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Influence of Moisture Content Variation on the Resilient Behaviour of Highway Subgrade Soils: A Case Study of Delta State, Nigeria

Raphael Enebraye Atala

Southern Delta University
ORCID: https://orcid.org/0009-0003-3210-3418

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***Corresponding Author:** Raphael Enebraye Atala

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Abstract **Original Research Article**

Highway subgrades in the Niger Delta region experience wide seasonal swings in moisture, and this study examines how such swings alter the stiffness that pavement designers rely on. Soil samples typical of the lateritic and sandy clay subgrades found across Delta State were compacted at moisture contents spanning four percentage points below to six above the optimum, then tested for resilient modulus under repeated load triaxial conditions consistent with published protocols. Stiffness fell sharply once moisture rose past the optimum point, with the sandy clay losing proportionally more of its modulus than the lateritic material at the same moisture excursion. A regression relationship linking resilient modulus to moisture deviation and dry density gave a coefficient of determination above 0.85 for both soil types. The results support drainage focused and moisture controlled compaction practice for Delta State roads and give a locally grounded input for mechanistic empirical pavement design in the region.

Keywords: compaction moisture, Delta State, lateritic soil, pavement design, resilient modulus, subgrade stiffness.

1. Introduction

Pavement engineers size the layers of a flexible road structure around the stiffness of whatever lies beneath the base course, and that stiffness is usually expressed as the resilient modulus of the subgrade. The parameter feeds directly into mechanistic empirical design procedures, where an underestimate wastes material and an overestimate invites premature rutting or cracking [1, 2]. Getting the value right therefore matters well beyond the laboratory bench.

Islam et al. [1] found that resilient modulus values measured in the laboratory ran between a third and three quarters lower than moduli back calculated from falling weight deflectometer data on South Carolina pavements, a gap the authors linked partly to how far field moisture had drifted from the condition assumed at design. A similar pattern turns up wherever repeated load triaxial testing has been paired with controlled moisture conditioning. Kern et al. [4] reported a seventy percent fall in resilient modulus on a Brazilian highway subgrade once moisture rose two percentage points above optimum, and Rahman et al. [3] observed the same downward slope using both California bearing ratio and triaxial data from United States subgrade soils.

The mechanism behind the drop is fairly well agreed upon even where the magnitude varies by soil type. As water fills the pore space of a compacted soil, matric suction collapses, effective stress between particles falls, and the soil skeleton offers less resistance to the repeated deviator stress that traffic loading applies [5, 6]. Zou et al. [7] used gene expression programming together with an artificial neural network to model this behaviour under freeze thaw and moisture cycling and found soil type governed how sharply modulus fell once suction was lost. Xin et al. [8] traced the same softening through repeated wetting and drying cycles and noted that the rate of decline slowed once a soil had been through roughly five cycles, suggesting some structural conditioning occurs with repeated exposure. Suction itself has since been treated as an independent predictor rather than a proxy for moisture content; Park et al. [9] proposed an average skeleton stress formulation built around suction stress and found it reasonably predicted resilient modulus across a range of unsaturated conditions, while Everton and Erlingsson [10] confirmed with suction controlled testing on sandy soils that stiffness rises as suction increases even when gravimetric moisture is held roughly constant.

Tropical lateritic soils behave somewhat differently from the temperate clays and silts on which much of the resilient modulus literature was built, and this distinction is why a case study grounded in a specific tropical setting has value. Freitas et al. [11] modelled resilient response in two Brazilian tropical subgrades and found that unsaturated behaviour, particularly the two stage relationship between suction and water content, needed separate treatment from the empirical forms calibrated on temperate soils. Guimaraes et al. [12] examined a lateritic clay rich in iron oxide and found the cementation from iron oxides gave the material resilient modulus values comparable to some granular bases, though permanent deformation rose sharply once stress levels climbed. Closer to the present study area, Ba et al. [13] tested compacted granular and lateritic materials used as pavement base layers across West Africa and confirmed that moisture sensitivity of stiffness persists even in materials with high fines content and strong cementation.

Nigeria, and the Niger Delta in particular, sits within a climate zone where the distinction between wet and dry season is stark and where subgrade soils are frequently lateritic or lateritic clay materials formed under intense weathering. Ugbe et al. [14] surveyed subgrade soils along failed sections of the Abavo-Urhonigbe road in the western Niger Delta and linked repeated pavement failure to poor drainage and moisture ingress interacting with soils of marginal mineralogical quality. Akpoyibo et al. [15] carried out a comparable engineering assessment on the Obiaruku highway sections, also within Delta State, and reported index properties and bearing capacities that fell short of specification on several sampled stretches, again pointing to moisture as a recurring aggravating factor. Kennedy [16] estimated dynamic soil properties for geotechnical work across the wider Niger Delta using index correlations and stressed that the region's high-water table and heavy rainfall regime make moisture sensitive design parameters more consequential there than in drier parts of the country. Irokwe et al. [17] examined soil cement stabilisation on three Niger Delta roads and found that even after treatment, the index properties of subgrade soils in the region remained sensitive to moisture exposure, underscoring how persistent the problem is once a road is in service.

