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Development of a Hydro-Mechanical Stability Index for Assessing Moisture-Induced Instability of Tropical Black Clay Subgrades in North-Central Nigeria

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Abstract

Moisture-induced deterioration is a major cause of premature pavement failure in tropical regions where expansive clay soils are widely used as subgrade materials. Conventional evaluation methods assess engineering properties such as soaked California Bearing Ratio (CBR), compaction characteristics, moisture demand, and hydraulic conductivity independently, limiting holistic assessment of subgrade performance. This study developed a dimensionless Hydro-Mechanical Stability Index (HMSI) for evaluating the hydro-mechanical stability of tropical black clay subgrades. Representative soil samples were collected from twenty trial pits across four locations in North-Central Nigeria, namely Gwagwalada, Gidigidi, Sunti, and Zungeru. Laboratory investigations included determination of index properties, compaction characteristics, hydraulic conductivity, and soaked CBR in accordance with relevant ASTM and British Standard procedures. The investigated soils were classified as CH, CL, and CL–CH under the Unified Soil Classification System (USCS) and as A-7-5 and A-7-6 according to AASHTO, confirming their generally poor suitability as untreated pavement subgrades. The proposed HMSI integrates soaked CBR, normalized maximum dry density, optimum moisture content, and normalized hydraulic conductivity into a single dimensionless engineering parameter. Computed HMSI values ranged from 0.0397 to 0.2263, enabling the investigated deposits to be ranked according to their relative hydro-mechanical stability. Sensitivity analysis demonstrated that the index responds consistently to variations in its constituent engineering parameters, with soaked CBR and maximum dry density exerting positive influences, whereas optimum moisture content and hydraulic conductivity reduced the computed stability. The proposed preliminary classification framework identified Gwagwalada, Gidigidi, Zungeru, and Sunti deposits as exhibiting Very Poor, Poor, Moderate, and Good hydro-mechanical stability, respectively. Although broader validation is required, HMSI provides a practical screening tool for subgrade ranking, stabilization prioritization, and preliminary pavement assessment using routinely determined laboratory parameters, thereby supporting climate-resilient pavement engineering in tropical environments.

Keywords: Hydro-Mechanical Stability Index (HMSI); Tropical Black Clay; Expansive Soil; Pavement Subgrade; Moisture-Induced Instability.

INTRODUCTION

Expansive soils are among the most problematic geomaterials encountered in highway and foundation engineering because of their pronounced volume changes under varying moisture conditions. Seasonal wetting and drying induce swelling and shrinkage, leading to pavement cracking, differential settlement, embankment distress, reduced bearing capacity, and increased maintenance costs. Consequently, the engineering performance of expansive soils is strongly governed by hydro-

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mechanical interactions involving moisture migration, suction variation, and soil mechanical behaviour (Fredlund and Rahardjo, 1993; Vanapalli *et al.,* 1996).

In Nigeria, expansive tropical black clays, commonly referred to as black cotton soils, occur extensively within the North-Central, North-Eastern, and North-Western regions, where they are widely encountered as pavement subgrades and foundation materials. Previous investigations have shown that these soils generally exhibit high plasticity, low soaked strength, appreciable swelling potential, poor drainage characteristics, and significant sensitivity to seasonal moisture fluctuations (Ola, 1978; Amadi *et al.,* 2012; Abdulaziz *et al.,* 2022; Irabor, 2023; Yunusa *et al.,* 2024). These characteristics contribute significantly to premature pavement deterioration and increased maintenance requirements in tropical environments.

Conventional geotechnical evaluation of expansive soils relies on laboratory parameters such as Atterberg limits, compaction characteristics, California Bearing Ratio (CBR), hydraulic conductivity, consolidation behaviour, and soil classification systems. Although these parameters provide valuable engineering information, they are generally interpreted independently and therefore do not adequately represent the combined influence of strength retention, compaction state, moisture demand, and seepage behaviour on long-term subgrade performance.

The increasing occurrence of intense rainfall events and climate-induced environmental variability has further highlighted the need for integrated performance-based approaches for evaluating moisture-sensitive pavement subgrades. Recent studies have demonstrated that hydro-mechanical deterioration is controlled by the coupled effects of moisture migration, mechanical degradation, and environmental loading, which collectively influence the long-term performance of transportation infrastructure (Soltani *et al.,* 2021; Cai *et al.,* 2025; Pham, 2025). Consequently, practical engineering tools capable of integrating multiple hydro-mechanical properties into a single stability indicator are becoming increasingly important.

Despite extensive research on expansive tropical clays in Nigeria, limited attention has been devoted to developing unified engineering indices for assessing hydro-mechanical stability. Existing classification approaches, including the American Association of State Highway and Transportation Officials (AASHTO) and the Unified Soil Classification System (USCS), remain primarily descriptive and do not quantify the combined effects of moisture sensitivity, permeability, density, and strength on subgrade performance. This limitation often requires engineers to interpret several independent laboratory parameters simultaneously, thereby complicating engineering decision-making.

To address this gap, the present study develops a Hydro-Mechanical Stability Index (HMSI), a dimensionless engineering parameter that integrates soaked California Bearing Ratio (CBR), maximum dry density (MDD), optimum moisture content (OMC), and hydraulic conductivity into a unified framework for assessing the hydro-mechanical stability of tropical black clay subgrades. The index was developed using representative clay deposits obtained from selected locations within North-Central Nigeria.

