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Comparison of the Geotechnical Properties of Lateritic Soils of Borrow Pits for Road Construction in Ado Ekiti

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Abstract: *Lateritic soils are key materials in road construction across tropical regions, but their performance varies based on their geotechnical properties. This study analyzes the geotechnical properties and characteristics of lateritic soils from selected borrow pits in Ado Ekiti, Nigeria, to determine their suitability for subbase and subgrade applications. Four borrow pits, labeled A to D, were randomly selected, and twelve undisturbed soil samples (three from each pit) were collected for laboratory testing. The tests include natural moisture content, specific gravity, grain size distribution, Atterberg limits, permeability, compaction, California Bearing Ratio (CBR), unconfined compressive strength (UCS), and triaxial test. Soil samples from Borrow Pit A, identified as Silty Sand (SM) and classified as A-2-4, showed the highest Maximum Dry Density (1750–1753 kg/m³), low Optimum Moisture Content (12%–14%), fines content of 12%, adequate permeability (2.0×10^{-5} to 2.2×10^{-5} cm/s), and unsoaked CBR values of 70%–75%, making them ideal for subbase applications. Borrow Pit B soil samples, categorized as Clayey Sand (SC) and A-2-6, had moderate MDD values (1650–1660 kg/m³), permeability between 1.2×10^{-5} and 1.4×10^{-5} cm/s, unsoaked CBR values of 58%–60%, and shear strength of 205–210 kPa, making them suitable for improved subgrades or low-traffic subbases. Borrow Pits C and D, classified as Low Plasticity Clay (CL) under USCS and A-6 and A-7-6 under AASHTO, had MDD values between 1500–1551 kg/m³, fines content of 20%–30%, permeability between 0.4×10^{-5} and 0.1×10^{-5} cm/s, unsoaked CBR values below 42%, and shear strength of 180–192 kPa, making them more appropriate for subgrade applications. The study concludes that Borrow Pit A is the most suitable for subbase layers, while Borrow Pits B, C, and D require stabilization, such as lime or cement treatment, to improve their strength and plasticity properties.*

Keywords: *Compaction, Geotechnical, Lateritic, Stabilization, Subgrade*

1. INTRODUCTION

The use of substandard materials has majorly contributed to the causes of road failures in Nigeria [1], [2], [3], [4], often due to cost-cutting measures or inadequate quality control [3]. Proper material selection for pavement layers is crucial for road longevity, maintenance costs, and safety [5]. Frequent road pavement failures has proved that, it is not all the borrow pits in Ado Ekiti that contain suitable lateritic soils for road construction. Lateritic soils, though widely available, are not always ideal for road construction in their natural state [6]. The post maintenance cost of repairing failed road portions has always been huge. Such huge costs can be reduced when suitable materials are used and adequate quality control is ensured. The suitability of lateritic soils for road construction depends on moisture properties, compaction characteristics, and strength parameters. Some lateritic soils exhibit high plasticity, leading to excessive shrinkage and swelling, which causes pavement instability [7]. Variations in mineral composition, clay content, and grain size distribution also affect their load-bearing capacity [2].

Another major challenge is the inadequate testing of soils from borrow pits [8], [9]. Records have shown that many lateritic soils are used in road construction without prior laboratory testing, resulting in early road failures. The lack of classification for borrows pits leads to the use of unsuitable materials in critical pavement layers. This research aims to evaluate and classify lateritic soils from different borrow pits in Ado Ekiti based on geotechnical properties. By providing a scientific basis for material selection, the study ensures compliance with engineering standards and improves road construction quality.

While several studies have analyzed lateritic soils in tropical regions, research specific to Ado Ekiti remains limited. The unique geological and climatic conditions of the area influence soil properties, necessitating localized investigations. Additionally, existing studies often lack comprehensive geotechnical testing to determine lateritic soil suitability.

To address these gaps, twelve undisturbed lateritic soil samples were collected from four borrow pits in Ado Ekiti. Laboratory tests conducted include grain size analysis, Atterberg limits, compaction tests, permeability tests, California Bearing Ratio (CBR), and unconfined compressive strength (UCS). The findings will aid engineers, planners, and policymakers in making informed decisions, reducing maintenance costs, and improving road durability.

2. LITERATURE REVIEW

Lateritic soils are materials with lower oxide concentrations, displaying properties akin to fine-grained sands, gravels, and soft rocks [5], [6]. They typically feature a porous or vesicular structure. The use of lateritic soils in road construction has gained significant attention in civil and geotechnical engineering due to their abundance in tropical and subtropical regions [1], [10]. These soils, formed through the prolonged weathering of underlying parent rocks, are rich in iron and aluminium oxides [11], giving them a distinctive reddish-brown colour. In Ado Ekiti, Nigeria, lateritic soils are common materials for road infrastructure, primarily sourced from borrow pits. However, their engineering performance vary widely based on geotechnical properties such as grain size distribution, plasticity, compaction characteristics, shear strength, and permeability. Understanding these properties is crucial for determining their suitability for use in subbase and subgrade layers of road pavements.

Given the rapid infrastructure development in Ado Ekiti, borrow pits provide a readily available source of lateritic soils for road construction. However, the variability in soil composition across different pits necessitates thorough geotechnical evaluation to ensure that the materials meet engineering standards. While studies have been conducted on lateritic soils in different regions, limited research specifically examines the geotechnical properties of lateritic soils from borrow pits in Ado Ekiti. This gap in knowledge highlights the need for localized investigations to determine their suitability for road construction.

