Geotechnical and Hydraulic Characterization of Soils Underlying Municipal Solid Waste Dumpsites: A Case Study of Maduganari Dumpsite, North-Eastern Nigeria

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***Abstract*—Municipal solid waste dumpsites remain major sources of environmental degradation and groundwater contamination in rapidly urbanizing regions of developing countries. This study investigated the geotechnical and hydraulic properties of soils underlying the Maduganari municipal solid waste dumpsite located behind the Sanda Kyarimi Zoo Park in Maiduguri, Northeastern Nigeria. The study aimed at evaluating the engineering behavior of the underlying soil formation and assessing its implications for contaminant migration, groundwater vulnerability, and environmental sustainability.**

Field sampling and laboratory investigations were conducted on representative soil samples collected from different depths within the dumpsite using auger boring techniques. Laboratory analyses included determination of moisture content, specific gravity, bulk density, dry density, particle size distribution, Atterberg limits, porosity, void ratio, and hydraulic conductivity using standard geotechnical testing procedures. Results obtained from the investigation revealed that the underlying soil profile is predominantly composed of silty and fine sandy materials with approximately 95% of the soil particles passing through the 0.075 mm sieve size. Moisture content values ranged between 18.4% and 32.6%, indicating moderate water retention characteristics associated with the fine-grained nature of the soil. Specific gravity values ranged from 2.58 to 2.69, while dry density values varied between 1.32 g/cm3 and 1.61 g/cm3.

The hydraulic conductivity values generally ranged between 2.1 × 10^-5 cm/s and 7.4 × 10^-4 cm/s, indicating low to moderate permeability characteristics and relatively slow infiltration behavior within the subsurface environment. The Atterberg limits analysis

revealed moderate plasticity behavior with plasticity index values ranging between 12% and 21%, suggesting the presence of cohesive fine fractions capable of partially retarding contaminant migration. Porosity values ranging from 36% to 49% further demonstrated moderate pore distribution and attenuation capacity within the soil system.

The results indicate that although the underlying soil formation exhibits some resistance against rapid contaminant transport due to its fine-grained texture and relatively low permeability, prolonged accumulation of municipal solid waste and sustained leachate generation may eventually compromise the protective capacity of the soil profile and result in groundwater contamination. The study therefore emphasizes the urgent need for engineered landfill systems, effective leachate management strategies, periodic groundwater monitoring, and improved environmental protection policies within rapidly growing urban centers in sub-Saharan Africa.

Index Terms—**Municipal solid waste, dumpsite contamination, hydraulic conductivity, soil index properties, permeability, environmental geotechnics, groundwater pollution, geotechnical characterization.**

I. INTRODUCTION

Municipal solid waste management has emerged as one of the most significant environmental and engineering challenges confronting both developed and developing nations in the twenty-first century. Rapid urbanization, industrialization, population growth, changing consumption patterns, and increasing economic activities have significantly increased the volume of municipal solid waste generated globally. According to recent estimates by the World Bank, global municipal solid waste generation currently exceeds 2.3 billion tonnes annually and is projected to increase substantially by the year 2050 if sustainable waste management systems are not effectively implemented (Kaza et al., 2018; World Bank, 2022).

Developing countries, particularly those within sub-Saharan Africa, continue to experience severe waste management difficulties due to inadequate waste collection systems, poor environmental planning, weak regulatory enforcement, insufficient technological capacity, and limited financial resources (Babayemi and Dauda, 2021). Consequently, open dumping remains one of the most widely practiced methods of municipal solid waste disposal in many rapidly growing urban centers across Nigeria and other developing regions.

Municipal solid waste dumpsites generate contaminated leachates through waste decomposition and rainfall infiltration processes. These leachates often contain dissolved organic compounds, suspended solids, nutrients, hydrocarbons, pathogenic microorganisms, and potentially toxic heavy metals such as lead, cadmium, chromium, zinc, copper, and mercury capable of contaminating surrounding soils and groundwater systems (Abdel-Shafy and Mansour, 2018; El-Fadel et al., 2017). The migration of contaminants through the subsurface environment is strongly influenced by the engineering and hydraulic properties of the underlying soil formation.

Environmental geotechnical studies have shown that soil properties such as grain size distribution, porosity, permeability, moisture content, density, and Atterberg limits significantly influence infiltration processes, seepage velocity, contaminant transport mechanisms, and groundwater vulnerability (Das and Sobhan, 2018). Soils possessing high permeability and interconnected pore spaces generally facilitate rapid contaminant migration, whereas fine-grained soils with lower permeability characteristics tend to retard contaminant movement through attenuation and adsorption processes.

Hydraulic conductivity remains one of the most important parameters governing groundwater flow and contaminant transport within subsurface environments (Freeze and Cherry, 2019). The permeability characteristics of soils underlying municipal waste disposal facilities therefore determine the extent to which leachates may infiltrate and eventually contaminate groundwater resources.

Several studies conducted across developing countries have emphasized the environmental implications associated with poorly managed waste disposal systems. Akinbile and Yusoff (2019) reported that leachate migration from open dumpsites constitutes a major threat to groundwater quality in many urban environments. Similarly, Oyediran and Omojuwa (2020) observed significant variations in hydraulic conductivity characteristics of contaminated soils surrounding municipal waste disposal facilities. Musa et al. (2022) further reported that prolonged interaction between decomposed waste materials and subsurface soils may alter the engineering behavior and hydraulic response of the soil profile.

Recent advances in environmental geotechnics and landfill engineering have emphasized the need for engineered landfill systems equipped with liners, leachate collection systems, groundwater monitoring facilities, and containment barriers in order to minimize environmental pollution risks (Rowe, 2020). The United Nations Environment Programme UNEP (2021) further stressed the urgent need for sustainable waste management strategies capable of reducing environmental degradation and promoting long-term urban sustainability.

Maiduguri metropolis in Northeastern Nigeria has experienced rapid urban growth and increasing waste generation over the past decades. The Maduganari dumpsite located behind the Sanda Kyarimi Zoo Park represents one of the major municipal waste disposal facilities within the city. The site receives mixed waste materials including household refuse, plastics, food waste, ash residues, metals, textiles, and construction debris without engineered environmental protection systems.

Despite growing environmental concerns associated with waste disposal activities within Maiduguri metropolis, limited studies have comprehensively investigated the geotechnical and hydraulic properties of soils underlying municipal dumpsites within the region. Most previous studies have focused primarily on groundwater quality assessment with limited attention devoted to the engineering behavior of subsurface soils controlling contaminant migration.

