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Geotechnical Evaluation of Subgrade Soil Properties and Their Impact on Pavement Failure: A Case Study of Ugbowo, Benin City, Nigeria

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Abstract

Pavement failure remains a critical issue in Nigeria, significantly affecting road safety, economic activities, and infrastructure longevity. This study investigates the causes of flexible pavement deterioration in Nigeria, focusing on subgrade soil properties, drainage conditions, material quality, and traffic loading. Through field investigations and laboratory tests including compaction, sieve analysis, moisture content, and California Bearing Ratio (CBR) tests soil samples from three boreholes (BH1, BH2, BH3) were analyzed. Results revealed that BH1, with a maximum dry density (MDD) of 1.92 g/cm³, optimum moisture content (OMC) of 11.28%, and 32% clay content, exhibited the best compaction and stability, making it suitable for construction. BH2 (MDD: 1.79 g/cm³, OMC: 14.73%, clay: 54.3%) showed moderate suitability but required stabilization due to high plasticity. BH3 (MDD: 1.60 g/cm³, OMC: 19.05%, clay: 35%) was deemed unsuitable without significant improvement. The study highlights the importance of proper material selection, soil stabilization, and drainage systems to mitigate pavement failure. Recommendations include enforcing construction standards, adopting stabilization techniques, and implementing routine maintenance to enhance road durability and sustainability.

Keywords: Pavement failure, subgrade soil, geotechnical evaluation, soil stabilization, California Bearing Ratio (CBR), compaction, moisture content, Benin City, road infrastructure, flexible pavement

INTRODUCTION

The construction and upkeep of roads play a key role in the development of any nation, particularly in developing countries. Roads impact market access, economic development, the exploration of natural resources, and also contribute to issues like habitat loss, deforestation, and the decline of wildlife. Roads continue to be the most widely used and effective form of transport for moving people and goods globally (Alo & Oni, 2018). Their popularity stems from the door-to-door service they provide, making transportation more accessible and especially suitable for short-distance trips involving both passengers and cargo. In Nigeria, road transport is considered the most practical and affordable option for most people, mainly because other transportation methods are either too costly or not well-developed. This has led to excessive axle loads on many Nigerian roads. As stated by (Onuoha and Onwuka, 2014), road failure occurs when there are visible issues in the pavement such as cracks, potholes, and surface bulging. Generally, anything that disrupts a smooth journey can be considered a road failure.

Being able to accurately predict rutting on roads is crucial for managing pavement systems effectively, especially in places where testing and maintenance are not up to standard. Road defects are physical signs that something is wrong with the pavement, and they affect how well the road works, how long it lasts, and how it looks. According to the Wisconsin Department of Transport, pavement damage is closely linked to the amount and weight of traffic loads. They also point out that wheel pressure, the number of truck axles and tires, the strength of the ground layer, pavement thickness, and seasonal changes all play a role in road failures (Wee et al., 2009). Climate also has a noticeable impact on how roads deteriorate. It influences not just the road surface but also vehicle maintenance costs, safety, and the surrounding environment (Antala et al., 2011). Transport Canada (2015) highlights that weather conditions like extreme temperature, freezing and thawing cycles, and moisture are leading factors in pavement damage. These effects can become worse when combined with heavy vehicle usage. Harischandia (2004) observed common defects like cracks, potholes, edge breakage, and surface depressions during field inspections. He pointed out that traffic volume, road age, design, weather, drainage, quality of construction and materials, and maintenance policies all significantly contribute to road deterioration.

In their study, (Abdulkareem and Adeoti, 2004) discussed how road maintenance is handled in Nigeria. They outlined several causes of road failure, including weather conditions like rain and heat, unstable soil, poor drainage, substandard materials and construction methods, and activities like digging near roads after construction. They also mentioned poor craftsmanship and lack of proper maintenance as serious issues. Similarly, (Okikbo, 2012) looked into the reasons why Nigerian highways often fail. He identified causes such as poor design, low-quality construction, lack of maintenance, and use of materials that do not meet required standards. He also listed factors such as inadequate infrastructure, lack of technical knowledge, weak enforcement of standards, absence of local road guidelines, limited soil testing facilities, and underdeveloped professional bodies involved in highway engineering. Pavement failure in Nigeria has become a serious and embarrassing issue. In some regions, normal daily activities are being disrupted due to the poor state of road pavements. Many road users are frustrated, especially since the specific reasons behind highway deterioration from the perspective of clients are not clearly identified or compared with the views of contractors. Understanding how both groups clients and contractors see these issues, along with the priorities consultants and major road construction firms place on them, is essential.

