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Geotechnical Investigation of Road Pavement Failure along the Mubi Bypass Road, Jambutu, Jimeta, Yola, Adamawa State

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ABSTRACT
The persistent failure of road pavements manifesting as severe cracks, potholes, partial or complete collapse has left residents of communities along the Mubi Bypass Road in Jambutu in a highly distressed and disrupted condition. A geotechnical investigation was conducted to determine the causes of road pavement failure within the study area. Particle size distribution analysis revealed a predominance of fines (25.9–30.8%) and sand (59.5–64%), suggesting the presence of silty clay and silty sand. Atterberg limits indicated low plasticity, with liquid limits ranging from 20.0–23.2%, plasticity index between 20–23.2%, and shrinkage limits from 1.79–2.50%. The plastic limit was largely 0%, further confirming low plasticity soils. Specific gravity values ranged from 2.5–2.54 in failed sections and 2.29–2.51 in stable sections. Compaction characteristics showed slightly lower maximum dry densities in failed sections (2.09–2.2 g/cm³) compared to stable ones (2.19–2.2 g/cm³), with similar optimum moisture contents (8.0–8.6%). California Bearing Ratio (CBR) results demonstrated a significant drop in strength under soaked conditions. Soaked CBR values ranged from 53.9–91.1% in failed sections and 17.7–51.4% in stable sections, while unsoaked values ranged from 88.3–125.4% and 36.2–59.3% respectively. This confirmed a strong influence of moisture on subgrade strength and stability. The study attributes pavement failure to weak subsurface materials, specifically incompetent silty clay and silty sand, compounded by poor drainage and the flood-prone nature of the study area. It is recommended that effective drainage systems and soil stabilization measures be implemented. These findings provide essential guidance for the rehabilitation of existing pavements and the design of new roads.

Keywords:
Geotechnical method,
Subsurface layer,
Strength parameters,
Road pavement failure.

INTRODUCTION

The failure of road pavements along the Mubi Bypass Road, which traverses the communities of Jambutu, Jimeta, Yola in Adamawa State, has become a major source of concern for residents and road users. These failures are evident through the widespread occurrence of severe cracks, potholes, surface wear, and in some instances, partial or complete collapse of the pavement structure. As a result, the affected communities are faced with significant daily challenges, including restricted mobility, increased vehicle maintenance costs, safety hazards, and disrupted socio-economic activities. The deteriorating road condition has not only compromised the comfort and safety of travelers but has also adversely impacted commerce, emergency services, and access to essential facilities. The situation has reached a critical stage, warranting an urgent and comprehensive investigation into the underlying causes of the pavement failures and the implementation of appropriate remedial measures. Most road failures occur shortly after construction as a results of poor supervision, presence of structural factors like shear zones, faults, fractures, stream channels, lack of adherence to specifications, and insufficient knowledge of the geotechnical properties of the soils over which the pavements were constructed. In addition, the effects of aforementioned factors can be exacerbated by climatic alterations such as variations in temperature and incidence of acid rain (Emmanuel et al.,, 2021; Hijab et al.,, 2012; Layade et al.,, 2017). Therefore, the planning, design, and building of roads must be reliant on vast knowledge of the geotechnical properties of the underlying soil and their condition. Fortunately, recent years have witnessed a resurgent use of geotechnical analysis in subsurface engineering research to gather data on the subsurface's geotechnical characteristics, such as strength, stability, and competence, which acts as host for engineering structure foundations (Adewuwi & Olorunfemi, 2005; Aina et al.,, 1996; Idornigie et al.,, 2006). Evaluation of the competence of a site prior to any road construction ensures safe, durable and viable design, as well as alternative for any unforeseen difficulty during the actual construction. This engineering cum safety practice is very fundamental and must be considered with every seriousness to avoid unnecessary loss of lives and properties (Falowo, 2020). Adequate knowledge of the subsurface is acquired by ascertaining the spatial distribution or stratification of the subsurface materials, their engineering properties and response under applied load (Oyedele et al.,, 2016) so as to determine the bearing capacity, cohesion and friction between soil particles that would support any intended infrastructure (Akinlabi & Adegboyega, 2021; Kodicherla & Nandyala, 2016; Kumar & Rao, 2003). These geotechnical parameters are very important to the integrity, stability and longevity of road pavement. The geotechnical analysis applies ex-situ technique to scrutinize the subbase and subgrade course materials through sieve analysis, consistency limit tests, specific gravity test, compaction test, California bearing ratio test.

Ifabiyi and Kekere (2013) used geotechnical methods to investigate the failure susceptibility of the Ilorin–Ajase-Ipo highway in Kwara State. Their findings showed that the soil was 50% sand, with poor gradation indicated by a coefficient of curvature of 28.1% and uniformity of 14.1%. They concluded that weak subbase/subgrade materials and poor engineering practices were the main causes of road pavement failure. Mohammed and Moruf (2013) used geotechnical analysis to investigate subsoil conditions causing road failures along the Irrua–Auchi road in Edo State, South-South Nigeria. Their study revealed that the road is underlain by the Ameki Formation, Imo Shale, and Ajali Sandstone, with fine-grained subgrade soils showing plasticity indices of 4–19%, Maximum dry density of 1.83–1.92 Mg/m³, and soaked CBR values of 0.86–1.12%. They concluded that subsurface geological stratification contributed to pavement deflections and failures. Ademila (2017) conducted a geotechnical assessment of lateritic subsoils from deteriorated sections of roadways in Akure, Southwestern Nigeria. The study revealed that subsoils from the stable sections exhibited higher specific gravity values (ranging from 2.73 to 2.86) and lower clay content (23.68%) in comparison to those from the damaged areas. Furthermore, these stable subsoils demonstrated greater fluid absorption capacity, a higher proportion of fine particles (silt and clay exceeding 57%), and increased linear shrinkage values (above 8%) relative to the compromised sections. The soils from the failed zones were characterized by hydro-pressure within the soil voids, which precipitated a significant reduction in strength, reaching up to 79%. This degree of structural deficiency was ascribed to suboptimal strength parameters, including an angle of internal friction between 13 o and 17o, shear strength ranging from 79 to 108 kN/m², and low California Bearing Ratio (CBR) values (14–32% unsoaked and 3–11% soaked). Consequently, the lateritic soils from the failed sections exhibited inadequate engineering properties, rendering them unsuitable for use as subgrade materials in road construction projects. Odunfa et al., (2018) conducted a geotechnical investigation along the Lagos–Ibadan Expressway and found high moisture content (13.11–268.89%), liquidity index (33–55%), and plasticity (13–26%). These values, when compared with (FMW&H, 1997) standards, indicate that subgrade soil conditions significantly contributed to pavement failure. Adebayo and Adigun (2018) conducted an investigation of the subbase and subgrade materials along the Papalanto–Sagamu route within the Sagamu Local Government Area of Ogun State. The study aimed to assess the structural properties, physical characteristics, and integrity of the soils underlying the road pavement through geotechnical methods. Their findings revealed that the natural moisture content varied between 1% and 12%. Sieve analysis indicated that the soils were predominantly sandy clayey, with sand content ranging from 44.7% to 93.4%. Gravel content varied from 5.6% to 51.2%, while fines ranged between 0.3% and 6.3%. The Plasticity Index values ranged from 6% to 28%, and liquid limits varied between 23% and 41%. The authors further noted that the subsurface soils were generally gap-graded, consisting of poorly graded clayey sand and gravel with high plasticity. Additionally, some soil samples exhibited low to medium plasticity clay content alongside elevated natural moisture content. Using geotechnical methods, Kazeem et al., (2019) evaluated the engineering properties of subsurface soils, asphalt pavement thickness, drainage, and traffic loads along the Awotan-Akufo route in Oyo State, Nigeria. Their analysis revealed that grain size distribution from deteriorated sections of the Awotan-Lifeforte and Adaba routes contained over 35% fines passing through the 75 μm sieve. The natural moisture content ranged from 5.73% to 20.21% in the Awotan-Lifeforte section and from 16.20% to 23.20% in the Adaba section. The liquid limits were between 12% and 56% for the Awotan-Lifeforte area, and between 26% and 40% for the Adaba section. Plastic limits ranged from 8.43% to 49.10% in Awotan-Lifeforte and from 23.10% to 35.50% in Adaba, while the plasticity indices were 1.01% to 7.0% and 1.50% to 7.10%, respectively. Linear shrinkage values varied from 0.80% to 9.60% for