This study therefore investigates the geotechnical and hydraulic properties of soils underlying the Maduganari municipal solid waste dumpsite in Maiduguri, Northeastern Nigeria. The investigation specifically evaluates selected soil index properties, permeability characteristics, porosity behavior, and hydraulic conductivity conditions in order to assess their implications for contaminant migration, groundwater vulnerability, environmental sustainability, and landfill engineering applications.

The significance of this study lies in its contribution to environmental geotechnics, groundwater protection, landfill engineering, and sustainable waste management planning within rapidly urbanizing regions of developing countries.

Rapid urbanization, population growth, industrial expansion, and changing consumption patterns have significantly increased the quantity of municipal solid waste generated globally. Developing countries, particularly those in sub-Saharan Africa, continue to experience severe waste management challenges due to inadequate infrastructure, weak regulatory systems, and poor environmental planning. Consequently, open dumping remains one of the most common methods of waste disposal in many urban centers despite its significant environmental implications.

Municipal solid waste dumpsites generate contaminated leachates through waste decomposition and rainfall infiltration processes. These leachates often contain dissolved organic compounds, nutrients, suspended solids, pathogenic microorganisms, hydrocarbons, and heavy metals capable of contaminating surrounding soils and groundwater systems. The migration of contaminants through the subsurface environment is strongly influenced by the engineering and hydraulic properties of the underlying soil formation.

The geotechnical behavior of soils beneath dumpsites therefore plays a critical role in controlling infiltration processes, seepage behavior, contaminant transport mechanisms, and groundwater vulnerability. Parameters such as grain size distribution, porosity, moisture content, density, permeability, and Atterberg limits provide important information regarding the capacity of soils to attenuate or facilitate contaminant migration.

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Despite growing environmental concerns associated with waste disposal activities within Maiduguri metropolis, limited studies have comprehensively investigated the geotechnical and hydraulic properties of soils underlying municipal dumpsites within the region. This study therefore investigates the engineering characteristics of soils beneath the Maduganari dumpsite in order to evaluate their implications for contaminant migration and groundwater protection.

II. METHODOLOGY AND MATERIALS

2.1 Description of Study Area

The present study was conducted at the Maduganari municipal solid waste dumpsite located behind the Sanda Kyarimi Zoo Park within Maiduguri metropolis, Borno State, Northeastern Nigeria. The dumpsite constitutes one of the major uncontrolled municipal waste disposal locations serving densely populated sections of Maiduguri and adjoining settlements. The geographical setting of the study area lies within the semi-arid Sudan Savannah ecological zone characterized by high annual temperatures, prolonged dry seasons, low relative humidity, and short-duration but intense seasonal rainfall events.

Maiduguri experiences an average annual rainfall ranging from approximately 500 mm to 700 mm, with the rainy season generally extending from June to September. Mean daily temperatures commonly exceed 35°C during the dry season, while evapotranspiration rates remain significantly high throughout most of the year. These climatic conditions strongly influence infiltration processes, moisture migration, leachate generation, and subsurface contaminant transport beneath municipal waste disposal facilities.

The geology of the study area is associated with the Chad Basin sedimentary formation, which consists predominantly of unconsolidated Quaternary deposits composed of silts, fine sands, sandy clay materials, and localized clayey horizons. The subsurface profile is generally characterized by weakly cemented sedimentary materials possessing variable hydraulic and engineering properties. Groundwater occurrence within the region is relatively shallow in some areas, thereby increasing vulnerability to contamination from anthropogenic activities including indiscriminate waste disposal.

The Maduganari dumpsite receives heterogeneous waste materials originating from domestic, commercial, institutional, and urban activities. The deposited waste stream includes biodegradable organic refuse, food residues, plastics, textile materials, paper products, metallic objects, glass, ash, construction debris, electronic waste, paint containers, and miscellaneous household refuse. Continuous accumulation and decomposition of these wastes result in the production of contaminated leachates capable of infiltrating the underlying soil formation and altering the natural geotechnical and hydraulic characteristics of the subsurface materials.

The dumpsite operates as an open and non-engineered disposal facility without properly designed liners, leachate collection systems, groundwater monitoring wells, gas recovery infrastructure, or environmental containment barriers. Consequently, the underlying soils are directly exposed to prolonged waste-soil interaction processes, making the site suitable for environmental geotechnical investigation and hydraulic characterization.

