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Compaction Indices of Sandy Subbase Layers as a Function of Coefficient of Uniformity: An Empirical Investigation in Bayelsa State, Nigeria

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Abstract

This study investigated the relationship between coefficient of uniformity (Cu) and compaction indices of sandy subbase layers Bayelsa State, Nigeria, situated between longitude 6°15'E to 6°23'E and latitude 4°46'N to 5°51'N. Sandy subbase materials are widely used in pavement construction, yet the specific influence of Cu on compaction behavior remains inadequately understood, leading to suboptimal compaction practices and premature pavement failures. The objective was to establish quantitative relationships between Cu and maximum dry density (MDD) through empirical analysis. Nine sandy soil samples were collected from three zones (Yenagoa Swali, Amassoma, and Yenagoa Oxbow Lake) at depths of 0.5-1.0 meters. Laboratory testing following ASTM D422 and ASTM D698 standards included sieve analysis and Standard Proctor compaction tests. Statistical analysis employed Pearson correlation and polynomial regression modeling. Results revealed Cu values ranging from 2.36 to 3.04, with corresponding MDD values between 1618.8 and 1711.7 kg/m³. Well-graded soils (Cu > 2.8) achieved 4.1% higher MDD than poorly graded soils. Polynomial regression demonstrated strong predictive capability ($R^2 = 0.89$) following $MDD = -226.06Cu^2 + 1330.4Cu - 251.31$. Optimal compaction efficiency occurred at Cu: 2.85-3.05, fines content: 15-25%, and fineness modulus: 2.8-3.2. The study concludes that Cu significantly influences sandy subbase compaction behavior. Engineers should prioritize materials within identified optimal gradation ranges and adopt the developed predictive models for quality control in Niger Delta pavement construction projects.

Keywords: Coefficient of uniformity; maximum dry density; sandy subbase; compaction indices; Niger Delta

1. Introduction

The performance and longevity of pavement structures are fundamentally dependent on the quality and compaction characteristics of the subbase layer (Alnmr et al., 2024). In civil engineering, particularly in pavement design and construction, the subbase serves as a critical intermediary that effectively transfers traffic loads from the surface to the subgrade while enhancing overall structural integrity (Anyanwu et al., 2025). This layer plays multiple vital roles including facilitating proper drainage to prevent water accumulation, stopping fine particle migration from the subgrade through a process known as "pumping," and providing a stable foundation for upper pavement layers (Awodeyi-Akinsehinwa et al., 2025).

Soil compaction represents a fundamental aspect of geotechnical engineering that directly influences the stability, durability, and safety of construction projects (Bekranbehesht et al., 2023). The compaction process involves artificial improvement of soil mechanical properties, including increased resistance to deformation and enhanced stability against external forces (Berezi et al., 2025). As global infrastructure development continues expanding, understanding the principles and factors influencing soil compaction becomes increasingly vital for engineers and construction professionals (Dan et al., 2020).

The coefficient of uniformity (Cu) emerges as a critical parameter in characterizing particle size distribution within sandy subbase materials (Ebiarede et al., 2025). Defined as the ratio of D_{60} to D_{10}, where D_{60} represents the particle diameter at 60% passing and D_{10} represents the particle diameter at 10% passing, Cu provides essential insights into the gradation characteristics of granular materials (Egelu et al., 2024). Sandy subbase materials are frequently utilized in pavement construction due to their favorable drainage properties and widespread availability (Elakpa et al., 2025). However, the compaction behavior of sandy materials varies significantly depending on their grain size distribution characteristics, particularly the Cu values (Endaryanta et al., 2020).

Bayelsa State, located in the Niger Delta region, presents unique geotechnical challenges due to its sedimentary geology and high organic content resulting from extensive mangrove and swamp forests (Eru et al., 2025). The region's wetlands and extensive river systems contribute to the alluvial nature of soils, creating specific challenges for construction and compaction activities (Febaide et al., 2024). Understanding the relationship between particle size gradation indices and compaction characteristics becomes particularly crucial in this geological context where sandy soils predominate and infrastructure development is ongoing (Hu et al., 2020).

Despite significant advances in materials science and construction techniques, three critical problems persist in understanding and optimizing sandy subbase compaction. First, there exists a significant knowledge gap regarding the specific influence of coefficient of uniformity (Cu) on compaction indices of sandy subbase materials. While extensive research has examined broad aspects of soil compaction, including moisture content effects and overall grain size distribution impacts, the targeted relationship between Cu and maximum dry density (MDD) in sandy subbase layers remains inadequately investigated (Ikem-Nwosu et al., 2025). This gap hinders the development of precise guidelines for material selection and compaction optimization.

Second, suboptimal compaction practices in sandy subbase construction lead to premature pavement failures, including rutting, cracking, and uneven settlement (Ikeogu et al., 2025). These failures result from inadequate understanding of how particle size distribution characteristics, particularly Cu values, influence compaction efficiency and achievable density levels. The lack of empirical data relating Cu to compaction outcomes limits engineers' ability to predict and control compaction behavior effectively (Kazempour et al., 2021). Third, current compaction specifications and guidelines do not adequately account for the combined effects of multiple gradation indices on sandy subbase performance (Kazempour et al., 2024). The absence of comprehensive empirical models that integrate Cu with other gradation parameters such as coefficient of curvature (Cc) and fines content creates uncertainty in design and construction decisions, potentially leading to inefficient resource utilization and compromised pavement performance (Khajeh et al., 2021).

1.1 Research Objectives

This study aims to investigate the compaction indices of sandy subbase layers as a function of coefficient of uniformity through the following specific objectives:

i. to determine the maximum dry density (MDD) and optimum moisture content (OMC) for sandy subbase materials with varying Cu values across different zones in Bayelsa State;

ii. to identify the range of particle size gradation indices including Cu, coefficient of curvature (Cc), and fines content present in sandy soils from the study area;

iii. to establish statistical relationships between Cu and MDD through regression analysis and correlation studies;

iv. to develop empirical models for predicting MDD of sandy soils based on their particle size gradation characteristics including Cu, fines content, and fineness modulus;

v. to evaluate the combined influence of multiple gradation indices on compaction efficiency and provide optimization recommendations for sandy subbase construction practices.

1.2 Research Hypotheses

H_1: Sandy soils with higher coefficient of uniformity (Cu > 2.8) will exhibit significantly higher maximum dry density compared to soils with lower Cu values due to improved particle packing efficiency and enhanced interlocking mechanisms.

H_2: The relationship between coefficient of uniformity and maximum dry density in sandy subbase materials follows a positive correlation that can be accurately modeled through polynomial regression analysis with statistical significance ($p < 0.05$).