Road construction requires large volumes of soil for the formation of various pavement layers, including subgrade, subbase, and base courses [10]. In many cases, the balance between cut and fill along road alignments is insufficient, making it necessary to source additional materials from borrow pits or alternative sources such as dredged river sand. In Ado Ekiti and other parts of south-western Nigeria, borrow pits remain the primary source of lateritic soils for roadwork. These borrow pits supply the necessary earth materials, which should ideally undergo rigorous laboratory testing before being utilized in construction. A borrow pit is an excavation site where soil, sand, or gravel are extracted for use in construction projects [2]. The materials sourced from borrow pits should be subjected to geotechnical tests to determine their engineering properties and ensure they meet required specifications. The suitability of these materials is assessed by comparing test results with established engineering standards. Geotechnical properties such as grain size distribution, plasticity, shear strength, and specific gravity influence the stability of civil engineering structures, particularly [7], [12]. Understanding these properties allows engineers to classify and select appropriate materials for different layers of road pavements.

One of the major challenges in road construction in Nigeria, including Ado Ekiti, is the rapid deterioration of road pavements due to poor material selection. Weak or improperly classified soils contribute to premature failures, leading to increased maintenance costs [13]. To mitigate these issues, engineers must analyse the geotechnical properties of borrow pit materials through various laboratory tests [8], [14]. These tests provide essential data for categorizing the soils as suitable or unsuitable for specific pavement layers.

Despite that they are readily available, untested lateritic soils are not always ideal for road construction. [3] [15]. The suitability of lateritic soils for road construction depends on factors such as; moisture content, compaction characteristics, and strength parameters. The level of plasticity of lateritic soils is another crucial parameter to be considered. When plasticity is high, it leads to excessive shrinkage and swelling of the soil, thereby, causing road pavement failure. In addition, wrong proportions of clay, mineral composition and grain size distribution can affect their load-bearing capacity.

Another significant challenge is the inadequate testing and categorizations of soils from borrow pits. Most times, road contractors (believing they are smart), make use of lateritic soils in road construction without prior laboratory testing, leading to roads constructed with unsuitable materials and hence, early and frequent failure of such road pavement. The absence of classification for borrow pits also means that unsuitable materials may be used in critical pavement layers, resulting in large portions of road failures of most of the roads in that particular locality. To address these challenges, this research aims to evaluate and classify lateritic soils from different borrow pits in Ado Ekiti based on their geotechnical properties.

3. METHODOLOGY

Ado Ekiti, the administrative capital of Ekiti State, Nigeria, is an urban township situated at latitude of 7°37' N and a longitude of 5°13' E. The city is located at an elevation of approximately 455 meters above sea level. Geologically, the area falls within the Precambrian crystalline rocks of the basement complex of southwestern Nigeria, characterized by a dominant presence of crystalline and schistose rock formations. These formations include the migmatite-gneiss-quartzite complex, older granites, quartzite, charnockites, and fine to medium-grained granites, which define the geological composition of the region.

The study area, Ado Ekiti, was selected due to its importance in road construction projects and the abundance of borrow pits containing lateritic soils in the area. Notably, approximately 80% of the borrow pits in Ado Ekiti are concentrated along New Ado Ekiti-Iyin Ekiti road. That is the road connecting both Ado Ekiti and Irepodun/Ifelodun local government Areas of Ekiti State, Nigeria

The study area's geological and land-use maps, of selected borrow pits, are presented in Figure 1 to further illustrate the spatial distribution and characteristics of lateritic soil deposits in Ado Ekiti.