Awotan-Lifeforte and from 3.10% to 8.80% for Adaba. Maximum dry density (MDD) for the Lifeforte-Awotan section ranged between 1.625 and 1.835 mg/m³, with optimum moisture content (OMC) of 13.4% to 17.3%, whereas the Adaba section exhibited MDD values of 1.752 to 1.975 mg/m³ and OMC within the same range. Asphalt pavement thickness averaged 0.60 to 1.10 inches in the Awotan-Lifeforte section, compared to 0.57 to 1.46 inches in the Adaba section. The study concluded that the subgrade materials primarily consist of silty clay, and the geotechnical properties of soils in the collapsed segments fall below the standards recommended by the Federal Ministry of Works and Housing (FMW&H, 1997). Furthermore, the asphalt pavement thicknesses were insufficient relative to recommendations, which contributed to the observed deterioration. Ogunribido and Fadairo (2020) conducted a geotechnical investigation to determine the causes of the collapse of the Arigidi–Oke Agbe Akoko Road in Southwest Nigeria. Their study revealed that the Optimum Moisture Content (OMC) ranged from 14.2% to 32.4%, while the Maximum Dry Density (MDD) varied between 1301 kg/m³ and 2002 kg/m³. The natural moisture content of the soil was found to range from 17.7% to 37.8%, indicating high in-situ moisture conditions. The Atterberg limits showed a liquid limit between 48.5% and 62.4%, a plastic limit from 18.3% to 26.8%, and a plasticity index ranging from 25.7% to 37.7%, suggesting that the soils possess high plasticity and a significant potential for volumetric changes under varying moisture conditions. In terms of mechanical strength, the unconfined compressive strength ranged from 112.8 kPa to 259.7 kPa, while the shear strength was recorded between 56.4 kPa and 129.9 kPa. Hydrometer analysis indicated that the percentage of fine particles ranged from 48.5% to 72.1%, implying a dominance of silt and clay-sized materials which are typically moisture-sensitive and less stable under load. The California Bearing Ratio (CBR) results ranged from 5% to 17% under soaked conditions, and 15% to 38% under unsoaked conditions, falling below the recommended thresholds for both subgrade and subbase materials in road construction. Based on these findings, the authors concluded that the failure of the Arigidi–Oke Agbe road was primarily due to a combination of inadequate drainage infrastructure and poor geotechnical properties of the subgrade materials, particularly their high moisture sensitivity and low bearing capacity, which facilitated pothole formation and pavement collapse. Ademila and Olayinka (2020) conducted an assessment of factors contributing to road pavement deterioration along the Ibadan-Iwo-Osogbo highway employing geotechnical techniques. Their findings revealed liquid limits ranging from 22% to 64% for the failed sections (FS) and 32% to 40% for the stable sections (SS), while plasticity indices were from 13% to 41% (FS) and 12% to 18% (SS). The percentage of fines ranged from 47% to 59% in the failed areas and 32% to 41% in the stable zones, suggesting that the subgrade materials were classified from fair to poor in the failed sections and fair to good in the stable sections. Soils from the failed sections exhibited medium to high plasticity and elevated clay content, indicative of moderate to high swelling potential. Triaxial compression tests showed cohesion values between 72.6 and 127.0 kN/m² and internal friction angles ranging from 12.7° to 33.3°, reflecting moderate to good shear strength in the tested soils. However, the coefficient of compressibility values, ranging from 0.1 to 0.5 kN/m², indicated that the soils were generally unsuitable for road construction. The failed section's subsoil was noted to be impervious, and its relatively low permeability coefficient suggested high saturation levels in the area. Prolonged exposure to excessive moisture was identified as a key factor leading to significant strength reductions in the soils (Olayanju et al.,, 2017). The study concluded that road pavement failure was primarily caused by the presence of fluid-absorbing clayey soils, poor geotechnical properties, and inadequate drainage systems. Ubido et al. (2020) investigated the engineering properties of soils along the flood- and erosion-prone Sagamu–Papalanto road in Ogun State through geotechnical methods. Their results showed moisture content between 9.4% and 18.2%, specific gravity from 2.54 to 2.58, liquid limits ranging from 26.8% to 42.6%, plastic limits between 18.2% and 25.2%, and plasticity indices from 7.1% to 21.6%. Particle size analysis revealed fine fractions of 12% to 32.5% and coarse fractions between 49.4% and 80.5%. The maximum dry density (MDD) ranged from 1.64 to 1.74 g/cm³, with optimum moisture content (OMC) between 12% and 17%. California Bearing Ratio (CBR) values varied from 3% to 12%. Soils from the failed sections were predominantly clayey and did not conform to the standards established by the Federal Ministry of Works and Housing (FMW&H, 1997). The study concluded that inadequate soil strength, high moisture susceptibility, and poor drainage were key contributors to pavement failure. Obioha et al. (2021) investigated the factors contributing to pavement failures along the Imo-Abia states route in Southeast Nigeria using geotechnical methods. Their findings revealed that the mean in-situ moisture content ranged from 5.0% to 21.5%, with an average value of 13.25%. Particle size analysis indicated that the subsurface materials comprised poorly graded and texturally immature gravel (less than 3%), sand (15%), and fines exceeding 80%. The study concluded that an inadequate drainage system, combined with intermittent soil swelling and shrinking attributable to a shallow water table and low permeability of the fines within the subgrade significantly contributed to the observed pavement failures. Nwachukwu et al., (2022) investigated the impact of subgrade material quality beneath pothole-ridden road surfaces along the Mbaitolu-Ikeduru-Ahiara Mbaise route in Imo State, Southeastern Nigeria, using geotechnical methods. Their results showed that the plastic limit ranged from 26.1% to 31.6%, while the liquid limit varied between 36.0% and 48.6%. Natural soil moisture content ranged from 10.4% to 18.9%, and the plasticity index was between 9.2% and 17.0%. Grain size analysis indicated a predominance of sand, with fines accounting for 22% to 38%, and coarse to medium-sized particles comprising 62% to 78%. Maximum dry density values ranged from 1.29 to 1.93 kg/m³, and California Bearing Ratio (CBR) values varied widely from 3.7% to 91.9%. Cohesion and internal friction angle ranged from 39 to 42 kPa and 14° to 20°, respectively, while specific gravity values were between 2.56 and 2.61. The study concluded that variations in subgrade moisture and the depth of the water table were the primary factors responsible for the deterioration of the road pavement. Omorogieva and Okiti (2022) evaluated the breaking strength of pavement structures along the Benin-Auchi-Igarra Highway utilizing geotechnical methods. Their results indicated that plastic limits ranged from 9.05% to 16.8%, moisture content varied between 1.75 and 1.78 mg/m³, maximum dry density was observed between 21.4% and 43%, and liquid limits ranged from 14.4% to 24.55%. The study concluded that the ongoing deterioration of the road pavement is primarily attributable to the improper use of red tropical soils (RTSs).

The present study aims to systematically evaluate the causes of road pavement failure along the Mubi Bypass Road traversing Jambutu, Jimeta, and Yola in Adamawa State (Figure 1). Employing geotechnical sampling and analysis, the research investigates the interrelationship between the intrinsic soil properties, pavement structural characteristics, and the mechanisms leading to pavement distress and failure. By integrating these factors, the study seeks to identify critical geotechnical and structural deficiencies contributing to pavement deterioration. The findings are expected to provide a robust scientific foundation for developing improved pavement design methodologies, optimized construction techniques, and effective maintenance strategies tailored to the local geotechnical conditions. Ultimately, the outcomes of this investigation will not only support the targeted rehabilitation of the compromised road sections but also inform the planning and design of future road infrastructure projects in the region, thereby enhancing the durability and sustainability of road pavements in similar environments.

Location and Geology of the Study Area

The Mubi Bypass Road, located in Jambutu, Jimeta, lies within the Benue Trough, positioned between latitudes 9°17'20"N and 9°18'26"N and longitudes 12°25'E and 12°29'E (Figure 1), along the southern bank of the Benue River. The terrain is predominantly characterized by smooth to gently undulating landscapes, extensively drained by the Benue River, which forms extensive floodplains hosting Lake Geriyo and Lake Njuwa. Both lakes border the Jimeta area and are intersected by numerous small streams and tributaries (Ntekim & Bello, 2001). In contrast, Yola is bordered to the east by Lake Njuwa (Ishaku, 2011). Geologically, the study area is underlain by the oldest stratigraphic formation within the Upper Benue Trough, known as the Albian-Aptian Bima Sandstone. This formation is present on the northeastern, southeastern, and southwestern margins, forming the base of the sedimentary succession and unconformably overlying the Basement Complex. The central portion of the study area, particularly around the Yola arm, is traversed by sedimentary deposits associated with the rift system. Quaternary-aged river coarse alluvium, comprising poorly graded clays, siltstone, sand, and pebbly sand, is widely distributed along the main course of the Benue River and extends toward the northeastern and southern regions of Jimeta (Ishaku, 2011).