The novelty of the proposed HMSI lies in integrating four routinely determined laboratory parameters into a single performance-based engineering index capable of evaluating the relative stability of expansive subgrades under moisture-sensitive conditions. Unlike conventional approaches that assess these parameters separately, the proposed framework provides an integrated basis for subgrade ranking, stabilization prioritization, and preliminary pavement assessment. The study therefore contributes to the growing emphasis on performance-based and climate-resilient geotechnical evaluation methods for expansive soils.

The specific objectives of this study are to: (i) evaluate the hydro-mechanical characteristics of selected tropical black clay deposits in North-Central Nigeria; (ii) develop and compute the Hydro-Mechanical Stability Index (HMSI); (iii) establish preliminary HMSI stability classifications; (iv) examine the influence of selected hydro-mechanical parameters on HMSI; and (v) evaluate the applicability of HMSI as a practical engineering tool for assessing moisture-induced subgrade instability.

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MATERIALS AND METHODS

Study Area and Sampling Procedure

The study was conducted on tropical black clay deposits obtained from four locations within North-Central Nigeria, namely Gwagwalada (Federal Capital Territory), Gidigidi (Nasarawa State), Sunti (Niger State), and Zungeru (Niger State). These locations were selected because they contain extensive occurrences of moisture-sensitive clay deposits commonly encountered as pavement subgrades and foundation materials. The geographical distribution of the study areas is presented in Figure 1, while their coordinates are summarized in Table 1.

North-Central Nigeria experiences a tropical wet-and-dry climate characterized by distinct rainy and dry seasons. Annual rainfall ranges from approximately 1,000 to 1,600mm, while mean annual temperatures generally exceed 25°C. Seasonal wetting and drying associated with this climate significantly influence the engineering behaviour of expansive soils.

The investigated areas are underlain predominantly by weathered Basement Complex rocks comprising granites, gneisses, migmatites, and schists. Prolonged tropical weathering of these parent materials has produced residual clay-rich deposits with varying proportions of clay, silt, sand, and iron-rich constituents. Previous studies have shown that such deposits commonly exhibit high plasticity, appreciable swelling potential, low soaked strength, and significant moisture sensitivity (Ola, 1978; Abdulaziz *et al.,* 2022; Yunusa *et al.,* 2024).

Table 1: Geographical Coordinates of the Study Locations

Location	Trial Pits	Latitude Range (°N)	Longitude Range (°E)
Gwagwalada (GW)	GW-TP1 to TP5	8.909167–8.979167	7.120000–7.263889
Gidigidi (GD)	GD-TP1 to TP5	8.469506–8.546003	8.446781–8.495561
Sunti (SN)	SN-TP1 to TP5	9.102213–9.104281	5.231924–5.234019
Zungeru (ZG)	ZG-TP1 to TP5	9.738153–9.746127	6.129702–6.136636

