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Geotechnical Characterization And Stabilization Of Floodplain Subgrade Soils For Road Infrastructure Development In The Niger Delta Region, Nigeria

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Abstract:
Road infrastructure development in floodplain environments is often constrained by weak subgrade conditions, high groundwater levels, prolonged soil saturation, and recurrent flooding. These challenges are particularly severe in the Niger Delta region of Nigeria, where extensive floodplain deposits and intense rainfall frequently contribute to pavement distress and premature road failures. This study evaluated the geotechnical characteristics of selected floodplain soils in the Niger Delta and assessed the effectiveness of cement stabilization in improving their engineering performance for road construction applications. Soil samples were collected from representative flood-prone locations and subjected to laboratory testing, including particle size distribution, Atterberg limits, compaction characteristics, and California Bearing Ratio (CBR) analyses. The results revealed that the soils were predominantly fine-grained, with percentages passing the 75 µm sieve ranging from 49% to 57%, indicating significant silt and clay fractions. The soils exhibited moderate to high plasticity, with liquid limit values varying between 35.6% and 53.7%, while plasticity index values ranged from 14.7% to 25.9%. These characteristics suggest high susceptibility to moisture-induced deformation and reduced structural stability under saturated conditions. Subgrade strength evaluation showed soaked CBR values ranging from 18% to 30%, indicating weak to moderate load-bearing capacity unsuitable for long-term pavement performance in flood-prone environments. The computed pavement failure index varied between 28.08 and 66.39, demonstrating a strong relationship between geotechnical properties and infrastructure vulnerability under flood conditions. To enhance soil performance, cement stabilization was applied to selected soil samples. The stabilization process significantly improved engineering properties, increasing CBR values from 22.0% to 48.4%, representing an improvement of approximately 120%. In addition, the plasticity index decreased from 25.9% to 10.4%, indicating substantial reduction in soil expansiveness and moisture sensitivity. The treated soils exhibited improved strength, stiffness, and resistance to deformation under saturated conditions. The findings demonstrate that cement stabilization can effectively transform marginal floodplain soils into suitable pavement subgrade materials capable of supporting sustainable road infrastructure development. The study concludes that the poor geotechnical characteristics of floodplain soils are major contributors to pavement failures in the Niger Delta. However, appropriate stabilization techniques can significantly enhance subgrade performance and improve the durability and resilience of road infrastructure in flood-prone environments. The findings provide valuable guidance for geotechnical design and pavement engineering practice in tropical floodplain regions.
Keywords: *Floodplain soils, Geotechnical characterization, Soil stabilization, California Bearing Ratio, Plasticity index, Subgrade performance, Pavement resilience, Fine-grained soils, Flood-prone environments, Niger Delta, Road infrastructure, Cement stabilization.*

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I. Introduction

Transportation infrastructure plays a fundamental role in economic development, regional integration, and social connectivity by facilitating the movement of people, goods, and services. Among the various components of transportation systems, road networks remain the most widely used mode of inland transportation in many developing countries, including Nigeria. The effectiveness of these road networks is closely linked to their structural integrity, durability, and ability to withstand environmental stresses. However, the performance of road infrastructure is often influenced by local geotechnical and hydrological conditions, particularly in flood-prone environments where prolonged water exposure can significantly reduce pavement service life and increase maintenance requirements (World Bank, 2024; Mushtaq et al., 2024).

Floodplain environments present unique challenges for road infrastructure development due to their complex interaction of geomorphological, hydrological, and geotechnical factors. Floodplains are low-lying depositional landscapes located adjacent to rivers and streams that are periodically inundated during flood events

(Leopold et al., 1964; Nanson & Croke, 1992). These environments are typically composed of unconsolidated alluvial sediments, including clay, silt, sand, and organic materials, which are deposited during successive flooding cycles. While floodplains support ecological productivity and agricultural activities through nutrient replenishment and groundwater recharge, they also create difficult conditions for civil engineering infrastructure because of poor drainage characteristics, high groundwater levels, and weak subgrade soils (Knighton, 1998; Tockner & Stanford, 2002).

The engineering behaviour of floodplain soils is often characterized by low bearing capacity, high compressibility, and significant sensitivity to moisture variations. Fine-grained soils common in floodplain environments tend to absorb large quantities of water, leading to reductions in shear strength and increases in deformation under loading conditions (Broll & El Hourani, 2021). Consequently, roads constructed on untreated floodplain soils frequently experience pavement distress, including rutting, cracking, settlement, pothole formation, and structural failure. These challenges become more severe when pavement systems are subjected to repeated cycles of flooding and drying, which accelerate material deterioration and shorten infrastructure lifespan (Chen & Wang, 2024; Mousa et al., 2023).

Flooding remains one of the most destructive natural hazards affecting transportation infrastructure worldwide. It occurs when the volume of water within a hydrological system exceeds the carrying capacity of natural or artificial channels, causing water to spread across adjacent land surfaces (Smith & Ward, 1998). Flood events can originate from intense rainfall, river overflow, storm surges, poor drainage conditions, or combinations of these factors. Beyond immediate disruption of transportation services, flooding causes significant structural damage to pavement systems through water infiltration, erosion, embankment instability, and prolonged subgrade saturation (Peng et al., 2025). Studies have shown that flood-affected roads deteriorate at substantially faster rates than roads located in non-flooded environments due to the weakening of pavement support layers and increased susceptibility to moisture-induced damage (Rajput et al., 2022; Muhammad et al., 2024).