The Bima Sandstone formation is primarily composed of pebble beds and feldspathic sandstone, interspersed with occasional clay layers. This formation is subdivided into three distinct units—the Lower Bima (B1), Middle Bima (B2), and Upper Bima (B3)—as classified by Guiraud (1991), Allix (1983), and Carter et al., (1968). The Lower Bima (B1) is exposed at the core of the Lamurde anticline and consists of coarse-grained feldspathic sandstone interbedded with red and purple shales, along with occasional calcareous sandstone and siltstone bands. This unit exhibits significant variability in thickness, ranging from 0 m to over 500 m (Meludu et al., 2010), and has been assigned an upper Aptian to Albian age (Kogbe, 1989). The Middle Bima (B2) is a relatively uniform formation characterized by highly coarse-grained feldspathic sandstone with thin intercalations of clay, silt, shale, and intermittent calcareous sandstone layers. Its thickness varies between 300 and 1200 m (Meludu et al., 2010). These deposits are proximal to the Benue River (Guiraud, 1991; Zaborski et al., 1997) and are marked by distinctive trough and platy cross-bedding (Ishaku, 2011). Palynological and radiometric analyses of intercalated volcanic layers suggest a provisional middle Albian age for this unit (Whiteman, 1982).

The Upper Bima (B3) consists predominantly of fairly mature sandstone, ranging from fine- to coarse-grained, with sedimentary structures such as planar cross-bedding, fold-like overlapping bedding, and capsized cross-bedding (Zaborski et al., 1997). This unit is thick-bedded and widely distributed, with thickness varying between 500 and 1700 m. Deposited in a fluvial to deltaic environment (Carter et al., 1968), the geological sequence in the area also includes laterites, mudstones, ironstones, clays, and siltstones. The Upper Bima has been assigned a late Albian to early Cenomanian age based on stratigraphic and radiometric data (Whiteman, 1982).

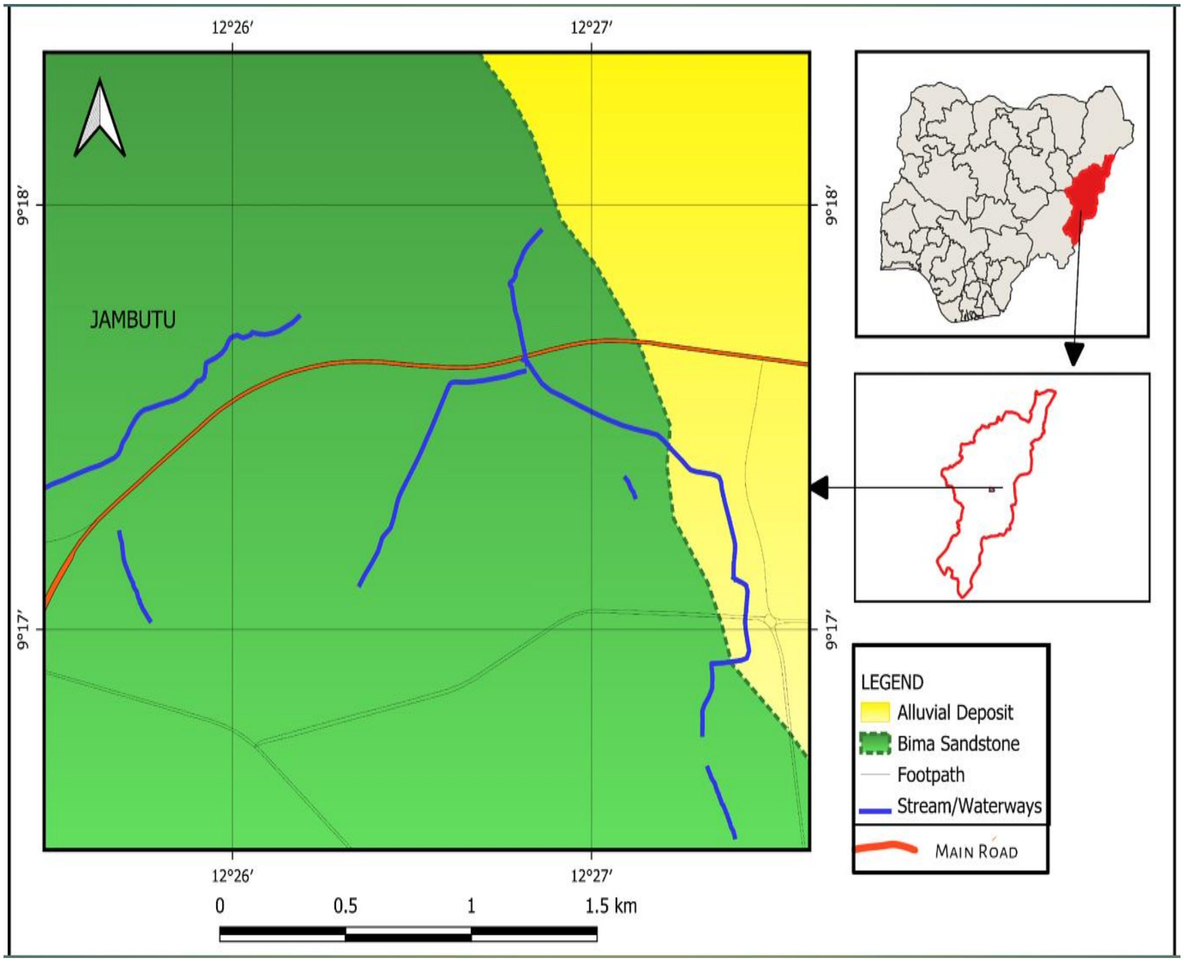

Figure 1: Geologic map of the study area (after Ike et al., (2025))

MATERIALS AND METHODS

Subsurface soil samples were collected at a depth of 1 meter from five (5) sampling stations strategically located along both the failed and stable sections of the roadway (Figure 3). The choice of a 1-meter depth was deliberate, as it ensures penetration through various soil strata that may be susceptible to shear failure or consolidation under repeated vehicular loading. This depth is considered optimal for obtaining data relevant to predicting settlement potential and assessing subgrade stability (Evinemi et al., 2016; Falowo, 2021; Kumar & Rao, 2003). Each soil sample was carefully sealed in airtight polythene bags immediately after collection to prevent moisture loss or contamination. The samples were then transported without delay to the Geotechnical Laboratory of the Civil Engineering Department, Modibbo Adama University, Yola, for detailed testing.

All laboratory tests were conducted in compliance with standardized procedures as outlined by the American Society for Testing and Materials (ASTM D2487-11, 2011) and British Standards Institution (BSI, 1990). The suite of tests performed included Sieve Analysis, Specific Gravity (Gs) Test, Natural Moisture Content (NMC) Test, Atterberg Limits (Consistency Limit Tests), Compaction Test, and the California Bearing Ratio (CBR) Test. These procedures ensured accurate characterization of the subsurface conditions and provided the necessary data for evaluating the performance of the soil in road construction.

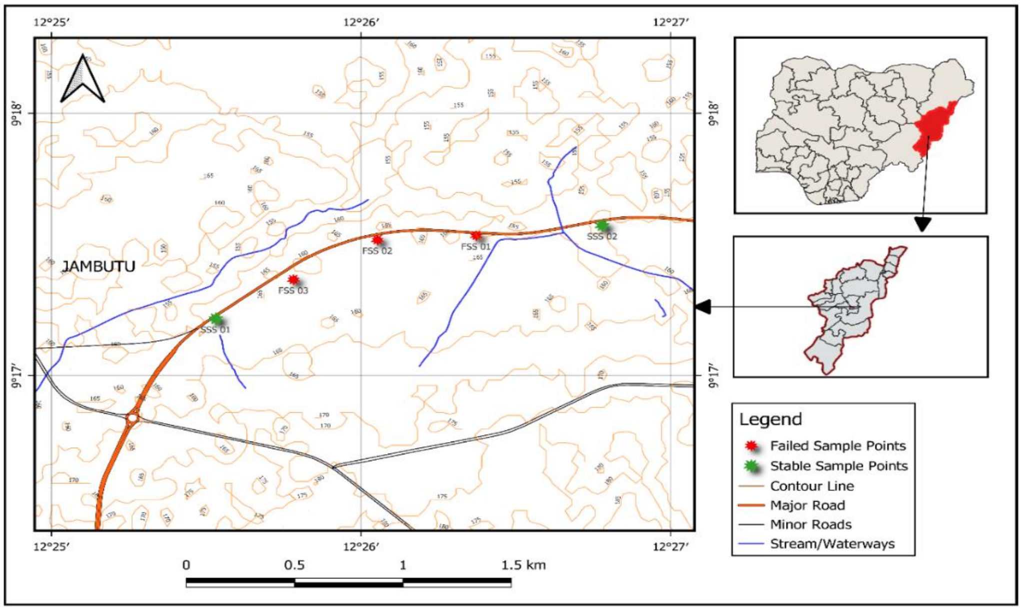

Figure 3: Map of the study area showing the road pavement under investigation, geophysical survey points and geotechnical sampling points (after Ike et al., (2025))

RESULTS AND DISCUSSION

Particle Size Distribution (PSD)

The results of the grain size distribution analyses are presented in Table 1 and illustrated in Figure 3. These data provide insight into the relative proportions of gravel, sand, and fines in both the failed and stable soil samples, which are critical for evaluating the suitability of the subgrade materials for road construction.