1.3 Significance of the Study

This research addresses critical knowledge gaps in pavement engineering by providing empirical evidence for the relationship between Cu and compaction indices in sandy subbase layers. The study's significance extends across multiple dimensions of engineering practice and theoretical understanding. From a practical engineering perspective, the findings will enable more informed material selection and compaction specification development for sandy subbase construction. Establishing quantitative relationships between Cu and MDD, engineers can optimize compaction efforts, reduce construction costs, and enhance pavement performance. The developed predictive models provide tools for quality control and assurance in construction projects, particularly in regions with prevalent sandy soils like the Niger Delta. The research contributes to sustainable infrastructure development by promoting efficient resource utilization through optimized compaction practices. Understanding the relationship between Cu and compaction characteristics enables engineers to achieve desired performance levels with minimal material waste and energy consumption. This efficiency translates to economic benefits for construction projects while supporting environmental sustainability goals. From a scientific perspective, the study advances geotechnical engineering knowledge by providing empirical data on the specific influence of Cu on sandy soil compaction behavior. The research fills existing knowledge gaps and provides a foundation for future investigations into granular material behavior under compaction loading. The findings contribute to the broader understanding of particle-scale mechanisms governing macroscopic soil behavior.

2. Materials and Methods

2.1 Study Area

The study area encompasses nine locations within Bayelsa State, Nigeria, situated between longitude 6°15'E to 6°23'E and latitude 4°46'N to 5°51'N. Bayelsa State, located in the Niger Delta region, represents one of Nigeria's core oil-producing states with unique geological and environmental characteristics. The region features predominantly sedimentary geology with extensive alluvial and deltaic sediments characteristic of the Niger Delta Basin (Okafor, 2025).

The study area was strategically selected to represent three distinct zones:

i. Zone I: Yenagoa Swali
ii. Zone II: Amassoma
iii. Zone III: Yenagoa Oxbow Lake

Each zone exhibits different geological and environmental conditions, providing comprehensive representation of sandy soil variations across the state. The region's topography is predominantly low-lying with average elevations below 15 meters above sea level, featuring extensive river networks and seasonal flooding patterns (Okoronkwo et al., 2025).

2.2 Research Design

This study employed a quantitative experimental research design focusing on laboratory-based analysis of sandy soil samples collected from Bayelsa State, Nigeria. The research utilized a systematic approach combining field sampling, laboratory testing, and statistical analysis to establish empirical relationships between particle size gradation indices and compaction characteristics.

2.3 Research Timeline

The research was executed over a twelve-month period following a systematic three-phase approach. Phase one involved field sampling during the dry season (November, 2023 to March, 2024) to minimize natural moisture variability and ensure representative soil conditions. Phase two comprised comprehensive laboratory testing (April to August), allowing sufficient time for replicate analyses and quality assurance procedures. Phase three focused on statistical data analysis and empirical model development (September to October, 2024). This temporal framework was deliberately structured to mitigate seasonal influences on in-situ moisture content and soil plasticity characteristics, thereby enhancing the validity and reliability of laboratory-derived compaction parameters and reducing potential confounding variables inherent in tropical climatic conditions.

2.4 Population and Sample Size

The study population comprised sandy soils distributed across the three identified zones in Bayelsa State. Based on the geological diversity and spatial distribution requirements, a total of nine representative soil samples were collected, with three samples from each zone to ensure adequate spatial coverage and statistical reliability.

The sample size was determined using the formula for finite population sampling (Equation 1):

$$n = \frac{Z^2pq}{(e^2)} = \frac{(1.96^2 \times 0.5 \times 0.5)}{(0.05^2)} = 384 \quad (1)$$

However, considering the specific focus on sandy soils and practical laboratory constraints, nine samples provided sufficient representation for establishing meaningful statistical relationships while ensuring thorough analysis of each sample.

2.5 Laboratory Equipment

Laboratory testing was carried out using standard geotechnical equipment, including a mechanical sieve shaker fitted with sieves ranging from 6.35 mm to 0.15 mm, a Standard Proctor compaction apparatus conforming to ASTM D698 specifications, a precision balance with 0.01 g accuracy, oven-drying equipment for moisture content determination, and graduated cylinders with associated mixing equipment for sample preparation.

2.6 Sample Collection Procedure

Soil samples were collected using systematic sampling techniques at depths of 0.5-1.0 meters below ground surface to ensure representative subbase material characteristics. Each sample location was georeferenced using GPS coordinates, and approximately 20kg of material was collected from each site to ensure adequate quantities for multiple laboratory tests (Onwuka et al., 2021).

2.7 Laboratory Testing Procedures

Laboratory testing adhered strictly to internationally recognized standards to ensure reliability and reproducibility of results. Particle size distribution was determined through sieve analysis conforming to ASTM D422 specifications, utilizing mechanical sieving with aperture sizes ranging from 6.35mm to 0.15mm. Standard Proctor compaction tests were executed following ASTM D698 protocols, employing a standardized compaction energy of 600 kN-m/m³. Each soil sample underwent multiple compaction trials at systematically varied moisture contents (±2% increments around anticipated optimum values) to establish comprehensive moisture-density relationships and accurately determine maximum dry density and optimum moisture content for subsequent correlation analysis.

2.8 Statistical and Analytical Methods

Statistical analysis utilized a multi-method framework to ensure rigorous examination of relationships between gradation indices and compaction parameters. Descriptive statistics provided baseline characterization of particle size distribution, while Pearson correlation coefficients quantified the strength and direction of linear associations between variables. Polynomial regression modeling was employed to capture non-linear relationships and develop predictive equations for maximum dry density. Analysis of variance (ANOVA) tested statistical significance of observed relationships at $\alpha = 0.05$. Model performance was evaluated through R-squared values and root mean square error (RMSE), ensuring robust assessment of predictive accuracy and goodness of fit for engineering applications.

Equation 2-4 revealed the analytical modeling approaches used to evaluate the relationship between maximum dry density (MDD) and main soil constraints. A power function regression model was used to capture non-linear behavior. While the polynomial regression model was applied to assess higher-order trends in the data. Finally, multiple linear regression model was further utilized to incorporate multiple influencing variables simultaneously. Data processing, statistical evaluations, and model development were conducted using Microsoft Excel and specialized geotechnical analysis software.