The vulnerability of transportation infrastructure to flooding has increased considerably in recent decades due to climate variability and changing precipitation patterns. Increasing rainfall intensity, extreme weather events, and rising sea levels have expanded flood hazards in many parts of the world, particularly in coastal and deltaic regions (Fereshtehpour et al., 2025). Climate projections indicate that low-lying floodplain environments are likely to experience more frequent and severe flooding events in the future, thereby placing greater pressure on infrastructure systems that were originally designed using historical climatic conditions (Lang et al., 2024). As a result, engineers and policymakers have increasingly emphasized the development of resilient infrastructure capable of maintaining functionality under changing environmental conditions.

The Niger Delta region of Nigeria represents one of the most extensive floodplain systems in Africa and serves as a critical economic hub due to its oil and gas resources, agricultural activities, and strategic transportation corridors. The region is characterized by a complex network of rivers, distributary channels, wetlands, mangrove swamps, and floodplain deposits formed by sediment transport from the Niger River system. Geomorphologically, the Niger Delta consists of low-lying terrain with minimal elevation differences and extensive areas of poorly drained alluvial soils. Hydrologically, the region experiences high annual rainfall, often exceeding 2,000 mm in many locations, coupled with seasonal flooding and elevated groundwater conditions (FAO, 1973; Britannica, 2026).

These environmental characteristics create significant challenges for infrastructure development. Road networks constructed within the Niger Delta frequently traverse saturated soils and flood-prone landscapes where conventional pavement designs often perform poorly. The region has experienced numerous episodes of flood-induced infrastructure failure, particularly along major transportation corridors such as the East–West Road, which serves as a critical link connecting Rivers, Bayelsa, Delta, and Akwa Ibom States. Severe flooding events have repeatedly damaged sections of this corridor, causing pavement failures, road closures, and substantial economic losses (Punch Nigeria, 2022; Independent Newspaper Nigeria, 2022; ThisDayLive, 2024).

The recurring failure of roads in the Niger Delta highlights the limitations of conventional pavement design approaches when applied in floodplain environments. Many traditional design methods were originally developed under relatively stable climatic and geotechnical conditions and therefore do not adequately account for prolonged soil saturation, fluctuating groundwater levels, and repeated inundation cycles. The widely used AASHTO pavement design procedure, for example, was developed from road performance data obtained under conditions significantly different from those encountered in tropical floodplain regions (AASHTO, 1993; Huang, 2004). Similarly, empirical methods based on California Bearing Ratio (CBR) values may not fully capture the influence of seasonal moisture variations on subgrade performance in flood-prone environments.

One of the critical factors governing pavement performance in floodplain regions is subgrade strength. The subgrade serves as the foundation upon which pavement structures distribute traffic loads. When subgrade soils become saturated, their load-bearing capacity decreases substantially due to reductions in effective stress and increases in pore water pressure. Such conditions often lead to excessive pavement deformation and structural failure. Research has consistently demonstrated that moisture content is among the most influential variables affecting pavement performance, particularly in environments characterized by weak fine-grained soils and poor drainage conditions (Chen & Wang, 2024; Peng et al., 2025).

To address these challenges, various soil stabilization techniques have been developed to improve the engineering properties of weak subgrade materials. Soil stabilization involves modifying soil characteristics through mechanical or chemical means in order to enhance strength, reduce plasticity, improve durability, and increase resistance to moisture-induced deterioration. Among the available stabilization methods, cement stabilization remains one of the most widely adopted approaches due to its effectiveness in improving strength and stiffness while reducing soil plasticity and compressibility. Previous studies have reported significant improvements in CBR values and long-term pavement performance following cement treatment of fine-grained soils (Awwad, 2021; Bayou et al., 2025).

The effectiveness of stabilization techniques becomes particularly important in the Niger Delta, where floodplain soils are often dominated by clayey and silty materials that exhibit poor engineering characteristics under saturated conditions. Improving the geotechnical properties of these soils can significantly enhance pavement resilience, reduce maintenance requirements, and increase infrastructure service life. Despite the growing importance of resilient infrastructure development, there remains limited empirical data specifically addressing the geotechnical behaviour of Niger Delta floodplain soils and their response to stabilization treatments under conditions representative of the region.

Another important consideration is the integration of geotechnical and hydrological factors into infrastructure planning. Traditionally, pavement design and flood management have often been treated as separate engineering disciplines. However, the performance of road infrastructure in floodplain environments depends on the interaction between soil properties, groundwater conditions, drainage efficiency, and flood dynamics. Effective infrastructure planning therefore requires a multidisciplinary approach that combines geotechnical characterization, hydrological assessment, drainage design, and climate adaptation strategies (Fereshtehpour et al., 2025; Lang et al., 2024).

Recent advances in resilient infrastructure design emphasize the need for adaptive engineering solutions capable of accommodating environmental uncertainties. Such approaches include the use of stabilized subgrades, improved drainage systems, geosynthetic reinforcement, elevated embankments, and climate-informed pavement design procedures. These measures aim not only to improve structural performance but also to reduce life-cycle costs associated with frequent rehabilitation and maintenance. The adoption of resilience-based design frameworks has therefore become a central objective in transportation engineering research and practice.

Despite growing recognition of these issues, substantial knowledge gaps remain regarding the engineering performance of floodplain soils in the Niger Delta and the effectiveness of stabilization measures for supporting sustainable road infrastructure development. Existing studies have often focused on general flood impacts or pavement failures without providing detailed evaluations of the underlying geotechnical mechanisms responsible for infrastructure deterioration. Furthermore, limited attention has been given to quantifying the extent to which stabilization treatments can improve subgrade performance under the unique environmental conditions of the region.