Table 1: Summary of the Particle Size Distribution (PSD) of the Failed and Stable Soil Samples

Sample	Fine Grain soil					
	Silt (%)	Coarse silt (%)	Clay (%)	Sand (%)	Fine gravel (%)	Gravel (%)
FSS1	19.6	8.9	0.2	59.5	3.1	8.7
FSS2	22.9	2.9	0.1	62.1	4.5	7.5
FSS3	19.0	11.7	0.1	64.0	1.7	3.5
SSS1	21.1	8.3	0.1	43.8	11.4	15.3
SSS2	25.6	3.4	0.3	65.6	3.4	1.7

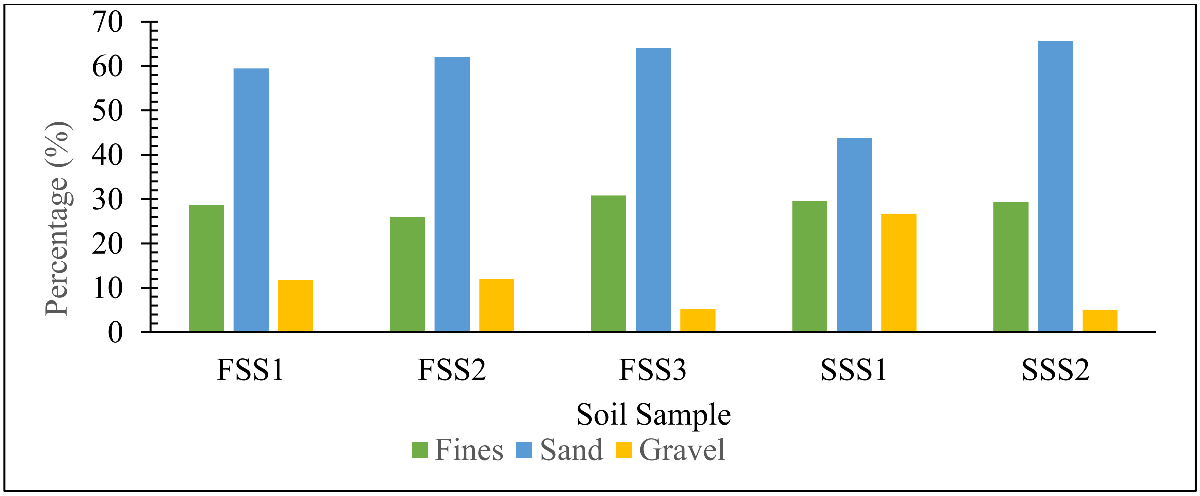

Figure 3: Percentage of Soil Types across the Stable and Failed Soil Samples

The failed section samples (FSS) exhibited fines content ranging from 25.9% to 30.8%, with an average value of 28.47%. In comparison, the stable section samples (SSS) showed a slightly narrower range of fines content, between 29.3% and 29.5%. The sand and gravel fractions in the FSS varied between 59.5% to 64% and 5.2% to 12%, respectively. For the SSS, sand content ranged from 43.8% to 62.6%, while gravel content ranged from 5.1% to 56.7%. Overall, the soil composition in both sections is predominantly composed of fines and sand, classifying the materials generally as silty sand.

Generally, fine-grained soils which comprises of percentage passing 0.002 mm sieve (Ike et al., 2025) are known to possess poorer geotechnical properties for road construction compared to coarse-grained soils (Akintorinwa & Adesoji, 2009; Odunfa et al., 2018). The failures observed at the failed sections (FS1, FS2, FS3, FS4) of the road are likely attributable to these unfavorable soil characteristics particularly under wet conditions unlike the more stable conditions observed in areas underlain by very hard clay, sand, silt or sandstone deposit (SS1, SS2, SS3, SS4). According to the Unified Soil Classification System (Standard, 2011), soils with fines (silt and clay) content ranging from 0–5% are considered well-graded, 5–15% fines indicate well-graded clayey sand or gravel, and 15–35% fines are classified as very clayey soils. Based on this classification, the soils in the study area with fines content between 25.9% and 30.8% fall within the "very clayey" category, suggesting low suitability as foundation materials (Ogunribido & Fadairo, 2020). Additionally, the fines content passing the No. 200 sieve (75 µm) is lower than the ≥35% recommended for subgrade and subbase materials by the Federal Ministry of Works and Housing (FMW&H, 1997), further indicating inadequacy for road construction. It is also noteworthy that the fines in both the failed and stable sections are predominantly composed of silt (Ike et al.,, 2025), which is known to exhibit low cohesion (Ike et al., 2024; Ike et al., 2023) and poor load-bearing capacity. Consequently, a considerable degree of stabilization is necessary to enhance the engineering properties of these soils (Okogbue & Onyeobi, 1999).

Consistency Limit

The liquid limit (LL) of the failed section samples ranges from 20.0% to 23.2%, with a plastic limit (PL) of 0% (Table 2), resulting in a plasticity index (PI) ranging from 20.0% to 23.2% (Table 3). In contrast, the stable section samples exhibit a liquid limit ranging from 21.1% to 26.0%, a plastic limit ranging from 0.0% to 24.3%, and a corresponding plasticity index ranging from 1.7% to 21.1%.

Table 2: Liquid Limit and Plastic Limit Test Results and Soil Classification (after Bell, 2007; Ukor et al., 2023)

S/No.	Sample	Liquid Limit (LL) (%)	Plastic Limit (PL) (%)	Range of LL (%)	Plasticity	Description
1	FSS1	20.0	0.0	<35	Low	Lean or Silty
2	FSS2	20.0	0.0	<35	Low	Lean or Silty
3	FSS3	23.2	0.0	<35	Low	Lean or Silty
4	SSS1	26.0	24.3	<35	Low	Lean or Silty
5	FSS1	20.0	0.0	<35	Low	Lean or Silty

Table 3: Sample Classification Based on Plasticity Index and Potential Expansiveness (after Bell, 2007; Ukor et al., 2023)

S/No.	Sample	Plasticity index (%)	Range of Plasticity Index (%)	Swelling Potential
1	FSS1	20.0	16–25	Medium
2	FSS2	20.0	16–25	Medium
3	FSS3	23.2	16–25	Medium
4	SSS1	1.7	0–15	Low
5	SSS2	21.1	16–25	Medium

Table 4: Sample Classification Based on Shrinkage Limit (after Bell, 2007; Falowo, 2020)

S/No.	Sample	Shrinkage limit (%)	Range of Shrinkage Limit (%)	Description
1	FSS1	2.50	<5	Good
2	FSS2	1.79	<5	Good
3	FSS3	2.50	<5	Good
4	SSS1	8.57	5-10	Medium
5	SSS2	1.54	<5	Good

