Quantifying Moisture Sensitivity and Collapse Risk in Tropical Black Clay Pavement Subgrades

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Abstract

This study presented a performance-based evaluation of tropical black clays obtained from four locations in North-Central Nigeria (Gwagwalada, Gidigidi, Sunti, and Zungeru) with the aim of quantifying moisture sensitivity and subgrade collapse risk. Laboratory investigations integrated index properties, particle size distribution, compaction characteristics under three energy levels: British Standard Light, West African Standard, and British Standard Heavy (BSL, WAS, BSH), soaked and unsoaked California Bearing Ratio (CBR), swelling potential, and hydraulic conductivity within a unified hydro-mechanical framework. The soils were fines-dominated (55–77% clay + silt) with liquid limits of 31.62–56.32% and plasticity indices of 14.78–22.87%, classifying them as A-6 to A-7 under AASHTO. Maximum dry density increased from 1.66 to 2.04Mg/m³ with increasing compactive effort, while optimum moisture content decreased from approximately 19 to 13%. Although unsoaked CBR values reached 1.93–15.60%, soaked CBR values declined drastically to 0.77–4.54%, representing strength reductions exceeding 70–90%. Swelling potentials ranged from 1.54–4.48%, and permeability values were extremely low (10^{-10}–10^{-9} m/s), indicating restricted drainage and prolonged saturation effects. Strength Collapse Ratio (SCR), defined as the ratio of soaked to unsoaked CBR, ranged from 0.07 to 0.33, revealing severe to very severe collapse behaviour. The results demonstrated that compaction improved dry-state strength but did not prevent hydro-mechanical instability under saturation. The study established that strength-retention metrics provided clearer differentiation of subgrade risk than index-based classification alone. A collapse-oriented performance framework was therefore proposed as a practical basis for moisture-sensitive pavement design in humid tropical expansive-soil terrains.

Keywords: Hydro-mechanical coupling; Matric suction dissipation; Strength collapse ratio (SCR); Unsaturated soil behavior; Expansive clay subgrades; Moisture-induced degradation; Performance-based pavement design

1. Introduction

Expansive clay subgrades continue to pose major engineering challenges in tropical and subtropical environments, where seasonal moisture fluctuations exert dominant control over soil behaviour. Unlike granular materials, fine-grained expansive soils exhibit strong hydro-mechanical coupling: variations in moisture alter matric suction, modify effective stress, and significantly influence stiffness and shear strength. Repeated wetting and drying cycles therefore induce swelling, shrinkage, and progressive loss of load-bearing capacity (Fredlund and Rahardjo, 1993; Vanapalli *et al.,* 1996). In regions characterised by intense rainfall and prolonged wet seasons, these processes accelerate pavement deterioration and increase maintenance demands.

International experience links expansive clay subgrades to premature pavement distress across Asia, Australia, and Africa (Chen and Zhang, 2021; Soltani *et al.,* 2022). The governing mechanism is primarily suction-dependent strength transition. Under dry or near-optimum moisture conditions, matric

suction contributes to apparent cohesion and moderate penetration resistance. As saturation develops, suction dissipates, interparticle forces weaken, and shear strength may decline abruptly (Fredlund and Rahardjo, 1993; Vanapalli *et al.,* 1996). This moisture-induced strength collapse represents a fundamental hydro-mechanical instability in fine-grained pavement foundations.

Tropical black clays (black cotton soils) are particularly susceptible to this behaviour. Characterised by high clay fractions, moderate to high plasticity, and very low permeability, these soils exhibit strong water affinity and slow drainage response. Once saturated, suction recovery is delayed and the soil may remain weakened for extended periods (Mamatha and Dinesh, 2017; Wang *et al.,* 2026). Studies on compactive energy and stabilisation confirm that black cotton soils often display substantial reductions in bearing capacity under soaked conditions (Ikeagwuani and Nwonu, 2019; Soltani *et al.,* 2022).

In Nigeria, tropical black clays are widely distributed across the North-Central and North-Eastern regions, underlying strategic highways and expanding urban corridors. Field observations show that pavements may perform satisfactorily during dry periods but deteriorate rapidly after rainfall, exhibiting rutting, cracking, and subgrade softening (Ola, 1978). Similar seasonal performance trends have been documented in other humid tropical environments (Chen and Zhang, 2021).

Traditional evaluation of expansive soils relies largely on index properties such as natural moisture content, Atterberg limits and particle size distribution. While these parameters indicate plasticity and consistency, they do not directly quantify strength degradation under environmental loading. Soils with comparable plasticity may respond differently depending on compaction state and moisture history (Fredlund and Rahardjo, 1993). Consequently, index-based classification alone may underestimate collapse vulnerability.

Performance-oriented assessment therefore emphasises strength parameters measured under realistic service conditions. The California Bearing Ratio (CBR) remains widely used for subgrade evaluation (Terzaghi *et al.,* 1996). However, in moisture-sensitive clays, the disparity between unsoaked and soaked CBR responses is critical. Unsoaked strength reflects both mechanical densification and suction-derived apparent cohesion, whereas soaked strength reflects the loss of suction and the true load-bearing condition under saturation (Pule and Yendaw, 2024; Soltani et al., 2022). The magnitude of strength reduction between these states provides a direct measure of seasonal performance risk.

This study presents a performance-based evaluation of tropical black clay subgrades from four representative locations in North-Central Nigeria: Gwagwalada, Gidigidi, Sunti, and Zungeru. Laboratory testing included index properties, compaction characteristics under varied energy levels, swelling potential, permeability, and both soaked and unsoaked CBR responses. The central objective is to quantify moisture-induced strength degradation and establish a practical collapse risk classification framework suitable for humid tropical pavement design.

2. Materials and Methods

2.1 Study Area and Sampling Framework

Field investigations were conducted at four strategically selected locations within North-Central Nigeria: Gwagwalada (Federal Capital Territory), Gidigidi (Nasarawa State), and Sunti and Zungeru (Niger State). These sites were chosen based on documented occurrences of tropical black clay deposits and recurring

reports of pavement deterioration linked to seasonal moisture fluctuations. The selection strategy was designed to capture spatial variability within a shared humid tropical climatic regime while representing different geological parent materials typical of the region.

The study area is characterised by a humid to sub-humid tropical climate with distinct wet and dry seasons. Extended rainfall during the wet season promotes sustained subgrade saturation, whereas high evapotranspiration rates in the dry season induce desiccation and shrinkage cracking in fine-grained soils. Such cyclic hydro-climatic loading directly influences matric suction, effective stress conditions, and stiffness response in expansive clays (Fredlund and Rahardjo, 1993; Vanapalli *et al.,* 1996). The climatic context is therefore integral to evaluating moisture sensitivity and collapse risk.

Geologically, the sampled localities include materials derived from sedimentary shale sequences, weathered Basement Complex formations, and alluvial deposits. These contrasting parent materials contribute to differences in clay mineralogy, particle-size distribution, and degree of weathering factors known to govern swelling behaviour, permeability characteristics, compaction response, and shear strength evolution in tropical clays (Ola, 1978; Soltani *et al.,* 2022). The multi-site design thus enables comparative assessment of hydro-mechanical performance across varied geological settings under similar climatic exposure.