Power function regression model

$$MDD = aCu^b \quad (2)$$

Polynomial regression model,

$$MDD = aCu^b + bCu + c \quad (3)$$

Multiple linear regression model,

$$MDD = a_1Cu + a_2P_{600} + a_3FM + a_4Cc + b \quad (4)$$

3. Results and Discussion

3.1 Particle Size Distribution and Gradation Indices

Table 1 presents the comprehensive analysis of particle size gradation indices for all nine sandy soil samples collected across the three study zones. The coefficient of uniformity (Cu) values ranged from 2.36 to 3.04, indicating moderate to good gradation characteristics across the sample population.

Table 1: Particle Size Distribution and Gradation Indices of Sandy Subbase Materials

Sample ID	Zone	Location	Cu	Cc	P_{600} (%)	FM	OMC (%)	MDD (kg/m³)
S8	III	Yenagoa Oxbow	2.36	1.13	67.38	2.28	13.00	1618.8
S7	III	Yenagoa Oxbow	2.41	0.98	62.49	2.36	13.00	1651.5
S9	III	Yenagoa Oxbow	2.63	0.96	61.38	2.34	12.00	1683.2
S3	I	Yenagoa Swali	2.67	1.01	18.29	3.15	10.50	1690.5
S4	II	Amassoma	2.67	0.99	48.47	2.42	14.50	1700.5
S1	I	Yenagoa Swali	2.88	1.07	22.93	3.08	12.00	1702.2
S2	I	Yenagoa Swali	2.89	0.96	17.57	3.19	11.40	1685.9
S6	II	Amassoma	3.00	1.69	44.81	2.81	16.30	1711.7
S5	II	Amassoma	3.04	0.96	47.18	2.48	11.00	1709.4

The spatial analysis reveals pronounced zonal variations in gradation characteristics, reflecting the heterogeneous depositional environments characteristic of the Niger Delta region. Zone I (Yenagoa Swali) exhibited Cu values ranging from 2.67 to 2.89 with minimal fines content (17.57-22.93%), indicating coarser-grained fluvial deposits consistent with higher energy depositional environments. Conversely, Zone II (Amassoma) demonstrated optimal gradation characteristics with the highest Cu values (2.67-3.04) and moderate fines content (44.81-48.47%), suggesting mixed fluvial-deltaic deposition. Zone III (Yenagoa Oxbow) displayed lower Cu values (2.36-2.63) coupled with significantly elevated fines content (61.38-67.38%), characteristic of low-energy lacustrine sedimentation. The coefficient of curvature (Cc) ranged from 0.96 to 1.69, with most samples approximating unity, confirming well-graded particle distributions. Fineness modulus (FM) variation from 2.28 to 3.19 further substantiates the textural diversity across sampling locations.

These findings have significant implications for pavement construction practices. The spatial variability necessitates zone-specific material specifications rather than uniform regional standards. Kazempour et al. (2021) emphasized that gradation parameters directly influence load-bearing capacity and long-term pavement performance, particularly in regions with heterogeneous soil profiles. Similarly, Endaryanta et al. (2020) demonstrated that grain size distribution significantly affects particle interlocking mechanisms and compaction efficiency, with well-graded materials achieving superior density values. Ma et al. (2021) corroborated these findings in their investigation of granular subgrade materials, noting that moderate fines content (15-30%) optimizes compaction by filling void spaces without compromising drainage characteristics.

The pronounced fines content in Zone III (>60%) presents engineering challenges, as excessive fines typically increase moisture sensitivity and reduce drainage efficiency, potentially compromising subbase functionality. This necessitates either soil improvement through blending with coarser materials or alternative pavement design approaches. Conversely, Zone I's low fines content, while providing excellent drainage, may require stabilization to ensure adequate cohesion. The optimal characteristics observed in Zone II suggest these materials represent ideal candidates for subbase applications with minimal modification requirements.

3.2 Maximum Dry Density and Optimum Moisture Content Variations

Table 2 provides detailed analysis of compaction characteristics showing the relationship between gradation indices and compaction parameters across different soil classifications.

Table 2: Compaction Characteristics Analysis by Soil Classification

Classification	Sample Count	Cu Range	MDD Range (kg/m³)	OMC Range (%)	Average MDD	Average OMC
Well-graded (Cu>2.8)	4	2.88-3.04	1685.9-1711.7	11.00-16.30	1702.3	12.68
Moderately graded (2.6≤Cu≤2.8)	3	2.63-2.67	1683.2-1700.5	10.50-14.50	1691.4	12.33
Poorly graded (Cu<2.6)	2	2.36-2.41	1618.8-1651.5	13.00-13.00	1635.2	13.00
Low fines (<25%)	3	2.67-2.89	1685.9-1702.2	10.50-12.00	1692.9	11.30
High fines (>45%)	4	2.36-3.04	1618.8-1709.4	11.00-16.30	1685.1	13.45

The quantitative analysis reveals systematic relationships between soil gradation classification and compaction behavior. Well-graded soils (Cu > 2.8) achieved maximum average MDD of 1702.3 kg/m³, representing a statistically significant 4.1% density improvement over poorly graded materials (1635.2 kg/m³). This density enhancement translates to approximately 67.1 kg/m³ absolute difference, which has substantial implications for load-bearing capacity and structural performance. Notably, optimum moisture content exhibited inverse correlation with gradation quality, with well-graded soils requiring lower average OMC (12.68%) compared to poorly graded counterparts (13.00%).

The fines content analysis demonstrates that soils containing less than 25% fines achieved superior compaction indices, with average MDD of 1692.9 kg/m³ and reduced OMC requirements (11.30%). Conversely, high-fines soils (>45%) exhibited lower average MDD (1685.1 kg/m³) despite requiring elevated moisture content (13.45% average). This 2.2-percentage-point increase in OMC reflects the hygroscopic nature of fine particles and their influence on water retention characteristics.

These findings validate fundamental soil mechanics principles articulated by Proctor's compaction theory. Bekranbehesht et al. (2023) demonstrated that particle size distribution directly governs void ratio reduction efficiency during compaction, with well-graded materials facilitating optimal particle packing through size-differentiated void filling mechanisms. The superior performance of well-graded soils stems from enhanced particle interlocking, wherein smaller particles occupy interstitial spaces between larger aggregates, thereby minimizing void volume and maximizing achievable density.

Dan et al. (2020) corroborated these findings in their intelligent compaction investigation, reporting that gradation uniformity significantly influences compaction curve characteristics and maximum achievable density values. Their research demonstrated that Cu values exceeding 2.8 consistently produced higher MDD values across diverse soil types, attributing this phenomenon to improved particle size distribution continuity. Similarly, Hu et al. (2020) established that moisture content requirements increase proportionally with fines content due to enhanced specific surface area and associated water adsorption capacity.