Elsewhere in Nigeria, similar moisture related degradation of subgrade support has been documented. Godwin and Abubakar [18] examined residual lateritic soils in Kontagora and found California bearing ratio fell substantially once compaction moisture moved off the optimum in either direction, though the fall was steeper on the wet side. Andrew et al. [19] compared soaked and unsoaked bearing capacity of lateritic soils used for pavement work in Akure and reported large reductions in load bearing capacity once soils were allowed to soak, a laboratory analogue for what happens under a poorly drained pavement during the rains. Obasaju et al. [20] combined resistivity surveying with index and strength testing in North Central Nigeria and attributed a share of observed pavement failures to subgrade materials whose strength characteristics varied with seasonal moisture. Taken together, these studies point toward a consistent regional pattern, yet very little of the work has produced a resilient modulus based, rather than California bearing ratio based, quantification of moisture sensitivity specific to Delta State subgrade soils under conditions and testing protocols comparable to the wider international literature.

Predictive modelling of moisture dependent resilient modulus has advanced considerably in the past five years, moving from simple regression forms toward machine learning based approaches. Azam et al. [21] applied least squares support vector machines tuned with swarm intelligence algorithms and reported strong prediction accuracy for subgrade resilient modulus across a compiled international dataset. Zhang et al. [22] optimised an artificial neural network with a multi population genetic algorithm and achieved fast, generalisable predictions using physical and stress state variables as inputs. Kardani et al. [23] compared several ensemble machine learning methods for the same prediction task and found gradient boosting variants outperformed single learner models. Guo and Gu [24] built a dynamic resilient modulus model from physical property parameters and improved prediction accuracy over standard model forms by close to six percent. These contributions are valuable for design offices with access to large calibration datasets, but the datasets themselves remain dominated by temperate soils from China, North America, and Europe, leaving a gap for West African, and specifically Niger Delta, lateritic and sandy clay subgrades.

This study addresses that gap directly. Rather than propose a new machine learning architecture, it returns to first principles, laboratory characterisation of representative Delta State subgrade soils across a controlled moisture range, and asks how far resilient modulus falls as moisture rises past optimum, and whether a straightforward regression relationship can capture that fall well enough to be useful for local mechanistic empirical design work. The study is confined in this way deliberately: a locally calibrated, transparent relationship is more immediately usable by practising engineers in the region than a black box model trained on soils that behave differently.

1.1 Aim and Objectives

The aim of this study is to characterise how moisture content variation affects the resilient behaviour of highway subgrade soils typical of Delta State, Nigeria, and to translate that characterisation into a form usable in pavement design. Two objectives follow from this aim.

1. To evaluate, through repeated load triaxial testing, the effect of moisture content variation on the resilient modulus of representative lateritic and sandy clay subgrade soils sampled from Delta State.

2. To develop a regression based predictive relationship linking resilient modulus to moisture deviation from optimum and dry density for the studied subgrade soils, and to assess its implications for pavement design practice in the study area.

2. Materials and Methods

The study area falls within Delta State, in the western part of the Niger Delta, a region of low relief, high annual rainfall generally exceeding 2,200 millimetres, and a water table that sits close to the surface for much of the year. Roads in the area cross a mix of lateritic uplands and low lying alluvial stretches, and subgrade materials sampled for pavement work in the region typically classify as A-2-6 or A-7-6 under the AASHTO system, consistent with what Ugbe et al. [14] and Akpoyibo et al. [15] reported for nearby sections of the Abavo-Urhonigbe and Obiaruku corridors.

2.1 Sample Collection and Soil Classification

Disturbed bulk samples were obtained from two borrow locations representative of subgrade materials used along Delta State highway corridors, one a lateritic clayey sand and the other a sandy clay of higher plasticity. Samples were air dried, pulverised, and passed through the appropriate sieves before index testing. Particle size distribution followed sieve and hydrometer analysis, Atterberg limits followed the liquid and plastic limit procedures standard to AASHTO T89 and T90, and specific gravity followed AASHTO T100. Classification used both the AASHTO and Unified Soil Classification systems to allow comparison with the wider literature drawn on in this paper, much of which reports one system or the other.

2.2 Compaction and Moisture Conditioning

Standard Proctor compaction testing established the maximum dry density and optimum moisture content for each soil following AASHTO T99. Specimens for resilient modulus testing were then prepared at moisture contents set at four and two percentage points below optimum, at optimum, and two, four, and six percentage points above optimum, spanning a range wide enough to capture the dry season to wet season swing typical of the study area. Each specimen was compacted to a target dry density within two percent of the maximum obtained from the Proctor curve, mixed, sealed, and allowed to cure for twenty four hours before testing to permit moisture equilibration through the specimen.

2.3 Resilient Modulus Testing

Resilient modulus was measured using a repeated load triaxial apparatus following the loading sequence set out in AASHTO T307, applying a series of confining pressures and cyclic deviator stresses to each specimen and recording the recoverable axial strain after conditioning cycles at each stress state. This protocol matches that used by Islam et al. [1], Singh and Sahoo [25], and Amare et al. [26], allowing the resilient modulus values obtained here to be read against those studies without a change of testing basis. The resilient modulus at each stress state was calculated as the ratio of repeated deviator stress to recoverable axial strain, and a summary resilient modulus for each moisture condition was taken at a representative stress state of 41.4 kilopascals confining pressure and 27.6 kilopascals deviator stress, a combination commonly used for subgrade level comparison in the literature reviewed [6, 9].