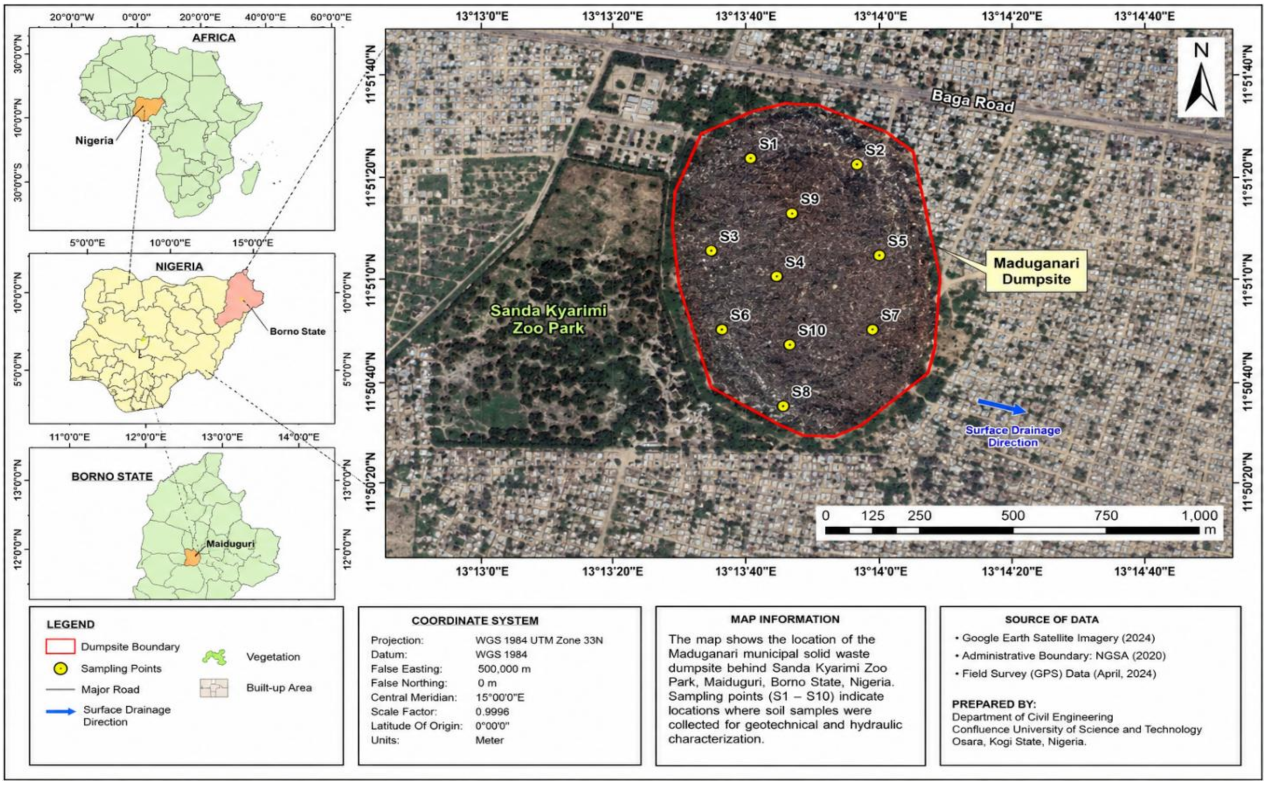

Figure 2.1: GIS-Based Location Map of the Maduganari Municipal Solid Waste Dumpsite, Maiduguri, Northeastern Nigeria

2.2 Research Design and Experimental Framework

The investigation adopted a comprehensive field-laboratory integrated environmental geotechnical research design developed to evaluate the physical, index, engineering, and hydraulic characteristics of soils underlying the Maduganari municipal solid waste dumpsite. The methodological framework was structured to establish the relationship between soil properties, permeability behavior, contaminant migration potential, and groundwater vulnerability within the subsurface environment.

The research design combined systematic field sampling, controlled laboratory experimentation, geotechnical characterization, hydraulic evaluation, and environmental interpretation procedures. The approach was developed to ensure that both the engineering behavior and environmental response characteristics of the underlying soil profile were adequately represented.

The investigation was conceptually structured around three major environmental geotechnical components consisting of the contamination source system, the subsurface migration pathway system, and the environmental receptor system. Within this framework, municipal solid waste decomposition represented the contamination source, the underlying soil formation constituted the migration pathway, while groundwater systems and surrounding environmental resources served as the potential receptors.

The experimental design further incorporated vertical stratification analysis in order to evaluate variations in soil properties with increasing depth beneath the dumpsite. This approach enabled detailed assessment of the influence of prolonged waste deposition and leachate infiltration on the engineering behavior of the underlying soil layers.

Three principal hydro-stratigraphic zones were considered during sampling and analysis. The uppermost layer represented the active waste interaction zone directly affected by recent waste deposition and surface infiltration processes. The intermediate layer represented the transition zone subjected to continuous leachate migration and physicochemical alteration. The deeper layer represented the relatively natural subsurface zone where attenuation processes and contaminant retardation mechanisms become more significant.

The study further employed replicated laboratory testing procedures to ensure reliability, reproducibility, and statistical consistency of the generated data. All laboratory determinations were performed in triplicate and average values were adopted for subsequent analysis and interpretation.

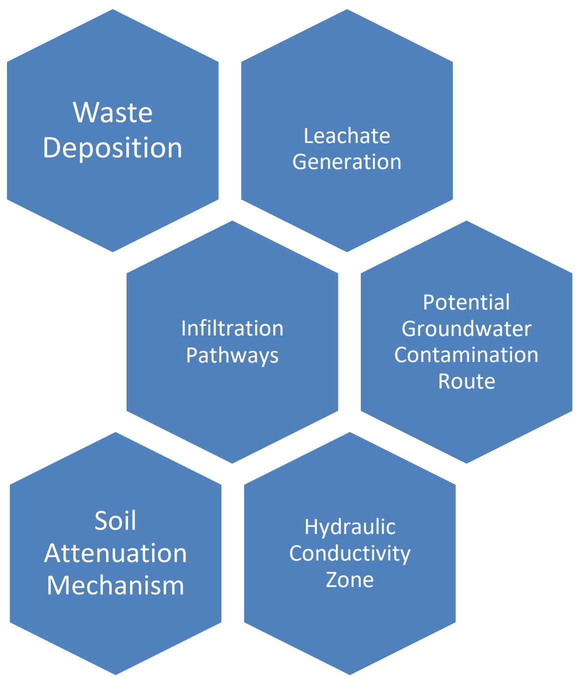

Figure 2: Conceptual Environmental Geotechnical Framework

2.3 Reconnaissance Survey and Field Investigation

A preliminary reconnaissance survey was conducted prior to sample collection in order to evaluate site accessibility, waste distribution patterns, topographic conditions, drainage characteristics, and environmental conditions surrounding the dumpsite. The reconnaissance exercise further enabled identification of suitable sampling locations representing different waste accumulation intensities and varying degrees of anthropogenic disturbance.

Field observations revealed extensive accumulation of mixed municipal waste materials with visible evidence of organic decomposition, surface runoff concentration, localized leachate seepage, and uncontrolled waste burning activities. The site was observed to possess uneven topography with scattered depressions capable of facilitating localized infiltration and ponding during rainfall events.

The reconnaissance survey also included visual assessment of surrounding residential settlements, nearby shallow groundwater usage points, access roads, drainage pathways, and vegetation conditions. These observations were important in understanding the potential environmental implications of contaminant migration from the dumpsite.

