress conditions. Liu et al. (2020) used triaxial tests to assess the shear behavior of soils with varying particle size distributions, noting that well-graded soils exhibited higher shear resistance and reduced strain at failure compared to soils with narrow PSDs.

The influence of PSD on shear behavior can also be explored through other methods such as torsional shear tests and cyclic loading tests, which help investigate the behavior of soils under dynamic conditions, as seen in studies by Rezvani, Nabizadeh, and Tutunchian (2021). These methods provide a more comprehensive understanding of how PSD affects soil performance under different loading scenarios.

## 2.9. Influence of External Factors

The shear behavior of soils is not only influenced by particle size distribution (PSD) but also by several external factors, including environmental conditions, loading history, and soil composition. These factors can significantly alter the mechanical properties of soils and affect their response to shear forces.

**2.9.1. Water Content and Saturation**

One of the most influential external factors on soil shear behavior is the water content, which impacts soil cohesion and frictional resistance. When soils are saturated, pore water pressure can reduce the effective stress between particles, leading to lower shear strength. Wang, Zhou, Yin, and Jie (2019) observed that the shear strength of soils decreased under saturated conditions due to the reduced interparticle friction caused by water lubrication. The interaction between water and particles is particularly pronounced in soils with high clay content, where water absorption can change the size and shape of particles, altering the shear strength and causing volumetric changes during loading (Cao et al., 2019).

**2.9.2. Temperature**

Temperature also affects the shear behavior of soils, particularly in regions where seasonal variations are significant. The changes in temperature can influence the moisture content of soils, causing volumetric changes, which, in turn, affect shear strength. Saravanan et al. (2020) found that increasing temperatures led to soil desiccation, which resulted in an increase in shear strength in soils with high clay content. In contrast, higher temperatures in granular soils with well-distributed PSD tend to cause changes in the particle cohesion, leading to reduced shear strength under repeated cyclic loading.

**2.9.3. Stress History**

The loading history of a soil sample, including factors like prior compression or cyclic loading, can significantly influence its shear strength. Soils subjected to overburden stress or repeated loading may exhibit strain hardening or softening behavior depending on the PSD. Wang et al. (2022) noted that soils with a broader PSD showed less strain hardening under repeated loading cycles, as the varied particle sizes contributed to a more stable structure.

**2.9.4. Soil Composition**

The mineral composition of soil plays an important role in determining its shear behavior. Fine-grained soils, such as clays, exhibit different shear properties compared to coarse-grained soils. Clays, for instance, have high plasticity and cohesion, which affect the shear strength under different moisture contents. Kim and Ha (2014) highlighted that the shear strength of soils reinforced with geogrids was influenced by PSD, where finer soils exhibited lower shear strength than coarser soils with a similar grading, even after reinforcement.

## 2.10. Applications and Implications

Understanding the relationship between particle size distribution (PSD) and shear behavior has broad implications across various geotechnical engineering applications, including slope stability, foundation design, and earthquake resistance. This section discusses the practical relevance of these findings.

**2.10.1. Slope Stability**

The shear strength of soils is crucial in determining the stability of slopes, particularly in areas prone to landslides or soil erosion. Well-graded soils with optimized PSD offer greater resistance to shear failure, making them ideal for slope stabilization. Li (2013) noted that in natural slopes, soils with broader PSDs tend to exhibit higher shear strength, reducing the risk of catastrophic failure under loading. For engineered slopes, understanding how to manipulate PSD to achieve maximum shear strength can significantly enhance the safety and durability of civil infrastructure projects.

**2.10.2. Foundation Design**

In foundation engineering, the shear strength of the underlying soil directly impacts the design of load-bearing structures. A well-graded soil with optimized PSD enhances the performance of shallow foundations by providing a more stable and less compressible base. Liu et al. (2020) demonstrated that soil layers with optimal PSD can reduce settlement in structures, ensuring that the foundation remains stable over time. Furthermore, PSD optimization in soil also helps in minimizing the risk of differential settlement, which can cause damage to buildings and other infrastructure.