At each locality, five trial pits were excavated to depths sufficient to intercept representative subgrade strata while avoiding organic-rich topsoil horizons. This yielded a total of twenty sampling points across the study region. Geographic coordinates were recorded using a handheld Global Positioning System (GPS) device to ensure spatial traceability and reproducibility of the sampling programme. The coordinates of all trial pits are presented in Table 1.

Disturbed soil samples were collected from each pit for laboratory determination of index properties, compaction characteristics, swelling potential, permeability, and California Bearing Ratio (CBR) under both soaked and unsoaked conditions. The dataset generated forms the basis for evaluating moisture-induced strength degradation and quantifying collapse risk.

Immediately after extraction, samples were sealed in airtight polyethylene bags and placed in rigid containers to minimise moisture exchange with the environment. Transport to the laboratory was undertaken promptly to preserve field moisture conditions and structural integrity prior to testing. Sample handling and preparation procedures followed established protocols for moisture-sensitive fine-grained soils in accordance with BS 1377 and relevant ASTM standards.

Table 1: Coordinates of the Trial Pits

Locality	Pit Code	Latitude (N)	Longitude (E)
Gwagwalada	GW-TP1	8.978056	7.120000
	GW-TP2	8.978611	7.121944
	GW-TP3	8.979167	7.120278
	GW-TP4	8.909167	7.263056
	GW-TP5	8.909722	7.263889
Gidigidi	GD-TP1	8.519450	8.491683
	GD-TP2	8.522403	8.495561
	GD-TP3	8.546003	8.474792
	GD-TP4	8.533589	8.480697
	GD-TP5	8.469506	8.446781
Sunti	SN-TP1	9.102213	5.232732
	SN-TP2	9.103752	5.233181
	SN-TP3	9.103502	5.232906
	SN-TP4	9.103541	5.234019
	SN-TP5	9.104281	5.231924
Zungeru	ZG-TP1	9.746127	6.136636
	ZG-TP2	9.743008	6.131425
	ZG-TP3	9.738153	6.131023
	ZG-TP4	9.739625	6.130235
	ZG-TP5	9.738452	6.129702

2.2 Laboratory Testing Programme

The laboratory programme was structured to characterise the hydro-mechanical behaviour of the sampled tropical black clays within a performance-oriented framework. Testing was designed not only to classify the soils but to quantify moisture-induced strength degradation relevant to pavement service conditions. The experimental matrix therefore included determination of index properties, compaction characteristics under multiple energy levels, soaked and unsoaked California Bearing Ratio (CBR), swelling potential, and hydraulic conductivity. All procedures were conducted in accordance with BS 1377 (2022; 1990 editions as applicable) and relevant ASTM standards to ensure reproducibility and comparability with established geotechnical practice.

2.2.1 Sample preparation

Disturbed samples were air-dried at ambient laboratory conditions and gently pulverised to break down aggregations without altering primary particle characteristics. Material was sieved through a 4.75mm mesh prior to testing. Care was taken to minimise mechanical disturbance of clay fractions, consistent with recommended procedures for fine-grained soils (Mitchell and Soga, 2005).

2.2.2 Index properties

Natural moisture content was determined using the oven-drying method at 105–110°C to constant mass in accordance with BS 1377-2 (2022). The in-situ moisture condition provides a baseline indicator of degree of saturation and expected compaction and strength behaviour. For expansive clays, moisture state is a primary control on matric suction and effective stress response (Fredlund and Rahardjo, 1993).

Particle size distribution (PSD) was established using mechanical sieve analysis for coarse fractions and hydrometer sedimentation for fine fractions in accordance with BS 1377-2 (2022), ASTM D6913/D6913M, and ASTM D7928. Grain-size distribution governs permeability, plasticity, and compressibility characteristics, thereby influencing both swelling potential and strength evolution (Mitchell and Soga, 2005).

Liquid limit (LL), plastic limit (PL), and plasticity index (PI) were determined using the Casagrande cup and rolling-thread methods in accordance with BS 1377-2 (2022) and ASTM D4318. Atterberg limits provide quantitative measures of soil consistency and plastic range, serving as indirect indicators of moisture sensitivity and shrink–swell susceptibility (Mitchell an Soga, 2005; Vanapalli et al., 1996).

2.2.3 Compaction characteristics

Compaction behaviour was evaluated under three energy regimes: British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH). Testing followed BS 1377-4 (1990) and ASTM D698 procedures as applicable. Moisture–density relationships were developed for each energy level, from which Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) were obtained. Compactive effort influences soil structure, pore distribution, and suction development, all of which affect post-compaction strength and moisture susceptibility. Evaluating multiple energy levels enables assessment of how densification modifies collapse vulnerability under subsequent saturation (Soltani *et al.,* 2022).

2.2.4 California bearing ratio (CBR) testing

CBR tests were performed on specimens compacted at their respective MDD and OMC under both unsoaked conditions, and 96-hour soaked conditions. Testing followed BS 1377-4 (1990) and ASTM D1883. The soaked–unsoaked comparison directly captures strength transition associated with suction

dissipation and pore-water pressure development. In expansive fine-grained soils, apparent cohesion contributed by matric suction under unsoaked conditions may artificially elevate short-term strength. Upon saturation, this suction component diminishes, potentially causing significant reductions in penetration resistance (Vanapalli *et al.,* 1996; Soltani *et al.,* 2022).

2.2.5 Swelling potential and hydraulic conductivity

Swelling potential was estimated using plasticity-based empirical correlations, which provide preliminary quantification of expansion susceptibility in fine-grained soils (Wang *et al.,* 2026; Mitchell and Soga, 2005). Although empirical, these relationships remain widely applied for screening expansive behaviour and supporting interpretation of shrink–swell risk and pavement heave potential.

Hydraulic conductivity was determined using laboratory permeability testing for fine-grained soils in accordance with BS 1377-5 (1990) and ASTM D5084. Permeability governs the rate of water ingress, suction dissipation, and pore-pressure equilibration under field wetting. Low hydraulic conductivity may prolong saturation effects and delay strength recovery, thereby increasing collapse risk in humid climates (Fredlund and Rahardjo, 1993; Chen and Zhang, 2021).

2.3 Quantification of strength collapse

A central objective of this study is to quantify moisture-induced degradation in load-bearing capacity. To achieve this, a Strength Collapse Ratio (SCR) was defined as:

$$SCR = \frac{\text{Soaked CBR}}{\text{Unsoaked CBR}} \qquad (1)$$

The SCR represents the proportion of dry-state strength retained after saturation. Values approaching unity indicate low moisture sensitivity, whereas lower ratios signify severe strength collapse upon soaking. Unlike conventional approaches that interpret soaked CBR values in isolation, the SCR framework captures relative degradation and directly reflects hydro-mechanical vulnerability. Collapse-based performance indicators have been increasingly recommended for expansive soil assessment because they provide more realistic prediction of field distress than classification indices alone (Puppala, 2021; Eze *et al.,* 2024).

Average parameter values were computed for each locality to enable spatial comparison. Integrated interpretation combine index properties, compaction response, swelling potential, permeability, and SCR values to develop a performance-based evaluation of subgrade collapse risk consistent with expansive soil geotechnics (Soltani *et al.,* 2022; Vanapalli *et al.,* 1996).