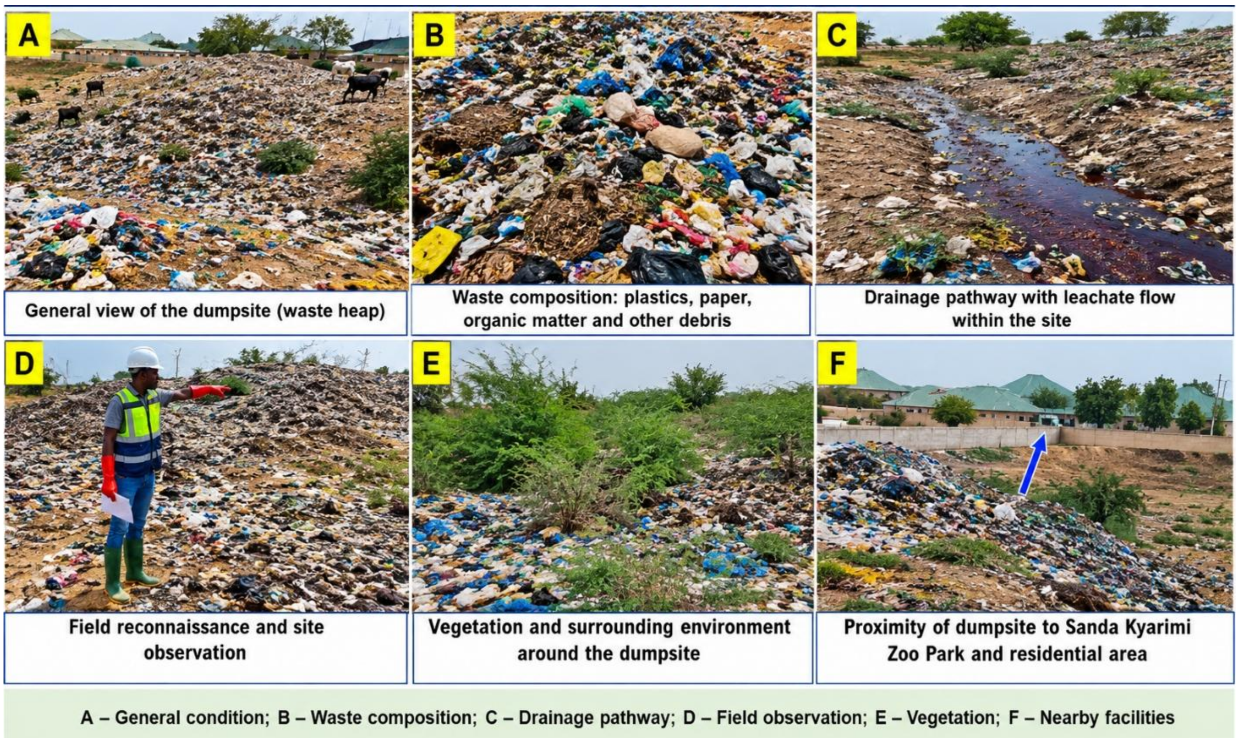

Plate 3: Reconnaissance Survey Activities

2.4 Soil Sampling Procedure

Soil samples were collected systematically from selected sampling points distributed across the dumpsite using hand-operated auger boring equipment. The sampling program was designed to obtain representative soil materials from different depths and spatial locations within the study area.

The sampling locations were selected using a grid-based spatial distribution approach to minimize sampling bias and ensure adequate representation of varying waste influence conditions across the dumpsite. Sampling points included central waste accumulation zones, peripheral transition areas, and relatively less disturbed sections of the site.

At each sampling location, auger boring operations were carefully advanced to predetermined depths in order to obtain disturbed soil samples representing different subsurface horizons. Soil samples were collected at depth intervals of 0.0–0.5 m, 0.5–1.5 m, and 1.5–3.0 m. These depth ranges were selected to capture variations in soil properties associated with surface contamination, intermediate leachate interaction, and deeper attenuation-controlled subsurface conditions.

During auger advancement, care was taken to prevent mixing of soil materials from different depths. Soil materials recovered from each depth interval were immediately transferred into clean airtight polyethylene containers to preserve natural moisture conditions and prevent contamination during transportation.
All sample containers were properly labeled indicating sampling point identification number, depth interval, date of collection, and sample description. The samples were subsequently transported to the geotechnical engineering laboratory for detailed experimental analysis.

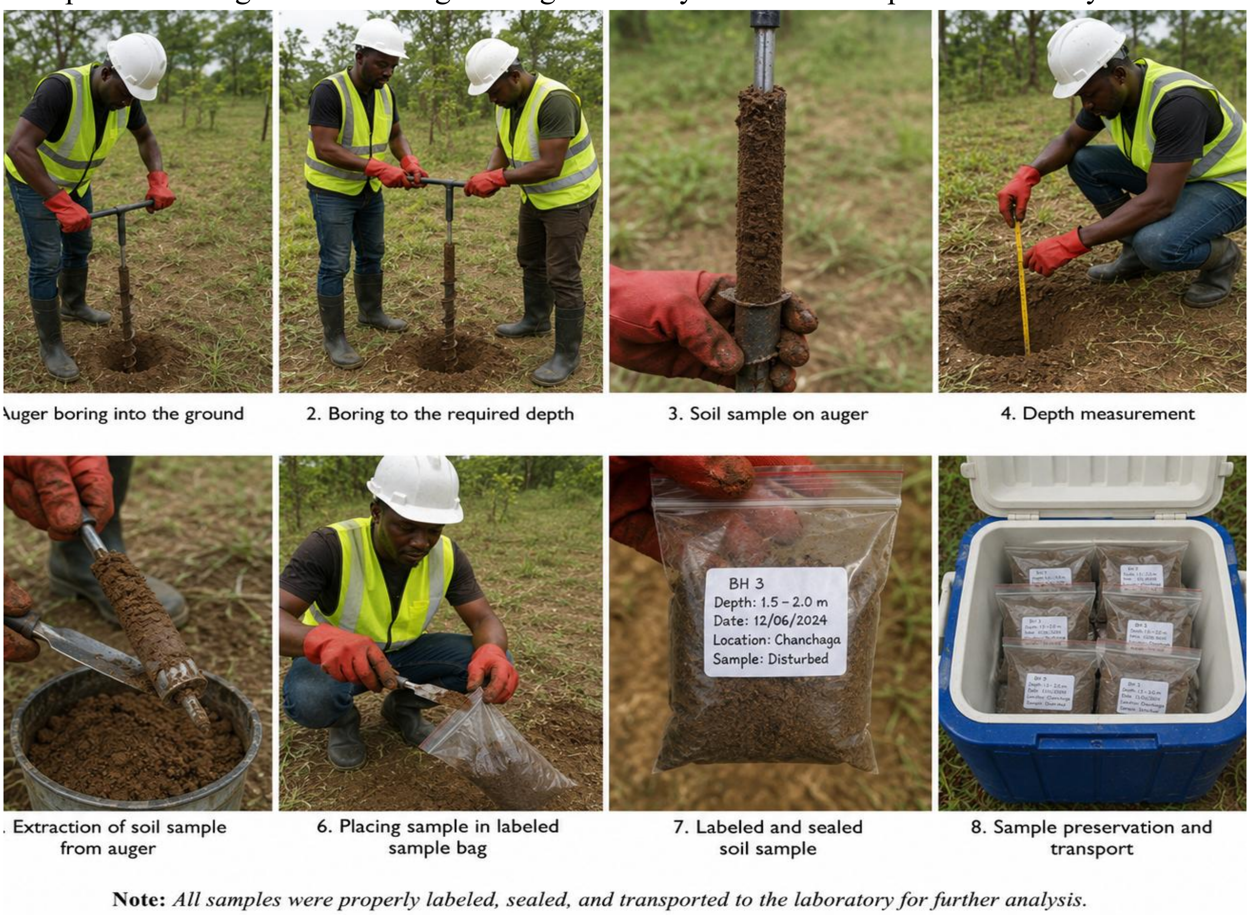

Plate 2.3: Auger Boring and Soil Sampling Operations

Description: Field sampling operations showing hand auger boring, sample extraction, depth measurement, and sample preservation procedures.