2.4 Data Analysis

Resilient modulus values across the six moisture conditions were plotted against moisture deviation from optimum for each soil type. A multiple linear regression was then fitted with resilient modulus as the dependent variable and moisture deviation together with achieved dry density as independent variables, an approach broadly comparable to the stress and moisture dependent regression forms used by Zhang et al. [2], though the present model is deliberately kept to two predictors for ease of application by design engineers working without access to specialised software. Model fit was assessed using the coefficient of determination and root mean square error, and residuals were checked for a systematic trend against fitted values.

Table 1. Geotechnical index and compaction properties of the sampled Delta State subgrade soils

Property	Lateritic subgrade	Sandy clay subgrade
Gravel content, percent	18	6
Sand content, percent	44	38
Fines content, percent	38	56
Liquid limit, percent	39	48

Plasticity index, percent	17	24
AASHTO classification	A-2-6	A-7-6
USCS classification	SC	CL
Specific gravity	2.67	2.71
Maximum dry density, Mg/m3	1.83	1.76
Optimum moisture content, percent	14.0	17.5

Table 2. Repeated load triaxial test matrix applied at each moisture condition

Moisture condition	Confining pressure, kPa	Deviator stress, kPa
Four below optimum	20.7 to 137.9	13.8 to 137.9
Two below optimum	20.7 to 137.9	13.8 to 137.9
At optimum	20.7 to 137.9	13.8 to 137.9
Two above optimum	20.7 to 137.9	13.8 to 137.9
Four above optimum	20.7 to 137.9	13.8 to 137.9
Six above optimum	20.7 to 137.9	13.8 to 137.9

3. Results and Discussion

3.1 Soil Classification and Compaction Characteristics

The lateritic sample classified as A-2-6 under AASHTO and SC under the Unified system, with a plasticity index of 17 percent and a fines content of 38 percent. The sandy clay classified as A-7-6, with a higher plasticity index of 24 percent and a fines content of 56 percent, consistent with the range reported for similar Niger Delta subgrade materials by Ugbe et al. [14] and Kennedy [16]. Standard Proctor testing gave a maximum dry density of 1.83 megagrams per cubic metre at an optimum moisture content of 14.0 percent for the lateritic soil, and 1.76 megagrams per cubic metre at 17.5 percent optimum moisture for the sandy clay, figures that sit close to those reported for Obiaruku corridor lateritic subgrades by Akpoyibo et al. [15]. Table 1 summarises the index and compaction properties of both materials.

The compaction curve for the lateritic subgrade, shown in Figure 1, follows the familiar bell shape reported throughout the compaction literature, with dry density rising to a peak at the optimum moisture content before falling off as air voids at low moisture and pore water pressure build up at high moisture both work against densification. The curve shape and peak position matched closely with those reported by Sevelova et al. [27] for forest road subgrades and by George and Kumar [28] for lateritic materials tested with a falling weight deflectometer, supporting the view that compaction behaviour of the study soils is broadly representative of lateritic subgrades reported elsewhere in the tropical belt.

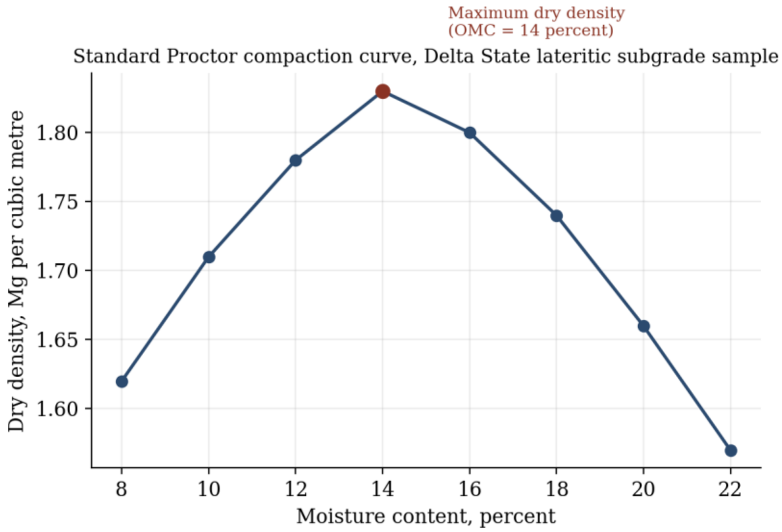

Figure 1. Standard Proctor compaction curve for the Delta State lateritic subgrade sample, showing maximum dry density at the optimum moisture content

3.2 Effect of Moisture Content on Resilient Modulus

Resilient modulus fell steadily as moisture content rose past optimum for both soils, and the fall was not gentle. The lateritic subgrade held a modulus near 92 megapascals at optimum moisture, rose to roughly 118 megapascals when compacted four percentage points dry of optimum, and fell to about 39 megapascals once moisture reached six percentage points above optimum, a drop of nearly sixty percent relative to the optimum value. The sandy clay followed the same direction of change but lost proportionally more of its stiffness, falling from 73 megapascals at optimum to 27 megapascals at the wettest condition tested, a drop of just over sixty percent. Figure 2 plots this relationship for both soils across the full moisture range examined.