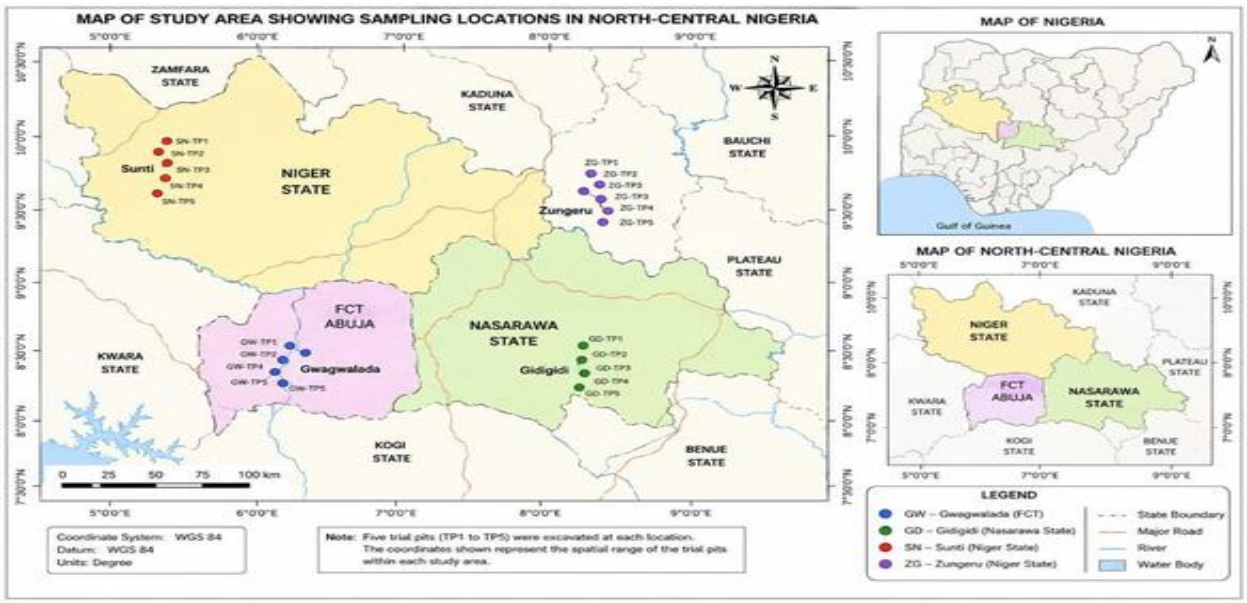


Figure 1: Location Map of the Study Areas

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Field investigations involved the excavation of five exploratory trial pits at each study location, giving a total of twenty sampling points. Trial pits were excavated to depths of approximately 1.0–1.5m, corresponding to the typical pavement subgrade zone. Disturbed bulk samples were collected from the clay horizons, sealed immediately in airtight polyethylene bags to minimize moisture loss, and transported to the geotechnical laboratory for testing. Representative samples from each location were subsequently prepared and tested in accordance with the relevant ASTM and British Standard (BS) procedures for the determination of the hydro-mechanical properties used in developing the proposed Hydro-Mechanical Stability Index (HMSI).

Sample Preparation

The collected soil samples were transported to the geotechnical laboratory, where roots, organic debris, and other extraneous materials were removed. The samples were air-dried under ambient laboratory conditions for approximately 72 hours to reduce excess moisture while minimizing disturbance to their natural physical characteristics.

The air-dried samples were gently pulverized using a wooden mallet and ceramic mortar and pestle to disaggregate soil lumps without crushing individual particles. The processed materials were then sieved according to the requirements of the respective laboratory tests. Samples intended for index property determination were passed through a 425μm sieve, while representative portions for particle-size analysis and other laboratory investigations were prepared in accordance with the relevant testing standards.

To ensure uniformity, the prepared materials were thoroughly mixed and homogenized using the quartering method before representative subsamples were obtained for laboratory testing. The prepared samples were subsequently used to determine index properties, compaction characteristics, hydraulic conductivity, and soaked California Bearing Ratio (CBR), from which the parameters required for the Hydro-Mechanical Stability Index (HMSI) were derived.

All sample preparation procedures were carried out in accordance with the applicable ASTM and British Standard (BS) specifications to ensure consistency and reliability of the laboratory results.

Hydro-Mechanical Laboratory Testing

A laboratory testing programme was conducted to determine the engineering properties of the investigated tropical black clay deposits and to obtain the parameters required for developing the Hydro-Mechanical Stability Index (HMSI). The testing programme comprised index property determination, compaction testing, hydraulic conductivity measurement, California Bearing Ratio (CBR) testing, and soil classification.

Index property tests, including natural moisture content, particle-size distribution, and Atterberg limits, were carried out in accordance with the relevant ASTM and BS 1377 procedures. The results were used to characterize the physical properties of the soils and support classification.

Compaction characteristics, comprising optimum moisture content (OMC) and maximum dry density (MDD), were determined using the Standard Proctor method in accordance with ASTM D698-12 (2021). Hydraulic conductivity tests were conducted under saturated conditions following ASTM D5084-16 (2021), while California Bearing Ratio (CBR) tests were performed under both soaked and unsoaked conditions in accordance with ASTM D1883-16 (2021). A four-day soaking period was adopted for the soaked CBR tests to simulate prolonged field saturation, and the soaked CBR values were subsequently used in the computation of HMSI because they better represent subgrade performance under adverse moisture conditions (Vanapalli *et al.,* 1996; Soltani *et al.,* 2021).

The investigated soils were classified using the American Association of State Highway and Transportation Officials (AASHTO M145) and the Unified Soil Classification System (USCS). All laboratory tests were conducted in accordance with the applicable ASTM and British Standard specifications to ensure the consistency, repeatability, and reliability of the experimental results.

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Development of the Hydro-Mechanical Stability Index (HMSI)

The Hydro-Mechanical Stability Index (HMSI) was developed as a dimensionless engineering parameter for assessing the susceptibility of tropical black clay subgrades to moisture-induced deterioration. The index integrates soaked California Bearing Ratio (CBR), maximum dry density (MDD), optimum moisture content (OMC), and hydraulic conductivity (k) into a single quantitative measure of hydro-mechanical stability.

The formulation was based on the premise that pavement performance is governed by the combined interaction of strength, compaction state, moisture demand, and water migration. To eliminate dimensional effects and facilitate comparison among soils, maximum dry density and hydraulic conductivity were normalized using the mean values obtained from the investigated dataset. The normalized parameters were computed using Equations (1) and (2):

$$MDD_n = \frac{\text{MDD}}{MDD_{mean}} \quad \text{Equation (1)}$$

$$k_n = \frac{\text{k}}{k_{mean}} \quad \text{Equation (2)}$$

Where:

MDD_{mean} = 1.86Mg/m^3 and k_{mean} = 1.08 × 10^{-9}m/s

The Hydro-Mechanical Stability Index (HMSI) was subsequently computed using Equation (3):

$$HMSI = \frac{CBR_S \times MDD_n}{\text{OMC} \times k_n} \quad \text{Equation (3)}$$

where:

HMSI = Hydro-Mechanical Stability Index (dimensionless); CBR_s = soaked California Bearing Ratio (%); MDD_n = normalized maximum dry density; OMC = optimum moisture content (%); and k_n = normalized hydraulic conductivity.