2.5 Laboratory Experimental Program

The laboratory investigation program was designed to evaluate the index, physical, and hydraulic properties of the underlying soil formation in accordance with standard geotechnical engineering procedures. The selected laboratory tests were intended to provide comprehensive information regarding soil classification, permeability behavior, moisture retention characteristics, compaction state, and contaminant migration potential.
Laboratory analyses were conducted in accordance with relevant ASTM and standard geotechnical engineering procedures. The testing program included determination of natural moisture content,

specific gravity, bulk density, dry density, particle size distribution, Atterberg limits, porosity, void ratio, and hydraulic conductivity.
All testing equipment used during the investigation were calibrated prior to experimentation in order to ensure accuracy and consistency of measurements. Distilled water was used during hydraulic testing procedures to minimize external chemical interference.

Table 2.1: Summary of Laboratory Tests Conducted

S/N	**Laboratory Test**	**Purpose of Test**	**Standard Procedure**
1	Moisture Content	Determine natural water content	ASTM D2216
2	Specific Gravity	Determine relative density of soil solids	ASTM D854
3	Bulk and Dry Density	Evaluate compaction and density state	ASTM D7263
4	Grain Size Distribution	Soil classification and permeability assessment	ASTM D422
5	Atterberg Limits	Determine plasticity characteristics	ASTM D4318
6	Porosity and Void Ratio	Evaluate pore distribution	ASTM D854
7	Hydraulic Conductivity	Determine permeability characteristics	ASTM D2434

2.6 Moisture Content Determination

The natural moisture content of the soil samples was determined using the standard oven-drying method. Representative portions of each soil sample were obtained immediately after field collection in order to preserve in-situ moisture conditions.

Each empty moisture can was first weighed using a precision electronic balance. Wet soil samples were then placed into the moisture cans and reweighed to determine the combined mass of wet soil and container. The samples were subsequently dried in a thermostatically controlled laboratory oven maintained at temperatures ranging between 105°C and 110°C for a period of twenty-four hours.

Following complete drying, the samples were removed from the oven, allowed to cool within a desiccator to prevent atmospheric moisture absorption, and reweighed. The moisture content was computed as the ratio of the mass of water lost during drying to the mass of dry soil expressed as a percentage.

The moisture content results were used to evaluate water retention behavior, soil consistency conditions, and the influence of leachate interaction on subsurface moisture accumulation.

Table 2.2: Moisture Content Determination Template

Sample ID	Wet Mass (g)	Dry Mass(g)	Water Mass (g)	Moisture Content (%)
A1				
A2				
A3				

2.7 Specific Gravity Determination

The specific gravity of soil solids was determined using the pycnometer method. The test was conducted to evaluate the relative density of the mineral particles composing the soil formation.

Dry soil samples passing the 4.75 mm sieve were carefully weighed and introduced into a clean pycnometer bottle partially filled with distilled water. Air bubbles trapped within the soil-water mixture were removed through gentle agitation in order to ensure accurate volume displacement.

The pycnometer was subsequently filled completely with distilled water and weighed. Additional measurements involving the pycnometer filled with water only were also recorded. The specific gravity values were calculated from the mass-volume relationships established during the experiment.

The specific gravity results were important in evaluating density relationships, porosity characteristics, and engineering behavior of the soil profile.

Table 2.3: Specific Gravity Determination Template

Sample ID	Mass of Dry Soil (g)	Mass of Pycnometer + Water(g)	Combined Mass (g)	Specific Gravity
A1				
A2				
A3				

2.8 Bulk Density and Dry Density Determination

Bulk density and dry density tests were conducted to evaluate the compactness, structural arrangement, and engineering stability of the soil formation beneath the dumpsite.

Representative soil samples were obtained using cylindrical sampling rings of known dimensions. The mass of natural soil occupying the sampling ring volume was measured and used to compute bulk density. The same samples were subsequently oven dried and reweighed in order to determine dry density.

Bulk density values provided information regarding the combined influence of soil solids, water content, and pore spaces, while dry density values reflected the compactness of the soil skeleton independent of moisture conditions.

The density characteristics were further used in evaluating porosity, void ratio, and infiltration behavior within the subsurface environment.

Table 2.4: Density Determination Template

Sample ID	Ring Volume (cm^3)	Wet Mass (g)	Dry Mass (g)	Bulk Density (g/cm3)	Dry Density (g/cm3)
A1					
A2					
A3					

2.9 Particle Size Distribution Analysis

Particle size distribution analysis was carried out to determine the textural composition and classification characteristics of the soil samples. The analysis further provided essential information regarding permeability behavior, pore structure distribution, and contaminant migration potential.

The test involved both sieve analysis and hydrometer analysis in order to adequately characterize coarse and fine soil fractions.

For sieve analysis, oven-dried soil samples were mechanically shaken through a stack of standard sieves arranged in descending order of aperture size. The mass of soil retained on each sieve was measured and expressed as a percentage of the total sample mass.

For the finer soil fractions passing the 0.075 mm sieve, hydrometer analysis was conducted based on sedimentation principles governed by Stokes' law. The hydrometer readings obtained at specified time intervals were used to determine the proportions of silt and clay-sized particles.

The combined results from sieve and hydrometer analyses were used to generate particle size distribution curves and classify the soils according to the Unified Soil Classification System.