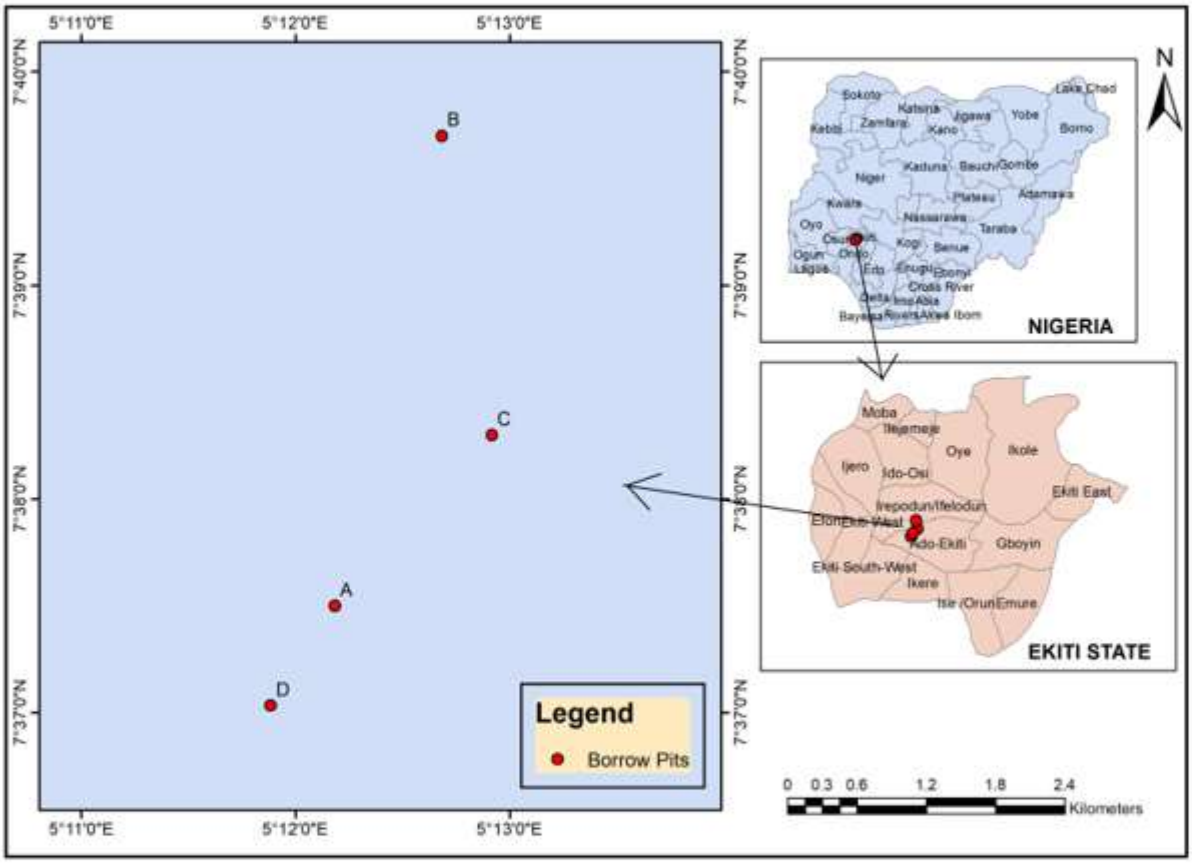

Figure 1: Study Area Map

3.2. Sampling

Four borrow pits sited on the coordinates 7°37'30"N, 5°12'11"E; 7°39'42"N, 5°12'41"E; 7°38'18"N, 5°12'55"E, and 7°37'02"N, 5°11'53"E and designated as A, B, C, and D respectively were selected for this research. From each borrow pit, three samples were collected and labeled accordingly (e.g., A1, A2, A3, etc.). In total, twelve undisturbed samples were obtained. Each sample was carefully placed in a sack and labeled as A1, A2, A3, B1, B2, B3, C1, C2, C3, D1, D2, and D3.

3.3. Materials

The primary materials utilized in this research comprised of twelve undisturbed lateritic soil samples, which served as the foundation for the study. These samples were carefully collected to ensure their natural structure and properties remained intact for accurate testing and analysis. Additional materials included sample collection sacks, which were used for safely storing and transporting the soil specimens without contamination. Water was also an essential component, as it was mixed with the soils in appropriate proportions to assess its moisture-related properties. Various tools, such as augers and cutting rings, were employed to extract the undisturbed soil samples while minimizing disturbances to their original state. Furthermore, specialized laboratory equipment was used to conduct a range of classification and geotechnical tests on the collected samples.

Table 1 outlines various geotechnical tests conducted to assess soil properties relevant to road construction. Each test serves a specific purpose, employs specialized equipment, follows established standards, and was performed at the Geotechnical Laboratory of Federal Polytechnic Ado Ekiti. The Natural Moisture Content test determines the water content in a soil sample using moisture content cans, following BS 1377-2:1990. Particle Size Distribution (Grain Size Analysis) assesses the percentage of different grain sizes within the soil using a BS sieve analysis, adhering to the same standard. Consistency Limits (LL, PL, SL) measure the liquid, plastic, and shrinkage limits of the soil using a Casagrande liquid limit device and grooving tool, also based on BS 1377-2:1990.

The Specific Gravity Test evaluates soil density by comparing the mass of soil solids to an equal volume of water using a volumetric flask, conforming to BS 1377-2:1990. The Compaction Test (West African Method) establishes the relationship between moisture content and dry density at specific compactive effort using a West African Standard Compaction Apparatus, following BS 1377-4:1990. The Permeability Test determines the hydraulic conductivity of soil using a permeability apparatus and the falling head method, also under BS 1377-4:1990.

The California Bearing Ratio (CBR) test examines the force-penetration relationship of soil using a CBR test machine, providing load-deformation data in compliance with BS 1377-7:1990. Finally, the Unconfined Compressive Strength (UCS) test measures the maximum axial compressive stress a soil sample can withstand under zero confining stress, utilizing a compression device with load and deformation dial gauges, following ASTM D2166/D2166M.

3.3.1 Classification tests and methods

The following tests (Table 1) were carried out on the soil samples to determine their properties as described below;

Table 1: Standard method acquired for the soil testing

S/N	Description of Test	Purpose	Equipment	Test Location	Test Standard
1.	Natural Moisture Content (water content)	To determine the amount of water contained in a particular soil sample	Moisture content cans	Geotechnic Laboratory, Federal Polytechnic Ado Ekiti	BS 1377-2 1990
2.	Particle Size Distribution (Grain Size analysis)	To determine the percentage of different grain sizes contained in a soil sample	BS Sieve analysis	Ditto	BSS-1377-2 1990
3.	Consistency Limits (LL, PL, SL)	To determine the Liquid limit, shrinkage limit and plasticity index of the soils.	Cassagrade liquid limit device, grooving tool	Ditto	BS 13377-2 1990
4.	Specific Gravity Test	To determine the density of the soil mass by comparing the mass of the solids in the soil to the mass of equal volume of water	Specific gravity apparatus (volumetric flask)	Ditto	BS-1377-2 1990
5.	Compaction Test (West African Method)	To determine the relationship between the moisture content and the dry density of the soil sample at specific compactive effort	Western African Standard Compaction Apparatus	Ditto	BS1377-4-1990
6.	Permeability test	To determine the hydraulic conductivity of a soil sample by falling head method	Permeability Apparatus	Ditto	BS 1377-4-1990
7.	California Bearing Ratio (CBR)	To determine the relation between force and penetration when a cylindrical plunger with a standard cross-sectional area is made to penetrate the soil at a given rate (load-deformation curve of the soil).	CBR Test machine	Ditto	BS-1377-7 1990
8.	Unconfined Compressive Strength (UCS)	To determine the maximum axial compressive stress a soil sample can bear under zero confining stress	Compression Device, Load, and Deformation Dial Gauges	Ditto	ASTM D2166/D2166M

4. RESULTS AND DISCUSSIONS

The results of the various laboratory tests on the selected soil samples from four borrow pits in Ado Ekiti are presented below;

4.1 Result and Discussion of Classification Tests on Soil Samples

The results and discussion of the classification tests conducted on lateritic soils obtained from selected borrow pits in Ado Ekiti are presented in this section. These tests were carried out to evaluate the geotechnical properties of the soil samples, including their grain size distribution, Atterberg limits, and specific classification parameters. The findings provide insights into the suitability of these soils for various engineering applications, particularly in road construction and foundation works. Additionally, the discussion highlights the implications of the soil characteristics in relation to standard classification systems such as the Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) classification. The results are analyzed to determine the variability among different borrow pits and their potential for use in road construction projects.