This research focuses on identifying the major causes of road cracks and defects across Nigerian highways, especially from the client's point of view, and compares those findings with insights from contractors (Tarawneh and Sarireh, 2013). The aim is to rank these factors based on their importance to help guide future road and highway improvement programs. The study mainly targets those factors believed to significantly impact the overall performance and durability of highway pavements.

MATERIALS AND METHOD

The methodology for this study involved a combination of field investigations and laboratory tests to evaluate the subgrade soils of selected roads in Ugbowo, Benin City. The study focused on three locations: Dentistry Road (BH1), Basement Road (BH2), and BDPA 19th Street (BH3). The field investigations included soil sampling and in-situ testing, while the laboratory analyses encompassed specific gravity, moisture content, particle size distribution, compaction, and Atterberg limits tests.

Soil samples were collected from each borehole at depths of 1.0 to 1.5 meters to ensure representation of the subgrade layer. The samples were carefully sealed in airtight containers to preserve their natural moisture content during transport to the laboratory. Field testing was conducted using a Dynamic Cone Penetrometer (DCP) to assess the in-situ strength and stiffness of the subgrade soils. The DCP measurements provided preliminary data on the bearing capacity of the soils, which was later correlated with the laboratory results.

In the laboratory, the specific gravity of the soil particles was determined using the pycnometer method, following ASTM D854 standards. This test involved measuring the weight of a soil sample in air and in water to calculate its relative density. The natural moisture content was determined by oven-drying the samples at 105°C for 24 hours, as per ASTM D2216. Particle size distribution was analyzed using sieve analysis for the coarse fraction and hydrometer analysis for the fines, adhering to ASTM D422.

The compaction characteristics of the soils were evaluated using the Standard Proctor Test (ASTM D698), which involved compacting soil samples at varying moisture contents to determine their maximum dry density (MDD) and optimum moisture content (OMC). The Atterberg limits tests, including liquid limit (LL), plastic limit (PL), and plasticity index (PI), were conducted in accordance with ASTM D4318. These tests involved measuring the moisture content at which the soil transitions between different states of consistency, providing critical data on its plasticity and suitability for subgrade construction.

The California Bearing Ratio (CBR) test was also performed to evaluate the strength of the subgrade soils under simulated traffic loads. This test involved compacting soil samples at their OMC, soaking them for 96 hours to simulate worst-case moisture conditions, and then measuring their resistance to penetration under a standard load. The CBR values were used to assess the load-bearing capacity of the soils and their potential for use in pavement construction.

The data collected from these tests were analyzed to classify the soils and evaluate their engineering properties. The Unified Soil Classification System (USCS) and AASHTO soil classification system were employed to categorize the soils based on their particle size distribution and plasticity characteristics. The results were compared with established standards and previous studies to assess their implications for road construction in the study area.

The methodology adopted in this study ensured a comprehensive evaluation of the subgrade soils, providing reliable data for identifying the causes of pavement failure and recommending appropriate remedial measures. The combination of field and laboratory tests allowed for a detailed understanding of the soil properties and their impact on pavement performance, contributing to the development of sustainable solutions for road infrastructure in Ugbowo, Benin City.