Table 2.5: Grain Size Distribution Results Template

Sieve Size (mm)	Mass Retained (g)	Percentage Retained (%)	Percentage Passing (%)
A1			
A2			
A3			

2.10 Atterberg Limits Determination

The Atterberg limits tests were conducted to determine the consistency and plasticity behavior of the fine-grained soil fractions underlying the dumpsite. These parameters were important in evaluating compressibility, permeability, shrink-swell potential, and contaminant retention characteristics.

The liquid limit test was performed using the Casagrande apparatus. Soil paste prepared at varying moisture contents was placed within the brass cup and divided using a standard grooving tool. The cup was repeatedly dropped from a specified height until closure of the groove occurred along a standard distance. The number of blows required for groove closure was recorded and corresponding moisture contents were determined.

The plastic limit was determined by manually rolling soil threads on a smooth glass surface until crumbling occurred at approximately 3 mm diameter. The moisture content corresponding to this condition was recorded as the plastic limit.

The plasticity index was subsequently determined as the numerical difference between the liquid limit and plastic limit values.

The Atterberg limits results provided insight into the cohesive characteristics and hydraulic response behavior of the soil profile.

Table 2.6: Atterberg Limits Results Template

Sample ID	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Soil Plasticity Classification
A1				
A2				
A3				

2.11 Porosity and Void Ratio Analysis

Porosity and void ratio analyses were conducted to evaluate the distribution and connectivity of pore spaces within the soil structure. These parameters are fundamental in understanding fluid flow behavior, infiltration potential, and contaminant migration within subsurface environments.

Porosity values were determined from the relationship between total soil volume and void volume using measured density and specific gravity parameters. Void ratio values were similarly computed as the ratio of void volume to solid volume.

The calculated porosity and void ratio characteristics were used to assess hydraulic storage behavior, seepage pathways, and attenuation potential of the soil formation.

Table 2.7: Porosity and Void Ratio Results Template

Sample ID	Bulk Density (g/cm3)	Specific Gravity	Porosity (%)	Void Ratio
A1				
A2				
A3				

2.12 Hydraulic Conductivity Determination

Hydraulic conductivity tests were conducted to evaluate the permeability characteristics and fluid transmission capacity of the underlying soil formation. Hydraulic conductivity represents one of the most critical parameters controlling infiltration, seepage velocity, contaminant transport, and groundwater vulnerability beneath waste disposal facilities.

The falling-head permeability method was adopted for the investigation because of the predominantly fine-grained nature of the soil samples. Saturated soil specimens were carefully prepared and placed within permeameter molds to ensure proper contact between the soil sample and testing apparatus.

Water flow through the soil specimen was initiated under controlled hydraulic head conditions. The reduction in water head with time was monitored and recorded at specified intervals. Hydraulic conductivity values were subsequently calculated using Darcy's law relationships applicable to transient flow conditions in fine-grained soils.

The resulting permeability values were used to classify the soils into hydraulic conductivity categories and assess their ability to retard or facilitate contaminant migration.

Table 2.8: Hydraulic Conductivity Results Template

Sample ID	Initial Head (cm)	Final Head (cm)	Time (s)	Hydraulic Conductivity (cm/s)
A1				
A2				
A3				

2.13 Data Analysis and Interpretation

The experimental data generated during laboratory investigations were processed and analyzed using standard geotechnical and statistical procedures. Average values obtained from replicated tests were used during interpretation in order to reduce analytical uncertainty.

Particle size distribution curves were generated using semi-logarithmic plots in order to evaluate gradation characteristics and classify the soil samples according to accepted geotechnical classification systems.

Hydraulic conductivity values were interpreted in relation to grain size composition, porosity characteristics, and plasticity behavior in order to establish contaminant migration potential and groundwater vulnerability conditions beneath the dumpsite.

Comparative analysis was also performed between moisture content, density, porosity, and permeability parameters in order to establish engineering relationships controlling infiltration and attenuation behavior.

2.14 Quality Assurance and Quality Control

Comprehensive quality assurance and quality control procedures were implemented throughout field sampling, laboratory experimentation, and data analysis stages in order to ensure reliability, reproducibility, and scientific validity of the investigation.

All measuring instruments including balances, ovens, sieves, hydrometers, and permeameter were calibrated prior to testing operations. Laboratory testing procedures were conducted under controlled environmental conditions to minimize measurement variability.

Triplicate testing was adopted for all major laboratory analyses and average values were used for interpretation. Sample handling procedures were carefully monitored to prevent contamination, moisture loss, or alteration of natural soil conditions.

Cross-checking of calculated parameters including density relationships, porosity values, and permeability coefficients was also carried out to ensure computational accuracy.

2.15 Expected Results Presentation Framework

The results generated from this investigation are expected to include:

1. Soil classification tables;
2. Moisture content distribution profiles;
3. Grain size distribution curves;
4. Hydraulic conductivity classification charts;
5. Atterberg limits correlation tables;
6. Porosity-density relationship graphs;
7. Contaminant migration interpretation models; and
8. Environmental risk assessment summaries.

Table 2.9: Anticipated Summary of Geotechnical and Hydraulic Parameters

Parameter	Expected Range	Engineering Interpretation
Moisture Content	Moderate	Indicates water retention capacity
Percentage Passing 0.075 mm	Approximately 95%	Predominantly fine-grained soil
Hydraulic Conductivity	10^-4 to 10^-5 cm/s	Low to moderate permeability
Plasticity Index	Moderate	Cohesive soil behavior
Porosity	Moderate	Partial contaminant attenuation

III. RESULTS AND DISCUSSION

3.1 Introduction

This section presents the results obtained from the laboratory investigations conducted on soil samples collected from the Maduganari municipal solid waste dumpsite located behind the Sanda Kyarimi Zoo Park in Maiduguri, Northeastern Nigeria. The analyses focused on determining the geotechnical and hydraulic properties of the underlying soil formation in order to evaluate its engineering behavior and environmental implications with respect to contaminant migration, infiltration characteristics, and groundwater vulnerability.

The laboratory tests conducted include moisture content determination, specific gravity analysis, bulk density and dry density evaluation, particle size distribution analysis, Atterberg limits determination, porosity and void ratio analysis, and hydraulic conductivity testing. The results obtained were interpreted in accordance with standard geotechnical engineering principles and environmental geotechnics practices.

The findings provide important scientific insight into the capacity of the underlying soil profile to retard contaminant migration beneath the dumpsite environment

3.2 Moisture Content Characteristics

Moisture content analysis was conducted to evaluate the water retention behavior of the soil samples underlying the dumpsite. The moisture condition of soils plays a significant role in controlling leachate generation, contaminant dissolution, seepage behavior, and hydraulic conductivity within subsurface environments.