The formulation assumes that soaked CBR and normalized MDD contribute positively to hydro-mechanical stability, whereas higher OMC and normalized hydraulic conductivity are associated with increased moisture susceptibility. Consequently, higher HMSI values indicate greater resistance to moisture-induced deterioration, while lower values represent comparatively poorer hydro-mechanical stability.

HMSI Classification Framework

Since no established Hydro-Mechanical Stability Index (HMSI) classification system currently exists, a preliminary stability framework was developed using the computed HMSI values obtained from the investigated tropical black clay deposits. The framework was established by ranking the computed HMSI values in ascending order and grouping soils according to their relative hydro-mechanical stability. Similar data-driven approaches have been adopted during the preliminary development of engineering classification systems prior to broader validation (Das and Sobhan, 2018).

The proposed framework assumes that higher HMSI values represent greater resistance to moisture-induced deterioration and improved subgrade performance, whereas lower values indicate increased susceptibility to hydro-mechanical instability. The resulting stability classes provide a practical basis for comparing the relative engineering performance of the investigated soils and for supporting preliminary subgrade evaluation and stabilization prioritization.

It should be noted that the proposed classification boundaries were derived solely from the investigated dataset and therefore represent preliminary engineering categories rather than universal threshold values. Consequently, further validation using larger datasets covering different geological settings, climatic conditions, and expansive soil types is recommended before the framework is adopted for broader engineering applications.

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Statistical Analysis

Descriptive statistical analyses were conducted to summarize the hydro-mechanical characteristics of the investigated tropical black clay deposits and the computed Hydro-Mechanical Stability Index (HMSI). Statistical measures, including the minimum, maximum, mean, and standard deviation, were determined to evaluate the variability of the measured engineering parameters and the resulting HMSI values (Montgomery *et al.,* 2011).

In addition, a sensitivity analysis was undertaken to examine the response of HMSI to variations in its constituent engineering parameters, namely soaked California Bearing Ratio (CBR), maximum dry density (MDD), optimum moisture content (OMC), and hydraulic conductivity. The analysis was intended to assess the relative influence of each parameter on the computed HMSI values and to verify that the index exhibited behaviour consistent with established engineering principles governing expansive soil performance.

The statistical analyses provided a quantitative basis for evaluating the consistency of the proposed HMSI framework and its potential application as a preliminary engineering tool for assessing the hydro-mechanical stability of tropical black clay subgrades.

RESULTS AND DISCUSSION

Index Properties and Soil Classification

The physical characteristics and engineering classifications of the investigated tropical black clay deposits are presented in Tables 2 and 3. These results provide the basis for understanding the hydro-mechanical behaviour of the soils and their suitability for pavement subgrade applications.

Table 2: Physical Characteristics of the Investigated Deposits

Location	Natural Moisture Content (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Clay Fraction (%)
Gwagwalada	24.49	56.32	33.45	22.87	55.76
Gidigidi	24.46	31.62	16.84	14.78	22.90
Sunti	21.19	32.87	16.84	16.02	28.10
Zungeru	17.07	37.90	17.44	20.46	29.94

The investigated soils exhibited moderate to high natural moisture contents together with appreciable plasticity and clay fractions, confirming their moisture-sensitive nature. Gwagwalada deposit recorded the highest liquid limit, plasticity index, and clay fraction, indicating a greater capacity for water adsorption and volumetric change than the other deposits. In contrast, Gidigidi deposit exhibited the lowest clay fraction and plasticity characteristics, suggesting comparatively lower expansivity. These findings are consistent with previous investigations on tropical black clays in Nigeria, which reported that increases in clay content and plasticity are commonly associated with greater swelling potential and reduced engineering performance (Irabor, 2023; Yunusa *et al.,* 2024).

The observed variability in plasticity and clay fraction indicates differences in the hydro-mechanical response of the investigated deposits despite their occurrence within the same climatic region. Higher clay contents generally increase specific surface area and enhance moisture retention, thereby increasing susceptibility to shrink–swell behaviour and strength loss under fluctuating environmental conditions (Fredlund and Rahardjo, 1993; Abdulaziz *et al.,* 2022).

The soil classification results presented in Table 3 further confirm the expansive nature of the investigated deposits.

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Table 3: Soil Classification and Engineering Description of the Investigated Deposits

Location	USCS Classification	AASHTO Classification	Engineering Description
Gwagwalada	CH	A-7-6	High-plasticity clay exhibiting pronounced moisture sensitivity and poor subgrade quality
Gidigidi	CL	A-7-5	Low- to medium-plasticity clay with moderate moisture susceptibility
Sunti	CL	A-7-5	Low- to medium-plasticity clay exhibiting moderate expansive characteristics
Zungeru	CL–CH	A-7-6	Transitional clay exhibiting characteristics of both low- and high-plasticity materials

The USCS classification identified the investigated soils as CH, CL, and CL–CH materials, confirming that the deposits consist predominantly of fine-grained expansive clays with varying degrees of plasticity. The CH classification obtained for Gwagwalada deposit indicates the greatest potential for compressibility and moisture sensitivity, whereas the CL and CL–CH classifications suggest comparatively lower, but still significant, expansive behaviour. These observations agree with recent studies that reported similar engineering characteristics for tropical clay deposits developed over weathered Basement Complex rocks (Irabor, 2023; Abdulaziz *et al.,* 2022).