3. Results and Discussion

3.1 Index Properties and Soil Classification

3.1.1 Natural moisture content

The calculated average natural moisture content (NMC) of the tropical black clays varied between 17.07 and 24.49% across the study locations as presented in Table 2. These values indicated that the soils exist under moderate to relatively high field moisture states prior to any laboratory conditioning. In humid tropical environments, such moisture levels indicate partial suction reduction and an increased susceptibility to further strength degradation during seasonal wetting.
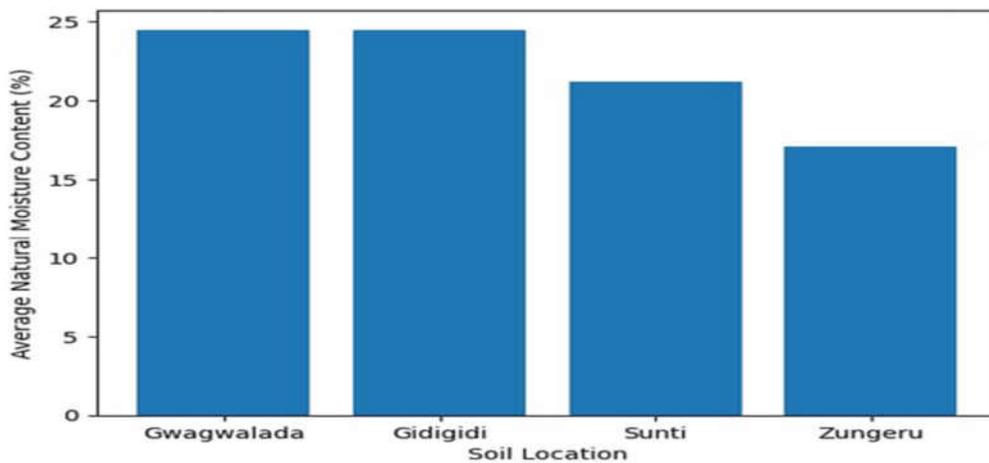
Table 2: Average Natural Moisture Content of the Soil Samples

Soil Location	Average NMC (%)	Moisture Condition Interpretation
Gwagwalada	24.49	High moisture affinity; near softened field state
Gidigidi	24.46	High natural moisture; moisture sensitive

Sunti	21.19	Moderate field moisture
Zungeru	17.07	Relatively low field moisture

Figure 1 illustrated the systematic increase in Gwagwalada and Gidigidi soils which exhibited the highest average NMC values (24.49% and 24.46%, respectively), whereas Sunti recorded intermediate moisture levels (21.19%), and Zungeru showed comparatively lower values (17.07%). Although the numerical differences appear modest, their hydro-mechanical implications are significant. Fine-grained soils near or approaching their compaction optimum moisture content typically experience reduced matric suction and diminished apparent cohesion. Consequently, additional wetting result in rapid transition toward near-saturated conditions, accompanied by stiffness reduction and collapse in penetration resistance.

In expansive clay systems, natural moisture state acts as a precursor to seasonal performance behaviour. Soils existing closer to equilibrium moisture or softened field conditions required relatively small increments of water ingress to trigger suction dissipation and effective stress loss (Fredlund and Rahardjo, 1993; Vanapalli *et al.,* 1996). The elevated NMC values observed in Gwagwalada and Gidigidi soils therefore indicated higher intrinsic moisture sensitivity compared to Zungeru soils, where lower field moisture implies greater initial suction and potentially higher dry-season strength retention.

Figure 1: Average Natural Moisture Content of the Studied Soils

Importantly, natural moisture content alone does not define collapse risk; however, it established the initial hydro-mechanical boundary condition from which strength transitions occur. In the present study, the NMC results indicated that subgrades at Gwagwalada and Gidigidi will operate closer to softened states under field conditions, thereby increasing vulnerability to saturation-induced strength loss during prolonged rainfall events.

### 3.1.2 Atterberg limits and plasticity characteristics

The Atterberg limit results indicated that the investigated soils span moderate to high plasticity, with liquid limit (LL) values ranging from 31.62 to 56.32% and plasticity index (PI) values between 14.78 and 22.87% as presented in Table 3. These ranges implied varying degrees of moisture sensitivity and suction-dependent strength behaviour across the study locations.

Table 3: Average Atterberg Limits, Gradation and Soil Classification

Soil Location	LL (%)	PL (%)	PI (%)	% Clay	% Silt	% Sand	% Gravel	USCS Classification
Gwagwalada	56.32	33.45	22.87	55.76	21.08	16.64	6.33	CH (High

								plastic clay)
Gidigidi	31.62	16.84	14.78	22.74	40.72	35.86	0.65	CL (Low–medium plastic clay)
Sunti	32.87	16.84	16.02	24.48	49.47	25.29	0.75	CL (Low–medium plastic clay)
Zungeru	37.90	17.44	20.46	29.94	51.33	14.21	4.49	CL (Upper range plastic clay)

Figure 2 illustrated that Gwagwalada soils recorded the highest LL (56.32%) and PI (22.87%), classifying the soil as CH under the Unified Soil Classification System (USCS). This classification reflected a high plasticity clay with significant shrink–swell potential and strong affinity for water. Elevated PI values are commonly associated with increased clay activity, higher surface area, and greater susceptibility to volumetric and strength changes upon wetting (Mitchell and Soga, 2005). In hydro-mechanical terms, high-plasticity clays tend to derive a substantial proportion of their short-term strength from matric suction; consequently, loss of suction during saturation can result in pronounced collapse behaviour (Vanapalli *et al.,* 1996). Gidigidi and Sunti soils fall within the CL category, exhibiting lower LL and PI values indicative of low to medium plasticity. Although less plastic than the Gwagwalada deposit, these soils still contained appreciable clay fractions (22.74–49.47%) and therefore retained moisture-sensitive characteristics. Zungeru soils, while classified as CL, occupy the upper plasticity range within this category, with a PI of 20.46%. This places them near the threshold where expansive tendencies become more pronounced.
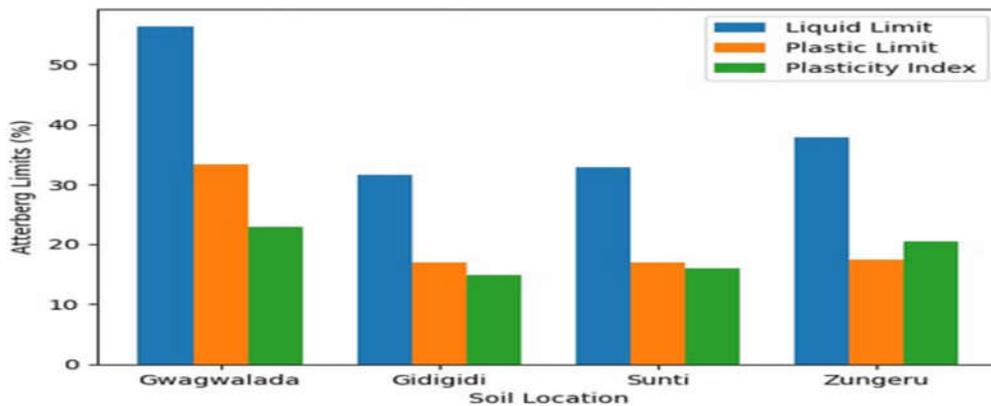
Figure 2: Average Atterberg Limits of theoils

The gradation data further support these interpretations. Gwagwalada soils exhibited the highest clay fraction (55.76%), reinforcing its CH classification and explaining its elevated PI. In contrast, Gidigidi soils contained a comparatively higher sand fraction (35.86%) and lower clay content, which likely moderated its plasticity and reduces swelling intensity. Sunti and Zungeru soils displayed intermediate clay contents, indicating moderate but non-negligible expansion potential. From a performance perspective, plasticity index values exceeding approximately 20% are frequently associated with increased moisture sensitivity and transition toward suction-controlled strength behaviour (Mitchell and Soga, 2005; Soltani *et al.,* 2022). The Gwagwalada deposit clearly exceeded this threshold, while Zungeru deposit approached it. These observations implied that, even before strength testing, the plasticity characteristics already signal elevated collapse susceptibility under seasonal wetting.