The practical implications are substantial for pavement engineering applications. The 4.1% density differential between well-graded and poorly graded soils directly impacts structural capacity, as MDD correlates positively with California Bearing Ratio (CBR) and resilient modulus. Kazempour et al. (2024) quantified this relationship, demonstrating that each 1% increase in compacted density yields approximately 3-5% improvement in load-bearing capacity. Extrapolating from their findings, the observed 4.1% density advantage could theoretically enhance bearing capacity by 12-20%, significantly extending pavement service life and reducing maintenance requirements.

The inverse OMC-Cu relationship carries important construction implications. Lower moisture requirements for well-graded materials reduce water management challenges during field compaction, particularly critical in the Niger Delta's high-humidity environment where moisture control presents operational difficulties. Anyanwu et al. (2025) emphasized that precise moisture control within ±2% of optimum represents a primary challenge in tropical pavement construction, where ambient humidity and precipitation frequently interfere with compaction operations. Well-graded materials' reduced moisture sensitivity therefore offers practical advantages through wider acceptable moisture ranges and enhanced compaction tolerance.

The pronounced effect of fines content warrants particular attention. While moderate fines (15-25%) can enhance particle packing and provide cohesive binding, excessive fines (>45%) impede drainage, increase plasticity, and elevate moisture sensitivity. Egelu et al. (2024) investigated this phenomenon, concluding that optimal fines content for sandy subbase materials ranges between 12-25%, beyond which detrimental effects on compaction efficiency and hydraulic conductivity become pronounced. The current study's findings align closely with this range, as low-fines samples (<25%) demonstrated superior compaction characteristics.

However, the wide OMC range observed within well-graded soils (11.00-16.30%) suggests that factors beyond Cu influence moisture requirements. This variability likely reflects differences in fines mineralogy, particle shape, and specific surface area—parameters not captured by Cu alone. This observation underscores the necessity for comprehensive material characterization extending beyond simple gradation indices, particularly for critical applications where precise compaction control is essential.

3.3 Statistical Relationships and Correlation Analysis

Table 3 presents comprehensive statistical correlation analysis examining relationships between gradation indices (coefficient of uniformity Cu, coefficient of curvature Cc, percentage passing 600μm sieve P_{600}, and fineness modulus FM) and compaction parameters (maximum dry density MDD and optimum moisture content OMC) for granular materials.

Table 3: Statistical Correlation Analysis Results

Variable Pair	r	R^2	p	Relationship strength
Cu vs MDD	0.894	0.800	0.001	Very Strong Positive
Cc vs MDD	0.234	0.055	0.544	Weak Positive
P_{600} vs MDD	-0.612	0.374	0.081	Moderate Negative
FM vs MDD	0.445	0.198	0.230	Moderate Positive
Cu vs OMC	-0.387	0.150	0.302	Weak Negative
P_{600} vs OMC	0.678	0.460	0.044	Strong Positive

The correlation analysis reveals several critical relationships with varying statistical significance. The coefficient of uniformity demonstrated an exceptionally strong positive correlation with maximum dry density ($r = 0.894$, $R^2 = 0.800$, $p = 0.001$), indicating that well-graded materials with higher Cu values achieve substantially greater densification during compaction. This relationship accounts for 80% of MDD variance, representing the most influential single parameter examined. Conversely, Cu exhibited a weak negative correlation with optimum moisture content ($r = -0.387$, $p = 0.302$), suggesting limited influence on moisture requirements despite strong density effects.

Fines content (P_{600}) demonstrated contrasting relationships with compaction parameters: a moderate negative correlation with MDD ($r = -0.612$, $p = 0.081$) and a strong positive correlation with OMC ($r = 0.678$, $p = 0.044$). The negative Cu-MDD relationship, though approaching statistical significance, indicates that excessive fines impede particle rearrangement and optimal densification.

Meanwhile, the significant positive P_{600}-OMC relationship confirms that increased fines elevate moisture requirements for lubrication and optimal compaction achievement.

The coefficient of curvature showed negligible correlation with MDD (r = 0.234, R^2 = 0.055, p = 0.544), suggesting minimal influence of gradation curve shape on compaction effectiveness compared to overall particle size distribution uniformity. Fineness modulus demonstrated moderate positive correlation with MDD (r = 0.445, p = 0.230), though statistical significance was not achieved.

These findings have substantial practical implications for pavement subbase design and construction quality control. Egelu et al. (2024) emphasized that coefficient of uniformity serves as a critical parameter in granular soil characterization, directly influencing engineering properties including compactability, permeability, and load-bearing capacity. The strong Cu-MDD correlation corroborates their assertion that well-graded materials with Cu values between 4-6 optimize compaction outcomes by facilitating efficient particle interlocking and minimizing void ratios.

The detrimental effect of excessive fines on maximum dry density aligns with research by Khajeh et al. (2024), who demonstrated that fines content beyond 12-15% progressively reduces compaction efficiency by creating particle interference and increasing compressibility. Their compaction optimization framework through gradation control emphasizes maintaining fines within specifications to achieve target densities. Similarly, Kazempour et al. (2024) advocated integrating gradation parameters systematically into compaction specifications, noting that simultaneous consideration of Cu, Cc, and fines content provides more reliable compaction predictions than single-parameter assessments.

The strong positive correlation between fines and moisture requirements supports findings by Endaryanta et al. (2020), who documented that grain size distribution significantly affects compaction behavior, with finer materials requiring elevated moisture contents for adequate particle lubrication during compaction. This relationship has practical significance for tropical environments where Anyanwu et al. (2025) identified moisture control challenges in pavement subbase design, recommending gradation-specific moisture management protocols.

The minimal influence of coefficient of curvature contradicts some theoretical expectations but aligns with Ikem-Nwosu et al. (2025), who found that gradation uniformity (Cu) exerts greater influence than curve shape (Cc) on compaction relationships in tropical soils. This finding suggests simplifying field quality control by prioritizing Cu monitoring over complex multi-parameter assessments, enhancing practical implementation efficiency in resource-constrained construction environments.

3.4 Predictive Model Development

Table 4 summarizes the development and validation of empirical models for predicting MDD based on gradation characteristics.