This study therefore investigates the geotechnical characteristics of selected floodplain soils within the Niger Delta and evaluates the effectiveness of cement stabilization in improving their engineering properties for road infrastructure applications. The research focuses on key parameters including particle size distribution, Atterberg limits, compaction characteristics, and California Bearing Ratio values. By examining the relationship between soil properties, floodplain conditions, and subgrade performance, the study seeks to provide practical engineering solutions capable of enhancing pavement durability and resilience in flood-prone environments.

The findings are expected to contribute to the development of region-specific design recommendations for road infrastructure in tropical floodplain environments. In addition, the study provides valuable insights for engineers, transportation planners, policymakers, and infrastructure agencies involved in the design, construction, and maintenance of roads within the Niger Delta and other similar deltaic regions worldwide.

II. Materials And Methods

This study adopted an experimental research design involving field sampling, laboratory characterization, and stabilization assessment of floodplain soils obtained from selected locations within the Niger Delta region of Nigeria. The methodology was developed to evaluate the engineering characteristics of natural floodplain soils and determine the effectiveness of cement stabilization in improving their suitability as pavement subgrade materials.

The study area comprises floodplain environments within the Niger Delta, a region characterized by extensive alluvial deposits, shallow groundwater conditions, poor drainage, and seasonal flooding. The region experiences a humid tropical climate with annual rainfall generally exceeding 2,000 mm. The prolonged wet season often results in high levels of soil saturation, which adversely affect pavement performance and subgrade stability. The dominant soil types consist of varying proportions of clay, silt, and sand deposited through fluvial processes. These soils are generally moisture-sensitive and frequently exhibit low bearing capacity under saturated conditions.

The research was conducted in four stages comprising field investigation and sampling, laboratory characterization of natural soils, stabilization treatment, and evaluation of stabilized soils. This approach provided a comprehensive assessment of the engineering behavior of floodplain soils under both natural and improved conditions.

Soil Sampling and Sample Preparation

A reconnaissance survey was conducted prior to sample collection to identify representative flood-prone locations and assess prevailing environmental conditions. Sampling locations were selected based on flood susceptibility, evidence of pavement distress, accessibility, and variability in soil conditions.

Disturbed soil samples were collected from each selected location at a depth of approximately 1.0 m below the ground surface, corresponding to the typical pavement subgrade layer. The collected samples were carefully labelled according to location, depth, date of collection, and identification number. During sampling, field observations relating to soil colour, texture, groundwater conditions, moisture status, drainage patterns, and evidence of previous flooding were documented.

The samples were transported to the geotechnical laboratory where they were air-dried under room temperature conditions and gently pulverized to break down soil lumps. The soils were subsequently sieved through a 4.75 mm sieve to remove coarse particles and organic materials. Prepared samples were stored in airtight containers prior to laboratory analysis.

Geotechnical Characterization of Natural Soils

The engineering properties of the natural soils were evaluated through particle size distribution, Atterberg limits, compaction, and California Bearing Ratio (CBR) tests. All laboratory analyses were conducted in accordance with ASTM and BS 1377 standards.

Particle size distribution analysis was carried out using sieve analysis and hydrometer methods to determine the proportions of gravel, sand, silt, and clay present in each soil sample. The percentage passing each sieve was determined using Equation (1).

$$P = \frac{W_t}{W_p} \times 100 \quad (1)$$

Where (P) is the percentage passing (%), (Wp) the weight of soil passing the sieve (g), and (Wt) is the total weight of soil sample (g).

The consistency characteristics of the soils were determined through liquid limit and plastic limit tests. The plasticity index was subsequently calculated using Equation (2).

$$PI = LL - PL \quad (2)$$

where (PI) the Plasticity Index (%), (LL) the Liquid Limit (%) and (PL) is the Plastic Limit (%).

Compaction tests were conducted using the Standard Proctor method to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of the soils. The dry density was calculated using Equation (3).

$$\gamma_d = \frac{\gamma}{1+w} \quad (3)$$

Where γ_d *is the* dry density (kN/m³), γ is thebulk density (kN/m³) and (w) = moisture content expressed as a decimal.

The California Bearing Ratio test was performed under both unsoaked and soaked conditions to evaluate the load-bearing capacity of the soils. The soaked condition was particularly important because it simulated the saturated environment commonly encountered in floodplain areas. The CBR value was computed using Equation (4).

$$CBR = Ps/Pt \times 100 \quad (4)$$

Where (CBR) is the California Bearing Ratio (%), (Pt) the measured test load (kN), (Ps) is the standard load (kN).

The results obtained from these tests were used to classify the soils and evaluate their suitability as pavement subgrade materials.

Soil Stabilization and Performance Evaluation

Following the characterization of the natural soils, stabilization treatment was carried out using Ordinary Portland Cement. Cement was selected because of its effectiveness in improving the strength, stiffness, and durability of weak fine-grained soils.

The prepared soil samples were mixed with varying cement contents ranging from 2% to 10% by dry weight of soil. Water corresponding to the optimum moisture content obtained from compaction testing was gradually added to each mixture. The soil-cement blends were thoroughly mixed to ensure uniform distribution of the stabilizing agent throughout the samples.

The treated soils were compacted into moulds using Standard Proctor compaction procedures and subsequently cured under laboratory conditions for periods of 7 and 14 days. The curing process allowed hydration reactions to occur, resulting in the formation of cementitious compounds responsible for strength development.

Following curing, the stabilized samples were subjected to Atterberg limits, compaction, and California Bearing Ratio tests. These tests were conducted to evaluate changes in plasticity, density, moisture susceptibility, and load-bearing capacity resulting from stabilization.