It is important to emphasise, however, that plasticity indices alone do not quantify strength degradation. While they provide indirect indication of expansive behaviour, the true measure of collapse vulnerability lies in the magnitude of strength reduction upon saturation. The plasticity results therefore serve as

preliminary indicators that must be evaluated alongside compaction response and soaked–unsoaked CBR behaviour to establish a performance-based collapse risk classification.

3.1.3 Particle size distribution and textural implications

The investigated soils are predominantly fine-grained, with combined clay and silt contents ranging from approximately 55 to 77% as presented in Table 4. Such fines-dominated gradation profiles are characteristic of subgrades exhibiting low permeability, high moisture retention capacity, and suction-sensitive mechanical behaviour.

Table 4: Average Particle Size Fractions of the Soils

Soil Location	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Texture Interpretation
Gwagwalada	55.76	21.08	16.64	6.33	Clay dominated cohesive soils
Gidigidi	22.74	40.72	35.86	0.65	Silty clay with sandy influence
Sunti	24.48	49.47	25.29	0.75	Silty clay
Zungeru	29.94	51.33	14.21	4.49	Fine grained silty clay

Figure 3 illustrated that Gwagwalada soils contains the highest clay fraction (55.76%), confirming its classification as a clay-dominated cohesive soil. High clay content implies greater surface area, enhanced water adsorption, and stronger physico-chemical interaction between particles and pore fluid. These characteristics typically result in low hydraulic conductivity and pronounced shrink–swell tendencies. The textural composition therefore supports the elevated plasticity and moisture sensitivity observed. Gidigidi soils exhibited a comparatively lower clay fraction (22.74%) and a higher sand proportion (35.86%). The increased coarse fraction introduced greater particle interlocking and improved drainage pathways relative to the other locations. This gradation profile likely moderates plasticity and reduces extreme expansion behaviour. However, the substantial silt content (40.72%) still rendered the soil sensitive to moisture variation, particularly under prolonged wetting. Sunti and Zungeru soils are predominantly silty clays, with silt fractions exceeding 49% and clay contents between 24 and 30%. Although less clay-rich than Gwagwalada deposit, the high proportion of fine particles indicate restricted permeability and delayed pore-pressure dissipation during saturation. Silty clays often exhibited moderate plasticity but can experience significant strength degradation when suction is reduced, especially under cyclic wetting–drying regimes.
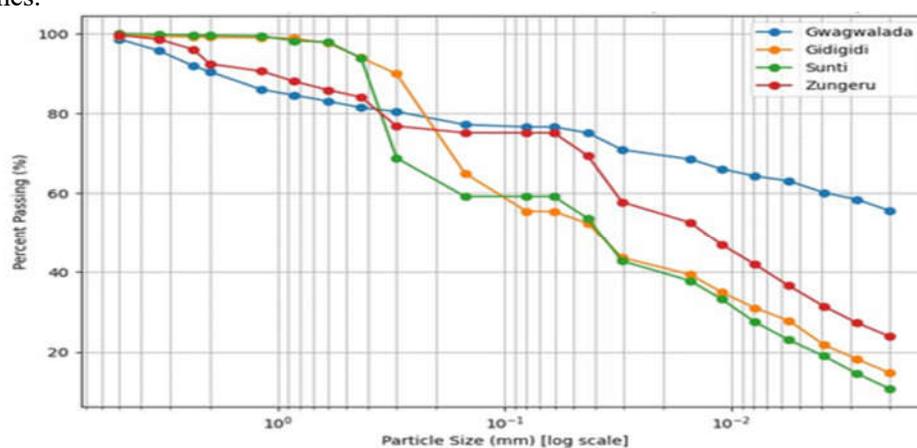
Figure 3: Combined Particle Size Distribution + Sedimentation Curves for Studied Soils

From a hydro-mechanical perspective, fine-grained dominance governed two critical aspects of subgrade behaviour: (i) Hydraulic response, through low permeability and slow drainage, and (ii) Mechanical response, through suction-controlled apparent cohesion and moisture-dependent stiffness.

Soils with high fines content tend to maintain elevated matric suction under partially saturated conditions. When subjected to saturation, dissipation of suction will occur gradually due to low permeability, prolonging the softened state and exacerbating strength loss (Fredlund and Rahardjo, 1993; Chen and Zhang, 2021).

Importantly, the gradation data reinforce the earlier plasticity interpretation: Gwagwalada soils represented the most clay-rich and potentially collapse-prone deposit, while Gidigidi's higher sand content will offer comparatively improved drainage and structural stability. Sunti and Zungeru soils occupied intermediate positions, where high silt fractions contributed to moderate but persistent moisture sensitivity. Thus, particle size distribution established the structural and hydraulic foundation for compaction behaviour and moisture-induced strength.

3.1.4 AASHTO subgrade classification

The soils were classified in accordance with the American Association of State Highway and Transportation Officials (AASHTO) M 145 system using liquid limit and plasticity index parameters (Table 5). The grouping placed the investigated soils within A-6 and A-7 categories, confirming their classification as poor to very poor subgrade soils from a pavement design perspective.

Table 5: AASHTO Classification of the Investigated Soils

Soil Location	Liquid Limit, LL (%)	Plasticity Index, PI (%)	AASHTO Group	Subgrade Interpretation
Gwagwalada	56.32	22.87	A-7 (A-7-6)	Very poor subgrade; highly plastic clay
Gidigidi	31.62	14.78	A-6	Poor subgrade; moderate plastic clay
Sunti	32.87	16.02	A-6	Poor subgrade; moderate plastic clay
Zungeru	37.90	20.46	A-6	Poor subgrade; moderate plastic clay

Gwagwalada soils was assigned to the A-7-6 subgroup, which represented highly plastic clayey soils exhibiting pronounced moisture sensitivity and low bearing capacity under saturated conditions. Soils within this category are typically associated with significant shrink–swell behaviour and substantial reduction in strength upon wetting. The A-7-6 designation therefore aligned with the earlier identification of high plasticity and elevated clay content for this deposit. Gidigidi, Sunti, and Zungeru soils were classified as A-6 soils. Although less plastic than A-7 soils, A-6 soils are still regarded as unsuitable for direct use as pavement subgrades without modification, particularly in climates subjected to seasonal saturation. Their moderate plasticity and fine-grained composition indicated susceptibility to moisture-induced strength loss, even if volumetric expansion is less severe than in highly plastic clays. From a pavement engineering standpoint, A-6 and A-7 soils are generally associated with low soaked CBR values and reduced resilient performance under repeated loading. Field and laboratory observations in humid environments frequently reported soaked CBR values below 5% for untreated A-6/A-7 subgrades, necessitating stabilisation or structural reinforcement to ensure durability (Soltani *et al.,* 2022).