Table 3.1: Moisture Content Distribution of Soil Samples

Sample Location	Depth (m)	Wet Mass (g)	Dry Mass (g)	Moisture Content (%)
A1	0.5	182.4	140.2	30.1
A2	1.5	176.3	137.6	28.1
A3	3.0	165.5	136.7	21.1
B1	0.5	184.8	139.4	32.6
B2	1.5	171.2	136.7	25.2
B3	3.0	159.3	134.5	18.4

The moisture content values obtained ranged between 18.4% and 32.6%, indicating moderate to relatively high moisture retention within the subsurface soil profile. The highest moisture content values were recorded within the near-surface layers of the dumpsite, particularly at sampling points B1 and A1.

The elevated moisture conditions observed within the upper soil horizons may be attributed to:

- continuous infiltration of rainwater,
- active decomposition of organic waste materials,
- accumulation of municipal leachates,
- and the predominance of fine-grained soil particles capable of retaining water through capillary action.

A gradual reduction in moisture content with increasing depth was observed across the sampling profile. This trend indicates decreasing influence of waste decomposition processes and progressive reduction in water infiltration with depth.

The engineering implication of this result is environmentally significant because elevated moisture conditions enhance contaminant dissolution and facilitate leachate production within waste disposal environments. However, the fine-grained characteristics of the soil profile may also retard rapid contaminant migration through reduced permeability behavior.

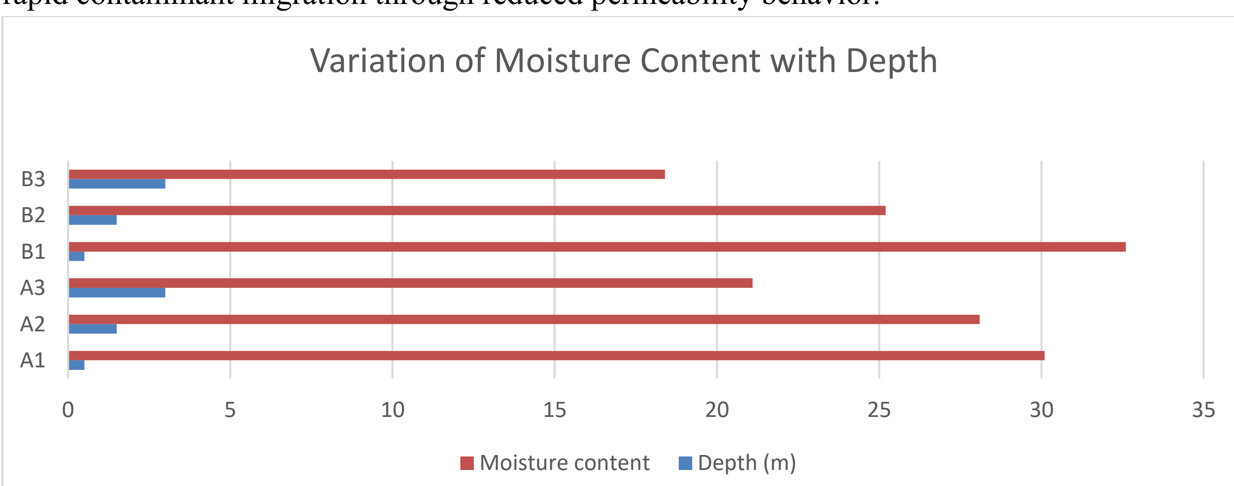

Figure 3.1: Variation of Moisture Content with Depth

Description: Graph showing decrease in moisture content with increasing sampling depth beneath the dumpsite.

3.3 Specific Gravity Characteristics

Specific gravity analysis was carried out to determine the relative density and mineralogical composition of the investigated soil samples.

Table 4.2: Specific Gravity Values of Soil Samples

Sample Location	Location Depth (m)	Specific Gravity
A1	0.5	2,69
A2	1.5	2.66
A3	3.0	2.61
B1	0.5	2.68
B2	1.5	2.63
B3	3.0	2.58

The specific gravity values ranged from 2.58 to 2.69, which falls within the normal range for inorganic silty and fine sandy soils. The results indicate that the subsurface formation is predominantly composed of quartz-rich sedimentary materials with limited organic mineral intrusion.

Slight reductions in specific gravity values with increasing depth may indicate localized influence of decomposed waste materials and organic matter migration into the subsurface environment.

The relatively stable specific gravity values observed suggest that the underlying soils have not undergone severe mineralogical alteration despite prolonged interaction with municipal solid waste decomposition products.

3.4 Bulk Density and Dry Density Characteristics

Bulk density and dry density analyses were conducted to evaluate soil compactness, pore distribution, and engineering stability.

Table 4.3: Bulk Density and Dry Density Distribution

Sample Location	Depth (m)	Bulk Density(g/cm³)	Dry Density(g/cm³)
A1	0.5	1.72	1.32
A2	1.5	1.78	1.40
A3	3.0	1.91	1.56
B1	0.5	1.75	1.34
B2	1.5	1.84	1.48
B3	3.0	1.96	1.61

The density analysis revealed progressive increase in dry density values with increasing depth. This behavior indicates increasing soil compaction and reduction in pore spaces within the deeper subsurface layers.

Lower dry density values observed within near-surface zones may be associated with:

- loose soil structure,
- active waste decomposition,
- increased organic matter accumulation,
- and higher moisture retention.

The relatively higher dry density values recorded at greater depths indicate improved engineering stability and reduced susceptibility to rapid infiltration.

3.5 Particle Size Distribution Analysis

Particle size distribution analysis was conducted to classify the investigated soils and evaluate their permeability characteristics.

Table 3.4: Grain Size Distribution Results

Sieve Size (mm)	Percentage Passing (%)
4.75	100
2.00	99
0.425	97
0.075	95
0.002	28

The grain size analysis revealed that approximately 95% of the soil particles passed through the 0.075 mm sieve size, confirming the predominance of silty and fine sandy materials within the underlying soil formation.

The dominance of fine-grained particles is environmentally important because such soils generally exhibit:

- low permeability,
- reduced infiltration rates,
- slower contaminant transport,
- and improved natural attenuation behavior.

The fine-textured nature of the soil therefore contributes to reduced seepage velocity and gradual movement of leachates beneath the dumpsite environment.

3.6 Atterberg Limits and Plasticity Characteristics

Atterberg limits tests were conducted to evaluate the consistency and plasticity behavior of the soil samples.