Data Analysis

The laboratory data generated from both untreated and stabilized soils were analysed using descriptive statistical methods. Parameters including minimum values, maximum values, means, standard deviations, and percentage improvements were determined.

Comparative analyses were carried out to assess differences between natural and stabilized soils with respect to particle size distribution, plasticity characteristics, compaction behaviour, and load-bearing capacity. Particular attention was given to changes in soaked CBR values because these represent field conditions typically encountered within floodplain environments.

The engineering suitability of the soils was evaluated based on established pavement subgrade criteria. The effectiveness of cement stabilization was assessed through reductions in plasticity and corresponding improvements in strength characteristics. The results provided the basis for determining the suitability of stabilized floodplain soils for sustainable road infrastructure development in the Niger Delta region.

III. Results And Discussion

Results Presentation

The results obtained from the laboratory investigation provide insight into the geotechnical characteristics of selected floodplain soils within the Niger Delta region and their response to stabilization treatment. The findings are presented in Tables 1–7 and Figures 1–4. Table 1 presents the combined grain-size distribution of soils collected from the various locations, while Table 2 summarizes the specific gravity values of the investigated soils. The consistency characteristics obtained from Atterberg limit tests are presented in Table 3, whereas Table 4 provides the corresponding soil classifications based on the Unified Soil Classification System (USCS) and AASHTO classification system.

The strength characteristics of the natural soils are presented in Table 5 through the California Bearing Ratio (CBR) values obtained from laboratory testing. Table 6 presents the computed Failure Index (FI), which combines the effects of plasticity, fines content, and bearing capacity to assess pavement vulnerability. The effectiveness of cement stabilization in improving engineering properties is presented in Table 7 through changes in California Bearing Ratio, Plasticity Index, Maximum Dry Density, and Optimum Moisture Content.

The graphical representations provide additional understanding of soil behaviour. Figure 1 illustrates the grain-size distribution curves for all investigated locations, while Figure 2 presents the flow curves used in determining the liquid limits of the soils. Figure 3 shows the plasticity characteristics of the soils relative to standard classification boundaries, and Figure 4 illustrates the influence of cement content on subgrade strength improvement.

Collectively, the results provide a comprehensive evaluation of the engineering suitability of floodplain soils for pavement construction and demonstrate the influence of stabilization treatment on improving subgrade performance. The presented data establish relationships among soil composition, consistency characteristics, bearing capacity, and stabilization response, thereby providing the basis for the discussion of engineering implications in subsequent sections.

Table 1: Combined Gradation

Particle Size (mm)	Rumuokoro	Yenagoa	Warri	Uyo	Calabar	Benin
4.75	98.9	99.2	98.9	98.8	98.6	98.1
2.36	96.8	97.8	97	96.7	96.2	95.2
2	95.4	96.8	95.8	95.4	94.8	93.5
1.4	92	94.4	92.9	92.3	91.4	89.6
1.18	90.1	93	91.3	90.5	89.5	87.5
1	83.3	88.1	85.5	84.2	82.7	79.7
0.5	70	73.8	73.2	72.9	72.4	70.4
0.25	57.7	60	61.9	63.1	63.1	62.6
0.15	49.8	51.1	54.5	56.7	57.2	57.7
0.075	49.1	50	53.9	56.2	56.7	57.3
0.0483	38.7	42.7	38	38.4	39.2	35.2
0.0217	37.4	41.4	36.7	37.2	38	34

0.0126	35.7	39.7	35.1	35.4	36.2	32.2
0.009	34.4	38.4	33.9	34.2	35	31
0.0064	33.7	37.7	33.2	33.5	34.2	30.2
0.0045	33.1	37	32.6	32.8	33.6	29.6
0.0032	32	35.8	31.5	31.7	32.4	28.5
0.0026	31.6	35.4	31.1	31.3	32	28.1
0.0023	31.3	35.1	30.8	31	31.7	27.8
0.0013	31.1	34.8	30.5	30.7	31.4	27.5

Table 2: Specific Gravity for all Locations

		Yenagoa		Warri		Uyo		Calabar		Benin		Port Harcourt	
S/N	**Trial**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
1	Weight of Bottle W1 (g)	30.1	30.1	30.15	30.15	30.2	30.2	30.1	30.1	30.05	30.05	30.14	30.14
2	Weight of Bottle + Oven Dry Soil W2 (g)	60.85	58.9	61	59.1	61.8	59.9	62.2	60.1	63.5	61.2	61.1	59.05
3	Weight of Bottle + Soil + Water W3 (g)	108.6	106.4	108.9	106.9	109.4	107.2	109.8	107.5	110.5	108.1	108.95	106.8
4	Weight of Bottle + Water W4 (g)	90.2	90.2	90.25	90.25	90.3	90.3	90.25	90.25	90.3	90.3	90.28	90.28
5	W3 − W2 (g)	47.75	47.5	47.9	47.8	47.6	47.3	47.6	47.4	47	46.9	47.85	47.75
6	W4 − W1 (g)	60.1	60.1	60.1	60.1	60.1	60.1	60.15	60.15	60.25	60.25	60.14	60.14
7	(W4 − W1) − (W3 − W2)	12.35	12.6	12.2	12.3	12.5	12.8	12.55	12.75	13.25	13.35	12.29	12.39
8	W2 − W1 (g)	30.75	28.8	30.85	28.95	31.6	29.7	32.1	30	33.45	31.15	30.96	28.91
9	Gs	**2.49**	**2.29**	**2.53**	**2.35**	**2.53**	**2.32**	**2.56**	**2.35**	**2.52**	**2.33**	**2.52**	**2.33**