However, it is important to recognise the limitations of the AASHTO system. While it provided a practical index-based assessment of subgrade quality, it does not quantify the magnitude of strength degradation between dry and saturated states. Two soils within the same AASHTO group may exhibit markedly different collapse severity depending on compaction energy, suction state, and hydraulic response. Consequently, AASHTO classification should be interpreted as an initial screening tool rather than a definitive predictor of hydro-mechanical vulnerability. In the present study, the A-6/A-7 grouping confirmed that all deposits possess inherently weak subgrade characteristics. Nonetheless, the true extent of seasonal collapse risk must be evaluated through quantitative strength comparisons under soaked and unsoaked conditions, as developed in subsequent sections.

3.2 Compaction Characteristics

The compaction results demonstrated a consistent response to increasing compactive effort across all locations as presented in Table 6. Maximum dry density (MDD) increased progressively from British Standard Light (BSL) to West African Standard (WAS) to British Standard Heavy (BSH), while optimum moisture content (OMC) generally decreased with increasing energy input. This behaviour is characteristic of fine-grained soils subjected to incremental densification.

Table 6: Summary of Average MDD and OMC of the Soils

Soil Location	BSL		WAS		BSH	
	OMC (%)	MDD (Mg/m³)	OMC (%)	MDD (Mg/m³)	OMC (%)	MDD (Mg/m³)
Gwagwalada	19.46	1.66	15.70	1.75	13.23	1.90
Gidigidi	16.36	1.75	16.41	1.80	14.22	1.93
Sunti	16.36	1.77	16.50	1.82	14.22	1.96
Zungeru	15.03	1.81	15.77	1.90	14.33	2.04

From a mechanistic standpoint, higher compactive effort reduced void ratio by forcing closer particle arrangement and breaking down weak interparticle bonds. The accompanying reduction in OMC reflected a shift in the moisture–density relationship: at higher energy levels, less water is required to achieve lubrication sufficient for particle rearrangement because mechanical energy increasingly dominates over capillary effects (Mitchell and Soga, 2005).

Across the study locations, average MDD values ranged from 1.66 to 2.04Mg/m³. Zungeru soils consistently exhibited the highest dry densities under all compactive efforts, reaching 2.04Mg/m³ under BSH. This relatively high densification potential is consistent with its lower clay fraction and greater proportion of silt and sand, which facilitate improved packing and reduced interparticle repulsion. In contrast, Gwagwalada soils recorded the lowest MDD values, particularly under BSL (1.66Mg/m³). The elevated clay content and high plasticity of this deposit likely promote dispersed fabric structures and increased water adsorption, both of which restrict efficient particle packing. The reduction in OMC with increasing compactive effort is particularly relevant to collapse assessment. Under higher compaction energies, soils are compacted at lower moisture contents, meaning that the compacted state will retain higher matric suction. While this condition will enhance short-term penetration resistance under unsoaked testing, it also created greater potential for strength reduction upon subsequent wetting. In other words, densification will improve immediate bearing capacity, but it does not eliminate hydro-mechanical vulnerability.

The interplay between density and suction is therefore central to understanding collapse behaviour. Higher MDD generally corresponds to lower initial void ratio and improved interparticle contact. However, in highly plastic clays, the structural fabric formed during compaction remained moisture-sensitive. Upon saturation, suction dissipation can lead to rapid softening regardless of achieved density. Thus, although compactive effort enhances structural stiffness in the dry state, it does not necessarily prevent strength degradation in saturated conditions. A comparative assessment showed that soils with lower clay content (Zungeru soils) achieved higher densities and exhibited comparatively reduced collapse severity, whereas highly plastic soils (Gwagwalada soils) achieved lower densities and are structurally predisposed to greater moisture-induced degradation.

3.3 California Bearing Ratio Behaviour

The CBR results revealed a pronounced contrast between dry-state and saturated strength, highlighting the hydro-mechanical vulnerability of the investigated tropical black clays. Across all locations and compactive efforts, soaked CBR values remained critically low, while unsoaked strengths increased substantially under higher densification. This disparity forms the basis for quantifying moisture-induced collapse.

3.3.1 Soaked CBR response

Soaked CBR values ranged between 0.77 and 4.54% as presented in Table 7, confirming extremely weak load-bearing capacity under saturated conditions. Even under British Standard Heavy (BSH) compaction, soaked values remained below 3% for most locations, indicating that densification alone did not mitigate saturation-induced softening.

Gwagwalada soils exhibited the lowest soaked strengths (0.77–0.99%), consistent with its high clay fraction and elevated plasticity. Such low values indicate near-complete loss of suction-derived apparent cohesion upon saturation. Gidigidi and Zungeru soils displayed slightly higher soaked strengths, yet these remained well below conventional pavement design thresholds. Sunti recorded comparatively higher values (up to 4.54%), but still within the range considered poor for untreated subgrades.

Table 7: Average Soaked CBR Values for the Soils

Soil Location	British Standard Heavy (BSH)	British Standard Light (BSL)	West African Standard (WAS)
Gwagwalada	0.99	0.86	0.77
Gidigidi	1.89	1.55	1.37
Sunti	3.46	4.54	4.03
Zungeru	2.02	1.56	2.21

From a mechanistic standpoint, the soaked condition eliminated matric suction, which contributed to apparent cohesion in partially saturated soils (Vanapalli *et al.,* 1996). Once suction dissipated, interparticle forces weaken, effective stress reduced, and the soil structure transitions toward a softened state. The consistently low soaked CBR values therefore confirmed that these deposits derive a substantial proportion of their dry-state strength from suction rather than frictional resistance alone. Similar trends have been widely reported for expansive clays subjected to saturation (Soltani *et al.,* 2022).

3.3.2 Unsoaked CBR response

In contrast, unsoaked CBR values varied from 1.93 to 15.60% as presented in Table 8, with strength increasing systematically under higher compactive effort. British Standard Heavy (BSH) compaction produced the highest unsoaked strengths across all locations, demonstrating the beneficial effect of densification under partially saturated conditions.

Zungeru soils achieved the highest unsoaked strength (15.60% under BSH), likely reflecting its higher achievable density and lower clay activity. Gwagwalada soils also exhibited substantial strength gain under BSH (13.84%), despite its high plasticity. This indicated that densification improved interparticle contact and stiffness in the dry state.

Table 8: Average Unsoaked CBR Values for the Soils

Soil Location	British Standard Heavy (BSH)	British Standard Light (BSL)	West African Standard (WAS)
Gwagwalada	13.84	1.93	7.04
Gidigidi	7.53	4.54	4.93
Sunti	10.59	4.66	5.88
Zungeru	15.60	8.53	14.06

However, the unsoaked strength enhancement must be interpreted cautiously. In fine-grained soils, unsoaked CBR reflected the combined effects of mechanical densification and suction-induced apparent cohesion. Consequently, elevated unsoaked values do not necessarily translate to reliable in-service performance in humid environments. The large disparity between unsoaked and soaked results indicated that a significant portion of dry-state resistance is suction-dependent and therefore vulnerable to seasonal wetting (Chen and Zhang, 2021).