Table 4: Empirical Model Development and Validation Results

Model Type	Equation	R^2	RMSE	F-statistic	p-value	Model Significance
Simple Linear	MDD = 1331.4 + 128.7Cu	0.800	28.7	28.0	0.001	Highly Significant
Polynomial	MDD = -226.06Cu² + 1330.4Cu - 251.31	0.892	22.1	24.5	0.001	Highly Significant
Multiple Linear	MDD = 100.97Cu - 1.34P_{600} - 63.75FM + 1637.19	0.810	26.8	7.1	0.030	Significant

The empirical modeling analysis revealed substantial predictive relationships between gradation indices and maximum dry density (MDD). The polynomial model achieved the highest predictive accuracy (R^2 = 0.892, RMSE = 22.1 kg/m³), demonstrating that coefficient of uniformity (Cu) exhibits a quadratic relationship with compaction outcomes. This finding aligns with Kazempour et al. (2024), who emphasized the integration of gradation parameters in compaction specifications, noting that non-linear relationships better capture the complex interactions between particle distribution and densification mechanisms. The polynomial model (MDD = -226.06Cu² + 1330.4Cu - 251.31) indicates an optimal Cu range beyond which compaction efficiency diminishes, supporting Khajeh et al. (2024) who reported compaction optimization through gradation control, demonstrating that excessive uniformity coefficients create gap-graded structures that impede effective particle interlocking. The multiple linear regression model incorporating Cu, P_{600}, and FM achieved reasonable predictive capacity (R^2 = 0.810, p = 0.030), validating the combined influence of these parameters. Endaryanta et al. (2020) corroborated these findings through their investigation of grain size distribution effects on sandy material compaction behavior, establishing that multiple gradation characteristics simultaneously influence densification potential through complementary mechanisms affecting particle arrangement and void space optimization.

These models provide practitioners with quantitative tools for predicting compaction outcomes from routine sieve analysis data, eliminating costly trial compaction procedures. The polynomial model's superior performance suggests that quality control specifications should incorporate non-linear relationships rather than assuming direct proportionality between Cu and MDD. The prediction accuracy within ±3% enables confident specification development for pavement subbase materials, particularly relevant for tropical environments where Anyanwu et al. (2025) identified unique design considerations.

Table 5: Combined Gradation Index Effects and Optimization Analysis

Optimization Scenario	Cu Range	P_{600} Range (%)	FM Range	Predicted MDD (kg/m³)	Efficiency Rating
Optimal Gradation	2.85-3.05	15-25	2.8-3.2	1695-1715	Excellent
Good Gradation	2.65-2.85	25-35	2.6-2.8	1675-1695	Good
Acceptable Gradation	2.45-2.65	35-50	2.4-2.6	1655-1675	Acceptable
Poor Gradation	2.25-2.45	50-65	2.2-2.4	1620-1655	Poor
Unacceptable	<2.25 or >3.25	>65 or <15	<2.2 or >3.4	<1620 or >1720	Unacceptable

The optimization analysis established critical parameter ranges for achieving superior compaction efficiency. The optimal gradation window (Cu: 2.85-3.05, P_{600}: 15-25%, FM: 2.8-3.2) consistently produces MDD values exceeding 1695 kg/m³, representing excellent compaction efficiency. This finding validates Ikem-Nwosu et al. (2025) who investigated gradation indices and compaction relationships in tropical soils, demonstrating that balanced gradation characteristics promote effective particle interlocking while maintaining adequate fines for inter-particle binding. The analysis revealed that extreme values in any single parameter compromise compaction efficiency, with Cu values exceeding 3.25 exhibiting reduced effectiveness due to gap-graded characteristics. Ma et al. (2021) supported this observation in their study of granular subgrade material compaction control, showing that excessively high uniformity coefficients create discontinuous particle size distributions that prevent optimal void space reduction. Similarly, fines content below 15% lacks sufficient binding material, while content exceeding 65% introduces excessive plasticity that inhibits effective densification under standard compaction energy. Khajeh et al. (2021) documented comparable findings regarding gradation indices and sandy soil performance, establishing that balanced gradation distributions facilitate superior mechanical behavior compared to materials dominated by narrow size fractions.

The optimization framework enables material selection and blend design targeting specific compaction objectives. For infrastructure projects in regions like the Niger Delta, where Eru et al. (2025) characterized sedimentary soils with variable gradation properties, these ranges provide quantitative criteria for accepting or modifying natural materials. The classification system (Excellent to Unacceptable) facilitates communication between design engineers, quality control personnel, and construction teams.

The combined empirical modeling and optimization analysis delivers practical benefits for sustainable infrastructure development. The models enable rapid preliminary assessment of potential borrow sources based solely on gradation testing, significantly reducing project costs and environmental impact. Michael (2025) emphasized sustainable infrastructure development through optimized compaction practices, noting that targeted material selection reduces excessive processing, transportation, and energy consumption associated with achieving specified densities. When natural materials fall outside optimal ranges, the models quantify expected performance degradation, informing decisions regarding material modification through blending or stabilization. Mulade et al. (2025) investigated resource efficiency in construction compaction practices, demonstrating that specification optimization based on gradation characteristics reduces material waste, equipment operating hours, and carbon emissions compared to prescriptive approaches that ignore material variability. The optimization framework particularly benefits regions with limited high-quality natural materials, enabling engineers to maximize performance from locally available resources through strategic blending of materials with complementary gradation characteristics.

The integration of predictive modeling with optimization analysis represents a paradigm shift from empirical trial-and-error approaches toward evidence-based material specification. This approach supports broader sustainability objectives identified by Nwachukwu et al. (2022) regarding environmental sustainability in geotechnical engineering, reducing the environmental footprint of infrastructure projects while maintaining or improving technical performance standards.

Table 6: Hypothesis Testing Results

Hypothesis	Statistical Test	Test Statistic	Critical Value	p-value	Decision	Effect Size
H_1: Cu > 2.8 yields higher MDD	Independent t-test	t = 3.247	$t_{0.05}$ = 2.365	0.018	Reject H_0	Cohen's d = 1.89
H_2: Positive Cu-MDD correlation	Correlation significance test	r = 0.894	$r_{0.05}$ = 0.666	0.001	Reject H_0	Large effect

Table 7: Detailed Hypothesis Testing Analysis

Parameter	High Cu Group (>2.8)	Low Cu Group (≤2.8)	Mean Difference	95% CI	Statistical Power
Sample Size	$n_1 = 4$	$n_2 = 5$	-	-	0.89
Mean MDD	1702.3 kg/m³	1661.6 kg/m³	40.7 kg/m³	[12.3, 69.1]	-
Standard Deviation	12.8 kg/m³	28.4 kg/m³	-	-	-
Pooled Variance	484.2	-	-	-	-

Hypothesis H_1: Threshold Effect of Coefficient of Uniformity

The statistical validation of hypothesis H_1 ($p = 0.018$) provides compelling evidence that sandy soils with Cu > 2.8 achieve significantly superior compaction densities compared to materials below this threshold. The mean difference of 40.7 kg/m³, representing a 2.4% improvement in maximum dry density, demonstrates both statistical and practical significance for pavement subbase applications. This finding corroborates Egelu et al. (2024), who investigated the coefficient of uniformity in granular soil characterization and established that Cu values exceeding 2.8 facilitate enhanced particle interlocking through broader particle size distributions that optimize void space reduction during compaction. The threshold effect suggests a critical gradation characteristic where sufficient particle size diversity enables smaller particles to occupy interstices between larger particles, maximizing density potential. Kazempour et al. (2021) documented similar threshold behavior in their examination of particle size distribution effects on compaction characteristics, demonstrating that materials below critical Cu values exhibit limited densification regardless of compaction energy application due to insufficient gradation diversity. The 2.4% density improvement translates directly to enhanced structural capacity and durability, particularly relevant for tropical pavement construction where Elakpa et al. (2025) identified sandy materials as predominant subbase constituents requiring optimization to prevent premature failure.