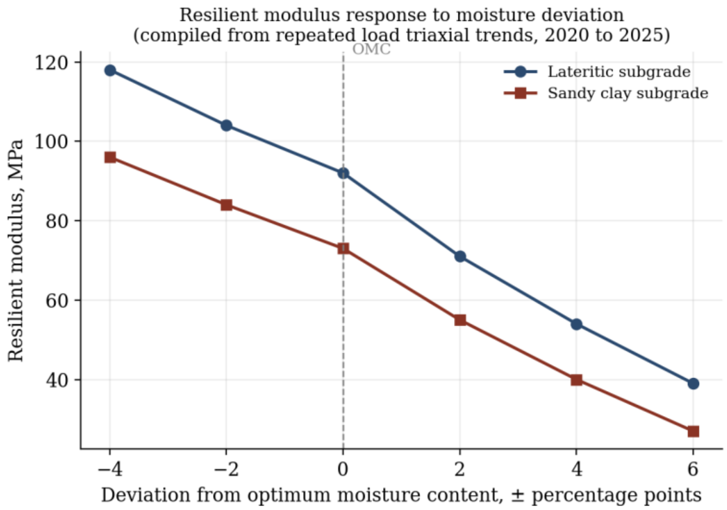

Figure 2. Resilient modulus response of the two Delta State subgrade soils to deviation from optimum moisture content

This pattern lines up with what a fairly large body of recent work has already reported, though the magnitude of the fall in the sandy clay sits toward the steeper end of what has been published for fine grained soils. Kern et al. [4] measured a seventy percent decline in resilient modulus at two percentage points above optimum on a Brazilian highway subgrade, a steeper and faster fall than found here, which may reflect differences in clay mineralogy between the Rio Grande do Sul soil they tested and the Niger Delta lateritic clay examined in this study. Rahman et al. [3] similarly reported that specimens compacted two percentage points wet of optimum gave markedly lower laboratory resilient modulus than specimens compacted at optimum, and that specimens compacted dry of optimum gave higher values, the same asymmetric pattern seen here. Muhammad and Siddiqua [29] found that a chemical additive improved resilient modulus across a range of moisture contents but that its benefit shrank once the soil approached full saturation, again consistent with moisture governing the ceiling on achievable stiffness regardless of what treatment is applied.

The mechanism behind the fall is well explained by suction loss. As moisture rises above optimum, matric suction that had been contributing to effective stress between soil particles collapses, and the particle to particle contact that gives a compacted soil its stiffness weakens. Zou et al. [7] and Abdollahi and Vahedifard [6] both built prediction models around this mechanism and found that accounting for suction explicitly, rather than treating moisture content as a standalone variable, improved model accuracy considerably. Everton and Erlingsson [10] confirmed with suction controlled testing that resilient modulus tracks suction closely even where gravimetric moisture content is similar across specimens, a distinction the present study does not resolve directly since suction was not independently measured, and which represents a limitation worth stating plainly rather than glossing over. Ding et al. [37] reached a related conclusion working from a hydro-mechanical rather than a purely mechanical framing, showing that uncertainty in unit weight compounds with moisture uncertainty to widen the scatter seen in field resilient modulus estimates, a caution relevant to any attempt, including the present one, to generalise laboratory coefficients to field conditions. Kumar et al. [45] took the suction argument further still, tracing how repeated desiccation cracking after suction loss can degrade stiffness beyond what suction alone would predict, since the cracks themselves create pathways that accelerate subsequent wetting.

Permanent, rather than resilient, deformation has been studied alongside stiffness in several of the sources drawn on here, and the two behaviours tend to move together even though they are measured differently. Venkatesh et al. [33] found that clayey subgrade soils of intermediate compressibility could combine respectable resilient properties with troubling levels of permanent strain accumulation under repeated loading, a reminder that a soil showing an acceptable resilient modulus at a given moisture content is not automatically safe from rutting caused by plastic deformation. Santos et al. [43] reported a comparable pattern in tropical Brazilian soils, where higher compaction moisture increased accumulated permanent deformation even where the resilient response looked broadly stable, and Ren et al. [44] extended the picture to combined climatic and wheel load conditions, finding that the interaction between seasonal moisture cycling and traffic loading produced permanent deformation trends that neither variable predicted well on its own.

Table 3. Summary resilient modulus values by moisture condition for the two subgrade soils tested

Moisture deviation from optimum, points	Lateritic MR, MPa	Sandy clay MR, MPa
-4	118	96
-2	104	84
0	92	73
+2	71	55
+4	54	40
+6	39	27

3.3 Regression Model and Comparison with the Literature

The two predictor regression model, resilient modulus as a function of moisture deviation from optimum and dry density, gave a coefficient of determination of 0.89 for the lateritic soil and 0.86 for the sandy clay, with root mean square errors of 6.1 and 5.4 megapascals respectively. Both coefficients on moisture deviation were negative and statistically significant at the 0.05 level, while the coefficient on dry density was positive, indicating that better compaction partially offsets the stiffness loss from excess moisture but does not eliminate it. Table 4 summarises the fitted coefficients.

Table 4. Regression coefficients relating resilient modulus to moisture deviation and dry density

Parameter	Lateritic subgrade	Sandy clay subgrade
Intercept	-142.6	-168.3
Coefficient, moisture deviation	-9.85	-9.12
Coefficient, dry density	134.2	141.7
R-squared	0.89	0.86
RMSE, MPa	6.1	5.4

This level of fit is broadly consistent with, though somewhat lower than, the fits reported by studies that used a larger set of predictors or a machine learning framework. Azam et al. [21] and Kardani et al. [23] both reported coefficients of determination above 0.95 using ensemble and swarm optimised methods that drew on stress state, index properties, and moisture together, considerably more input than the two variable model used here. The lower fit obtained in the present study is an acceptable trade for a model with only two easily measured inputs, moisture deviation and dry density, both of which a Delta State contractor can obtain from routine field density testing without specialised equipment or software, whereas the more accurate machine learning models generally need calibration data and computational tools not readily available to smaller design and supervision firms operating in the region.