4.1.1 The natural moisture content

Table 2: Natural moisture content and suitability for road construction

Sample ID	Natural Moisture Content (NMC) (%)	Specification for Road Construction	Source
A1	10.1	NMC ≤ 12% suitable for subbase; low moisture content ensures better compaction and stability.	Ola (1983); ASTM D2216; Adunoye *et al*. (2018); Federal Ministry of Works (1997); Oyeniyi and Oloruntola (2020)
A2	12.2	NMC ≤ 12% suitable for subbase; low moisture content ensures better compaction and stability.	
A3	11.3	NMC ≤ 12% suitable for subbase; low moisture content ensures better compaction and stability.	
B1	14.3	NMC > 12% requires moisture control; suitable for subgrade applications.	
B2	15.2	NMC > 12% requires moisture control; suitable for subgrade applications.	
B3	14.3	NMC > 12% requires moisture control; suitable for subgrade applications.	
C1	18.2	High NMC (> 15%) indicates plasticity; stabilization required for effective subgrade use.	
C2	19.2	High NMC (> 15%) indicates plasticity; stabilization required for effective subgrade use.	
C3	18.1	High NMC (> 15%) indicates plasticity; stabilization required for effective subgrade use.	
D1	21.1	Very high NMC (> 20%) unsuitable without stabilization; high water retention and plasticity.	
D2	22.2	Very high NMC (> 20%) unsuitable without stabilization; high water retention and plasticity.	
D3	21.3	Very high NMC (> 20%) unsuitable without stabilization; high water retention and plasticity.	

From Table 2, the natural moisture content results provide key insights into the water-retention capacity and compaction behavior of soils from Borrow Pits A, B, C, and D, which are critical for assessing their suitability for subbase and subgrade applications in road construction. The tests, conducted following ASTM D2216 and BS 1377-2 standards, reveal variations in moisture content among the borrow pits, influencing their engineering properties. Borrow Pit A has the lowest natural moisture content, ranging from 10% to 12%, indicating dry soils with minimal water retention. These properties enhance compaction efficiency and stability, making the soil highly suitable for subbase applications, particularly in regions with fluctuating moisture conditions. Borrow Pit B, with slightly higher moisture content (14%–15%), retains more water but remains manageable for compaction. While it can function as a subbase material under controlled conditions, it is better suited for subgrade applications where moderate load-bearing capacity is required. Borrow Pits C and D exhibit significantly higher moisture content, at 18%–19% and 21%–22%, respectively. These soils have high water retention, which increases plasticity and reduces shear strength, making them unsuitable for subbase applications without stabilization. However, they can serve as subgrade materials if properly treated with stabilizers such as lime or cement. Effective moisture control is essential to enhance their strength and ensure durability in road construction.

Overall, Borrow Pit A is ideal for subbase layers due to its low moisture content, while Borrow Pit B is more suited for subgrade applications. Borrow Pits C and D require stabilization to improve their performance as subgrade materials. Proper moisture management remains a crucial factor in optimizing soil performance for road construction projects

4.1.2 Specific gravity

The specific gravity values of soils from Borrow Pits A, B, C, and D provide critical insights into their mineral composition, density, and suitability for road construction (Table 3). High specific gravity correlates with denser materials that compact well and thereby make such soil desirable for a stable road subbase. Low specific gravity indicated porous particles, thereby reducing load bearing capacity. Heavier minerals e.g magnetite results in higher specific gravity. Soils rich in clay minerals have lower specific gravity indicating potential issues with water retention and volume change. Tests conducted following ASTM D854 and BS 1377-2 show that Borrow Pit A has the highest specific gravity (2.66–2.68), indicating a dense mineral composition suitable for subbase applications, especially in high-traffic areas. Borrow Pit B, with values of 2.61–2.63, suggests moderate mineral density, making it viable for subbase use under moderate loading or as an enhanced subgrade material.

Borrow Pits C and D exhibit the lowest specific gravity (2.55–2.57 and 2.53–2.54, respectively), indicating higher fine-grained or organic content, which reduces strength and compaction efficiency. These soils are unsuitable for subbase applications without stabilization but can function as subgrade materials with proper treatment. Since specific gravity below 2.60 often requires stabilization, lime or cement treatment may be necessary for improved performance.
Overall, Borrow Pit A is ideal for subbase layers, Borrow Pit B is marginally suitable, and Borrow Pits C and D require stabilization for effective use in road construction. These findings emphasize the need for thorough geotechnical evaluation in material selection.

Table 3: Specific gravity

Sample ID	Specific Gravity	Standard Range (ASTM D854)	Remarks
A1	2.68	2.60–2.80	Indicates dense mineral composition; highly suitable for subbase applications.
A2	2.66	2.60–2.80	Meets the threshold for strong and stable soils for subbase layers.
A3	2.67	2.60–2.80	Reflects excellent engineering properties; ideal for subbase applications.
B1	2.62	2.60–2.80	Within acceptable range; suitable for subbase or enhanced subgrade applications.
B2	2.61	2.60–2.80	Suitable for subbase use; may contain moderate fines or organics.
B3	2.63	2.60–2.80	Adequate for subbase or enhanced subgrade use.
C1	2.57	2.60–2.80	Slightly below threshold; potential fines or organics; suitable for subgrade layers.
C2	2.56	2.60–2.80	Indicates higher fines content; requires stabilization for subgrade applications.
C3	2.55	2.60–2.80	Below ideal range; stabilization needed for structural applications.
D1	2.53	2.60–2.80	Low specific gravity; indicates significant fines or organics; unsuitable without treatment.
D2	2.54	2.60–2.80	Below range; requires stabilization to enhance suitability for subgrade use.
D3	2.53	2.60–2.80	Low strength; stabilization or replacement needed.