**2.10.3. Earthquake Resistance**

The performance of soils during seismic events is another area where PSD plays a critical role. During an earthquake, the shear behavior of soils governs the extent of ground shaking and settlement. Soils with a narrow PSD may experience more severe liquefaction, leading to foundation failure and landslides. Vangla and Latha (2015) emphasized that well-graded soils exhibit better resistance to seismic forces due to their ability to distribute shear forces more evenly across the soil structure. Additionally, fine-grained soils with higher plasticity may experience pore pressure buildup, reducing the effective stress and increasing the likelihood of liquefaction during an earthquake.

**2.10.4. Geotechnical Risk Assessment**

The study of PSD and its impact on shear behavior is crucial for assessing geotechnical risks. When evaluating soil conditions for construction projects, engineers use shear strength data to predict how the soil will behave under different loading conditions. Saravanan et al. (2020) found that soils with optimized PSDs were more predictable in terms of their shear strength, making them easier to design with. By understanding how PSD influences shear behavior, engineers can make more accurate risk assessments and design safer, more durable infrastructure projects.

**2.11. Research Gaps**

Despite the extensive body of research on the effect of particle size distribution (PSD) on shear behavior, several gaps remain that hinder a comprehensive understanding of the complex interactions between PSD, shear strength, and soil behavior. These gaps present opportunities for further investigation to refine predictive models and improve geotechnical practice.

Much of the research on PSD and shear behavior has been conducted in laboratory settings, but translating these findings to real-world conditions remains a challenge. Field-scale studies that account for factors such as heterogeneity in soil properties, water content variations, and long-term loading effects are necessary. Although laboratory experiments provide valuable insights, they cannot always replicate the complexity of natural environments. Further research into field-scale behavior will enhance the accuracy of predictions based on laboratory data (Stefanow & Dudziński, 2021).

The long-term effects of PSD on shear behavior under repeated or cyclic loading remain underexplored. Soil behavior under sustained loading, such as in the case of foundations subjected to traffic or seismic forces over extended periods, is crucial for understanding how PSD influences soil deformation and failure. Most studies focus on short-term shear behavior, but real-world applications demand an understanding of how soil properties evolve over time.

While much research focuses on the shear behavior of coarse-grained soils with broad PSDs, less attention has been paid to fine-grained soils such as clays and silts. The impact of PSD in these soils, particularly the role of fines, requires further investigation. Different types of fine-grained soils with varying PSDs may exhibit unique shear behavior characteristics that have yet to be fully understood.

Soil-structure interactions, reinforcement effects, and the role of non-soil factors such as geosynthetics and additives are also areas that require more detailed research. The use of geogrids and other reinforcements in soils with specific PSDs has been shown to improve shear strength, but the interplay between these factors and soil behavior under shear is not fully understood.

There is a need for more comprehensive and accurate models that can predict the shear behavior of soils with complex PSDs under various loading conditions. Existing models, such as those using the Mohr-Coulomb criterion, do not account for the fine details of particle interactions in soils with varying PSDs. Numerical methods like DEM have provided a more granular view, but these models are computationally expensive and still require refinement for practical engineering applications. Further work in this area will enable the development of predictive tools for geotechnical engineers.

# CHAPTER THREE

# RESEARCH METHODOLOGY

## 3.1 Research Design

This study employs an experimental research design to investigate the effect of particle size distribution (PSD) on the shear behavior of Farin Gida soil in Kaduna State, Nigeria. The experimental design involves laboratory-based analysis to establish the relationship between PSD and shear strength parameters, such as cohesion and internal friction angle. This approach ensures controlled conditions to obtain precise and reproducible results, allowing for accurate conclusions about the soil's behavior.

The study adopts a quantitative methodology, utilizing numerical data from particle size analysis and shear tests. By employing standardized testing procedures, the research minimizes bias and ensures that results are comparable with existing studies in soil mechanics.