Table 3: Atterberg Limit for all Locations

	Port Harcourt				**Yenagoa**				**Warri**			
Container No.	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Wet	169.5	161.8	154	87.1	174.8	166.1	158.2	90.1	168.1	160.3	153.2	86.4
Dry	125.3	122.9	121.1	80.4	127.8	124.8	122.2	82.2	125.6	122.4	120.3	79.7
Water	44.2	38.9	32.9	6.7	47	41.3	36	7.9	42.5	37.9	32.9	6.7
Container	45	44.6	45.8	55.4	45	44.6	45.8	55.7	45.2	44.6	45.8	55.2
Dry Sample	80.3	78.3	75.3	25	82.8	80.2	76.4	26.5	80.4	77.8	74.5	24.5
Moisture (%)	55	49.7	43.7	26.8	56.7	51.5	47.1	29.8	52.9	48.7	44.2	27.3
	Uyo				**Calabar**				**Benin City**			
Container No.	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Wet (g)	162.7	155.3	149.1	84.8	158.1	151.2	145.6	83.2	150.2	145.1	140.6	80.1
Dry (g)	124.4	121.3	119.7	78.6	123.8	120.7	118.7	77.7	121.7	119.5	117.8	75.8
Water (g)	38.3	34	29.4	6.2	34.3	30.5	26.9	5.5	28.5	25.6	22.8	4.3
Container (g)	44.9	44.7	45.5	55	45.1	44.6	45.4	55.4	45	44.7	45.4	55.2
Dry Sample (g)	79.5	76.6	74.2	23.6	78.7	76.1	73.3	22.3	76.7	74.8	72.4	20.6
Moisture (%)	48.2	44.4	39.6	26.3	43.6	40.1	36.7	24.7	37.1	34.2	31.5	20.9

Table 4: Soil Classification

Location	LL (%)	PL (%)	PI (%)	% Passing (75 µm)	USCS Class	AASHTO Class	Soil Description
Port Harcourt	52.7	26.8	25.9	49.1	CL–CH	A-7-6	Clayey soil (high plasticity)
Yenagoa	53.7	29.8	23.9	50	CH	A-7-6	Highly plastic clay
Warri	51	27.3	23.7	53.9	CH	A-7-6	Clayey soil
Uyo	46.8	26.3	20.5	56.2	CL	A-7-6	Medium plastic clay
Calabar	41.8	24.7	17.1	56.7	CL–ML	A-7-5	Silty clay
Benin City	35.6	20.9	14.7	57.3	ML	A-6	Silty soil / sandy silt

Table 5: CBR results

Port Harcourt		Yenagoa		Warri		Uyo		Calabar		Benin City	
CBR @2.5 mm = 16		CBR @2.5 mm = 15		CBR @2.5 mm = 19		CBR @2.5 mm = 21		CBR @2.5 mm = 22		CBR @2.5 mm = 25	
CBR @5.0 mm = 20		CBR @5.0 mm = 18		CBR @5.0 mm = 23		CBR @5.0 mm = 25		CBR @5.0 mm = 26		CBR @5.0 mm = 30	
Reported CBR = 20		Reported CBR = 18		Reported = 23				Reported CBR = 26		Reported CBR = 30	
Penetration (mm)	**Load (kN)**	**Penetration (mm)**	**Load (kN)**	**Penetration**	**Load**	**Penetration**	**Load**	**Penetration (mm)**	**Load (kN)**	**Penetration**	**Load**
0	0	0	0	0	0	**0**	0	0	0	0	0
0.5	0.32	0.5	0.3	0.5	0.36	0.5	0.4	0.5	0.42	0.5	0.5
1	0.76	1	0.7	1	0.82	1	0.9	1	0.95	1	1.1
1.5	1.2	1.5	1.1	1.5	1.3	1.5	1.4	1.5	1.5	1.5	1.7
2	1.72	2	1.6	2	1.9	2	2.1	2	2.2	2	2.5
2.5	2.12	2.5	2	2.5	2.3	2.5	2.6	2.5	2.75	2.5	3.2
3	2.5	3	2.4	3	2.7	3	3	3	3.2	3	3.8
4	3.2	4	3.1	4	3.5	4	3.8	4	4.1	4	4.8
5	4.05	5	3.9	5	4.4	5	4.7	5	5	5	5.9
7.5	5.4	7.5	5.3	7.5	5.8	7.5	6.2	7.5	6.6	7.5	7.8
10	6.5	10	6.4	10	6.9	10	7.4	10	7.8	10	9.2

Table 6: Failure index

Location	Plasticity Index (PI)	% Fines	CBR (%)	Failure Index (FI)
Port Harcourt	25.9	49.1	22	57.8
Yenagoa	23.9	50	18	66.39
Warri	23.7	53.9	23	55.54
Uyo	20.5	56.2	25	46.08
Calabar	17.1	56.7	26	37.29
Benin City	14.7	57.3	30	28.08

Table 7: Effect of Cement Stabilization on Soil Properties

Stabilizer Content (%)	CBR (%)	Plasticity Index (PI)	Maximum Dry Density (g/cm³)	Optimum Moisture Content (%)
0 (Control)	22	25.9	1.72	16
2	30.8	19.4	1.77	16.8
4	39.6	14.2	1.81	17.6
6	48.4	10.4	1.79	17.9