3.3.3 Influence of compactive energy

Compactive effort had a clear and consistent influence on unsoaked CBR, but only marginal impact on soaked CBR. Increasing energy from BSL to BSH significantly enhanced dry-state strength, yet produced negligible improvement under saturated conditions. This behaviour highlights a critical design implication. While higher compaction reduces void ratio and improved dry density, it does not fundamentally alter the soil's mineralogical or physico-chemical response to water. Upon saturation, suction loss and clay–water interaction dominate mechanical behaviour, effectively overriding the benefits of densification. This limitation of compaction-only strategies in expansive subgrades has been widely recognised (Soltani *et al.,* 2022). In essence, compaction enhanced short-term structural stiffness but does not eliminate hydro-mechanical instability. The persistence of low soaked CBR values even at high compactive effort underscores the need for performance metrics that explicitly quantify collapse severity rather than relying solely on density improvement.

3.4 Swelling and Permeability Behaviour

The swelling and permeability characteristics provide important insight into the hydro-mechanical mechanisms governing long-term subgrade performance. While CBR testing quantifies strength degradation, swelling and hydraulic conductivity explain the persistence and progression of that degradation under field conditions.

3.4.1 Swelling behaviour

Estimated swelling potentials ranged from 1.54 to 4.48% as presented in Table 9, placing all soils within the moderate expansion category under United States Bureau of Reclamation (USBR) classification. Although not classified as highly expansive, these values are sufficient to induce pavement heave, cracking, and loss of surface integrity when cyclic wetting occurs.

Gwagwalada soils exhibited the highest swelling potential (4.48%), consistent with its elevated plasticity and clay fraction. Zungeru soils followed with 3.41%, reflecting its upper-range plasticity despite moderate clay content. Gidigidi and Sunti soils displayed lower expansion values, yet still within the moderate category, indicated that volumetric instability remained a concern across all locations.

Table 9: Degree of Expansion of Soil Samples (USBR Classification)

Soil Location	Plasticity Index (%)	Swelling Potential (%)	Degree of Expansion
Gwagwalada	22.87	4.48	Medium
Nasarawa	14.78	1.54	Medium
Sunti	16.02	1.88	Medium
Zungeru	20.46	3.41	Medium

From a hydro-mechanical perspective, swelling is driven by physico-chemical interaction between clay minerals and pore water. Upon wetting, absorbed water increased interparticle spacing and reduced effective stress, leading to volume increase and stiffness reduction. Although moderate in magnitude, repeated seasonal expansion and contraction can progressively degrade pavement support conditions (Fredlund and Rahardjo, 1993; Wang *et al.,* 2026). It is important to emphasise that even moderate swelling, when combined with very low soaked strength, can produce disproportionate structural damage. Therefore, swelling potential should be interpreted in conjunction with strength collapse indicators rather than as a standalone metric.

3.4.2 Hydraulic conductivity

The measured coefficients of permeability ranged between approximately 8.34×10^{-10} and 1.21×10^{-9} m/s as presented in Table 10, indicating extremely low hydraulic conductivity characteristic of fine-grained cohesive soils. Such low permeability values have two major implications: (i) Restricted drainage

capacity – Water infiltrating the subgrade during rainfall events dissipated slowly, prolonging the duration of near-saturated conditions. (ii) Delayed suction recovery – After saturation, pore-water pressure equalisation and suction re-establishment occur gradually, extending the softened state.

Although Gwagwalada, Gidigidi, and Sunti soils exhibited similar permeability magnitudes, Zungeru soils showed slightly lower hydraulic conductivity, indicating even slower drainage potential. However, all values fall within the same order of magnitude, reinforcing the fines-dominated hydraulic behaviour identified in the particle size analysis.

Table 10: Hydraulic Conductivity Results for the Soils

Soil Location	Coefficient of permeability, k (m/s)
Gwagwalada	1.19×10^{-9}
Gidigidi	1.21×10^{-9}
Sunti	1.08×10^{-9}
Zungeru	8.34×10^{-10}

In fine-grained tropical clays, low permeability amplified moisture-induced strength collapse by maintaining elevated water content and preventing rapid recovery of suction-dependent strength. Consequently, densification alone cannot compensate for hydraulic limitations; once saturated, the soil may remain weakened for extended periods.

3.4.3 Hydro-Mechanical implications for collapse risk

The combination of moderate swelling potential and extremely low permeability creates a hydro-mechanical environment conducive to long-term subgrade instability. Upon wetting, matric suction dissipated, apparent cohesion reduced, volume expansion occurred, drainage restricted, and softened conditions persisted. This coupled behaviour explained why soaked CBR values remained critically low despite increased compactive effort. In humid climates characterised by prolonged rainfall cycles, such hydro-mechanical interaction becomes a fundamental driver of pavement distress (Fredlund and Rahardjo, 1993; Chen and Zhang, 2021; Wang *et al.,* 2026). Therefore, swelling and permeability results provided the physical basis for the collapse severity observed in CBR behaviours. They demonstrated that moisture-induced degradation is not merely a short-term laboratory artefact, but a realistic and persistent field condition for tropical black clay subgrades.

3.5 Strength Collapse Ratio and Subgrade Risk Classification

The comparison between unsoaked and soaked CBR responses revealed pronounced moisture-induced strength degradation across all investigated soils. Reductions in bearing capacity commonly exceeded 70–90%, confirming that a substantial portion of dry-state strength is suction-dependent and vulnerable to seasonal saturation. To quantify collapse severity, the Strength Collapse Ratio (SCR) was computed under British Standard Heavy (BSH) compaction energy. The strength collapse ratio of the investigated soils are presented in Table 11. These values ranged from 0.07 to 0.33 which revealed severe collapse of the soils.

Table 11: Strength Collapse Ratio (SCR) of the Soils (BSH Condition)

| Location	Unsoaked CBR (%) – BSH	Soaked CBR (%) – BSH	Strength Collapse Ratio (SCR)	Collapse Severity Interpretation
Gwagwalada	13.84	0.99	0.07	Very severe collapse
Gidigidi	7.53	1.89	0.25	Severe collapse
Sunti	10.59	3.46	0.33	Moderate–severe collapse
Zungeru	15.60	2.02	0.13	Very severe collapse

Gwagwalada soils exhibited the lowest SCR (0.07), which implied that only 7% of dry-state strength is retained after soaking. This reflected extreme suction dependency and confirmed the hydro-mechanical instability observed from its high plasticity and clay fraction. Zungeru soils, despite achieving the highest

unsoaked CBR (15.60%), recorded an SCR of 0.13, demonstrating that high dry density does not necessarily translate to collapse resistance. This finding highlighted the limitation of relying solely on unsoaked strength for subgrade assessment.

Gidigidi soils displayed an SCR of 0.25, while Sunti soils recorded the highest ratio (0.33). Although Sunti deposit retained approximately one-third of its dry-state strength after saturation, this still represented substantial collapse relative to design expectations for durable pavement foundations.

From a performance-based perspective, SCR provided a more meaningful indicator of subgrade vulnerability than absolute soaked CBR values alone. Two soils can exhibit similar soaked strengths but differ significantly in collapse severity depending on their dry-state capacity. By capturing the proportion of strength retained after saturation, SCR directly reflected seasonal serviceability risk.