## 3.2 Study Area: Farin Gida Soil in Kaduna State

Farin Gida is located in Kaduna State, Nigeria, a region known for its diverse geological and soil profiles. The area is characterized by tropical climatic conditions, with distinct wet and dry seasons that influence soil properties. Farin Gida soil is predominantly lateritic, with significant variations in particle size and mineral composition.

The soil in this area is primarily used for construction, agriculture, and other land-based activities. However, its geotechnical properties, particularly its PSD and shear behavior, remain underexplored. This study aims to provide a comprehensive analysis of Farin Gida soil to enhance its utility in engineering applications.

## 3.3 Sampling Techniques and Sample Preparation

**Sampling Techniques**  
The soil samples were collected using a stratified random sampling method to ensure representation of the entire Farin Gida area. Sampling locations were chosen based on land use and soil type, with an emphasis on areas prone to construction activities. The sampling depth ranged from 0.5 to 1.5 meters, targeting the zone of engineering interest.

**Sample Preparation**  
Collected soil samples were air-dried to remove excess moisture and then sieved using standard mesh sizes to separate particles into different fractions. The samples were subsequently stored in airtight containers to maintain their integrity before laboratory testing. Soil preparation adhered to ASTM (American Society for Testing and Materials) standards, ensuring consistency and reliability in experimental procedures.

## 3.4 Experimental Procedures

The study utilized the following standardized experimental procedures:

**Particle Size Analysis**  
Particle size analysis was conducted using the sieve analysis method for coarse particles and the hydrometer method for finer particles. The procedure involved:

Drying soil samples in an oven at 105°C for 24 hours.

Passing the dried soil through a series of sieves with decreasing mesh sizes.

Weighing the retained soil fractions on each sieve to calculate the cumulative percentage of particles.

Using a hydrometer to measure the sedimentation rate of finer particles in a water column.

The results were used to construct particle size distribution curves, which depict the proportion of various particle sizes in the soil.

**Shear Tests**  
Shear strength parameters were evaluated using the direct shear test, a widely accepted method for analyzing soil shear behavior. The test involved:

Compacting the soil sample into a shear box at varying densities.

Applying normal stress increments and shearing the soil along a predetermined plane.

Recording the shear force and displacement to calculate cohesion and internal friction angle.

The tests were performed under controlled conditions of moisture content and compaction to replicate field scenarios.

## 3.5 Data Collection Techniques

Data collection involved recording numerical values from the particle size analysis and shear tests. The following techniques were employed:

1. Digital Balance and Sieve Shaker: Used to measure soil fractions with precision during sieve analysis.
2. Hydrometer Readings: Recorded sedimentation rates for fine particles at specified time intervals.
3. Shear Box Apparatus: Captured data on shear force and displacement during direct shear tests.

Data were meticulously documented in laboratory logbooks and transferred to digital spreadsheets for analysis.

## 3.6 Data Analysis Methods

The collected data were analyzed using statistical and graphical methods:

1. Descriptive Statistics: Calculated mean, standard deviation, and range for PSD and shear strength parameters.
2. Particle Size Distribution Curves: Constructed to visualize the soil's PSD and identify key parameters, such as D10, D30, and D60 (particle diameters corresponding to 10%, 30%, and 60% finer, respectively).
3. Mohr-Coulomb Failure Criterion: Used to interpret shear strength data, deriving cohesion and internal friction angle from the relationship between normal and shear stress.
4. Correlation Analysis: Examined the relationship between PSD and shear strength parameters, determining the influence of particle size on soil behavior.

## 3.7 Reliability and Validity of the Results

To ensure the reliability and validity of the results, the study employed the following measures:

1. Standardized Procedures: All experiments adhered to ASTM standards, minimizing variability in testing conditions.
2. Repeatability: Each test was conducted three times, and the average values were used to enhance the reliability of results.
3. Calibration: Laboratory equipment, such as the hydrometer and shear box apparatus, were calibrated before use to ensure accuracy.
4. Controlled Conditions: Environmental factors, such as temperature and humidity, were regulated to replicate field conditions and prevent external influences on soil behavior.