Table 1: Field Investigation Equipment

Equipment	**Purpose**	**Standard/Reference**
Dynamic Cone Penetrometer	In-situ strength assessment	ASTM D6951
Augers and Shovels	Soil sampling	ASTM D1587
Airtight Containers	Sample preservation	ASTM D4220

Table 2: Laboratory Tests and Standards

Test	**Parameter Measured**	**Standard**
Specific Gravity	Soil particle density	ASTM D854
Moisture Content	Natural water content	ASTM D2216
Particle Size Distribution	Grain size analysis	ASTM D422
Compaction Test	MDD and OMC	ASTM D698
Atterberg Limits	Soil plasticity	ASTM D4318
CBR Test	Subgrade strength	ASTM D1883

RESULTS

A. Geotechnical Properties Analysis

The laboratory testing program yielded comprehensive data on the subgrade soils' characteristics. The results are presented in the following tables with detailed interpretations:

Table 3: Specific Gravity and Moisture Content Results

Sample ID	Location	Depth (m)	Specific Gravity	Moisture Content (%)	Classification
BH1	Dentistry Road	1.5	2.49	12.09	Lateritic Soil
BH2	Basement Road	1.3	2.50	11.50	Clayey Sand
BH3	BDPA 19th St	1.0	2.35	10.11	Weathered Soil

The specific gravity values show BH1 and BH2 meet typical lateritic soil standards (2.4-2.75), while BH3's lower value (2.35) suggests weathering effects. Moisture contents are within normal tropical ranges but indicate BH3 may exhibit higher shrinkage potential.

Table 4: Particle Size Distribution Analysis

Sample ID	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	USCS Classification
BH1	0	68	22	10	SM (Silty Sand)
BH2	3.9	41.8	38.5	15.8	SC (Clayey Sand)
BH3	0	65	25	10	SM (Silty Sand)

The particle size distribution reveals BH2 contains significantly higher fines content (54.3% combined silt+clay) compared to BH1 and BH3 (32% and 35% respectively). This composition directly impacts compaction and stability characteristics.

Table 5: Compaction Test Results

Sample ID	Maximum Dry Density (g/cm³)	Optimum Moisture Content (%)	Relative Compaction (%)
BH1	1.92	11.28	98.5
BH2	1.79	14.73	93.2
BH3	1.60	19.05	87.4

Compaction results demonstrate BH1 achieves superior density at lower moisture content, while BH3 shows poor compaction performance. The 19.05% OMC for BH3 indicates high water demand for proper compaction.

Table 6: Atterberg Limits and Soil Classification

Sample ID	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index	AASHTO Classification
BH1	40.28	25.88	14.40	A-6
BH2	33.97	16.19	17.76	A-7-6
BH3	31.64	14.24	17.40	A-7-5

The plasticity characteristics show BH2 and BH3 have higher plasticity indices (17.76 and 17.40) compared to BH1 (14.40), indicating greater potential for volume changes with moisture variation.

Table 7: California Bearing Ratio (CBR) Results

Sample ID	Unsoaked CBR (%)	Soaked CBR (96 hrs) (%)	Swell Potential
BH1	18.5	15.2	Low
BH2	12.3	8.7	Moderate
BH3	9.8	5.4	High

CBR values confirm BH1's superior load-bearing capacity, maintaining 15.2% after soaking. BH3's dramatic reduction to 5.4% after soaking demonstrates its poor performance under wet conditions.

B. Comparative Performance Analysis

The test results collectively indicate that BH1 possesses the most favorable engineering properties for subgrade construction. Its combination of high specific gravity (2.49), optimal compaction characteristics (MDD 1.92 g/cm³ at 11.28% OMC), and good CBR values (15.2% soaked) make it suitable for direct use with minimal treatment.

BH2 presents moderate suitability but requires stabilization due to its high fines content (54.3%) and plasticity index (17.76). The 8.7% soaked CBR falls below the 10% threshold typically recommended for subgrade materials in moderate traffic conditions.

BH3 demonstrates poor performance across all parameters. Its low specific gravity (2.35), high OMC requirement (19.05%), and very low soaked CBR (5.4%) classify it as unsuitable for subgrade use without significant improvement through stabilization or replacement.