Figure 4 illustrated that horizontal threshold lines at SCR = 0.15 and SCR = 0.30 delineated collapse severity categories: SCR < 0.15 indicated very severe collapse, $0.15 \leq$ SCR < 0.30 indicated severe collapse, and SCR $\geq$ 0.30 indicated moderate–severe collapse. Gwagwalada and Zungeru deposits exhibited very severe strength loss despite differences in dry-state strength, while Gidigidi deposit falls within the severe category and Sunti deposit demonstrated comparatively higher but still inadequate strength retention. The figure highlighted the pronounced moisture-induced vulnerability of tropical black clay subgrades and supports collapse-based performance classification.
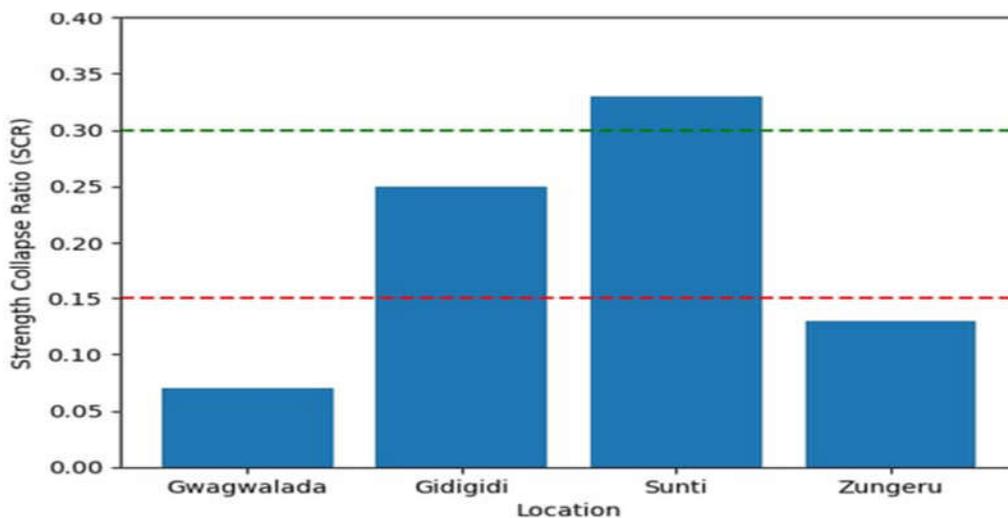
Figure 4: Strength Collapse Ratio (SCR) with Collapse Thresholds

Based on the computed ratios, a preliminary collapse risk classification is proposed and presented in Table 12.

Table 12: Collapse Risk Classification

SCR Values	Performance Behaviour	Risk Factor
SCR < 0.15	Very severe collapse	Very high risk
$0.15 \leq$ SCR < 0.30	Severe collapse	High risk
$0.30 \leq$ SCR < 0.50	Moderate–severe collapse	Moderate–high risk

According to this framework, Gwagwalada and Zungeru soils fall within the very severe to severe collapse range, Gidigidi soils represented severe collapse, and Sunti deposit falls within moderate–severe collapse.

Importantly, Zungeru's strong unsoaked performance but low SCR underscored a key insight of this study that dry strength alone is not a reliable predictor of long-term performance in humid tropical environments. Strength-loss-based evaluation more accurately reflected seasonal deterioration mechanisms governed by suction dissipation and moisture–clay interaction (Vanapalli *et al.,* 1996; Soltani *et al.,* 2022). Thus, collapse quantification provided the central analytical contribution of this work, shifting assessment from classification-based interpretation toward hydro-mechanically informed performance evaluation.

3.6 Comparison of unsoaked and soaked CBR with SCR and Collapse Thresholds (BSH)

In Figure 5, the bars represented unsoaked and soaked CBR values, while the line denoted the Strength Collapse Ratio (SCR). Horizontal dashed lines at SCR = 0.15 (red) and SCR = 0.30 (green) indicated collapse severity thresholds distinguishing very severe, severe, and moderate–severe strength degradation. The figure illustrated the pronounced disparity between dry-state and saturated strength and highlights the limited effectiveness of compaction in mitigating moisture-induced collapse in tropical black clay subgrades.

The composite representation of soaked CBR, unsoaked CBR, and SCR provided an integrated view of strength transition under environmental change. While unsoaked CBR values under BSH compaction reached 7.53–15.60%, soaked strengths declined sharply to 0.99–3.46%, confirming severe hydro-mechanical weakening upon saturation. The figure clearly demonstrated that densification substantially improved dry-state penetration resistance but exerted only marginal influence on saturated strength. For example, Zungeru deposit achieved the highest unsoaked CBR (15.60%), yet its SCR (0.13) placed it within the very severe collapse category. This indicated that a significant proportion of its dry-state strength was suction-dependent and therefore unstable under wet conditions. Similarly, Gwagwalada deposit exhibited relatively high unsoaked strength (13.84%) but retained only 7% of that capacity after soaking. The inclusion of collapse severity thresholds further highlighted the disparity between apparent performance and true serviceability risk. While absolute soaked CBR values alone classified all soils as weak, the SCR metric differentiated relative vulnerability. Sunti deposit retained approximately one-third of its dry-state strength (SCR = 0.33), positioning it in the moderate–severe category, whereas Gwagwalada and Zungeru deposits exhibited very severe collapse behaviour (SCR < 0.15). This integrated view reinforced a critical hydro-mechanical insight that compaction increased density and short-term stiffness but does not eliminate suction-governed instability. Once matric suction dissipated, pore-water pressure effects dominated, interparticle bonding weakened, and strength collapsed irrespective of achieved dry density (Vanapalli *et al.,* 1996; Soltani *et al.,* 2022).

From a pavement engineering perspective, the composite figure demonstrated that performance assessment based solely on unsoaked CBR or compaction compliance will significantly overestimate in-service capacity. Strength-retention metrics such as SCR provided a more realistic representation of seasonal performance under humid tropical conditions, where saturation events are unavoidable. The combined CBR–SCR representation therefore substantiated the central premise of this study: collapse severity, rather than absolute strength alone, governed long-term subgrade reliability in tropical black clays.
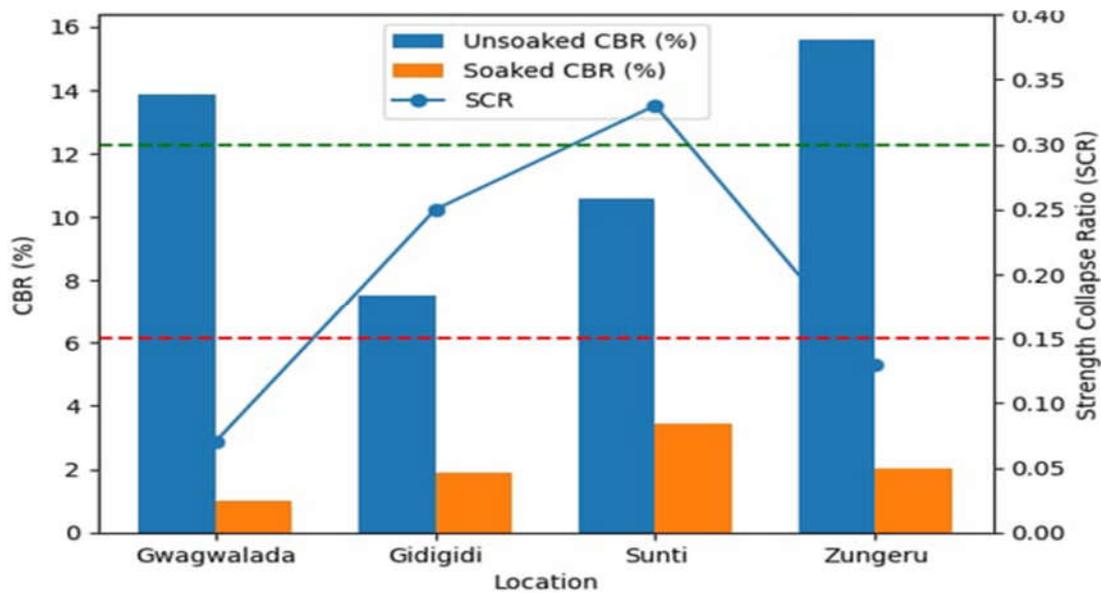
Figure 5: Composite comparison of unsoaked and soaked CBR with SCR and Collapse Thresholds (BSH)