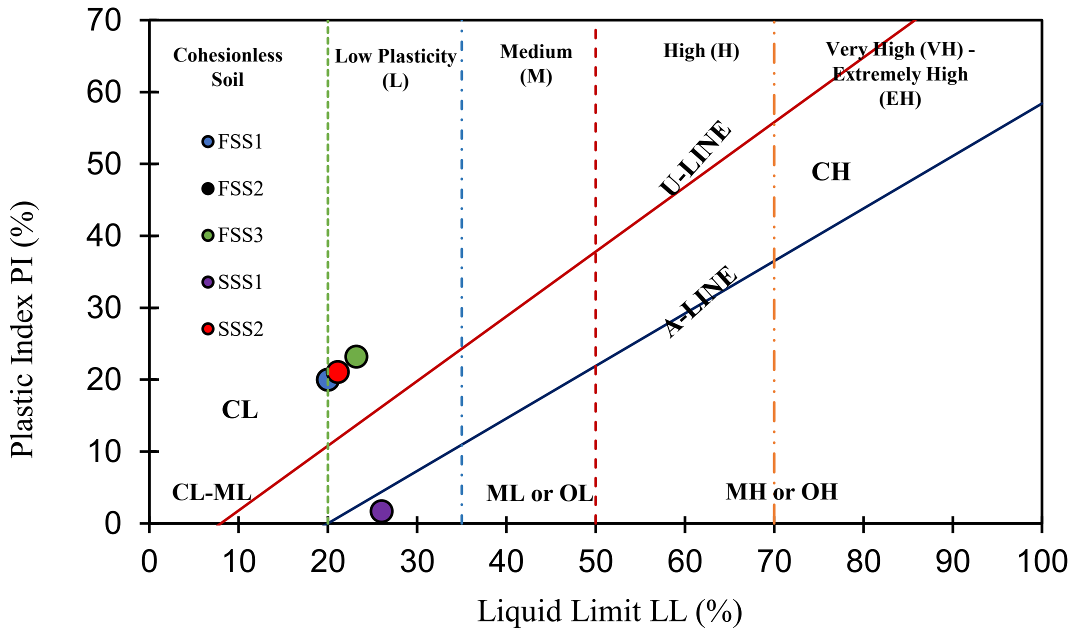

Figure 4: Plasticity Chart for the Tested Soil Samples

Liquid limit values ranging from 40% to 60% and above are typically associated with clay soils, while values between 25% and 50% are indicative of silty soils (BSI, 1990). According to the Federal Ministry of Works and Housing (FMW&H, 1997), the recommended maximum liquid limit is ≤ 50% for subgrade or fill materials and ≤ 35% for subbase materials. Similarly, the plasticity index (PI) should not exceed 30% for subgrade materials and 12% for subbase or base course materials. In this study, the observed liquid limit values for both the stable section samples (SSS) and the failed section samples (FSS) generally fall within the recommended thresholds for use as subgrade/fill and subbase materials. As summarized in Table 2, the soils are classified as low-plasticity, lean, or silty soils (Bell, 2007; Ukor et al., 2023), making them marginally suitable for light to moderate traffic loads, though potential stabilization may still be necessary in areas with elevated moisture content or plasticity index (PI) values approaching the upper limits.

However, although the liquid and plastic limit values for the tested soils fall within the recommended ranges, lower liquid or plastic limits are often associated with weak soil cohesion, implying lower shear strength. This condition makes road pavements more susceptible to erosion and slope failure, especially in high-rainfall areas or flood-prone areas such as the study site, which lies in close proximity to one of the major lakes along the Benue River. In terms of potential expansiveness (Table 3), samples FSS1, FSS2, FSS3, and SSS2 exhibit medium swelling potential, while SSS1 shows low swelling potential, based on classification guidelines by (Bell, 2007; Ukor et al., 2023). Shrinkage limit values further support these assessments. The failed section samples exhibited shrinkage limits ranging from 1.79% to 2.50%, while the stable section samples had values of 1.54% (SSS2) and 8.57% (SSS1), as shown in Table 4. According to Bell (2007) and Falowo (2020), FSS1, FSS2, FSS3, and SSS2 are classified as having good shrinkage characteristics, whereas SSS1 falls into the medium shrinkage category. The Federal Ministry of Works and Housing (FMW&H, 1997, 2010) recommends a maximum shrinkage limit of 8% for pavement materials. Madedor (1983) further specifies acceptable limits of 8% for highway sub-base and 10% for subgrade materials. The lower the linear shrinkage, the less the tendency of the soil to undergo volumetric change upon drying (Falowo, 2021). Based on these criteria, the shrinkage limit values for all failed section samples (FSS1, FSS2, FSS3) and stable section sample (SSS) 2 fall well within acceptable limits, indicating favorable behavior under drying conditions. However, the value for SSS1 (8.57%) slightly exceeds the recommendation for sub-base materials (FMW&H, 1997, 2010), though it remains within Madedor's upper threshold for subgrade materials while the value for SS2 (1.54 %) is far less than the maximum recommendation. The consistency limit results for both the failed and stable section samples indicate that the soils exhibit low to moderate plasticity, medium swelling potential, and acceptable shrinkage behavior. These factors, while within standard guidelines, suggest that the soils are marginally competent and may still require stabilization, particularly in areas vulnerable to moisture fluctuations, flood-prone or heavy traffic loading. The less cohesive nature of soil samples is attributed to the silty nature of

muscovite mica present in the subgrade soils, which diminishes the plasticity effects typically associated with higher clay content. The combination of low clay content, high silt fraction, and limited cohesion presents several geotechnical implications, including:
The soil samples, when used as subgrade or subbase materials, lack the ability to undergo significant deformation without breaking or yielding (Bell, 2007). This brittle behavior compromises their workability, making them less suitable for compaction and shaping during construction of pavement foundation layers. As a result, achieving the desired density and structural integrity becomes more difficult, potentially leading to early pavement failure.
The low cohesion and plasticity of the soil samples significantly reduce their capacity to distribute and support applied pavement loads, thereby increasing the risk of settlement, rutting, and structural deformation. These characteristics reflect the low clay content of the soils, which impairs their load-bearing strength. Additionally, such soils tend to dry rapidly and become brittle, leading to the formation of shrinkage cracks. Consequently, pavements constructed on these soils may experience excessive settlement, foundation failure, and embankment instability, particularly under heavy traffic loads, as noted by Fang and Daniels (2006). This behavior contributes to higher maintenance costs and a shorter pavement lifespan.
Soils with low liquid and plastic limits have a limited capacity to retain moisture, which leads to rapid drying. This not only contributes to dust-related issues in arid or semi-arid conditions but also increases the potential for brittle behavior and surface cracking because of the ease of rapid transition from plastic to brittle state within a narrow moisture content range. Additionally, the loose, fine-grained texture of silty soils makes them highly susceptible to erosion, particularly when exposed to heavy rainfall, surface runoff, or fording. These erosional processes can significantly compromise the integrity of roadways, especially along shoulders and embankments, leading to progressive pavement deterioration and slope instability.
These soils exhibit a notable loss of strength under wet conditions, rendering them unsuitable for use as subgrade or subbase materials in flood-prone or poorly drained areas without prior stabilization. The field conditions observed in this study suggest the need for chemical (e.g., lime or cement) or mechanical stabilization to enhance their engineering properties. However, such stabilization measures may result in increased project costs and potential construction delays, particularly in regions with high groundwater levels or seasonal flooding.

Specific Gravity (Gs)

Table 5 presents the results of the specific gravity (Gs) tests for both the failed section samples (FSS) and the stable section samples (SSS). The specific gravity of the failed section samples ranges from 2.51 to 2.54, with an average value of 2.52, while that of the stable section samples ranges from 2.29 to 2.51, with an average of 2.40. These values provide insight into the mineralogical composition and degree of laterization of the soils.

Table 5: Specific Gravity Results and Degree of Laterization (after Adeyemi et al., 2014)

S/No.	Sample	Specific Gravity (G_S)	Range of G_S	Degree of Laterisation
1	FSS1	2.54	< 2.6	Low
2	FSS2	2.51	< 2.6	Low
3	FSS3	2.52	< 2.6	Low
4	SSS1	2.29	< 2.6	Low
5	SSS2	2.51	< 2.6	Low

According to Falowo (2020), the specific gravity values obtained in this study indicate less resistant earth materials. As a geotechnical parameter, specific gravity (Gs) is strongly correlated with the bearing capacity and shear strength of subbase and subgrade materials (Eze et al., 2023; Ukor et al., 2023) It is influenced by factors such as the sand content, mineral composition, and the genesis (formation history) of the soil. Specific gravity is also a well-established index for evaluating the degree of laterization in subgrade soils (Table 5), as higher specific gravity values typically reflect greater lateritic development and, consequently, improved mechanical strength (Adeyemi et al., 2014). In this context, an increase in specific gravity corresponds to an increase in the degree of laterization, indicating more competent materials for pavement construction (Akpoyiboa et al., 2025; Badmus, 2010). According to classification guidelines by Bell (2007) and Fang and Daniels (2006), earth materials with specific gravity ranging between 2.60 and 3.40 are considered lateritic soils. Furthermore, Surendra and Bhalla (2017) emphasize that higher specific gravity values reflect stronger and more competent materials suitable for road pavement and foundation applications. In this study, the specific gravity values for both the failed section samples (FSS) and the stable section samples (SSS) are below the minimum threshold of 2.60 for lateritic soils. This indicates a low degree of laterization and suggests that the soils at these locations possess lower mechanical strength, making them unsuitable for use as subgrade or subbase materials without further treatment or stabilization.