The AASHTO classification further placed all investigated soils within the A-7 group (A-7-5 and A-7-6), which is generally regarded as unsuitable for untreated pavement subgrades because of poor performance under wet conditions. The predominance of A-7 materials indicates that moisture control or stabilization would generally be required before these soils could be used as pavement foundation materials. Similar conclusions have been reported for expansive tropical clays used in highway construction within tropical environments (Yunusa *et al.,* 2024).

In general, the physical characteristics and engineering classifications consistently indicate that the investigated deposits possess the principal attributes of expansive tropical black clays, including appreciable plasticity, high fines content, and pronounced moisture sensitivity. These characteristics justify the subsequent evaluation of their hydro-mechanical behaviour and the application of the proposed Hydro-Mechanical Stability Index (HMSI) as an integrated measure of subgrade stability.

Hydro-Mechanical Characteristics of the Investigated Tropical Black Clay Deposits

Following the characterization and classification of the investigated soils, the hydro-mechanical properties governing moisture-induced subgrade performance were evaluated. The measured optimum moisture content (OMC), maximum dry density (MDD), hydraulic conductivity (k), and soaked California Bearing Ratio (CBR) are presented in Table 4.

Table 4: Hydro-Mechanical Characteristics of the Investigated Tropical Black Clay Deposits

Location	OMC (%)	MDD (Mg/m³)	Hydraulic Conductivity (m/s)	Soaked CBR (%)
Gwagwalada	19.46	1.66	1.19×10^{-9}	0.87
Gidigidi	17.89	1.83	1.21×10^{-9}	1.60
Sunti	15.83	1.91	1.08×10^{-9}	4.01
Zungeru	14.71	2.04	8.34×10^{-10}	1.93

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The hydro-mechanical properties demonstrate clear differences in engineering behaviour among the investigated deposits. Although all soils exhibited low soaked CBR values characteristic of expansive clays, noticeable variations in compaction characteristics, moisture demand, and hydraulic conductivity indicate differing levels of susceptibility to moisture-induced deterioration.

The soaked CBR values obtained for all locations are below the minimum values generally recommended for untreated pavement subgrades, confirming that the investigated soils possess limited load-bearing capacity under saturated conditions. This behaviour is characteristic of expansive tropical clays, where moisture ingress reduces interparticle bonding and weakens the soil structure, leading to significant reductions in engineering performance (Soltani *et al.,* 2021; Alhassan *et al.,* 2021).

The progressive reduction in optimum moisture content together with the corresponding increase in maximum dry density from Gwagwalada to Zungeru deposits indicates improved compaction efficiency and greater structural densification. Higher dry densities generally promote better particle interlocking and reduced compressibility, thereby improving subgrade stability under traffic loading (Wang and Zhang, 2023; Zhang *et al.,* 2022).

The measured hydraulic conductivity values are typical of fine-grained expansive soils and indicate limited permeability. While low hydraulic conductivity restricts rapid water movement, it may also prolong moisture retention within the soil mass, thereby delaying pore-water pressure dissipation and extending periods of reduced subgrade strength following saturation. Similar hydro-mechanical behaviour has been reported for expansive clay deposits subjected to seasonal wetting and drying cycles (Soltani *et al.,* 2021; Cai *et al.,* 2025).

Among the investigated deposits, Sunti deposit exhibited the most favourable combination of hydro-mechanical properties, characterized by comparatively higher soaked CBR, lower moisture demand, and improved compaction characteristics. Conversely, Gwagwalada deposit displayed the least favourable hydro-mechanical response owing to its higher moisture demand, lower dry density, and reduced soaked strength. These differences indicate that the engineering performance of tropical black clays depends not on a single laboratory parameter but on the combined interaction of moisture demand, compaction characteristics, permeability, and strength.

The observed hydro-mechanical behaviour is consistent with the USCS and AASHTO classifications presented in Section 3.1. The predominance of CH, CL, and CL–CH soils classified within the A-7 group explains the generally poor soaked strength and moisture-sensitive behaviour of the investigated deposits. These findings provide the engineering basis for evaluating the integrated Hydro-Mechanical Stability Index (HMSI) presented in the subsequent section.

Computed Hydro-Mechanical Stability Index (HMSI)

The computed Hydro-Mechanical Stability Index (HMSI) values for the investigated tropical black clay deposits are presented in Table 5. Based on the distribution of the computed values, a preliminary stability classification framework was developed to facilitate engineering interpretation (Table 6).

Table 5: Computed HMSI Values and Preliminary Stability Classification

Location	HMSI	Stability Class
Gwagwalada	0.0397	Very Poor
Gidigidi	0.0744	Poor
Sunti	0.2263	Good
Zungeru	0.1722	Moderate

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Table 6: Proposed Preliminary HMSI Classification Framework

HMSI Range	Stability Class	Engineering Interpretation
< 0.05	Very Poor	Very high susceptibility to moisture-induced deterioration; unsuitable as an untreated pavement subgrade and stabilization is strongly recommended.
0.05–0.10	Poor	High moisture sensitivity with low resistance to hydro-mechanical deterioration; significant improvement measures are generally required before use.
0.10–0.20	Moderate	Moderate hydro-mechanical stability; suitable only under controlled conditions with appropriate drainage or stabilization measures.
0.20–0.25	Good	Good resistance to moisture-induced deterioration; satisfactory hydro-mechanical performance for most subgrade applications.
> 0.25	Excellent	Excellent hydro-mechanical stability with high resistance to moisture ingress and long-term engineering deterioration.