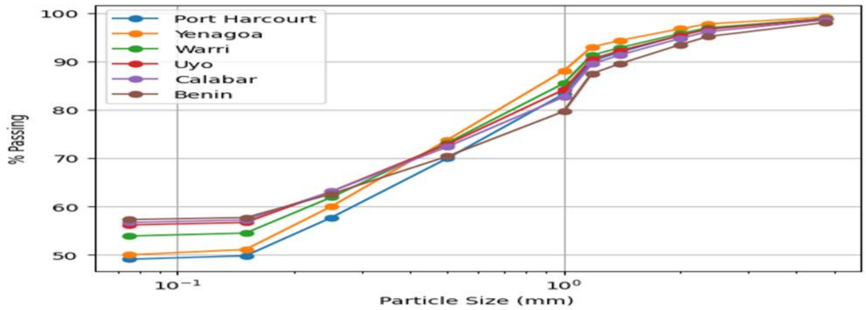

Figure 1: Grain Size Distribution

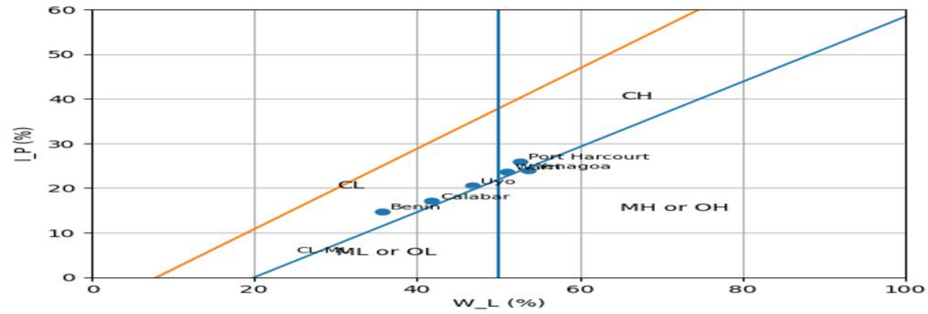

Figure 2: Plasticity chart

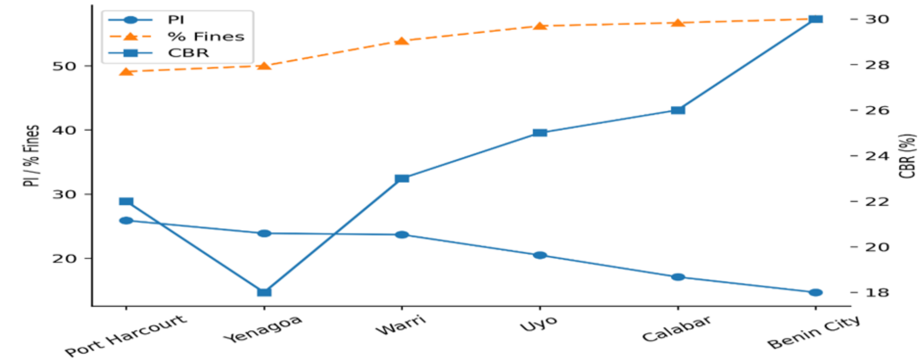

Figure 3: Multi-axis Soil Behaviour

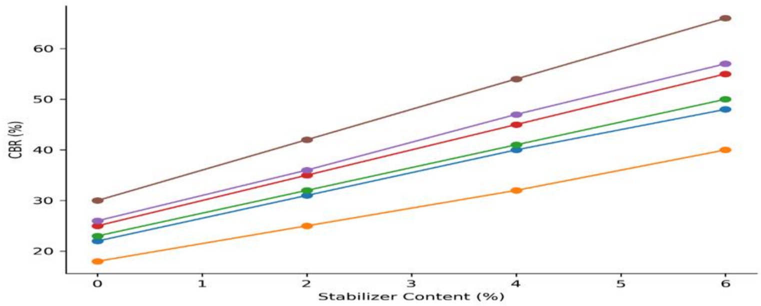

Figure 4: CBR vs Stabilizer

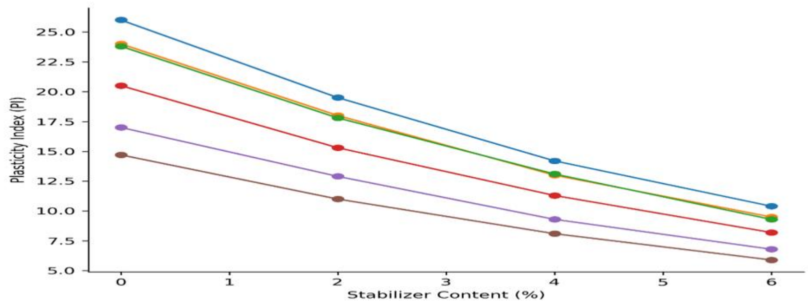

Figure 5: PI vs Stabilizer

IV. Discussion Of Results

The geotechnical characterization of the investigated floodplain soils revealed significant variability in engineering properties across the selected locations. The grain-size distribution results presented in Table 1 and Figure 1 showed that the soils contained substantial proportions of fine particles, with percentages passing the 75 µm sieve ranging from 49.1% in Port Harcourt to 57.3% in Benin City. This observation indicates that the soils were predominantly fine-grained and contained appreciable amounts of clay and silt fractions. Although all locations exhibited relatively high fines content, the trend showed a gradual increase from Port Harcourt and Yenagoa toward Benin City and Calabar. Such particle-size distributions are typical of floodplain deposits formed through repeated sedimentation processes in low-energy depositional environments.