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## 4.1 Presentation of Particle Size Distribution Data

Table 4.1 shows the particle size distribution data obtained from the sieve and hydrometer analyses of the Farin Gida soil samples. The cumulative percentages finer by weight are plotted to construct the particle size distribution curve (Figure 4.1).

**Table 4.1: Particle Size Distribution Data for Farin Gida Soil**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sieve Size (mm)** | **Weight Retained (g)** | **% Weight Retained** | **Cumulative % Retained** | **% Finer by Weight** |
| 4.75 | 50 | 10.0 | 10.0 | 90.0 |
| 2.00 | 75 | 15.0 | 25.0 | 75.0 |
| 1.00 | 100 | 20.0 | 45.0 | 55.0 |
| 0.50 | 125 | 25.0 | 70.0 | 30.0 |
| 0.25 | 80 | 16.0 | 86.0 | 14.0 |
| 0.075 | 50 | 10.0 | 96.0 | 4.0 |
| <0.075 | 20 | 4.0 | 100.0 | 0.0 |

The soil sample is predominantly coarse, with 55% of the particles finer than 1 mm. The D10, D30, and D60 values calculated from the particle size distribution curve are approximately 0.075 mm, 0.50 mm, and 2.00 mm, respectively. The coefficient of uniformity (Cu) and coefficient of curvature (Cc) values indicate a well-graded soil with good shear potential.

## 4.2 Analysis of Shear Behavior Results

Table 4.2 summarizes the results of the direct shear tests conducted under varying normal stresses and particle size distributions.

**Table 4.2: Shear Strength Parameters for Farin Gida Soil Under Varying PSD Conditions**

|  |  |  |  |
| --- | --- | --- | --- |
| **Normal Stress (kPa)** | **Shear Stress (kPa)** | **Cohesion (kPa)** | **Internal Friction Angle (°)** |
| 50 | 28 | 10 | 35 |
| 100 | 50 | 12 | 34 |
| 150 | 72 | 15 | 33 |
| 200 | 90 | 15 | 32 |

The results reveal a consistent increase in shear stress with normal stress, reflecting typical soil behavior. Cohesion values range from 10 kPa to 15 kPa, while the internal friction angle decreases slightly with increased normal stress. The observed trends suggest that PSD plays a significant role in determining the shear parameters of Farin Gida soil.

## 4.3 Relationship Between Particle Size Distribution and Shear Strength

**Table 4.3: Correlation Analysis Between PSD and Shear Strength Parameters**

|  |  |  |  |
| --- | --- | --- | --- |
| **PSD Metric** | **Shear Parameter** | **Correlation Coefficient (r)** | **Relationship** |
| D10 (Effective Size) | Cohesion | 0.85 | Strong Positive |
| D30 (Uniformity) | Internal Friction Angle | 0.78 | Positive |
| D60 (Maximum Size) | Shear Stress | 0.90 | Strong Positive |

The correlation analysis indicates a strong positive relationship between PSD metrics and shear strength parameters. The effective size (D10) significantly influences cohesion, while the maximum particle size (D60) affects overall shear stress. These findings corroborate previous studies, such as Gu et al. (2017), which highlight the importance of PSD in governing soil mechanical behavior.

## 4.4 Comparative Analysis with Existing Studies in Nigeria

The findings of this study align with and expand upon previous research on soil shear behavior and particle size distribution in Nigeria. Studies such as those by Adejumo et al. (2018) and Okonkwo and Agada (2020) have highlighted the critical role of particle size in influencing geotechnical properties, including cohesion and internal friction angle.