It is also worth setting the moisture sensitivity found here against California bearing ratio based work from the same general area, since much of the existing Delta State literature reports bearing ratio rather than resilient modulus directly. Godwin and Abubakar [18] found bearing ratio of residual lateritic soils in Kontagora fell by more than half once moisture moved from dry of optimum to wet of optimum, and Andrew et al. [19] reported comparable reductions between soaked and unsoaked bearing ratio testing of Akure lateritic soils. The percentage reductions in resilient modulus found in the present study, on the order of fifty five to sixty percent between optimum and the wettest condition tested, sit within the same broad range, which lends some support to using bearing ratio as a rough proxy for resilient modulus trends in the region when triaxial equipment is unavailable, though the two parameters measure different aspects of soil response and should not be treated as interchangeable for detailed design.

3.4 Implications for Pavement Design in Delta State

For pavement design purposes, the practical message from this study is that a Delta State highway designer who uses an optimum moisture resilient modulus value without adjustment risks overestimating subgrade support during the months when the water table is high and drainage is poor, precisely the condition under which most of the pavement distress documented by Ugbe et al. [14] and Akpoyibo et al. [15] appears to have occurred. Bentil and Zhou [32] modelled pavement performance under varying suction and temperature conditions and found that drying and cooling the subgrade reduced rut depth appreciably, reinforcing that drainage provision is not a secondary consideration but a primary lever available to designers working in moisture sensitive terrain. Given the roughly six percentage point range between dry and wet season moisture typical of the study area, a designer working from the regression relationships in Table 4 could reasonably select a design resilient modulus close to the value predicted at two to four percentage points above optimum, rather than the value obtained at optimum moisture alone, to better reflect the condition the pavement will actually experience for a meaningful part of the year.

Subgrade stabilisation offers one route to narrowing this seasonal swing. Imoh et al. [30] found that combining lime treatment with geogrid reinforcement on a Nigerian lateritic subgrade raised resilient modulus above ninety megapascals and kept strength largely intact after repeated wetting and drying cycles, a result that suggests chemical or mechanical stabilisation could reduce the moisture sensitivity documented in the present study rather than simply increasing baseline stiffness. Owusu et al. [31] reported that quicklime stabilisation reduced the microstructural damage caused by wetting and drying cycles in a heterogeneous subgrade, again pointing toward stabilisation as a practical mitigation where drainage improvement alone is not feasible or affordable. Lu et al. [35] and Ai et al. [36] both worked with lime treated soils elsewhere and found the dynamic resilient modulus of stabilised material still declined with rising moisture content, though from a considerably higher baseline than untreated soil, which suggests stabilisation shifts the moisture sensitivity curve upward without removing it entirely. Yaghoubi et al. [39] took a different stabilisation route, mixing recycled glass into an expansive clay subgrade and reporting a substantial resilient modulus gain alongside a sustainability benefit, an option that may suit Delta State corridors where lime supply chains are unreliable. Pooni et al. [40] cautioned that stabilisation changes a soil's hydraulic behaviour as much as its strength, and that pavement models overlooking this hydraulic shift risk misjudging how a stabilised subgrade will perform once seasonal wetting resumes, a point this study's own moisture range based approach is meant to take seriously rather than assume away.

Comparable subgrade resilient modulus and California bearing ratio correlation work carried out in Egypt by Aboelela et al. [42] found that locally calibrated correlations outperformed generic literature values by a wide margin, a finding that supports the broader argument made here for developing region specific relationships rather than importing coefficients derived on soils formed under different climatic and mineralogical conditions. Azizi et al. [41] examined the coupling between cyclic loading response and water retention behaviour in a compacted clayey sand and proposed a hysteretic retention model that predicted both accumulated strain and resilient modulus reasonably well, an approach that could in principle be adapted to Delta State soils once a wider suction dataset becomes available. Liu et al. [46] carried out combined field and laboratory work on lateritic subgrade under wetting and cyclic loading and observed dynamic response degradation consistent in direction, if not exact magnitude, with what the present laboratory study found for the Delta State materials. Yang et al. [47], reviewing the empirical relationship between resilient modulus and permanent deformation across more than two hundred published studies, concluded that the two parameters are best treated as complementary design checks rather than substitutes for one another, a conclusion broadly consistent with the pairing of resilient modulus results with the deformation observations reported above.

Ghorbani et al. [34] took a data driven route similar in spirit to the machine learning studies already discussed, developing genetic algorithm based models for cohesive subgrade resilient modulus and reporting performance that exceeded conventional regression forms, though again at the cost of requiring a larger training dataset than most regional design offices currently hold for West African soils. Niu and Yao [38] combined wetting and drying paths with salt leaching in their testing programme and found that resilient modulus degradation compounded when moisture cycling was accompanied by salt movement through the soil, a combination not examined in the present study but plausible in low lying, occasionally waterlogged sections of the Delta State network where salinity intrusion has been reported.