The computed HMSI values ranged from 0.0397 to 0.2263, indicating substantial differences in the hydro-mechanical stability of the investigated deposits. The observed variation reflects the combined influence of soaked strength, compaction characteristics, moisture demand, and hydraulic conductivity, demonstrating that no single engineering parameter adequately represents subgrade performance under moisture-sensitive conditions.

Sunti deposit recorded the highest HMSI value and was classified as Good stability, indicating the most favourable hydro-mechanical response among the investigated locations. This performance reflects the combined effect of relatively high soaked CBR, low moisture demand, favourable compaction characteristics, and moderate hydraulic conductivity. In contrast, Gwagwalada deposit exhibited the lowest HMSI value and was classified as Very Poor, indicating a greater susceptibility to moisture-induced deterioration resulting from its comparatively low soaked strength, high moisture demand, and lower dry density. Gidigidi and Zungeru deposits occupied intermediate positions, highlighting the influence of the combined engineering properties rather than any individual laboratory parameter.

The ranking produced by HMSI is consistent with the hydro-mechanical characteristics discussed in Section 3.2 and demonstrates that the proposed index provides a more integrated assessment of subgrade performance than conventional single-parameter approaches. While soaked CBR reflects load-bearing capacity under saturated conditions and compaction parameters describe soil densification, HMSI combines these properties with moisture demand and permeability into a single dimensionless measure of relative hydro-mechanical stability. This integrated assessment is particularly useful for comparing expansive soils with differing engineering characteristics.

The preliminary classification framework proposed in this study was derived directly from the distribution of the computed HMSI values obtained for the investigated tropical black clay deposits. Consequently, the threshold values should be regarded as initial engineering categories intended to facilitate comparative assessment rather than universally applicable classification limits. Further validation using larger datasets representing different geological formations, climatic conditions, and expansive soil types will be required before the proposed thresholds can be generalized.

The present results nevertheless demonstrate that HMSI provides a practical basis for ranking the relative stability of expansive tropical black clay subgrades using routinely determined laboratory parameters. This capability offers potential value for preliminary subgrade assessment, stabilization prioritization, and engineering decision-making, particularly where rapid evaluation of multiple moisture-sensitive deposits is required.

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Sensitivity Analysis and Preliminary Validation of the HMSI

To evaluate the robustness of the proposed HMSI, a local sensitivity analysis was performed to examine the influence of its constituent engineering parameters on the computed index values. The analysis was undertaken to verify that the proposed formulation responds consistently to variations in soaked California Bearing Ratio (CBR), maximum dry density (MDD), optimum moisture content (OMC), and hydraulic conductivity (k), which collectively govern the hydro-mechanical behaviour of expansive pavement subgrades.

A one-factor-at-a-time (OFAT) sensitivity approach was adopted, whereby each input parameter was varied independently by ±10% while the remaining parameters were maintained at their measured values. This approach is widely employed during the preliminary evaluation of engineering models to assess the influence of individual variables on model response (Montgomery *et al.,* 2011).

Table 7 summarizes the theoretical response of HMSI to variations in the constituent engineering parameters.

Table 7: Theoretical Response of HMSI to ±10% Variation in Individual Input Parameters

Parameter	−10 (%) Variation	Effect on HMSI	+10 (%) Variation	Effect on HMSI
Soaked CBR	−10	HMSI decreases	+10	HMSI increases
Maximum Dry Density	−10	HMSI decreases	+10	HMSI increases
Optimum Moisture Content	−10	HMSI increases	+10	HMSI decreases
Hydraulic Conductivity	−10	HMSI increases	+10	HMSI decreases

The sensitivity analysis demonstrates that the proposed HMSI exhibits a physically consistent response to variations in the governing hydro-mechanical parameters. Increases in soaked CBR and maximum dry density produced corresponding increases in HMSI because improved saturated strength and greater soil densification enhance subgrade stability. Conversely, increases in optimum moisture content and hydraulic conductivity reduced HMSI, indicating that greater moisture demand and enhanced water migration increase the susceptibility of expansive soils to hydro-mechanical deterioration.

The analysis further indicates that soaked CBR exerts the greatest engineering influence on the computed index because it directly represents the load-bearing capacity of the soil under saturated conditions. Maximum dry density also contributes positively by reflecting improved compaction and structural integrity, whereas optimum moisture content and hydraulic conductivity govern the moisture demand and permeability characteristics that influence long-term pavement performance. These observed trends are consistent with previous studies on expansive soils, which identified saturated strength, compaction characteristics, and moisture migration as the principal factors controlling hydro-mechanical behaviour (Soltani *et al.,* 2021; Wang and Zhang, 2023; Zhang *et al.,* 2022).