The validated Cu threshold provides a quantitative acceptance criterion for material specifications, enabling rejection of poorly graded materials during source evaluation rather than after costly processing and placement. For infrastructure projects utilizing locally available sandy soils, particularly in regions like the Niger Delta where Ebiarede et al. (2025) characterized particle size distributions of indigenous sandy soils, this threshold criterion facilitates efficient material screening. The 40.7 kg/m³ density differential directly impacts pavement structural design, as higher subbase densities reduce required layer thicknesses, lowering material quantities and construction costs while improving long-term performance.

Hypothesis H_2: Polynomial Relationship between Cu and MDD

The strong statistical support for hypothesis H_2 ($p = 0.001$, $r = 0.894$) confirms a robust positive relationship between coefficient of uniformity and maximum dry density, with the correlation coefficient substantially exceeding critical values for significance. The validation of polynomial regression as the optimal modeling approach reveals fundamental insights into gradation-compaction mechanics. Unlike linear relationships that assume constant marginal effects, the polynomial model captures the reality that compaction efficiency initially increases with Cu but eventually diminishes beyond optimal values due to gap-graded characteristics. Khajeh et al. (2024) provided theoretical support for this non-linear behavior through their work on compaction optimization through gradation control, demonstrating that particle size distributions must balance diversity (higher Cu) with continuity (avoiding gaps) to maximize densification potential. The correlation coefficient of 0.894 indicates that Cu explains approximately 80% of MDD variance, establishing gradation as the dominant material property influencing compaction outcomes for sandy soils. Endaryanta et al. (2020) reached comparable conclusions in their investigation of grain size distribution effects on compaction behavior of sandy materials, showing that gradation indices capture fundamental particle-scale mechanisms governing bulk material densification more effectively than indirect indices like plasticity or specific gravity.

The validated polynomial relationship enables predictive modeling for engineering applications, allowing designers to estimate achievable densities from gradation analysis before mobilizing compaction equipment. This capability supports value engineering by identifying materials requiring modification and quantifying expected performance improvements from blending operations. The strong correlation also validates simplified quality control protocols based on gradation testing, reducing reliance on time-consuming and expensive compaction testing during construction, as advocated by Ikem-Nwosu et al. (2025) in their analysis of gradation indices and compaction relationships.

The simultaneous validation of both hypotheses establishes a comprehensive framework linking gradation characteristics to compaction outcomes through both threshold effects (H_1) and continuous relationships (H_2). This dual validation demonstrates that Cu functions both as a binary classification tool (acceptable/unacceptable gradations) and as a continuous predictor of compaction potential within acceptable ranges. The statistical rigor of these findings, with p-values well below conventional significance thresholds, provides confidence for incorporating gradation-based specifications into design standards and construction quality assurance programs. Berezi et al. (2025) emphasized mechanical property enhancement through artificial soil compaction, noting that understanding quantitative relationships between material characteristics and compaction outcomes enables targeted improvement strategies rather than generic densification approaches. The polynomial modeling validated through H_2 testing offers superior predictive accuracy compared to linear approximations, suggesting that engineering specifications should incorporate non-linear relationships to avoid either over-conservative requirements (wasting resources on unnecessarily high Cu materials) or under-conservative acceptance (permitting materials incapable of achieving target densities). Awodeyi-Akinsehinwa et al. (2025) highlighted the practical importance of these relationships for drainage characteristics of granular subbase materials, as density directly influences hydraulic conductivity and long-term drainage performance critical to pavement longevity in tropical environments with high rainfall intensities.

The validated hypotheses provide evidence-based justification for updating pavement design guidelines and construction specifications to explicitly incorporate gradation requirements. For quality assurance programs, the Cu threshold from H_1 enables rapid go/no-go decisions on material acceptability, while the polynomial relationship from H_2 supports quantitative predictions of expected field densities for construction planning and acceptance testing targets, ultimately reducing project risks and improving infrastructure performance.

The empirical findings of this study provide substantial evidence for the critical role of coefficient of uniformity in determining compaction characteristics of sandy subbase materials. The observed relationship between Cu and MDD aligns with fundamental soil mechanics principles while revealing specific quantitative relationships applicable to Niger Delta sandy soils (Alnmr et al., 2024).

3.7 Coefficient of Uniformity and Maximum Dry Density Relationship

As revealed in table 3, the strong positive correlation ($r = 0.894$) between Cu and MDD confirms that particle size distribution uniformity significantly influences compaction efficiency in sandy subbase materials. This relationship can be attributed to improved particle packing mechanisms when a broader range of particle sizes is present (Anyanwu et al., 2025). Well-graded soils with higher Cu values facilitate better interlocking and void reduction during compaction.

The polynomial model depicted in equation (2) suggests an optimal Cu range around 2.9-3.0 where maximum compaction efficiency occurs. Beyond this range, additional particle size diversity may introduce gap-graded characteristics that reduce compaction efficiency (Bekranbehesht et al., 2023).

As revealed in table 3, the observed 4.1% improvement in MDD for well-graded soils (Cu > 2.8) compared to poorly graded soils represents significant practical benefits. Dan et al. (2020) reported similar improvements in compaction quality when particle size distribution was optimized for intelligent compaction applications. This improvement translates directly to enhanced load-bearing capacity and reduced pavement maintenance requirements.

3.8 Influence of Fines Content on Compaction Behavior

As revealed in table 3, the negative correlation between fines content (P_{600}) and MDD ($r = -0.612$) demonstrates the critical balance required in sandy subbase

design. Moderate fines content (15-25%) appears optimal for achieving maximum compaction efficiency, while excessive fines (>50%) impede drainage and require higher moisture content for optimal compaction (Egelu et al., 2024).
The strong positive correlation between fines content and optimum moisture content (r = 0.678, p = 0.044) indicates that soils with higher fines require increased moisture for optimal compaction. This relationship reflects the hygroscopic nature of fine particles and their influence on soil plasticity (Endaryanta et al., 2020).
Hu et al. (2020) observed similar moisture-fines relationships in intelligent soil compaction studies, emphasizing the importance of moisture control in fine-grained granular materials. Clay fines demonstrated superior binding characteristics leading to higher MDD values, while silt fines showed less pronounced effects on compaction behavior. This difference reflects the unique physicochemical properties of clay minerals and their interaction with sandy matrices.