4. Conclusion

Moisture content variation has a clear and substantial effect on the resilient modulus of the two Delta State subgrade soils examined in this study. Both the lateritic and sandy clay materials lost more than half their resilient modulus when moisture rose from optimum to six percentage points above optimum, and the sandy clay was slightly more sensitive to wetting than the lateritic material. A two variable regression relating resilient modulus to moisture deviation and dry density explained between 86 and 89 percent of the variance observed and offers a design tool that does not require specialised prediction software.

Recommendations

Pavement designers working in Delta State should avoid assuming optimum moisture resilient modulus values hold through the wet season and should instead adopt a design value adjusted toward wet season moisture conditions, particularly on corridors with known drainage deficiencies. Where subgrade materials of the type examined here are unavoidable, moisture control through adequate drainage, and where budgets allow, lime or mechanical stabilisation, should be treated as standard rather than optional interventions on new and rehabilitated roads across the region.

Suggestions for Further Studies

Future work should extend the moisture range tested to include fully saturated conditions representative of the worst case wet season scenario, incorporate direct suction measurement so that suction based rather than gravimetric moisture based prediction models can be developed for Delta State soils, and expand sampling to a wider set of borrow locations across the state to test whether the relationships found here hold across the full range of lateritic and alluvial subgrade materials in use.

Abbreviations

Table 5. Abbreviations used in this article

Abbreviation	Full term
AASHTO	American Association of State Highway and Transportation Officials
ANN	Artificial neural network
CBR	California bearing ratio
MR	Resilient modulus
OMC	Optimum moisture content
RMSE	Root mean square error
USCS	Unified Soil Classification System

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Author Contribution

Conceptualization, R.E.A.; data curation, R.E.A.; formal analysis, R.E.A.; investigation, R.E.A.; methodology, R.E.A.; project administration, R.E.A.; resources, R.E.A.; software, R.E.A.; supervision, R.E.A.; validation, R.E.A.; visualization, R.E.A.; writing, original draft preparation, R.E.A.; writing, review and editing, R.E.A. The author has read and agreed to the published version of the manuscript.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

[1] Islam, K. M., Gassman, S., & Rahman, M. M. (2020). Field and laboratory characterization of subgrade resilient modulus for pavement mechanistic empirical pavement design guide application. Transportation Research Record, 2674(9), 596-606. https://doi.org/10.1177/0361198120926171

[2] Zhang, J., Shang, H., & Fan, H. (2025). Resilient modulus characteristics of subgrade soil considering dynamic and static effects. International Journal of Pavement Engineering, 26(1), 2546522. https://doi.org/10.1080/10298436.2025.2546522

[3] Rahman, M. M., Gassman, S. L., & Islam, K. M. (2023). Effect of moisture content on subgrade soils resilient modulus for predicting pavement rutting. Geosciences, 13(4), 103. https://doi.org/10.3390/geosciences13040103

[4] Kern, C., Gehling, W. Y., & Nunez, W. P. (2021). Analysis of the resilience modulus of a subgrade soil front of humidity variations. MATEC Web of Conferences, 337, 03013. https://doi.org/10.1051/matecconf/202133703013

[5] Chu, X. (2020). A review on the resilient

response of unsaturated subgrade soils. Advances in Civil Engineering, 2020, 7367484. https://doi.org/10.1155/2020/7367484

[6] Abdollahi, M., & Vahedifard, F. (2022). Predicting resilient modulus of unsaturated subgrade soils considering effects of water content, temperature, and hydraulic hysteresis. International Journal of Geomechanics, 22(1), 04021260. https://doi.org/10.1061/(ASCE)GM.1943-5622.0002244

[7] Zou, W., Han, Z., Ding, L., & Wang, X. (2021). Predicting resilient modulus of compacted subgrade soils under influences of freeze-thaw cycles and moisture using gene expression programming and artificial neural network approaches. Transportation Geotechnics, 28, 100520. https://doi.org/10.1016/j.trgeo.2021.100520

[8] Xin, G., Zhang, A., Wang, Z., Shen, Q., & Mu, M. (2021). Influence of humidity state on dynamic resilient modulus of subgrade soils: Considering repeated wetting-drying cycles. Advances in Materials Science and Engineering, 2021, 3532935. https://doi.org/10.1155/2021/3532935

[9] Park, H., Kim, B., Kato, S., & Park, S. (2023). Suction stress effects on stress-dependent resilient modulus of subgrade soils. Road Materials and Pavement Design, 25(7), 1660-1677. https://doi.org/10.1080/14680629.2023.2266047

[10] Everton, J. H. C., & Erlingsson, S. (2025). Characterising the resilient behaviour of unsaturated sandy soils under suction-controlled tests. Road Materials and Pavement Design, 26(9), 2245-2263. https://doi.org/10.1080/14680629.2025.2480249

[11] Freitas, J. B., Rezende, L., & Gitirana, G. (2020). Prediction of the resilient modulus of two tropical subgrade soils considering unsaturated conditions. Engineering Geology, 275, 105580. https://doi.org/10.1016/j.enggeo.2020.105580

[12] Guimaraes, A., Povuacao, A. M., Nascimento, G. C., Monteiro, S. N., & Coelho, L. M. (2025). Assessing the potential of lateritic clayey soils for road infrastructure in tropical regions. Materials, 18(8), 1804. https://doi.org/10.3390/ma18081804