3.7 Implications for Pavement Engineering

The integrated findings of plasticity, compaction behaviour, hydraulic characteristics, and SCR analysis yielded several practical implications for pavement design in humid tropical regions:

Compaction alone is insufficient: While higher compactive effort improved dry density and unsoaked CBR, it does not prevent suction loss and strength collapse under saturation. Reliance on density improvement without moisture management may provide only short-term performance gains.

Moisture control is critical: Extremely low permeability combined with moderate swelling potential promotes prolonged saturation and delayed suction recovery. Effective drainage systems, surface sealing, and moisture barriers are essential to mitigate collapse risk.

Ground improvement may be required: For soils exhibiting SCR < 0.30, stabilisation using lime, cementitious additives, or other chemical modification techniques should be considered to reduce plasticity, improve stiffness, and enhance wet-state strength retention.

Performance-based evaluation should replace index-only classification: Traditional systems such as AASHTO grouping identify poor-quality subgrades but do not quantify collapse severity. Incorporating strength-retention metrics such as SCR enables more realistic prediction of seasonal serviceability failure.

These findings aligned with expansive soil management strategies, which emphasised hydro-mechanical coupling, moisture regulation, and stabilisation for resilient infrastructure in wet–dry climatic regimes (Chen and Zhang, 2021; Soltani *et al.,* 2022; Wang *et al.,* 2026).

4. Conclusions

This study presented a performance-based geotechnical evaluation of tropical black clay subgrades from Gwagwalada, Gidigidi, Sunti, and Zungeru in North-Central Nigeria. By integrating index properties, compaction behaviour, strength under soaked and unsoaked conditions, swelling potential, permeability,

and Strength Collapse Ratio (SCR), the research established a hydro-mechanical framework for quantifying moisture sensitivity and subgrade collapse risk.

Based strictly on the experimental results and their engineering interpretation, the following conclusions are drawn:

i. Moisture sensitivity governed subgrade behaviour.

The investigated soils are fines-dominated tropical clays with moderate to high plasticity and natural moisture contents ranging from 17.07 to 24.49%. These characteristics indicated field conditions near equilibrium suction and predisposed the deposits to rapid stiffness loss and bearing capacity reduction upon wetting. Moisture state therefore represented the primary controlling factor in their mechanical response.

ii. Compaction enhanced dry-state strength but does not prevent collapse.

Maximum dry density increased from 1.66 to 2.04Mg/m³ as compactive effort rose from BSL to BSH, while optimum moisture content decreased from approximately 19 to 13%. Although higher compaction significantly improved unsoaked CBR, the gains did not translate into durable soaked performance. Mechanical densification alone is therefore insufficient to mitigate hydro-mechanical instability in tropical black clays.

iii. Strength collapse upon saturation is severe and systematic.

Unsoaked CBR values ranged from 1.93 to 15.60%, indicating moderate short-term load-bearing capacity. However, soaked CBR values declined sharply to 0.77–4.54%, representing strength reductions commonly exceeding 70–90%. These results confirmed that loss of matric suction and increased pore-water pressure dominated in-service performance, overriding density-related improvements.

iv. Moderate swelling combined with extremely low permeability prolonged weakening.

Swelling potentials of 1.54–4.48% indicated medium expansivity, while permeability values on the order of 10^{-10}–10^{-9}m/s reflected very poor drainage capacity. This combination promotes sustained saturation and delayed suction recovery, explaining the persistently low soaked strength observed across all sites.

v. Strength Collapse Ratio (SCR) provided a more reliable risk indicator than index classification.

SCR values between 0.07 and 0.33 revealed severe to very severe collapse behaviour. Gwagwalada deposit exhibited the highest collapse risk, while Gidigidi and Zungeru deposits showed substantial collapse despite favourable dry-state strength. Sunti deposit demonstrated comparatively better but still inadequate strength retention. These findings demonstrated that collapse severity, rather than AASHTO grouping or plasticity index alone, provided clearer differentiation of subgrade vulnerability.
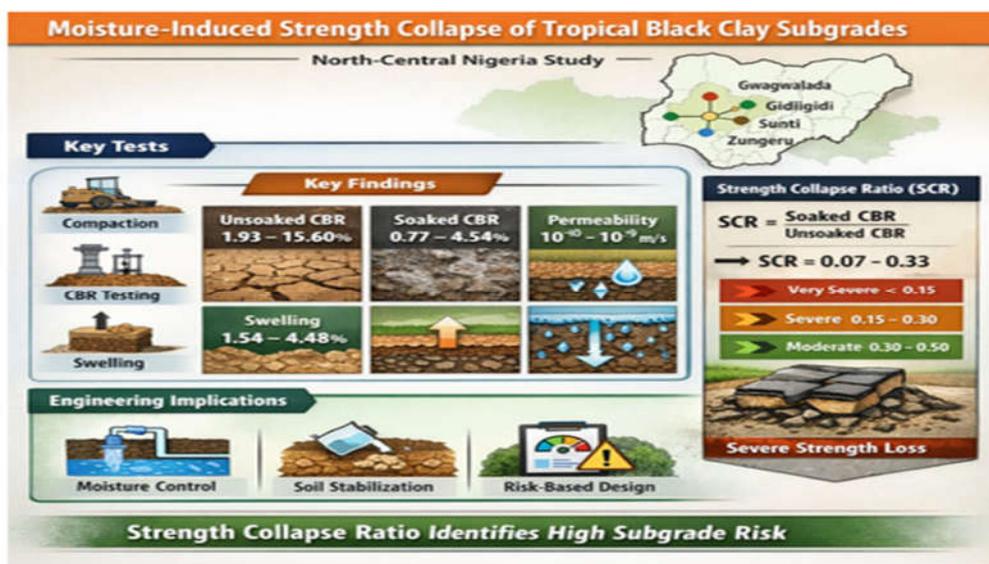
In general, the results confirmed that tropical black clays in North-Central Nigeria are inherently unsuitable for direct use as pavement subgrades under natural moisture conditions. Durable performance required integrated moisture control, effective drainage, chemical stabilisation, or selective replacement. More broadly, the study established a strength-collapse-oriented performance framework as a practical basis for risk-informed pavement design in humid tropical expansive-soil terrains. By shifting assessment from static classification to strength-retention evaluation, this framework offered a clearer pathway toward resilient infrastructure development in moisture-sensitive regions.

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Graphical Abstract