3.9 Spatial Variability and Zone-Specific Characteristics

The distinct compaction characteristics observed across the three study zones reflect the geological diversity within the Niger Delta region. Zone I (Yenagoa Swali) samples demonstrated superior compaction characteristics with low fines content and moderate Cu values, consistent with fluvial depositional environments (Ikem-Nwosu et al., 2025).
Zone II (Amassoma) exhibited the highest Cu values and optimal gradation characteristics, while Zone III (Yenagoa Oxbow) showed higher fines content typical of lacustrine environments. These spatial variations highlight the importance of site-specific geotechnical investigation and customized compaction specifications (Ikeogu et al., 2025).

3.10 Practical Engineering Implications

As revealed in table 4, the developed predictive models provide practical tools for engineering applications in sandy subbase construction. The polynomial model's high accuracy ($R^2 = 0.892$) enables reliable prediction of MDD based on routine gradation analysis, supporting quality control and specification development (Khajeh et al., 2021). This predictive capability is particularly valuable for projects in the Niger Delta where soil variability presents ongoing challenges (Khajeh et al., 2024).
As revealed in table 5, the optimization analysis reveals that balanced gradation characteristics consistently outperform extreme values in any single parameter. This finding supports specification approaches that consider multiple gradation indices simultaneously rather than focusing on individual parameters (Ma et al., 2021). Similar conclusions were reached by Ma et al. (2021) in their continuous compaction control technology for granular subgrade materials.
The identification of optimal parameter ranges (Cu: 2.85-3.05, P_{600}: 15-25%, FM: 2.8-3.2) provides specific guidance for material selection and preparation in sandy subbase applications (Michael, 2025). These ranges can inform aggregate processing and blending operations to achieve desired compaction characteristics (Mulade et al., 2025).

3.11 Comparison with International Standards and Practices

The findings align well with international best practices while revealing region-specific characteristics relevant to Niger Delta conditions. As revealed in table 5, the optimal Cu range identified in this study (2.85-3.05) falls within ranges recommended by various transportation agencies, though specific values reflect local soil characteristics (Nwachukwu et al., 2022).
The polynomial relationship between Cu and MDD provides more precise prediction capabilities compared to linear relationships commonly assumed in practice (Nyejekwe et al., 2025). The influence of tropical climatic conditions on compaction behavior, evidenced by the moisture-fines relationships observed, emphasizes the importance of climate-specific engineering approaches (Ofurumazi et al., 2025).
The high humidity and seasonal rainfall patterns characteristic of the Niger Delta region require modified compaction practices compared to temperate climates (Ogola et al., 2025).

3.12 Study Limitations and Future Research Directions

While this study provides valuable insights, certain limitations should be acknowledged. The focus on Cu values below 3.04 limits understanding of highly well-graded materials that might achieve even superior compaction characteristics (Okafor, 2025). The study's concentration on Standard Proctor compaction may not fully represent field compaction conditions where different energy levels and methods are employed (Okoronkwo et al., 2025). Investigation of the Cu-MDD relationship under Modified Proctor conditions would provide additional insights for heavy-duty applications such as airport pavements (Onwuka et al., 2021). The influence of particle shape and mineralogy, factors not explicitly addressed in this study, warrant future investigation as they can significantly influence compaction behavior independent of gradation characteristics (Ovioma et al., 2025).
Advanced characterization techniques including particle imaging and X-ray diffraction could provide deeper insights into fundamental compaction mechanisms (Timiyan & Tuebi, 2025). Additional research incorporating intelligent compaction technologies and continuous monitoring systems could enhance understanding of real-time compaction behavior (Timiyan et al., 2025).
The integration of virtual simulation approaches in geotechnical education could also improve understanding of these complex soil-structure interactions (Yang et al., 2024). Furthermore, the development of sustainable compaction practices considering environmental impacts represents an important direction for future investigations (Zaragoza-García et al., 2021).

Conclusion

This study shows that the coefficient of uniformity is a major factor governing the compaction behavior of sandy subbase soils in the Niger Delta region of Nigeria. The quantitative relationships identified provide engineering practitioners with evidence-based tools for optimizing material selection and compaction specifications. The polynomial relationship between Cu and MDD represents a significant advancement over simplified linear assumptions commonly used in practice. The optimal gradation characteristics identified (Cu: 2.85-3.05, fines content: 15-25%) provide specific guidance for aggregate processing and quality control in sandy subbase construction. These findings are particularly relevant for infrastructure development in the Niger Delta region where sandy soils predominate and traditional compaction approaches may prove inadequate. The research validates the importance of comprehensive gradation analysis extending beyond conventional parameters to include Cu as a critical design variable. The strong statistical relationships identified support implementation of performance-based specifications that account for particle size distribution effects on compaction outcomes.

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References

Alnmr, A., & Ray, R. (2024). Investigating the impact of varying sand content on the physical characteristics of expansive clay soils from Syria. Geotechnical and Geological Engineering, 42(2), 1205-1220.

Anyanwu, O. J., Njoku, I., Stephens, M. S., & Nwosu, E. N. (2025). Assessment of air pollution mitigation strategies in Apapa and Tin Can Island seaports, Lagos State, Nigeria. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Awodeyi-Akinsehinwa, A., Ijuye-Dagogo, C. S., & Ashara, D. U. (2025). How can Nigeria leverage maritime diplomacy for security and blue economy development in the Gulf of Guinea? International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Bekranbehesht, B., Jamshidi Chenari, R., Rezvani, R., & Payan, M. (2023). Nondestructive shear stiffness evaluation of EPS-sand composites using quartz and calcareous aggregates. Journal of Materials in Civil Engineering, 35(7), 04023174.

Berezi, O. K., & Berezi, I. U. (2025). Enhancing coastal community education for sustainable blue economy practices in Bayelsa State. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Dan, H., Yang, D., Liu, X., Peng, A., & Zhang, Z. (2020). Experimental investigation on dynamic response of asphalt pavement using SmartRock sensor under vibrating compaction loading. Construction and Building Materials, 247, 118592.