Although the present sensitivity analysis does not constitute external validation, it provides an important internal consistency check demonstrating that HMSI responds logically to changes in the governing engineering parameters. The results therefore support the conceptual basis of the proposed index. Nevertheless, the preliminary stability classes developed in this study were derived from the investigated dataset and should not be regarded as universal threshold values. Future studies should validate the proposed HMSI using larger datasets encompassing different geological formations, climatic conditions, and expansive soil types to establish more robust engineering classification boundaries.

Figure 2 presents a conceptual summary of the sensitivity of HMSI to changes in the constituent engineering parameters.

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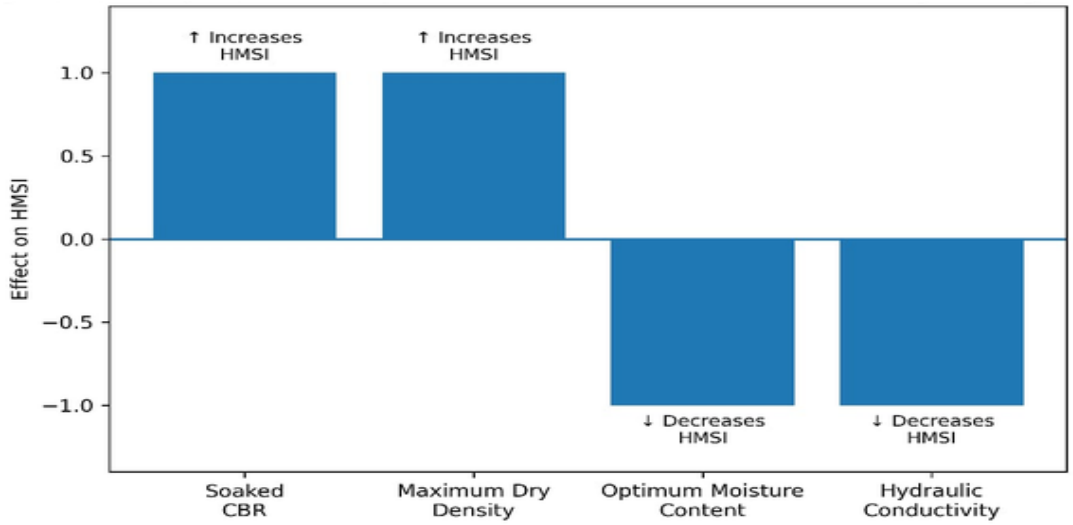


Figure 2: Conceptual Sensitivity of HMSI to Variations in Constituent Engineering Parameters
Figure 2 illustrate that positive changes in soaked CBR and maximum dry density increase HMSI, whereas increases in optimum moisture content and hydraulic conductivity reduce the computed index.

Engineering Implications of the Hydro-Mechanical Stability Index (HMSI)

The results demonstrate that the hydro-mechanical performance of expansive tropical black clays cannot be adequately described using a single conventional engineering parameter. Instead, subgrade behaviour is governed by the combined interaction of saturated strength, compaction characteristics, moisture demand, and hydraulic conductivity. This observation supports the need for an integrated evaluation framework capable of representing the coupled processes controlling moisture-induced deterioration.

The ranking produced by HMSI was consistent with the measured hydro-mechanical characteristics of the investigated deposits. Sunti and Zungeru deposits exhibited comparatively higher stability because they combined favourable compaction characteristics with lower moisture demand and improved saturated strength. Conversely, Gwagwalada and Gidigidi deposits displayed lower stability owing to their greater moisture sensitivity and reduced load-bearing capacity under saturated conditions. These findings agree with previous investigations showing that expansive soil performance depends on the combined influence of moisture migration, soil density, and strength degradation rather than any individual engineering property (Soltani *et al.,* 2021; Wang and Zhang, 2023; Zhang *et al.,* 2022).

From an engineering perspective, the proposed HMSI provides a practical means of comparing expansive subgrades using routinely determined laboratory parameters. Unlike conventional approaches that require separate interpretation of soaked CBR, compaction characteristics, permeability, and moisture content, HMSI integrates these variables into a single dimensionless index that facilitates rapid subgrade ranking and comparative assessment. Such an approach may assist engineers in identifying deposits requiring stabilization before construction and in prioritizing treatment where multiple expansive soil sites are encountered.

The proposed index is intended as a preliminary screening and decision-support tool rather than a replacement for detailed geotechnical investigation or pavement design procedures. Its principal advantage lies in providing a simple, integrated measure of relative hydro-mechanical stability that complements existing classification systems such as AASHTO and the Unified Soil Classification System (USCS). Consequently, HMSI has potential application in preliminary pavement investigations, subgrade evaluation, stabilization planning, and climate-resilient infrastructure development within tropical environments.

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Although the present results demonstrate the engineering usefulness of HMSI for the investigated tropical black clay deposits, the proposed framework should be regarded as preliminary. Future studies involving larger datasets from different geological settings and climatic regions are required to refine the classification boundaries, evaluate predictive performance, and establish the wider applicability of the proposed index.

3.6 Practical Applications of the Hydro-Mechanical Stability Index (HMSI)

The proposed HMSI provides a practical engineering tool for the preliminary evaluation of moisture-sensitive tropical black clay subgrades. By integrating soaked California Bearing Ratio (CBR), maximum dry density (MDD), optimum moisture content (OMC), and hydraulic conductivity into a single dimensionless parameter, the index facilitates rapid comparison of subgrade materials using laboratory tests routinely performed during geotechnical investigations.