Soils with low specific gravity tend to exhibit higher water absorption capacities and are generally more compressible, which increases the likelihood of settlement and deformation of road pavements (Bell, 2007). In addition, such soils typically have lower strength and reduced structural stability, making them more prone to failure under applied loads (Nwachukwu et al., 2022; Terzaghi et al., 1996). These geotechnical deficiencies align with the pavement damage and structural failures observed in the study area. Therefore, in the context of road construction and engineering applications, soils with low specific gravity require deeper foundations or more specialized foundation designs to compensate for their limited strength and stability. Alternatively, soil improvement techniques, such as stabilization or reinforcement, may be necessary to ensure long-term pavement performance and reduce maintenance costs.

Compaction Test (CT)

The compaction parameters for both the failed section samples (FSS) and the stable section samples (SSS) are summarized in Table 6. The maximum dry density (MDD) for the failed section samples ranges from 2.09 to 2.20 g/cm³, with an average value of 2.13 g/cm³, while the stable section samples exhibit slightly higher MDD values ranging from 2.19 to 2.20 g/cm³, averaging 2.195 g/cm³. Similarly, the optimum moisture content (OMC) for the failed section samples ranges from 8.0% to 8.4%, with a mean of 8.27%, while that of the stable section samples varies between 8.0% and 8.6%, with an average value of 8.3%. These values reflect slight differences in moisture-density relationships, which influence the compaction behavior and load-bearing potential of the subgrade materials.

Table 6: Compaction Test Results of the Failed and Stable Sections Soil Samples

Sample	Maximum Dry Density (g/cm3)	Optimum Moisture Content (%)
FSS1	2.09	8.4
FSS2	2.10	8.4
FSS3	2.2	8.0
SSS1	2.2	8.6
SSS2	2.19	8.0

According to the Federal Ministry of Works and Housing FMW&H (2010), the recommended minimum maximum dry density (MDD) is ≥1.8 g/cm³ for subgrade and ≥1.6 g/cm³ for subbase materials. The MDD values obtained for both the failed and stable soil samples in this study exceed these thresholds, ranging from 2.09 to 2.20 g/cm³ indicating that, from a compaction standpoint, the soils can be considered suitable for road construction. However, the optimum moisture content (OMC) values for both failed and stable samples—ranging from 8.0% to 8.6% exceed the recommended limits of 5–7% for subgrade and 6–7% for subbase materials (FMW&H, 2010). These relatively higher OMC values suggest that the soils are likely non-plastic or only slightly plastic, making them vulnerable to shrinkage and cracking, especially under drying conditions (Bell, 2007). Moreover, such soils may be more sensitive to moisture fluctuations, necessitating strict moisture control during construction to prevent settlement, deformation, or pavement failure. Despite meeting the MDD criteria, Ukor et al. (2023), classified the MDD range observed at both the failed and stable locations as only poor to fair for use as subgrade foundation material.

California Bearing Ratio (CBR)

The California Bearing Ratio (CBR) values for the soaked and unsoaked soil samples from both failed and stable sections are summarized in Table 7. For the soaked condition, CBR values ranged from 53.9% to 91.1% in the failed sections, and from 17.7% to 51.4% in the stable sections. Under the unsoaked condition, the CBR values ranged from 88.3% to 125.4% for the failed sections and from 36.2% to 59.3% for the stable sections.

Table 7: California Bearing Ratio (CBR) of the Failed and Stable Soil Samples

Soil Samples	California Bearing Ratio CBR	
	Soaked (%)	Unsoaked (%)
FSS1	91.1	113.3
FSS2	73.8	125.4
FSS3	53.9	88.3
SSS1	51.4	59.3
SSS2	17.7	36.2

According to the Federal Government of Nigeria's Standard Specifications for road design (FMW&H, 1997, 2010), the minimum CBR values required are ≥7% for subgrade and ≥30% for subbase under soaked conditions, and ≥15% for subgrade and ≥80% for subbase under unsoaked conditions. Based on the test results, the soaked CBR values for samples FSS1, FSS2, FSS3, and SS1 meet the minimum requirement for subgrade materials, and also satisfy the criteria for subbase materials, except SS2, which falls below the required 30% threshold for subbase. Similarly, the unsoaked CBR values for FSS1, FSS2, FSS3, SS1, and SS2 are within the acceptable range for subgrade materials, while FSS1, FSS2, and FSS3 also qualify as subbase materials. However, SS1 and SS2 do not meet the unsoaked CBR requirement for subbase applications. The results clearly show that soaked CBR values are significantly lower than their unsoaked counterparts, highlighting the adverse effect of moisture on soil strength. This moisture sensitivity suggests that increased wetness due to rainfall or water infiltration reduces the soil's bearing capacity, thereby contributing to pavement failures. Furthermore, the percentage reduction in CBR values due to soaking ranged from 22.2% to 51.6% for samples from the failed sections, and from 7.9% to 18.5% for the stable sections. This indicates a notable decrease in subgrade and subbase strength when exposed to water, underscoring the critical importance of adequate drainage and moisture control in road pavement design (Obasaju et al., 2022).

High CBR soaked values ranging from 53.9% to 91.1% in the failed sections indicate a high potential for moisture absorption, which can lead to softening of the soil, loss of strength and stability, and an increased risk of pavement failure. In contrast, the lower soaked CBR values ranging from 17.7% to 51.4% in the stable sections suggest reduced moisture absorption, which contributes to higher soil strength, greater stability, lower failure risk, and improved overall pavement performance (Bell, 2007; Eze et al., 2023; Falowo & Dayo, 2020; Fang & Daniels, 2006; Ukor et al., 2023). The marked difference in soaked CBR values between failed and stable sections underscores the critical role of moisture content in influencing soil stability. Similarly, the unsoaked CBR values in the range of 88.3% to 125.4% for the failed sections reflect high initial strength and stiffness. However, this may also indicate increased brittleness, a greater susceptibility to cracking, and a higher potential for deformation under load, which can contribute to failure under dynamic traffic stresses (Bell, 2007). On the other hand, the lower unsoaked CBR values of 36.2% to 59.3% observed in the stable sections are associated with greater ductility, better deformation absorption, reduced cracking risk, and improved long-term stability (Bell, 2007; Fang & Daniels, 2006).These findings suggest that both soil strength and stiffness are fundamental to subgrade and subbase stability, and that moisture sensitivity significantly influences pavement performance.

CONCLUSION

This study evaluated the geotechnical properties of soil samples collected from both failed and stable sections of a roadway, using series of tests such as sieve analysis, specific gravity (Gs), consistency limits, compaction, and the California Bearing Ratio (CBR). The consistency limit tests indicate that the soils are primarily lean, silty, or low-plasticity clays, with non-cohesive characteristics typical of sandy or silty soils. Sieve analysis results revealed a dominance of sand and fines, suggesting poor gradation and limited structural interlock. The specific gravity values, which correlate with mineralogy and strength, were below the threshold for lateritic soils, indicating a low degree of laterization and reduced mechanical strength. The compaction test results further support this, as the soils exhibited relatively low optimum moisture content (OMC), consistent with non-plastic or slightly plastic behavior, and thus prone to shrinkage, cracking, and brittleness, especially when subjected to drying conditions. The CBR test results underscored the influence of moisture on soil strength; saturated conditions resulted in significantly lower CBR values, highlighting the soil's sensitivity to moisture and reduced load-bearing capacity, which likely contributed to the pavement failures observed. Based on the Unified Soil Classification System (USCS), the failed soil samples were classified as silty clay, silty sand, and sandy materials which are considered fair to poor for subgrade use due to poor gradation and lack of cohesion. Overall, the findings reveal that the road pavement failures were primarily due to inadequate drainage, resulting in prolonged saturation and weakening of the subgrade; subgrade soils with a low percentage of fines, which fall below FMW&H (1997) recommendations for subgrade and subbase materials; the presence of nearby flood-prone infrastructure, including the Doubeli storm water channel, Jambutu axis, and the Goruba-Uku outlet culvert, which likely promote backflow and inundation, especially during peak runoff from Lake Gerio. We therefore make the following recommendations; (i) Excavation and Replacement: All failed road sections underlain by alluvial deposits of silt, sand, or clayey sand, particularly those prone to saturation, should be excavated and replaced with more competent materials or stabilized using cement, lime, or other suitable binders prior to asphalt overlay, (ii) Drainage Improvement: Implement adequate surface and subsurface drainage systems to manage storm water, prevent ponding, and minimize water infiltration into the subgrade. This is especially critical in flood-prone zones like Doubeli and Jambutu. By addressing both the geotechnical inadequacies of the soil and the hydraulic challenges in the area, future road reconstructions can achieve greater durability, structural stability, and reduced maintenance requirements.