Table 8: Comparative Soil Properties Summary

Parameter	BH1 (Dentistry)	BH2 (Basement)	BH3 (BDPA)	Ideal Range
Specific Gravity	2.49	2.50	2.35	2.4-2.75
Moisture Content (%)	12.09	11.50	10.11	8-15
Sand Content (%)	68	41.8	65	>50
Clay Content (%)	10	15.8	10	<15
MDD (g/cm³)	1.92	1.79	1.60	>1.85
OMC (%)	11.28	14.73	19.05	8-12
Soaked CBR (%)	15.2	8.7	5.4	>10

C. Implications for Pavement Design

These results explain the observed pavement failures in the study area. Roads constructed on BH3-type soils would experience rapid deterioration due to:

1. Excessive plasticity causing shrinkage cracks
2. Low bearing capacity leading to rutting
3. High swell potential resulting in uneven surfaces

The data supports the need for differentiated construction approaches based on subgrade soil properties, with BH1 locations requiring standard designs, BH2 needing stabilized subgrades, and BH3 demanding complete soil replacement or advanced stabilization techniques.

CONCLUSION

This comprehensive study of pavement failure mechanisms in Ugbowo, Benin City has yielded critical insights into the geotechnical factors contributing to road deterioration, with particular focus on subgrade soil characteristics. Through rigorous field investigations and extensive laboratory testing of samples from three strategic locations (Dentistry Road - BH1, Basement Road - BH2, and BDPA 19th Street - BH3), the research has established a clear correlation between subgrade soil properties and pavement performance. The findings present a compelling case for the implementation of soil-specific design and construction methodologies to enhance the longevity of road infrastructure in the study area and similar tropical environments.

The investigation revealed substantial variations in the engineering properties of subgrade soils across the study locations. BH1 exhibited the most favorable characteristics for pavement construction, with specific gravity of 2.49, maximum dry density of 1.92 g/cm³ at optimum moisture content of 11.28%, and California Bearing Ratio (CBR) values of 18.5% (unsoaked) and 15.2% (soaked). These parameters indicate that soils in the Dentistry Road area possess adequate strength and stability for supporting pavement structures without requiring extensive modification. The medium plasticity (Plasticity Index of 14.40) and well-graded particle size distribution (68% sand, 32% fines) contribute to its excellent performance as subgrade material. This explains the relatively better condition of pavements in this location compared to other study areas.

In contrast, BH2 demonstrated moderately suitable but problematic characteristics that necessitate careful engineering interventions. While its specific gravity of 2.50 compares favorably with BH1, the high fines content (54.3% silt and clay) and elevated plasticity (Plasticity Index of 17.76) make it susceptible to volume changes with moisture variation. The compaction results (MDD 1.79 g/cm³ at 14.73% OMC) and CBR values (12.3% unsoaked, 8.7% soaked) fall below optimal standards for untreated subgrade material. These properties account for the observed pavement distresses in the Basement Road section, particularly the development of cracks and localized failures during wet seasons when the subgrade undergoes expansion and subsequent loss of bearing capacity.

The most critical findings emerged from the analysis of BH3 samples, which exhibited profoundly inadequate properties for subgrade construction. With specific gravity of 2.35, extremely high optimum moisture content (19.05%), and alarmingly low CBR values (9.8% unsoaked, 5.4% soaked), these soils represent a significant challenge for pavement engineers. The high plasticity (Plasticity Index 17.40) combined with poor compaction characteristics (MDD 1.60 g/cm³) creates a perfect storm for pavement failure, explaining the severe deterioration observed along BDPA 19th Street. The soil's tendency to absorb and retain moisture leads to substantial strength reduction during rainfall, while the subsequent drying creates shrinkage cracks that propagate through the pavement structure.

The study's findings have several important implications for pavement engineering practice in tropical regions. First, they underscore the critical importance of comprehensive subgrade soil characterization before pavement design. The substantial variation in soil properties over relatively short distances (as evidenced by the differences between BH1, BH2, and BH3) demonstrates that blanket design approaches are inadequate and often lead to premature failures. Second, the results highlight the need for differentiated treatment strategies based on soil properties. While BH1-type soils may require only standard compaction and drainage provisions, BH2 and BH3 soils demand more sophisticated solutions including chemical stabilization, mechanical improvement, or complete replacement. The research also reveals significant deficiencies in current construction practices, particularly regarding quality control during subgrade preparation. The compaction results indicate that many failures could be mitigated through stricter control of moisture content and compaction effort during construction. Furthermore, the CBR tests demonstrate that conventional designs may be inadequate for areas with poor subgrade soils, necessitating either thicker pavement sections or improved subgrade through stabilization techniques.

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