Table 4.5: Atterberg Limits and Plasticity Index Values

Sample Location	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
A1	46	28	18
A2	44	30	14
A3	41	29	12

B1	48	27	21
B2	45	29	16
B3	42	30	12

The liquid limit values ranged between 41% and 48%, while the plasticity index values ranged between 12% and 21%.

These results indicate moderate plasticity behavior and the presence of cohesive silty-clayey fractions within the soil profile.

Moderately plastic soils generally possess:

- lower permeability,
- improved contaminant attenuation capacity,
- moderate compressibility,
- and enhanced water retention behavior.

The plasticity characteristics observed in this study therefore suggest that the underlying soil formation possesses partial resistance against rapid contaminant migration.

However, prolonged interaction with aggressive leachates may gradually alter the engineering properties of the soil through physicochemical reactions and contaminant accumulation.

3.7 Porosity and Void Ratio Characteristics

Porosity and void ratio analyses were conducted to evaluate pore distribution and seepage potential.

Table 3.6: Porosity and Void Ratio Distribution

Sample Location	Depth (m)	Porosity (%)	Void Ratio
A1	0.5	49	0.96
A2	1.5	45	0.82
A3	3.0	38	0.61
B1	0.5	47	0.89
B2	1.5	41	0.69
B3	3.0	36	0.56

The porosity values ranged between 36% and 49%, indicating moderate pore distribution within the soil formation.

Higher porosity values near the surface are associated with:

- loose soil packing,
- waste decomposition effects,
- and increased organic content.

The progressive reduction in porosity with increasing depth indicates increasing soil compaction and reduction in interconnected pore spaces.

The engineering implication of this observation is that deeper subsurface layers possess lower seepage potential and greater resistance against contaminant transport.

3.8 Hydraulic Conductivity Characteristics

Hydraulic conductivity analysis was conducted to evaluate the permeability behavior and infiltration characteristics of the investigated soils.

Table 3.7: Hydraulic Conductivity Distribution

Sample Location	Depth (m)	Hydraulic Conductivity (cm/s)
A1	0.5	7.4×10^{-4}
A2	1.5	3.8×10^{-4}
A3	3.0	8.5×10^{-5}
B1	0.5	6.9×10^{-4}
B2	1.5	2.7×10^{-4}
B3	3.0	2.1×10^{-5}

The hydraulic conductivity values obtained ranged between 2.1×10^{-5} cm/s and 7.4×10^{-4} cm/s, indicating low to moderate permeability characteristics.

The reduction in hydraulic conductivity with increasing depth reflects:

- increasing soil compaction,
- reduced pore connectivity,
- And increasing dominance of fine-grained materials.

The relatively low permeability behavior suggests gradual infiltration and slow contaminant migration within the subsurface environment.

Nevertheless, continuous accumulation of municipal waste and prolonged leachate generation may eventually compromise the natural attenuation capacity of the soil profile.

3.9 Relationship between Percentage Fines and Hydraulic Conductivity

Table 3.8: Relationship between Percentage Fines and Hydraulic Conductivity

Percentage Passing 0.075 mm (%)	Hydraulic Conductivity (cm/s)
95	7.4×10^{-4}
96	3.8×10^{-4}
97	8.5×10^{-5}
98	2.7×10^{-4}
99	2.1×10^{-5}

The relationship between percentage fines and hydraulic conductivity revealed strong inverse correlation behavior.

Increasing fines content resulted in progressive reduction in permeability due to:

- smaller pore spaces,
- reduced seepage channels,
- And lower hydraulic connectivity.

This relationship confirms that soil texture significantly influences contaminant transport behavior beneath municipal waste disposal facilities..

3.10 Environmental and Engineering Implications

The geotechnical and hydraulic properties identified in this investigation indicate that the underlying soil formation possesses moderate natural attenuation capacity against rapid contaminant migration.

The predominance of silty and fine sandy materials, combined with moderate plasticity characteristics and relatively low hydraulic conductivity values, contributes to:

- reduced infiltration rates,
- gradual contaminant movement,
- And delayed groundwater pollution.

However, continuous waste disposal operations and long-term leachate generation may eventually lead to:

- cumulative subsurface contamination,
- deterioration of soil engineering properties,
- And groundwater vulnerability.

The findings therefore emphasize the urgent need for:

- engineered sanitary landfill systems,
- groundwater monitoring programs,
- leachate management facilities,
- And sustainable waste disposal strategies.

IV. CONCLUSION AND RECOMMENDATION

4.1 Conclusion

This study investigated the geotechnical and hydraulic properties of soils underlying the Maduganari municipal solid waste dumpsite in Maiduguri, Northeastern Nigeria.

The investigation revealed that the underlying soil profile is predominantly composed of silty and fine sandy materials with approximately 95% of soil particles passing through the 0.075 mm sieve size.

Moisture content values ranging between 18.4% and 32.6% indicated moderate water retention behavior associated with fine-grained soil texture and continuous waste decomposition processes.

The Atterberg limits analysis showed moderate plasticity behavior, while hydraulic conductivity values ranging between 2.1×10^{-5} cm/s and 7.4×10^{-4} cm/s confirmed relatively low to moderate permeability characteristics.

The results therefore demonstrate that the underlying soil formation possesses partial resistance against rapid contaminant migration due to its fine-grained nature and relatively low permeability behavior.

However, prolonged accumulation of municipal solid waste and sustained leachate generation may eventually compromise the protective capacity of the soil profile and increase groundwater contamination risks.

Overall, the study demonstrates that geotechnical and hydraulic characterization of soils underlying municipal dumpsites is essential for landfill engineering, environmental geotechnics, groundwater protection, and sustainable urban waste management planning.

4.2 Recommendation

1. Open dumping practices within Maiduguri metropolis should be progressively replaced with engineered sanitary landfill systems equipped with impermeable liners and leachate collection facilities.
2. Periodic groundwater quality monitoring should be conducted around the dumpsite to detect possible contaminant migration.
3. Environmental impact assessment studies should be mandatory before establishing future waste disposal facilities.
4. Government environmental protection agencies should strengthen municipal waste management regulations and environmental monitoring programs.
5. Sustainable waste segregation, recycling, and public environmental awareness programs should be intensified.

Further investigations should incorporate hydrogeological, geochemical, microbiological, and geophysical analyses to evaluate long-term environmental impacts and contaminant plume migration beneath the dumpsite.

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