4.1.3 Grain size distribution

Table 4: Grain size distribution of Samples

Particle Size (mm)	Percentage Passing (%)											
	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3
9.5	96.03	99.43	100.00	100.00	98.87	94.90	100.00	100.00	100.00	100.00	97.73	99.43
4.75	85.26	97.73	94.33	98.30	90.36	89.23	97.16	99.74	99.76	98.30	96.03	97.73
2.36	71.65	93.76	77.89	96.60	77.32	81.29	92.06	99.31	99.19	92.63	90.93	94.89
1.18	55.20	87.52	54.07	92.06	72.21	72.78	86.96	97.61	98.06	74.48	85.82	85.82
0.6	39.89	68.81	27.99	74.48	68.81	61.44	80.72	81.17	96.36	53.50	76.18	59.74
0.3	30.82	45.56	14.95	48.97	65.98	51.24	75.62	66.99	92.39	42.16	58.60	47.83
0.15	27.99	36.49	10.98	39.89	63.71	45.00	72.78	59.05	86.15	37.63	53.50	43.86
0.075	27.42	35.36	9.84	38.76	62.57	44.43	71.65	57.35	83.88	36.49	52.39	42.73

The grain size distribution data reveals variations in soil gradation and suitability for road construction (Table 4). Borrow Pit A has well-graded soil with low fines (12% passing 0.075 mm), ensuring excellent compaction and drainage, making it ideal for subbase layers. Borrow Pit B, with slightly higher fines (15% passing 0.075 mm), retains more moisture and is marginally suitable for low-traffic subbase use but better as an enhanced subgrade.

Borrow Pit C has higher fines (20% passing 0.075 mm), classifying it as clayey soil with high moisture sensitivity, suitable for subgrade applications with lime stabilization. Borrow Pit D, with the highest fines content (30% passing 0.075 mm), has poor drainage and shrink-swell potential, requiring extensive stabilization for use in subgrade layers.

Overall, Borrow Pit A is best for subbase applications, Borrow Pit B is marginally suitable, and Borrow Pits C and D require stabilization for effective subgrade use.

4.1.4 Atterberg limits

Table 5: Atterberg limits for soil samples

Sample ID	Liquid Limit (LL) (%)	Plastic Limit (PL) (%)	Plasticity Index (PI) (%)	Specification for Road Construction	Source
A1	35	20	15	PI ≤ 20% suitable for subbase materials; LL ≤ 40% preferred for low-plasticity soils.	Ola (1983); Adunoye *et al*. (2018), Federal Ministry of Works (1997)
A2	34	20	14	PI ≤ 20% suitable for subbase materials; LL ≤ 40% preferred for low-plasticity soils.	
A3	36	21	15	PI ≤ 20% suitable for subbase materials; LL ≤ 40% preferred for low-plasticity soils.	
B1	38	22	16	PI ≤ 20% suitable for subbase materials; LL ≤ 50% acceptable for medium-plasticity soils.	
B2	37	22	15	PI ≤ 20% suitable for subbase materials; LL ≤ 50% acceptable for medium-plasticity soils.	
B3	39	23	16	PI ≤ 20% suitable for subbase materials; LL ≤ 50% acceptable for medium-plasticity soils.	
C1	45	25	20	PI ≤ 20% suitable for subgrade; LL > 40% indicates high plasticity; stabilization recommended.	
C2	44	24	20	PI ≤ 20% suitable for subgrade; LL > 40% indicates high plasticity; stabilization recommended.	
C3	46	26	20	PI ≤ 20% suitable for subgrade; LL > 40% indicates high plasticity; stabilization recommended.	
D1	48	28	20	PI = 20% indicates high plasticity; stabilization required for subgrade.	
D2	47	27	20	PI = 20% indicates high plasticity; stabilization required for subgrade.	
D3	49	29	20	PI = 20% indicates high plasticity; stabilization required for subgrade.	

The Atterberg Limits of soils from Borrow Pits A, B, C, and D highlight differences in plasticity, influencing their suitability for road construction (Table 6). Borrow Pit A has a Liquid Limit (LL) of 34%–36%, Plastic Limit (PL) of 20%–21%, and Plasticity Index (PI) of 14%–15%, indicating low to medium plasticity. These values meet engineering standards recommending PI below 20% for subbase materials, ensuring good compaction and stability. Borrow Pit B has slightly higher LL (37%–39%) and PI (15%–16%), suggesting increased moisture retention. While it may serve as a subbase in low-traffic roads, it is better suited for enhanced subgrade applications with proper drainage.

Borrow Pits C and D have higher LL (44%–49%) and consistent PI values of 20%, indicating high plasticity and susceptibility to volume changes, reducing workability and compaction efficiency. These soils are unsuitable for subbase applications but can function as subgrade layers with stabilization using lime or cement. According to regional standards, soils with LL above 50% or PI over 17% require stabilization to meet subbase requirements. Borrow Pit A is the most suitable for subbase applications, while Borrow Pits C and D require treatment to improve their performance as subgrade materials. These findings underscore the importance of proper soil analysis and material selection for durable road pavements.