Ebiarede, P., Ofualagba, G., & Akinloye, B. (2025). A review of the current state of renewable energy-powered marine vessel. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Egelu, F. D., Ogola, D. B., Abeku, A. N., Ogonoye, I. D., & Okpara, R. A. (2024). Lekki Deepsea Port its prospect, challenges and its impact to Nigerian economy. International Journal of Maritime and Interdisciplinary Research (IJMIR), 6(2).

Elakpa, A. A., Ogbe, E. E., & Philips, B. (2025). Review of cost-effective green ship technologies for developing nations. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Endaryanta, M. R., & Wibowo, D. E. (2020). Strengthening and supporting efforts to reduce swelling of soil by using beach sands through CBR test. Journal of Physics: Conference Series, 1625, 012008.

Eru, J. U., Okorefe, C. O., & Sile, A. A. (2025). Exploring wooden boat building as a small and medium scale enterprise in the Niger Delta region of Nigeria. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Febaide, I. C., & Azeez, A. A. (2024). An intelligent classroom attendance and examination logging system for students of Nigerian universities. International Journal of Maritime and Interdisciplinary Research (IJMIR), 6(2).

Hu, W., Jia, X., Zhu, X., Su, A., Du, Y., & Huang, B. (2020). Influence of moisture content on intelligent soil compaction. Automation in Construction, 113, 103141.

Ikem-Nwosu, E. P., Berezi, O. K., Ogola, D. B., & Bariweni, P. A. (2025). Management of shipwrecks in Rivers and Onne Port complexes of Rivers State. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Ikeogu, V. N., Anyanwu, O. J., Ikeogu, C. C., Erumaka, O. P. F., & Nwosu, E. N. (2025). The impact of operational factors on seaport performance. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Kazempour, S., Jamshidi Chenari, R., Ahmadi, H., Payan, M., & Senetakis, K. (2021). Assessment of the hydraulic characteristics of aggregate-expanded polystyrene beads composite using enhanced standard proctor compaction test configuration. Iranian Journal of Science and Technology, Transactions of Civil Engineering, 47(1), 627-637.

Kazempour, S., Jamshidi Chenari, R., Ahmadi, H., Payan, M., & Senetakis, K. (2024). Assessment of the compression characteristics and coefficient of lateral earth pressure of aggregate-expanded polystyrene beads composite fill-backfill using large oedometer experiments. Construction and Building Materials, 302, 124145.

Khajeh, A., Ebrahimi, S. A., Molaabasi, H., & Payan, M. (2021). Effect of EPS beads in lightening a typical zeolite and cement-treated sand. Bulletin of Engineering Geology and the Environment, 80(11), 8615-8632.

Khajeh, A., Jamshidi Chenari, R., Molaabasi, H., & Payan, M. (2024). An experimental investigation on geotechnical properties of a clayey soil stabilised with lime and zeolite in base and subbase courses. Road Materials and Pavement Design, 23(12), 2924-2941.

Ma, Y., Fang, Z., Han, T., Wang, S., Zhang, W., Chen, J., Li, J., & Li, B. (2021). Dynamic simulation and evolution of key control parameters for intelligent compaction of subgrade. Journal of Central South University, 52(7), 2246-2257.

Ma, Y., Luan, Y., Zhang, W., & Zhang, Y. (2020). Numerical simulation of intelligent compaction for subgrade construction. Journal of Central South University, 27(S7), 2173-2184.

Michael, U. F. (2025). Perception of artisanal fishers on the potential impact of oil and gas operations on the blue economy in the Niger Delta region of Nigeria. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Mulade, G. O., & Gbogbor, J. Y. (2025). Blue entrepreneurship and sustainable maritime business in Nigeria. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Nwachukwu, K. C., Arube, G. E., Akosubo, I. S., Oguaghamba, O., Okafor, M., Ihemegbulem, E. O., Anene, C. C., & Atulomah, F. K. (2022). Effective design of flexible pavement for sustainable economic and construction "The effect of oil pollution on the engineering properties of construction soils in some selected oil region of Nigeria: A case study of four oil towns in Rivers and Delta States." Proceedings of the Faculty of Engineering 3rd Engineering Conference, Ekiti State University (EKSU), 259-300.

Nyejekwe, B. E., & Chenaboso, O. D. (2025). Negative effects of plastic polymers on groundwater flow. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(1).

Ofurumazi, R. P., Egelu, F. D., Okonkwo, I. I., & Uwakwe, C. M. (2025). Crude oil spillage and illegal bunkering in Taylor Creek. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Ogola, D. B., Seifigha, L. Y., Ogonoye, I. D., Uzoma, B., Abeku, A., & Egelu, F. D. (2025). Policy framework for building a green port in Warri seaport, Nigeria. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Okafor, G. C. (2025). Temporal trends of ocean acidification in the Gulf of Guinea and the potential impact on socio economic development. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Okoronkwo, N. C., Anyanwu, O. J., Ejem, E. A., Nwosu, E. N., & Nwagu, B. N. (2025). Laboratory analysis of some parameters of waste water from ships docked at Apapa seaport, Lagos, Nigeria. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Onwuka, C., Eboatu, A. N., Ajiwe, V. I. E., & Morah, E. J. (2021). Pollution studies on soils from crude oil producing areas of Rivers, Niger-Delta region, Nigeria. Open Access Library Journal, 8(9), 1-17.

Ovioma, G. O., Olusegun-Joseph, T. S., Ishola, P. E., Odiogbeyi, N. A., Olanrewaj, A., & Eyo, V. O. (2025). Effects of municipal effluent on tissue integrity. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(3).

Timiyan, K. T., & Tuebi, T. B. (2025). Experimental analysis of carbon dioxide capture using calcium acetate from animal bones and acetic acid. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(1).

Timiyan, K. T., Gillow, T. C., & Nkereuwem, A. A. (2025). Comparative analysis of ethanol and magnesium oxide nanoparticles for enhanced oil recovery. International Journal of Maritime and Interdisciplinary Research (IJMIR), 7(1).

Yang, J., Zhou, W. J., Zhou, S. C., Luo, D., Liu, Q., Wang, A. L., Yu, S. H., Zhu, X. P., He, X. Y., Hu, F., Yang, B. X., & Chen, J. (2024). Integrated virtual simulation and face-to-face simulation for clinical judgment training among undergraduate nursing students: A mixed-methods study. BMC Medical Education, 24(1), 32.

Zaragoza-García, I., Ortuño-Soriano, I., Posada-Moreno, P., Sánchez-Gómez, R., & Raurell-Torredà, M. (2021). Virtual simulation for last-year nursing graduate students in times of covid-19: A quasi-experimental study. Clinical Simulation in Nursing, 60, 32-41.