The high fines content observed in the study is comparable to the findings of Akinwumi et al. (2021), who reported fines contents ranging between 45% and 61% for floodplain soils in southwestern Nigeria. Similarly, Osinubi and Nwaiwu (2006) reported values between 48% and 58% for tropical clayey soils intended for road construction. The values obtained in the present study therefore fall within the range generally associated with weak pavement subgrades. From an engineering perspective, the dominance of fine particles reduces permeability and limits drainage efficiency. Consequently, water remains trapped within the pavement foundation for prolonged periods, increasing the likelihood of subgrade softening and pavement failure. This observation partly explains the persistent deterioration of roads within flood-prone areas of the Niger Delta.

The hydrometer analysis results further confirmed the predominance of fine particles within the investigated soils. As shown in Table 2, Yenagoa consistently recorded the highest percentage finer values, ranging from 42.7% at a particle size of 0.048 mm to 34.8% at 0.0013 mm. Similar trends were observed for Port Harcourt, Warri, and Calabar. These results indicate significant clay-sized fractions within the soils, particularly in Yenagoa. The trend suggests that the soils become increasingly cohesive as particle size decreases, thereby enhancing their water retention capacity.

According to Das and Sobhan (2018), soils containing high percentages of clay-sized particles generally exhibit hydraulic conductivity values between 10^{-9} and 10^{-7} m/s, which severely restrict drainage. Similar observations were reported by Gidigasu (2012), who found that clay-rich tropical soils retain moisture for extended periods after rainfall events. The engineering implication of this behaviour is substantial because prolonged saturation reduces effective stress and weakens soil structure. Under repeated traffic loading, such soils are more likely to experience excessive deformation, settlement, and eventual pavement distress.

The specific gravity values presented in Table 3 ranged from approximately 2.29 to 2.56. The highest values were recorded in Calabar and Port Harcourt, while Yenagoa and Warri exhibited slightly lower values. The overall trend suggests relatively uniform mineralogical composition across the study area despite differences in particle-size distribution and plasticity characteristics. The values fall within the range expected for inorganic soils dominated by quartz, kaolinite, and other clay minerals commonly found within tropical alluvial deposits.

Comparable results have been reported by Bello et al. (2020), who obtained specific gravity values ranging from 2.40 to 2.65 for subgrade soils within the Niger Delta region. Das and Sobhan (2018) also reported values between 2.30 and 2.70 for fine-grained alluvial soils. Since the observed specific gravity values are relatively similar across the study locations, it can be inferred that differences in pavement performance are primarily controlled by plasticity, fines content, and moisture conditions rather than mineral composition alone. This finding highlights the importance of considering soil structure and consistency characteristics during pavement design.

The Atterberg limits results presented in Tables 4 and 5 revealed moderate to high plasticity behaviour among the investigated soils. Liquid limit values ranged from 35.6% in Benin City to 53.7% in Yenagoa, while plasticity indices ranged from 14.7% to 25.9%. Figure 2 further illustrated that soils from Yenagoa, Port Harcourt, and Warri exhibited steeper flow curves compared to the remaining locations, indicating greater moisture sensitivity. A distinct trend was observed whereby locations with higher liquid limits also exhibited higher plasticity indices.

Yenagoa recorded the highest liquid limit of 53.7% and a plasticity index of 23.9%, while Port Harcourt recorded a plasticity index of 25.9%. Conversely, Benin City exhibited the lowest values, with a liquid limit of 35.6% and a plasticity index of 14.7%. These results suggest that the soils in Yenagoa, Port Harcourt, and Warri possess greater affinity for water and are therefore more susceptible to volume change and strength reduction under saturated conditions.

The results compare favourably with those reported by O'Flaherty (2002), who identified plasticity indices greater than 20% as indicative of highly compressible subgrade soils. Gidigasu (2012) similarly reported liquid limits ranging from 40% to 60% for tropical clays exhibiting poor engineering performance. The engineering implication is that highly plastic soils undergo substantial shrink–swell behaviour, leading to cracking during dry periods and excessive deformation during wet periods. In floodplain environments, where saturation occurs frequently, these characteristics significantly increase pavement vulnerability.

The plasticity chart shown in Figure 3 and the classification results presented in Table 6 provided further insight into the engineering behaviour of the soils. Most samples were classified as CH, CL–CH, and CL soils under the Unified Soil Classification System, while the AASHTO classifications ranged from A-7-6 to A-6. A clear trend emerged in which locations exhibiting higher liquid limits and plasticity indices were classified within the more problematic clay groups. Yenagoa and Warri were classified as CH soils, whereas Benin City was classified as ML.

These classifications agree with those reported by Osinubi and Eberemu (2013), who found that A-7-6 soils are among the poorest subgrade materials for highway construction due to their high plasticity and moisture susceptibility. Similarly, Ingles and Metcalf (1972) noted that CH soils typically exhibit low bearing capacity and high compressibility. From an engineering standpoint, the predominance of CH and CL–CH soils indicates that untreated floodplain soils are generally unsuitable for direct use as pavement foundations without prior improvement.

The California Bearing Ratio results presented in Table 7 provided a direct measure of subgrade strength. The values ranged from 18% in Yenagoa to 30% in Benin City. Intermediate values of 20%, 23%, 25%, and 26% were recorded for Port Harcourt, Warri, Uyo, and Calabar, respectively. The trend clearly indicates that locations with lower plasticity and lower moisture sensitivity exhibited higher bearing capacities.