4.2 Result and Discussion of Geotechnical Properties of Sampled Lateritic Soils

The results and discussion of geotechnical properties carried out on sampled lateritic soils of selected borrow pits in Ado Ekiti are hereby presented below:

4.2.1 Hydraulic conductivity

The hydraulic conductivity values of soils from Borrow Pits A, B, C, and D indicate their suitability for road construction (Table 6). Borrow Pit A has the lowest permeability (1.2×10^{-5} to 1.4×10^{-5} cm/s), minimizing water infiltration and enhancing subbase stability under varying moisture conditions. Borrow Pit B shows moderate permeability (2.0×10^{-5} to 2.2×10^{-5} cm/s), which may still support subbase applications but requires proper drainage or stabilization for durability. Borrow Pits C and D have the highest permeability (3.4×10^{-5} to 4.1×10^{-5} cm/s), characteristic of coarse-grained soils with low cohesion. While unsuitable for subbase applications without stabilization, their high permeability benefits subgrade layers by improving drainage and reducing water retention. Proper drainage planning, including stabilization or design modifications, is necessary to optimize their use. Overall, Borrow Pit A is best suited for subbase applications, while Borrow Pits C and D function better as subgrade materials with enhanced drainage management.

Table 6: Hydraulic conductivity of samples

Sample ID	Hydraulic Conductivity (cm/s)	Application	Range (cm/s)	Reference
A1	$2.2\text{x}10^{-5}$	Subbase for high-traffic roads	10^{-5} to 10^{-3}	Washington State Department of Transportation (WSDOT), Geotechnical Design Manual (2019).
A2	$2.1.\text{x}10^{-5}$	Subbase for high-traffic roads	10^{-5} to 10^{-3}	Ditto
A3	$2.0\text{x}10^{-5}$	Subbase for high-traffic roads	10^{-5} to 10^{-3}	Ditto
B1	$1.2\text{x}10^{-5}$	Low-traffic subbase or improved subgrade	10^{-5} to 10^{-3}	Ditto
B2	$1.3\text{x}10^{-5}$	Low-traffic subbase or improved subgrade	10^{-5} to 10^{-3}	Ditto
B3	$1.4\text{x}10^{-5}$	Low-traffic subbase or improved subgrade	10^{-5} to 10^{-3}	Ditto
C1	$0.4\text{x}10^{-5}$	Subgrade; requires stabilization	10^{-5} to 10^{-3}	Ditto
C2	$0.3\text{x}10^{-5}$	Subgrade; requires stabilization	10^{-5} to 10^{-3}	Ditto
C3	$0.3\text{x}10^{-5}$	Subgrade; requires stabilization	10^{-5} to 10^{-3}	Ditto
D1	$0.2\text{x}10^{-5}$	Subgrade; requires stabilization	10^{-5} to 10^{-3}	Ditto
D2	$0.1\text{x}10^{-5}$	Subgrade; requires stabilization	10^{-5} to 10^{-3}	Ditto
D3	$0.1\text{x}10^{-5}$	Subgrade; requires stabilization	10^{-5} to 10^{-3}	Ditto

4.2.2 Compaction characteristics Test

The Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of soils from Borrow Pits A, B, C, and D vary significantly, influencing their suitability for subbase and subgrade applications. While ASTM D698 and BS 1377 outline test procedures, engineering guidelines suggest that MDD values above 1700 kg/m³ are ideal for subbase layers, while 1500–1600 kg/m³ is acceptable for subgrade materials. OMC values generally range between 8% and 20%, depending on soil type. Borrow Pit A has the highest MDD (1750–1753 kg/m³) and OMC (12%–14%), meeting subbase requirements with excellent compaction and stability. Borrow Pit B, with an MDD of 1650–1660 kg/m³ and OMC of 15%–16%, is slightly below the ideal subbase range but suitable for enhanced subgrade or low-traffic subbases with proper compaction and drainage. Borrow Pit C has an MDD of 1543–1551 kg/m³ and OMC of 17%–20%, making it suitable for subgrade applications but unsuitable for subbase layers without stabilization due to lower density and higher fines content. Borrow Pit D has the lowest MDD (1500–1521 kg/m³) and the highest OMC (20%–21%), indicating suitability for subgrade applications but requiring extensive stabilization to improve strength and reduce moisture susceptibility. Borrow Pit A is best suited for subbase applications, while Borrow Pit B is more appropriate for subgrade or low-traffic subbases. Borrow Pits C and D require stabilization to enhance their engineering properties. These findings highlight the importance of geotechnical analysis and stabilization techniques in optimizing lateritic soils for road construction

4.2.3 Unconfined compressive strength test

The Unconfined Compressive Strength (UCS) values for Borrow Pits A, B, C, and D vary significantly, influencing their suitability for subbase and subgrade applications (Table 8). While Nigeria's Highway Manual prioritizes properties like the California Bearing Ratio (CBR) and Atterberg limits, UCS offers additional insight into soil strength.

Table 7: Compaction characteristics of samples

Sample ID	MDD (kg/m³)	OMC (%)	Specification for Road Construction	Source
A1	1750	12	MDD ≥ 1700 kg/m³ suitable for subbase; OMC typically 8–12%.	Adejumo *et al*. (2020); ASTM D698, Adunoye *et al*. (2018)
A2	1753	13	MDD ≥ 1700 kg/m³ suitable for subbase; OMC typically 8–12%.	
A3	1751	14	MDD ≥ 1700 kg/m³ suitable for subbase; OMC typically 8–12%.	
B1	1650	16	MDD 1500–1700 kg/m³ suitable for subgrade; OMC typically 10–20%.	
B2	1660	15	MDD 1500–1700 kg/m³ suitable for subgrade; OMC typically 10–20%.	
B3	1659	16	MDD 1500–1700 kg/m³ suitable for subgrade; OMC typically 10–20%.	
C1	1543	18	MDD 1500–1700 kg/m³ suitable for subgrade; OMC typically 10–20%.	
C2	1551	17	MDD 1500–1700 kg/m³ suitable for subgrade; OMC typically 10–20%.	
C3	1548	20	MDD 1500–1700 kg/m³ suitable for subgrade; OMC typically 10–20%.	
D1	1500	20	MDD < 1500 kg/m³ indicates poor suitability; stabilization is recommended.	
D2	1520	22	MDD 1500–1700 kg/m³ suitable for subgrade; OMC typically 10–20%.	
D3	1519	21	MDD < 1500 kg/m³ indicates poor suitability; stabilization is recommended.	