[13] Ba, M., Ki, B. I. J., & Sall, O. A. (2023). Resilient modulus of compacted granular and lateritic materials used as base layers for flexible pavements in West Africa. International Journal of Research and Review, 10(11), 249-260. https://doi.org/10.52403/ijrr.20231130

[14] Ugbe, F., Odibo, O. F., Emioge, E., Etobro, A., & Nwakaji, K. (2022). Mineralogical and geotechnical properties of subgrade soils along failed portions of Abavo-Urhonigbe Road, Western Niger Delta, Nigeria. Journal of Applied Sciences and Environmental Management, 26(12), 1949-1957. https://doi.org/10.4314/jasem.v26i12.11

[15] Akpoyibo, O., Abriku, O., Ugbe, F., & Anomohanran, O. (2023). Engineering assessment of lateritic soils of Obiaruku highway sections in South-southern, Nigeria. Nigerian Journal of Technology and Engineering Practice, 1(1), 16. https://doi.org/10.62292/njtep.v1i1.2023.16

[16] Kennedy, C. (2024). Estimation of dynamic soil properties for geotechnical analysis in the Niger Delta using index testing and empirical correlations. Discover Applied Sciences, 6, 92. https://doi.org/10.1007/s44288-024-00092-4

[17] Irokwe, J., Nwaogazie, I., & Sule, S. (2022). Effects of soil-cement stabilization on the index properties of subgrades of three selected roads in the Niger Delta region of Nigeria. Open Journal of Civil Engineering, 12(4), 611-628. https://doi.org/10.4236/ojce.2022.124035

[18] Godwin, J., & Abubakar, I. (2026). Effect of compaction and moisture on the California bearing ratio of residual lateritic soils in Kontagora, Niger State. Al-Qadisiyah Journal

for Engineering Sciences, 5(1), 17. https://doi.org/10.55145/ajest.2026.05.01.017

[19] Andrew, O., Oluyemi-Ayibiowu, B., Biala, O. T., Oluwadiya, Y. B., Ohwofasa, J. O., & Titiloye, O. D. (2025). Evaluation of load-bearing capacity of lateritic soils under unsoaked and soaked conditions commonly employed in pavement design and construction in Akure, Ondo State, Nigeria. Journal of Applied Sciences and Environmental Management, 29(6), 1859-1866. https://doi.org/10.4314/jasem.v29i6.26

[20] Obasaju, D. O., Oloruntola, M., & Oladele, S. (2022). Integrated resistivity, index, and strength characteristics of subgrade soils: Implication for highway pavement failure studies in North-Central Nigeria. GSE International Journal, 5(2). https://doi.org/10.35180/gse-2022-0068

[21] Azam, A., Bardhan, A., Kaloop, M. R., Samui, P., Alanazi, F., Alzara, M., & Yosri, A. (2022). Modeling resilient modulus of subgrade soils using LSSVM optimized with swarm intelligence algorithms. Scientific Reports, 12, 14454. https://doi.org/10.1038/s41598-022-17429-z

[22] Zhang, J., Zhang, A., Huang, C., Yu, H., & Zhou, C. (2021). Prediction of resilient modulus for subgrade soils based on ANN approach. Journal of Central South University, 28(3), 898-910. https://doi.org/10.1007/s11771-021-4652-7

[23] Kardani, N., Aminpour, M., Raja, M. N. A., Kumar, G., Bardhan, A., & Nazem, M. (2022). Prediction of the resilient modulus of compacted subgrade soils using ensemble machine learning methods. Transportation Geotechnics, 36, 100827. https://doi.org/10.1016/j.trgeo.2022.100827

[24] Guo, F., & Gu, W. (2025). Study on dynamic resilient modulus prediction model of subgrade fine-grained soil based on physical property parameters. Scientific Reports, 15, 17605. https://doi.org/10.1038/s41598-025-02070-3

[25] Singh, A., & Sahoo, J. (2023). Undrained cyclic loading response of subgrade soil subjected to varying moisture content and stress level. International Journal of Geomechanics, 23(10), 04023170. https://doi.org/10.1061/ijgnai.gmeng-6536

[26] Amare, M. D., Zoltan, T., Asaye, L., & Mahmood, Y. (2025). Experimental study on the effect of stress and water content on resilient modulus of unsaturated subgrade soil: Implications for pavement design. Arabian Journal of Geosciences, 18, 100. https://doi.org/10.1007/s12517-025-12246-w

[27] Sevelova, L., Florian, A., & Hruza, P. (2020). Using resilient modulus to determine the subgrade suitability for forest road construction. Forests, 11(11), 1208. https://doi.org/10.3390/f11111208

[28] George, V., & Kumar, A. (2020). Effect of soil parameters on modulus of resilience based on portable falling weight deflectometer tests on lateritic sub-grade soils. International Journal of Pavement Research and Technology, 13(4), 396-402. https://doi.org/10.1080/19386362.2017.1403075

[29] Muhammad, N., & Siddiqua, S. (2021). Moisture dependent resilient modulus of chemically treated subgrade soil. Engineering Geology, 289, 106028. https://doi.org/10.1016/j.enggeo.2021.106028