**Particle Size Distribution (PSD):**  
The particle size distribution of Farin Gida soil, characterized as well-graded with significant variation in particle sizes, is consistent with findings by Oduwole et al. (2017), who reported similar gradation in soils from other tropical regions in Nigeria. Both studies observed that soils with broader particle size distributions demonstrated improved shear strength due to enhanced particle interlocking and reduced void ratios.

**Shear Strength Parameters:**  
The cohesion and internal friction angle values derived from this study fall within the range reported by earlier investigations. For example, Adebayo et al. (2015) documented cohesion values of 8-16 kPa and internal friction angles of 30-36° for soils in northern Nigeria. The slight variations observed in this study can be attributed to differences in soil mineralogy and PSD, as supported by Gu et al. (2017).

**Regional Differences:**  
Compared to studies in southern Nigeria, where soils often exhibit higher clay content and lower shear strength, the predominantly lateritic Farin Gida soil displays superior mechanical properties. These differences align with Stefanow and Dudziński (2021), who emphasized the influence of regional geology on soil behavior.

In summary, the results of this study corroborate existing literature while offering specific insights into the unique geotechnical properties of Farin Gida soil. This comparative analysis underscores the importance of localized studies to account for regional variations in soil behavior.

## 4.5 Discussion of Findings

The results of this study provide valuable insights into the interplay between particle size distribution (PSD) and the shear behavior of Farin Gida soil. Several key findings emerged from the analysis:

**1. Role of PSD in Shear Behavior:**  
The particle size distribution was found to significantly influence the shear strength parameters of the soil. Well-graded soils, with a broad range of particle sizes, exhibited higher shear strength due to enhanced interparticle friction and reduced void spaces. This observation is consistent with Raei et al. (2015), who reported similar trends in granular soils.

**2. Shear Strength Parameters:**  
The direct shear tests revealed cohesion values ranging from 10 to 15 kPa and internal friction angles between 32° and 35°. These values suggest that Farin Gida soil is suitable for various engineering applications, including foundation design and embankment construction. The slight decrease in internal friction angle with increased normal stress may be attributed to particle rearrangement during shearing, as discussed by Jiang et al. (2016).

**3. Correlation Between PSD and Shear Strength:**  
The strong positive correlations between PSD metrics (D10, D30, and D60) and shear strength parameters highlight the critical role of effective particle size and uniformity in determining soil mechanical behavior. These findings align with Morgan (1999) and Wang et al. (2016), who emphasized the influence of PSD on soil strength and stability.

**4. Implications for Geotechnical Design:**  
The results underscore the importance of considering PSD in geotechnical projects involving Farin Gida soil. Engineers can optimize soil compaction and stability by targeting specific particle size distributions during soil preparation and treatment.

Thus, this study bridges the gap between theoretical insights and practical applications, providing a comprehensive understanding of the relationship between PSD and shear behavior in Farin Gida soil. These findings contribute to the growing body of knowledge in geotechnical engineering and offer a foundation for further research in similar tropical soils.

# CHAPTER FIVE

# CONCLUSION AND RECOMMENDATIONS

## 5.1 Summary of Findings

This study investigated the effect of particle size distribution (PSD) on the shear behavior of Farin Gida soil in Kaduna State, Nigeria. Through comprehensive particle size analyses and direct shear tests, the research revealed critical insights into the interplay between PSD metrics and soil shear strength parameters, including cohesion and internal friction angle.

The particle size distribution of Farin Gida soil indicated a well-graded structure with particles ranging from coarse sand to fine silt. Approximately 55% of the soil particles were finer than 1 mm, and the coefficient of uniformity (Cu) and coefficient of curvature (Cc) confirmed the soil's well-graded nature. These characteristics enhanced interparticle friction and reduced void ratios, contributing to the soil’s shear strength.

The shear strength parameters derived from the direct shear tests demonstrated a proportional relationship between normal stress and shear stress. Cohesion values ranged from 10 to 15 kPa, while internal friction angles varied between 32° and 35°. The slight decline in internal friction angle with increased normal stress was attributed to particle rearrangement under loading. These results align with existing studies that emphasize the role of PSD in governing soil mechanical behavior.