Table 8: Unconfined compressive strength result

Sample ID	UCS (kN/m²)	Specification for Road Construction	Source
A1	225	UCS ≥ 200 kN/m² is suitable for subbase applications in high-traffic areas.	Adejumo *et al*. (2020); Giwangkara *et al*. (2020) Oyeniyi and Oloruntola (2020); Adunoye *et al*. (2018), FMWH (1997)
A2	220	UCS ≥ 200 kN/m² is suitable for subbase applications in high-traffic areas.	
A3	215	UCS ≥ 200 kN/m² is suitable for subbase applications in high-traffic areas.	
B1	210	UCS ≥ 200 kN/m² is suitable for subbase applications in moderate-traffic conditions.	
B2	205	UCS ≥ 200 kN/m² is suitable for subbase applications in moderate-traffic conditions.	
B3	210	UCS ≥ 200 kN/m² is suitable for subbase applications in moderate-traffic conditions.	
C1	185	UCS 150–200 kN/m² indicates suitability for subgrade; stabilization required for subbase use.	
C2	190	UCS 150–200 kN/m² indicates suitability for subgrade; stabilization required for subbase use.	
C3	188	UCS 150–200 kN/m² indicates suitability for subgrade; stabilization required for subbase use.	
D1	180	UCS < 200 kN/m² indicates suitability for subgrade only; stabilization required for improved performance.	
D2	190	UCS < 200 kN/m² indicates suitability for subgrade only; stabilization required for improved performance.	
D3	188	UCS < 200 kN/m² indicates suitability for subgrade only; stabilization required for improved performance.	

Borrow Pit A has the highest UCS (215–225 kN/m²), indicating a strong soil matrix capable of resisting deformation, making it ideal for subbase applications, especially in high-traffic conditions. Borrow Pit B, with UCS values of 205–210 kN/m², is slightly weaker but still within acceptable subbase limits, though better suited for enhanced subgrade applications with stabilization. Borrow Pits C and D, with UCS values of 180–190 kN/m², have weaker structures prone to deformation, making them more appropriate for subgrade use. Stabilization with lime or cement is recommended to enhance strength and durability. While Nigerian highway standards emphasize CBR, these UCS values highlight mechanical differences among the borrow pits. Borrow Pit A is best for subbase applications, Borrow Pit B is marginally suitable but better as an enhanced subgrade, and Borrow Pits C and D require stabilization for improved performance.

4.2.4 Triaxial test

Table 9: Triaxial test results and their implications for road construction

	Cohesion (kN/m²)	ϕ (°)	Shear Strength (kPa)	Specification for Road Construction	Source
A1	38	28	230	High cohesion and internal friction angle indicate suitability for subbase applications in road construction.	Giwangkara *et al.* (2020) ASTM D4767; Yao *et al.* (2024)
A2	36	27	225	High cohesion and internal friction angle suggest suitability for subbase applications in road construction.	
A3	35	26	220	Moderate cohesion and internal friction angle may require stabilization for subbase use; suitable for subgrade applications.	
B1	34	25	210	Moderate cohesion and internal friction angle; suitable for subgrade applications; stabilization recommended for subbase use.	
B2	33	24	205	Lower cohesion and internal friction angle; primarily suitable for subgrade; requires stabilization for subbase applications.	
B3	33	24	205	Lower cohesion and internal friction angle; suitable for subgrade; stabilization necessary for subbase use.	
C1	32	23	195	Low cohesion and internal friction angle; suitable for subgrade; stabilization required for subbase applications.	
C2	31	21	190	Low cohesion and internal friction angle; suitable for subgrade; stabilization required for subbase applications.	
C3	31	21	190	Low cohesion and internal friction angle; suitable for subgrade; stabilization required for subbase applications	
D1	30	20	180	Low cohesion and internal friction angle; suitable for subgrade applications. Stabilization will enhance performance	
D2	31	21	185	Low cohesion and internal friction angle; suitable for subgrade applications. Stabilization will enhance performance	
D3	30	20	180	Low cohesion and internal friction angle; suitable for subgrade applications. Stabilization will enhance performance	

The triaxial test results show significant variations in shear strength among Borrow Pits A, B, C, and D, affecting their suitability for subbase and subgrade applications (table 9). Borrow Pit A, with the highest shear strength (220–230 kPa), is ideal for subbase layers in high-traffic roads, offering strong load-bearing capacity and resistance to deformation. Borrow Pit B, with moderate values (205–210 kPa), is suitable for subbase use in low to moderate traffic roads but may require stabilization for enhanced performance. Borrow Pits C and D have lower shear strength (180–195 kPa), making them more appropriate for subgrade applications where foundational support is key. Due to their higher susceptibility to deformation, stabilization with lime or cement is recommended. Cohesion and internal friction angle further highlight soil strength variations. Borrow Pit A, with cohesion values of 35–38 kN/m² and friction angles of 26°–28°, exhibits superior stability, making it the best choice for subbase applications. Borrow Pit B, with slightly lower cohesion (33–34 kN/m²) and friction angles (24°–25°), remains marginally suitable for subbase use but is better suited for reinforced subgrade applications. Borrow Pits C and D, with the lowest cohesion (30–32 kN/m²) and friction angles (21°–23°), lack sufficient shear resistance for subbase layers without stabilization. These results emphasize the importance of shear strength properties in optimizing lateritic soils for road construction.