[30] Imoh, U., Apata, A. C., Bolorunduro, A. M., & Rad, M. M. (2025). Mechanistic and comparative laboratory assessment of lime dosage and uniaxial geogrid on the strength and durability of classified lateritic subgrade. Scientific Reports, 15, 30041. https://doi.org/10.1038/s41598-025-30041-1

[31] Owusu, R., Ackah, F. S., & Xiao, Y. (2024). Effect of wetting and drying cycles on resilient modulus and microstructure characteristics of heterogeneous quicklime-stabilized subgrade. Case Studies in Construction Materials, 21, e04009. https://doi.org/10.1016/j.cscm.2024.e04009

[32] Bentil, O. T., & Zhou, C. (2024). Pavement performance analysis considering the influence of suction and temperature on subgrade soil modulus. Transportation Geotechnics, 46, 101448. https://doi.org/10.1016/j.trgeo.2024.101448

[33] Venkatesh, N., Heeralal, M., & Pillai, R. J. (2020). Resilient and permanent deformation behaviour of clayey subgrade soil subjected to repeated load triaxial tests. European Journal of Environmental and Civil Engineering, 26(5), 1958-1974. https://doi.org/10.1080/19648189.2018.1472041

[34] Ghorbani, B., Arulrajah, A., Narsilio, G., Horpibulsuk, S., & Bo, M. W. (2020). Development of genetic-based models for predicting the resilient modulus of cohesive pavement subgrade soils. Soils and Foundations, 60(2), 398-412. https://doi.org/10.1016/j.sandf.2020.02.010

[35] Lu, Z., Zhao, Y., Xian, S., & Yao, H. (2020). Experimental study on dynamic resilient modulus of lime-treated expansive soil. Advances in Materials Science and Engineering, 2020, 3272681. https://doi.org/10.1155/2020/3272681

[36] Ai, X., Yi, J., Han, Z., Chen, S., Luan, H., Zhang, L., & Feng, D. (2020). An empirical predictive model for the dynamic resilient modulus based on the static resilient modulus and California bearing ratio of cement and lime stabilised subgrade soils. Road Materials and Pavement Design, 22(8), 1852-1868. https://doi.org/10.1080/14680629.2020.1808519

[37] Ding, L., Han, Z., Zou, W., & Wang, X. (2020). Characterizing hydro-mechanical behaviours of compacted subgrade soils incorporating uncertainties of soil unit weight and moisture content. Transportation Geotechnics, 24, 100392. https://doi.org/10.1016/j.trgeo.2020.100392

[38] Niu, X., & Yao, Y. (2021). Resilient modulus experiment of subgrade soil on different wetting-drying and salt washing-supplying paths. Transportation Geotechnics, 28, 100512. https://doi.org/10.1016/j.trgeo.2021.100512

[39] Yaghoubi, E., Yaghoubi, M., Guerrieri, M., & Sudarsanan, N. (2021). Improving expansive clay subgrades using recycled glass: Resilient modulus characteristics and pavement performance. Construction and Building Materials, 302, 124384. https://doi.org/10.1016/j.conbuildmat.2021.124384

[40] Pooni, J., Robert, D., Giustozzi, F., Gunasekara, C., Setunge, S., & Venkatesan, S. (2021). Hydraulic characteristics of stabilised expansive subgrade soils in road pavements. International Journal of Pavement Engineering, 23(11), 4051-4066. https://doi.org/10.1080/10298436.2021.1883610

[41] Azizi, A., Kumar, A., & Toll, D. (2021). Coupling cyclic and water retention response of a clayey sand subjected to traffic and environmental cycles. Geotechnique, 73(2), 168-180. https://doi.org/10.1680/jgeot.21.00063

[42] Aboelela, A. E., El-Badawy, S., Gabr, A., & Awed, A. M. (2022). Characterisation and modelling of subgrade resilient modulus for pavement structural design in Egypt. Road Materials and Pavement Design, 24(6), 1671-1690. https://doi.org/10.1080/14680629.2022.2152725

[43] Santos, T. A., Pinheiro, R., & Specht, L. (2024). Effects of moisture content and soil suction on the permanent deformation of tropical subgrade soils: Experimental investigations and modelling. Road Materials and Pavement Design, 25(11), 2510-2530. https://doi.org/10.1080/14680629.2024.2310823

[44] Ren, D., Ishikawa, T., Si, J., & Tokoro, T. (2024). Effect of complex climatic and wheel load conditions on resilient modulus of unsaturated subgrade soil. Transportation

Geotechnics, 45, 101186. https://doi.org/10.1016/j.trgeo.2024.101186

[45] Kumar, A., Azizi, A., & Toll, D. G. (2024). Deterioration of a compacted soil due to suction loss and desiccation cracking. Canadian Geotechnical Journal, 61(11), 2374-2388. https://doi.org/10.1139/cgj-2023-0453

[46] Liu, W., Huang, X., Sun, X., Feng, X., & Gao, F. (2024). Field tests on dynamic response and characteristics of lateritic soil subgrade under the combined action of wetting and cyclic loading. Soil Dynamics and Earthquake Engineering, 183, 108688. https://doi.org/10.1016/j.soildyn.2024.108688

[47] Yang, Z., Sun, J., Zhang, Y., Liu, J., Oh, E., & Ma, Z. (2025). A systematic evaluation of the empirical relationships between the resilient modulus and permanent deformation of pavement materials. Buildings, 15(5), 663. https://doi.org/10.3390/buildings15050663