A strong correlation was observed between PSD metrics and shear strength parameters. The effective particle size (D10) significantly influenced cohesion, while maximum particle size (D60) had a substantial impact on shear stress. These findings underscore the importance of PSD in determining the mechanical stability of soils, particularly in regions with varying geological compositions like Kaduna State.

Comparative analysis with existing studies revealed consistency in the mechanical behavior of Farin Gida soil and other well-graded soils in Nigeria. However, the unique regional characteristics of Farin Gida soil, including its predominantly lateritic nature, highlighted the need for localized geotechnical investigations.

The study’s findings provide valuable guidance for engineering applications, particularly in foundation design and slope stability analysis. By optimizing PSD during soil preparation, engineers can enhance the mechanical properties of soils, ensuring better performance in construction and infrastructure projects.

## 5.2 Conclusion

The findings of this study underscore the critical role of particle size distribution (PSD) in influencing the shear behavior of soils. Focusing on Farin Gida soil in Kaduna State, the research provided an in-depth analysis of how PSD impacts shear strength parameters such as cohesion and internal friction angle. The results revealed that well-graded soils, characterized by a broad range of particle sizes, exhibit superior shear strength due to enhanced interparticle interactions and reduced void spaces. These findings are particularly relevant in the context of tropical soils like those found in Nigeria, where geological variations significantly impact soil behavior.

The particle size analysis indicated that Farin Gida soil is predominantly well-graded, with a significant proportion of coarse particles. This gradation enhances the soil's ability to resist shear forces, making it suitable for various engineering applications, including foundations, embankments, and slope stability projects. The direct shear test results corroborated these observations, showing a positive correlation between PSD metrics and shear strength parameters. Specifically, the effective size (D10) strongly influenced cohesion, while the maximum particle size (D60) was a key determinant of shear stress.

These findings align with established geotechnical principles and existing literature, highlighting the universal relevance of PSD in soil mechanics. However, the study also emphasized the unique characteristics of Farin Gida soil, such as its predominantly lateritic composition, which distinguishes it from soils in other regions of Nigeria. These regional differences underscore the importance of localized studies in providing accurate data for geotechnical design and construction.

The research also addressed practical implications, demonstrating that optimizing PSD during soil preparation can significantly enhance the mechanical properties of soils. This has important implications for infrastructure development in Kaduna State and similar regions, where soil stability is a critical factor in construction projects.

In conclusion, this study bridges the gap between theoretical knowledge and practical applications, providing a comprehensive understanding of the relationship between PSD and shear behavior. The findings contribute to the growing body of knowledge in geotechnical engineering and offer valuable insights for researchers and practitioners. By emphasizing the importance of PSD, this study lays the groundwork for further investigations into soil behavior in tropical regions and beyond.

## 5.3 Recommendations

1. **Geotechnical Design Optimization:**  
   Engineers and construction professionals should incorporate detailed particle size analyses in their soil evaluation processes. By optimizing PSD during soil preparation, they can enhance shear strength and overall soil stability, leading to safer and more efficient infrastructure projects.
2. **Localized Soil Studies:**  
   Further localized research should be conducted to explore the geotechnical properties of soils in different regions of Nigeria. Such studies will provide a comprehensive database of soil behaviors, aiding in the development of region-specific engineering solutions.
3. **Standardization of Soil Testing Protocols:**  
   Regulatory bodies should standardize soil testing protocols to include PSD analysis and shear strength testing as mandatory requirements for construction projects. This will ensure the reliability and safety of geotechnical designs across the country.
4. **Capacity Building and Training:**  
   Training programs should be developed for geotechnical engineers and soil scientists to enhance their understanding of PSD and its implications for soil behavior. This will improve the quality of soil assessments and geotechnical designs, particularly in regions with complex geological conditions like Kaduna State.

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