4.2.5 California bearing ratio (CBR) analysis

The CBR values for Borrow Pits A, B, C, and D indicate varying soil strength and suitability for road construction (Table 10). Borrow Pit A, with unsoaked values of 70%–75% and soaked values of 54%–58%, exceeds the 30% subbase threshold and shows good resistance to water, making it ideal for high-traffic subbase applications. Borrow Pit B, with unsoaked values of 58%–60% and soaked values of 43%–45%, is suitable for low-traffic subbase or enhanced subgrade but requires proper drainage due to its 25% strength reduction when wet.

Borrow Pit C, with unsoaked values of 40%–42% and soaked values of 28%–30%, is more suited for subgrades, as its 30% strength loss under saturation limits its subbase application without stabilization. Borrow Pit D, with the lowest values (unsoaked 36%–38%, soaked 24%–25%), performs poorly under wet conditions and requires stabilization for any structural use. Borrow Pit A is the most suitable for subbase applications, while B may work with drainage measures, and C and D require stabilization to meet engineering standards.

Table 10: CBR results

Sample ID	Unsoaked CBR (%)	Soaked CBR (%)	Specification for Road Construction	Source
A1	75	58	CBR ≥ 50% unsoaked is suitable for subbase; soaked values above 30% ensure stability in wet conditions.	Adunoye *et al.* (2018); Federal Ministry of Works (1997) Oyeniyi and Oloruntola (2020)
A2	72	55	CBR ≥ 50% unsoaked is suitable for subbase; soaked values above 30% ensure stability in wet conditions.	
A3	70	54	CBR ≥ 50% unsoaked is suitable for subbase; soaked values above 30% ensure stability in wet conditions.	
B1	60	45	CBR 40–50% soaked is marginally suitable for subbase; additional drainage may be needed.	
B2	58	43	CBR 40–50% soaked is marginally suitable for subbase; additional drainage may be needed.	
B3	59	44	CBR 40–50% soaked is marginally suitable for subbase; additional drainage may be needed.	
C1	40	28	CBR < 50% unsoaked indicates suitability for subgrade only; stabilization required for improved performance.	
C2	42	30	CBR < 50% unsoaked indicates suitability for subgrade only; stabilization required for improved performance.	
C3	41	29	CBR < 50% unsoaked indicates suitability for subgrade only; stabilization required for improved performance.	
D1	36	24	CBR < 40% soaked indicates poor suitability; stabilization with lime or cement necessary for subgrade use.	
D2	38	25	CBR < 40% soaked indicates poor suitability; stabilization with lime or cement necessary for subgrade use.	
D3	37	24	CBR < 40% soaked indicates poor suitability; stabilization with lime or cement necessary for subgrade use.	

5. CONCLUSION

This study evaluated the geotechnical properties of lateritic soils from selected borrow pits in Ado Ekiti to determine their suitability for road construction. Results showed significant variations in soil composition, strength, and moisture retention, influencing their potential applications. Borrow Pit A, with low fines content, high Maximum Dry Density (MDD), and superior shear strength, is the most suitable for subbase applications without stabilization. Borrow Pit B, though marginally adequate for subbase use in low-traffic roads, requires stabilization to enhance strength and moisture resistance. Borrow Pits C and D, characterized by high fines content, lower strength, and greater permeability, are more appropriate for subgrade applications but require stabilization to improve performance.

For practical application, Borrow Pits C and D should be restricted to subgrade use, with lime stabilization recommended to reduce plasticity and improve compaction, while cement treatment can enhance their strength. Borrow Pit A should be prioritized for subbase layers, particularly in high-traffic roads, due to its high CBR values and excellent mechanical properties. Borrow Pit B, though moderately suitable, would benefit from stabilization to enhance its load-bearing capacity.

This research contributes localized data to aid road construction agencies and contractors in selecting appropriate materials, ensuring compliance with engineering standards, and improving the durability of road infrastructure in the region. It establishes correlations between soil properties and performance, reinforcing the importance of stabilization for marginal materials while confirming the suitability of high-quality lateritic soils for subbase applications. By comparing these results with prior studies, this research further validates the role of geotechnical assessment and stabilization in optimizing road construction materials.

Borrow Pit A soils, with its high Maximum Dry Density (MDD), adequate permeability, and excellent California Bearing Ratio (CBR) values, should be prioritized for use in subbase layers, particularly in high-traffic road construction projects. While Borrow Pit B soils are moderately suitable for subbase use, stabilization techniques such as lime or cement treatment should be employed to improve their load-bearing capacity and reduce moisture sensitivity, for low-traffic roads. Overall, Borrow Pit A is suitable for subbase applications without stabilization, while Borrow Pit B requires lime or cement stabilization to enhance strength, and Borrow Pits C and D need significant stabilization to reduce plasticity and improve compressive strength for subgrade use.

Borrow Pits C and D, with high fines content and low strength, should be limited to subgrade applications. Lime stabilization is recommended to reduce plasticity and improve compaction, while cement stabilization can enhance compressive strength for better performance under load.

It is recommended that this type of research work be extended to borrow pits of areas where Irepodun/Ifelodun local government area of Ekiti State, Nigeria shears boundary with Ado Ekiti, Ekiti State, Nigeria. This will assist the road agencies of Ekiti State and Ekiti State road contractors at large.

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