REFERENCES

Adebayo, O. A., & Adigun, A. O. (2018). Engineering properties of flexible pavement and subgrade soil along Papalanto – Sagamu road, Sagamu Local Government Area Ogun State. *Proceedings of First International Conference of the Nigerian Association of Engineering and Geology and Environment, Lagos 1*(1). https://www.researchgate.net/publication/351345756_Engineering_Properties_of_Flexible_Pave

Ademila, O. (2017). Engineering evaluation of lateritic soils of failed highway sections in Southwestern Nigeria. . *Geosciences Research*, *2*(3), 210 - 218. https://doi.org/https://dx.doi.org/10.22606/gr.2017.23006

Ademila, O., & Olayinka, A. I. (2020). Geotechnical investigation of pavement failure; causes and inherent solutions for sustainable highway construction in Sub-Saharan Africa. . *The Mining-Geology-Petroleum Engineering Bulletin:* (103-114). https://doi.org/10.17794/rgn.2020.4.9

Adewuwi, I., & Olorunfemi, M. O. (2005). Using geoinformatics in Construction management. *Journal of Applied Sciences and Environmental Management*, *5*(4), 761-767. https://doi.org/10.3923/jas.2005.761.767

Adeyemi, G. O., Oloruntola, M. O., & Adeleye, A. O. (2014). Geotechnical properties of subgrade soils along sections of the Ibadan–Ife Expressway, South-Western Nigeria. *Journal of Natural Sciences Research*, *4*(3), 67-75. https://doi.org/www.iiste.org

Aina, A., Olorunfemi, M. O., & Ojo, J. S. (1996). An integration of aeromagnetic and electrical resistivity methods in dam site investigation. *Geophysics*, *61*(2), 349-356. https://doi.org/10.1190/1.1443963

Akinlabi, I. A., & Adegboyega, C. O. (2021). Engineering geophysical investigation of road failure in a basement complex terrain, Southwestern Nigeria. *Journal of Geography, Environment and Earth Science International* *25*(2), 40-51. https://doi.org/10.9734/JGEESI/2021/v25i230270

Akintorinwa, O. J., & Adesoji, J. I. (2009). Application of geophysical and geotechnical investigations in engineering site evaluation. *International Journal of Physical Sciences* *4*(8), 443-454. http://www.academicjournals.org/IJPS

Akpoyiboa, O., Abrikub, E. O., Ugbec, F. C., & Anomohanran, O. (2025). Geophysical and geotechnical assessment of Obiaruku-Agbor road failure in Western Niger-Delta, Nigeria. *Journal of the Nigerian Society of Physical Sciences*, *7*(1), 1-9. https://doi.org/https://doi.org/10.46481/jnsps.2025.2328

Allix, P. (1983). Environments Mésozoiques de la partied u Nord- orientale du fossé de la Bénoué (Nigeria). Stratigraphie, Sédimentologie, evolution géodynamique. *Trav. Lab. Sci. Terre, St Jérome , Marseille (B)*, *21*(1), 1-200.

ASTM D2487-11. (2011). Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). *ASTM International*. https://doi.org/https://doi.org/10.1520/D2487-11

Badmus, B. S. (2010). Plasticity and Compressibility characteristic of lateritic soil from Southwestern Nigeria. *Research journal of soils and water Management*, *1*(1), 10-14. https://doi.org/10.3923/rjswm.2010.10.14

Bell, F. G. (2007). Engineering Geology *Elsevier*. https://doi.org/https://www.geokniga.org/bookfiles/geokniga-bellengineeringgeology2007.pdf

BSI. (1990). Methods of Test for Soil for Civil Engineering Purposes. *London*. https://doi.org/https://books.google.com.ng/books/about/British_Standard_Methods_of_Test_for_Soi.html?id=RvQhAAAACAAJ&redir_esc=y

Carter, J. D., Barber, W., & Tait, E. A. (1968). The Geology of Parts of Adamawa, Bauchi and Borno Province in North- Eastern Nigeria. *Geological Survey of Nigeria Bulletin, No. 30*.

Emmanuel, U. O., Ogbonnaya, I., & Uche U. B. (2021). An investigation into the cause of road failure along Sagamu-Papalanto highway southwestern Nigeria. *Geoenviron Disasters*, *8*(3). https://doi.org/https://doi.org/10.1186/s40677-020-00174-8

Evinemi, I. E., Adepelumi, A. A., & Adebayo, O. (2016). Canal structure subsidence investigation using ground penetrating radar and geotechnical techniques. *International Journal of Geo-Engineering*, *7*(1). https://doi.org/https://doi.org/10.1186/s40703-016-0023-x

Eze, K. N., Igwe, O., Okereke, D. N., Uwom, C. S., & Ukor, K. P. (2023). Foundation integrity assessment of failed buildings in Ehamufu and Aguamede, South East Nigeria. *Sci Rep*, *13*(1), 719. https://doi.org/https://doi.org/10.1038/s41598-023-28043-y

Falowo, O. O. (2020). Engineering Site Investigation and Shallow Foundation Design in Ore Area of Ondo State, Nigeria, RMZ *Material and Geoenvironment 67*(1), 1-13. https://doi.org/10.2478/rmzmag-2020-0004

Falowo, O. O. (2021). The Usefulness of Engineering Geological and Geotechnical Studies in Civil Engineering Sites Foundation Design Parameters Consideration and Construction: A Case Study in SW Nigeria *International Journal of Earth Sciences Knowledge and Applications 3*(3), 173-189. https://doi.org/https://www.ijeska.com/index.php/ijeska/article/view/77/427

Falowo, O. O., & Dayo, O. O. (2020). Geoengineering Assessment of Subgrade Highway Structural Material along Ijebu Owo– Ipele Pavement Southwestern Nigeria. *International Advanced Research Journal in Science, Engineering and Technology*, *7*(4), 1-10. https://doi.org/10.17148/IARJSET.2020.7401

Fang, H.-Y., & Daniels, J. L. (2006). Introductory Geotechnical Engineering: An Environmental Perspective. *CRC Press*. https://doi.org/https://doi.org/10.1201/9781315274959

FMW&H. (1997). Federal Ministry of Works and Housing's General Specification for Roads and Bridges Volume II. *Federal Highway Department, FMWH: Lagos, Nigeria*, *317*, 14. https://doi.org/https://fmw.gov.ng

FMW&H. (2010). General Specification for Roads and Bridges, . *Federal Highway Department, Nigerian Federal Ministry of Works and Housing: Lagos, Nigeria*, *II*, 317. https://doi.org/https://fmw.gov.ng

Guiraud, M. (1991). Mécanisme de formation du basin crétacé sur décrochements multiples de la Haute-Bénoué (Nigeria). *Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine*, *15*(1), 11-67.

Hijab, M., Zaynab, A. B., & Hadi, A. A. (2012). Road pavement failure induced by poor soil properties along Gombi-Biu highway, Northern Nigeria. In Medjor, W.O., Obia K.M., & Solomon S. (2022). Application of electrical resistivity tomography to investigating geological causes of road failure in Taraba state, Nigeria. . *Science World Journal 17*(2), 346-355. www.cenresinpub.org

Idornigie, A. I., Olorunfemi, M. O., & Omitogun, A. A. (2006). Integration of remotely sensed and geophysical data sets in engineering site characterization in a Basement complex of southwestern Nigeria. *Journal of Applied Sciences Research*, *2*(9), 541-552. https://doi.org/https://doi.org/10.4314/ijs.v8i2.32216

Ifabiyi, I. P., & Kekere, A. A. (2013). Geotechnical investigation of road failure along Ilorin-Ajase –Ipo Road Kwara State, Nigeria. *Journal of Environment and Earth Science 3*(1), 7. https://www.iiste.org/Journals/index.php/JEES/article/view/6367

Ike, E., Audu, J., Yerima, J. B., & Oniku, A. S. (2025). Geophysical Investigation of Road Pavement Failure along the Mubi Bypass Road, Jambutu, Jimeta, Yola, Adamawa State. *Nigerian Journal of Physics. In press*, *34*(1). https://njp.nipngr.org/index.php/njp

Ike, E., Ezike, S. C., Oniku, A. S., & Osumeje, J. O. (2024). A Review of the Revised Soil Classification System (RSCS) Based on Plasticity and Electrical Sensitivity to Pore-Fluid Chemistry. *Nigerian Journal of Physics (NJP)*, *33*(4), 59-77. https://doi.org/https://doi.org/10.62292/njp.v33i4.2024.269

Ike, E., Park, J., Ewusi-Wilson R., & Lee, C. (2025). Effect of Specific Surface, Mineralogy, and Pore-Fluid Chemistry on Fine-Grained Soil Classification Based on Plasticity and Electrical Sensitivity. *Geotech Geol Eng*, *43*(5). https://doi.org/https://doi.org/10.1007/s10706-025-03196-x