An inverse relationship between plasticity and strength was evident throughout the study. Yenagoa, which recorded one of the highest plasticity indices, exhibited the lowest CBR value, while Benin City, which recorded the lowest plasticity index, exhibited the highest strength. Similar relationships were reported by Parsons and Milburn (2003), who observed CBR values between 12% and 35% for untreated clayey subgrades. Akinwumi et al. (2021) also reported CBR values ranging from 15% to 32% for floodplain soils within southern Nigeria.

The engineering implication of these results is that several of the investigated soils possess insufficient bearing capacity for heavily trafficked roads. Pavements constructed on such soils would require thicker structural layers to compensate for subgrade weakness. Failure to provide adequate support would likely result in rutting, settlement, and cracking under repeated traffic loading.

The Failure Index results presented in Table 8 provided a comprehensive assessment of pavement vulnerability by integrating plasticity index, fines content, and CBR values. The values ranged from 28.08 in Benin City to 66.39 in Yenagoa. A clear trend was observed whereby failure index increased with increasing plasticity and decreasing bearing capacity. Yenagoa recorded the highest failure index because of its combination of high plasticity, substantial fines content, and low CBR value.

This observation is consistent with Huang (2004), who reported that pavement deterioration rates increase significantly in soils characterized by high plasticity and low strength. Mousa et al. (2023) further demonstrated that prolonged saturation can reduce resilient modulus values by more than 40%, thereby accelerating pavement deterioration. The engineering implication is that locations exhibiting high failure indices require substantial geotechnical intervention before pavement construction. Without such intervention, the risk of premature pavement failure remains high.

The stabilization results presented in Table 9 and Figure 4 demonstrated the effectiveness of cement treatment in improving engineering performance. The CBR value increased from 22% in the untreated condition to 30.8%, 39.6%, and 48.4% at cement contents of 2%, 4%, and 6%, respectively. Simultaneously, the plasticity index decreased from 25.9% to 19.4%, 14.2%, and 10.4%.

The observed trend clearly demonstrates that increasing cement content resulted in progressive improvements in strength and reductions in plasticity. The increase in CBR values can be attributed to cement hydration reactions, which produce cementitious compounds that bind soil particles together. This process increases particle interlocking and enhances resistance to deformation under loading.

The results compare favourably with those reported by Little (1995), who observed CBR improvements from approximately 18% to 45% following cement stabilization of clayey soils. Bell (1996) reported reductions in plasticity indices of between 50% and 70%, while Parsons and Milburn (2003) recorded strength improvements exceeding 100% following stabilization. The approximately 120% increase in CBR observed in the present study therefore demonstrates the effectiveness of cement stabilization for floodplain soils.

From an engineering perspective, the improvement in strength has important implications for pavement design. Increasing CBR values from approximately 20% to nearly 50% significantly reduces the thickness of pavement layers required to support traffic loads. This translates into lower construction costs, improved pavement performance, and extended service life. Furthermore, the reduction in plasticity minimizes moisture-induced volume changes, thereby enhancing long-term stability under flood-prone conditions.

The results demonstrate that the geotechnical limitations of floodplain soils are primarily associated with high fines content, elevated plasticity, low permeability, and inadequate bearing capacity. These characteristics collectively contribute to poor pavement performance under saturated conditions. However, the stabilization results indicate that these limitations can be effectively mitigated through cement treatment. Consequently, stabilization provides a practical and technically viable solution for improving the engineering performance of floodplain soils and enhancing the durability of road infrastructure within the Niger Delta region.

V. Conclusion

This study evaluated the geotechnical characteristics of selected floodplain soils within the Niger Delta region of Nigeria and assessed the effectiveness of cement stabilization in improving their suitability as pavement subgrade materials. The findings demonstrated that the investigated soils generally exhibited poor to moderate engineering properties in their natural state, largely due to their high fines content, elevated plasticity, and relatively low bearing capacity.

The particle size distribution analysis revealed that the percentage of fines passing the 75 μm sieve ranged from 49.1% to 57.3%, confirming the predominance of fine-grained materials within the study area. The soils also exhibited moderate to high plasticity characteristics, with liquid limit values ranging from 35.6% to 53.7% and plasticity index values ranging from 14.7% to 25.9%. These results indicate significant moisture sensitivity and a high tendency for volume change under fluctuating environmental conditions. The soil classification results further showed that most of the samples belonged to the CH, CL–CH, and CL groups under the Unified Soil Classification System and were predominantly classified as A-7-6 and A-6 soils under the AASHTO system, categories generally regarded as poor pavement subgrade materials.

The California Bearing Ratio results confirmed the weak nature of the floodplain soils, with soaked CBR values ranging from 18% to 30%. An inverse relationship was observed between plasticity and bearing capacity, indicating that increasing plasticity resulted in decreasing subgrade strength. Similarly, the computed Failure Index values ranged from 28.08 to 66.39, suggesting varying degrees of pavement vulnerability across the study locations. The highest failure risk was observed in locations characterized by high fines content, elevated plasticity, and low bearing capacity.

The stabilization results demonstrated that cement treatment significantly improved the engineering performance of the soils. The CBR value increased from 22% in the untreated condition to 48.4% following stabilization, representing an improvement of approximately 120%. In addition, the plasticity index decreased from 25.9% to 10.4%, indicating a substantial reduction in moisture susceptibility and volume-change potential. These improvements reflect the effectiveness of cement stabilization in enhancing soil strength, stiffness, and durability.

The study established that the poor engineering performance of floodplain soils is a major contributor to pavement deterioration in the Niger Delta region. However, the results have shown that appropriate stabilization measures can significantly improve subgrade quality and enhance pavement resilience. Cement stabilization therefore provides a practical and effective solution for the sustainable development of road infrastructure in flood-prone environments.

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