The results demonstrate that HMSI can effectively distinguish between deposits exhibiting relatively higher and lower hydro-mechanical stability. Such differentiation is particularly useful during preliminary site investigations, where rapid identification of problematic subgrades can assist engineers in selecting appropriate stabilization strategies and prioritizing treatment where financial or construction resources are limited.

The proposed framework also has potential application in climate-resilient pavement engineering. As seasonal rainfall variability and extreme precipitation events increasingly influence pavement performance in tropical environments, integrated evaluation methods capable of accounting for both strength and moisture-related behaviour are becoming increasingly important. Because HMSI combines these characteristics within a single engineering parameter, it provides a useful supplementary indicator for assessing the relative vulnerability of expansive subgrades to moisture-induced deterioration (Soltani *et al.,* 2021; Wang and Zhang, 2023; Cai *et al.,* 2025).

It should be emphasized that HMSI is intended to complement rather than replace conventional geotechnical investigations. The index provides a preliminary screening and decision-support tool for subgrade ranking, stabilization planning, and comparative assessment of expansive soils. Broader validation using larger datasets are required before the proposed framework can be adopted for routine engineering practice.

3.7 Limitations and Future Research

The proposed HMSI represents a preliminary engineering framework for assessing the stability of moisture-sensitive tropical black clay subgrades. Accordingly, several limitations should be considered when interpreting the present findings.

First, the index was developed using representative tropical black clay deposits from four locations within North-Central Nigeria. Although these deposits exhibited appreciable variability in hydro-mechanical characteristics, the dataset is not sufficiently extensive to establish universally applicable classification thresholds. Consequently, the proposed stability classes should be regarded as preliminary engineering categories derived from the investigated dataset and require validation using larger databases representing different geological settings and climatic conditions.

Second, the present study provides an initial evaluation of HMSI based primarily on laboratory-derived engineering properties. While the sensitivity analysis demonstrated that the index responds logically to variations in its constituent parameters, further verification using independent field datasets, long-term pavement performance records, and additional expansive soil deposits is required to establish its predictive capability under practical engineering conditions.

Third, HMSI was formulated using four routinely determined laboratory parameters: soaked CBR, MDD, OMC, and hydraulic conductivity. Although these variables capture the principal hydro-mechanical characteristics governing subgrade behaviour, additional factors such as mineralogical composition, swelling pressure, matric suction, shrink–swell behaviour, and repeated wetting–drying cycles may further improve the predictive capability of the proposed framework.

Despite these limitations, the study demonstrates that HMSI provides a rational and internally consistent means of integrating strength, compaction characteristics, moisture demand, and

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permeability into a single dimensionless engineering parameter. The proposed framework therefore offers a practical basis for preliminary subgrade evaluation and establishes a foundation for future refinement of integrated hydro-mechanical assessment methods for expansive soils.

Future research should focus on validating HMSI using larger and more diverse datasets, comparing its performance with conventional subgrade evaluation methods, investigating its relationship with long-term field performance, and refining the proposed classification framework through advanced statistical analyses. Such studies would improve the robustness, general applicability, and engineering reliability of the proposed index.

4. CONCLUSIONS

This study developed a dimensionless Hydro-Mechanical Stability Index (HMSI) for evaluating the susceptibility of tropical black clay subgrades to moisture-induced deterioration. The proposed index integrates soaked California Bearing Ratio (CBR), maximum dry density (MDD), optimum moisture content (OMC), and hydraulic conductivity into a single engineering parameter for assessing the hydro-mechanical stability of expansive soils.

The investigated tropical black clay deposits were classified as predominantly expansive, moisture-sensitive soils with generally poor subgrade characteristics according to the Unified Soil Classification System (USCS) and AASHTO classification. Their hydro-mechanical behaviour varied among the investigated locations, reflecting differences in saturated strength, compaction characteristics, moisture demand, and permeability.

The computed HMSI successfully differentiated the investigated deposits according to their relative hydro-mechanical stability, demonstrating that the combined influence of multiple engineering properties provides a more comprehensive assessment of subgrade performance than conventional single-parameter approaches. The proposed preliminary stability framework therefore offers a practical basis for comparing moisture-sensitive tropical clay deposits and identifying subgrades that may require stabilization before construction.

The sensitivity analysis demonstrated that HMSI responds consistently to changes in its constituent engineering parameters, supporting the conceptual basis of the proposed formulation. In particular, improved saturated strength and compaction characteristics enhanced hydro-mechanical stability, whereas increased moisture demand and hydraulic conductivity reduced the computed index.

From an engineering perspective, HMSI provides a simple and practical screening tool that can complement conventional geotechnical investigations by supporting preliminary subgrade evaluation, stabilization prioritization, and pavement planning using routinely determined laboratory parameters. Although the proposed framework requires validation using larger datasets, different geological settings, and long-term field performance records, it establishes a useful foundation for developing integrated hydro-mechanical assessment methods for expansive tropical soils and contributes to the advancement of climate-resilient pavement engineering.

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