Ike, E., Park, J., & Lee, C. (2023). Sedimentation Behavior of Clays in Response to Pore-Fluid Chemistry: Effect of Ionic Concentration and pH on Its Trends. *KSCE J Civ Eng*, *17*, 1502–1511. https://doi.org/https://doi.org/10.1007/s12205-023-0474-5

Ishaku, J. M. (2011). Assessment of groundwater quality index for JimetaYola area, Northeastern Nigeria. *Journal of Geology and Mining Research*, *3*(9), 219-231. http://www.academicjournals.org/JGMR

Ishaku, J. M. (2011). Hydrochemical Evolution of Groundwater in Jimeta-Yola Area. In Barde, M. M., Abdullahi, L. M. & Muhammadu, A. M. (2019). Detection and mapping of flood prone areas of Jimeta, Adamawa State, Nigeria. *ATBU, Journal of Science, Technology & Education (JOSTE)*, *7*(2), 185-201. https://doi.org/https://www.ajol.info/index.php/gjgs/article/view/79254

Kazeem, A. A., Olayiwola, H., & Anjonrin, A. (2019). Geotechnical evaluation of road pavement failure along the Awotan-Akufo Road, Oyo State Southwestern Nigeria. . *Journal of Geography, Environment and Earth Science International 23*(2), 1-11. https://doi.org/https://doi.org/10.9734/jgeesi/2019/v23i230166

Kodicherla, S. P. K., & Nandyala, D. K. (2016). Use of CPT and DCP based correlations in characterization of subgrade of a highway in Southern Ethiopia Region. *International Journal of Geo-Engineering*, *7*(1). https://doi.org/10.1186/s40703-016-0025-8

Kogbe, C. A. (1989). Paleogeographic History of Nigeria from Albian Times. *In Geology of Nigeria, Kogbe, C .A. (ed). Jos: Rock View (Nigeria) Limited*.

Kumar, J., & Rao, V. B. K. M. (2003). Seismic bearing capacity factors for spread foundations. *Géotechnique*, *52*(2), 79-88. https://doi.org/https://doi.org/10.1680/geot.52.2.79.40929

Layade, G. O., Adegoke, J. A., & Oyewole, I. T. (2017). Integrated geophysical investigation of the causes of road pavement failure along Ibadan-Lagos dual-carriage, South-western, Nigeria. In Medjor, W.O., Obia K.M., & Solomon S. (2022). Application of electrical resistivity tomography to investigating geological causes of road failure in Taraba state, Nigeria. *Science World Journal 17*(2), 346-355. https://doi.org/10.4314/jasem.v21i3.16

Madedor, A. A. (1983). Pavement design guidelines and practise for different geological areas in Nigeria. In Olawale, O. O, Akanji, A. O, & Akinmosin, A. (2011). Integrated geophysical and geotechnical investigation of the failed portion of a road in basement complex Terrain, Southwest Nigeria. . *RMZ – Materials and Geo-environment*, *58*(2), 143-162. https://doi.org/AJOGER.65508

Meludu, O. C., Kanu , M. O., & Oniku, A. S. (2010). Petrophysical Characteristics of Rocks in Girei Local Government Area of Adamawa State, Northeastern Nigeria. *Federal University of Technology, Yola (FUTY) Journal of the Environment*, *5*(1), 61-71.

Mohammed, H., & Moruf, B. S. (2013). Stratigraphic influence on geotechnical properties of subgrade soils along the Irrua-Auchi road, South Eastern Nigeria. *Journal of Environment and Earth Science 3*(18). https://doi.org/https://www.iiste.org/Journals/index.php/JEES/article/view/6756

Ntekim, E. E., & Bello, H. (2001). Evaluation of heavy metal contents of soils and well water around Jimeta bridge, Yola, northeastern. *Nigeria. J.Min. Geol.* , *37*(2), 103111. https://doi.org/https://research-nexus.net/paper/0b72b05e73d8376567f476ec1a801a56e0738871f383a77668f609dd990ee612/

Nwachukwu, M. C., Aleke, C. G., Aghamelu, O. P., & Joesph, E. U. (2022). Geotechnical evaluation of the causes of road pavement failure along the Mbaitoli-Ikeduru-Mbaise highway, Southeastern Nigeria. *The Asian Review of Civil Engineering 11*(1), 21-26. https://doi.org/https://doi.org/10.51983/tarce-2022.11.1.3302

Obasaju, D. O., Oloruntola, M. O., & Oladele, S. (2022). Integrated resistivity, index, and strength characteristics of subgrade soils: implication for highway pavement failure studies in North-Central Nigeria. *GeoScience Engineering 68*(1), 46-57. https://doi.org/10.35180/gse-2022-0068

Obioha, Y. E., Selemo, A. O., Sowa, A., & Nwagbara, J. (2021). Geological and geotechnical investigation of road failures in Nigeria: a case study of parts of Imo-Abia states, southeastern Nigeria. *Engineering Research Journal 1*(4). https://doi.org/www.doi.org/10.46654/ERJ

Odunfa, S. O., Owolabi, A. O., Aiyedun, P. O., & Sadiq, O. M. (2018). Geotechnical assessment of pavement failure. *Journal of Engineering and Technology*, *3*(2). https://doi.org/http://dx.doi.org/10.46792/fuoyejet.v3i2.237

Ogunribido, T. H. T., & Fadairo, T. E. (2020). Geotechnical investigation of road pavement failure along Arigidi/oke - agbe akoko, southwestern, Nigeria. *International Journal of Physical Research*, *8*(2), 35-39. https://doi.org/10.14419/ijpr.v8i2.30769

Okogbue, C. O., & Onyeobi, T. U. S. (1999). Potential of marble dust to stabilize red tropical soils for road Construction. *Engineering Geology*, *53*, 371-380. https://doi.org/ 10.1016/S0013-7952(99)00036-8

Olayanju, G. M., Mogaji, K. A., Lim, H. S., & Ojo, T. S. (2017). Foundation integrity assessment using integrated geophysical and geotechnical techniques: case study in crystalline basement complex, southwestern Nigeria. *Journal of Geophysics and Engineering*, *14*(3), 675-690. https://doi.org/https://doi.org/10.1088/1742-2140/aa64f7

Omorogieva, O. M., & Okiti, I. (2022). Geotechnical appraisal and geological influence on road failure. *International Journal of Earth Sciences Knowledge and*

Applications, *4*(1), 124-132. http://www.ijeska.com/index.php/ijeska

Oyedele, K., Oladele, S., & Salami, A. (2016). Geophysical investigation of banded iron ore mineralization at Ero, North – Central Nigeria. *Materials and Geoenvironment*, *63*(2), 109-118. https://doi.org/10.1515/rmzmag-2016-0010

Standard, A. (2011). D2487-11 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). *ASTM International, West Conshohocken, PA.*

Surendra, R., & Bhalla, S. K. (2017). Role of Geotechnical Properties of Soil on Civil Engineering Structures. . *Resources and Environment*, *7*(4), 103-109. https://doi.org/10.5923/j.re.20170704.03

Terzaghi, K., Peck, R. B., & Mesri, G. (1996). Soil mechanics in engineering practice. *John Wiley & Sons, Hoboken*. https://doi.org/https://cequcest.wordpress.com/wp-content/uploads/2015/09/terzaghi129883967-soil-mechanics-in-engineering-practice-3rd-edition-karl-terzaghi-ralph-b-peck-gholamreza-mesri-1996.pdf

Ubido, O. E., Ogbonnaya, I., & Ukah, B. U. (2020). Evaluation of road failure along an erosion prone highway in Ogun State southwestern Nigeria using integrated methods. . *SN Applied Sciences 2*(2094.94). https://doi.org/https://doi.org/10.1007/s42452-020-03849-x

Ukor, K. P., Igwe, O., Onwuka, O. S., Nzereogu, S. K., Eze, K. N., & Echezona, P. E. (2023). Integrated geotechnical and mineralogical evaluation of the subgrade of some failed pavements along Enugu-Onitsha expressway Southeastern Nigeria. *Scientific Reports*, *13*(1), 1-5. https://doi.org/https://doi.org10.1038/s41598-023-41289-w

Whiteman, A. (1982). Nigeria: Its Petroleum Geology, Resources and Potential. *Graham and Trotman, London*.

Zaborski, P., Ugodulunwa, F., Idornigie, A., Nnbo, P., & Ibe, K. (1997). Stratigraphy and Structure of the Cretaceous Gongola Basin, Northeast Nigeria. *Bulletin des Centres Research Exploration and Production Elf Aquataine*, *21*(1), 154-185.