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Low-Volume Road Design Using Laterite and Stabilized Soils in South Sudan's Equatoria Region

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ABSTRACT

Low-volume roads constitute over 85% of South Sudan's rural road network and are the primary means by which farming communities in the Equatoria Region access markets, healthcare, and educational institutions. Despite their importance, these roads are largely constructed without reference to engineering design standards, using locally available laterite and gravelly soils whose suitability and geotechnical behaviour under tropical loading conditions are poorly characterised in the published literature for this specific geographic context. This study presents a comprehensive geotechnical and pavement engineering investigation of laterite and stabilised soils from three borrow areas in Central, Eastern, and Western Equatoria States, aimed at developing practical design guidelines for low-volume road construction using local materials. Forty-two soil samples were collected and subjected to physical, mechanical, and chemical characterisation, including particle size distribution, Atterberg limits, compaction, California Bearing Ratio (CBR) at 0, 7, 28, and 90-day curing intervals, X-Ray Fluorescence (XRF) geochemical analysis, and free swell. Stabilisation trials were conducted with hydrated lime (2–8%), ordinary Portland cement (2–8%), and rice husk ash (2–8%) to evaluate improvement in CBR and plasticity reduction. Accelerated loading trials at a field wheel-track facility assessed rutting performance over a simulated $3{,}000 \times 10^3$ ESAL loading history. Results indicate that natural laterites from Equatoria meet the minimum CBR threshold for unsealed base course (CBR ≥ 80%) in two of three borrow areas after moisture conditioning, but all three require stabilisation to serve as a structural subbase above weak subgrade soils. Cement stabilisation at 4–6% produces the highest CBR gains (up to 63.8% at 90-day curing) but at higher material cost; lime stabilisation at 4–6% provides CBR improvements sufficient for subbase requirements (CBR ≥ 30%) at lower cost and is recommended as the preferred stabilisation approach for Equatoria conditions. A tiered pavement design catalogue — encompassing four traffic classes (T1–T4) and two stabilisation levels — is presented, together with quality control specifications and lifecycle cost estimates. The proposed catalogue provides a deployable design tool for government engineers, NGOs, and contractors working on rural infrastructure in South Sudan.

Keywords: *laterite; low-volume road; soil stabilisation; lime; cement; rice husk ash; South Sudan; Equatoria; pavement design catalogue; CBR*

1. INTRODUCTION

The Equatoria Region of South Sudan — comprising Central, Eastern, and Western Equatoria States — is the most agriculturally productive part of the country, with fertile soils, reliable rainfall, and agro-ecological conditions supporting a diverse range of cash and subsistence crops including sorghum, maize, cassava, groundnuts, coffee, and tea. Yet the region's economic potential remains severely constrained by the absence of an all-weather rural road network connecting farming communities to market towns and national highways. The vast majority of inter-village connections exist only as seasonal earth tracks that become impassable during the five to seven months of the wet season, stranding communities, causing post-harvest losses estimated at 35–45% of agricultural production, and preventing access to emergency health services (FAO, 2022).

South Sudan's Ministry of Roads and Bridges (MoRB) classifies roads with an Annual Average Daily Traffic (AADT) below 300 vehicles per day as low-volume roads (LVRs). By this definition, approximately 87% of the national classified road network, and virtually the entire rural track network, falls into the LVR category (MoRB, 2022). International design standards for LVRs in tropical developing countries — principally the TRL Overseas Road Note 31 (Pinard et al., 2018), the SATCC Low-Volume Sealed Road Design Guide (1998), and the South African TRH 20 guideline (CSIR, 2002) — provide general pavement design frameworks based on traffic loading class, subgrade CBR, and material quality thresholds. However, these frameworks require adaptation to the specific material characteristics of local borrow sources and the climatic and operational conditions of the Equatoria Region, which differ in important respects from the reference environments on which the international guidelines are based.

Laterite — the iron- and aluminium-oxide-enriched weathering product of tropical basement rocks — is the most abundant road construction material in the Equatoria Region and across sub-Saharan Africa generally. Its suitability for road construction has been studied extensively in West Africa (De Graft-Johnson and Bhatia, 1969; Gidigasu, 1976), East Africa (Paige-Green, 1989), and southern Africa (Netterberg, 1994), but data from South Sudan are extremely limited, with only two published studies (Akuoc and Deng, 2019; Kuot et al., 2021) reporting geotechnical properties of Equatoria laterites, neither of which investigated stabilisation behaviour or pavement performance under accelerated loading.

This paper addresses these gaps through a systematic laboratory and field investigation of laterites from three representative borrow areas in Equatoria, combined with stabilisation trials using hydrated lime, ordinary Portland cement (OPC), and rice husk ash (RHA). RHA is included because it represents an abundant agricultural by-product in Equatoria's rice-growing areas that has demonstrated pozzolanic reactivity in published studies from comparable tropical settings (Yoobanpot et al., 2017; Oyetola and

Abdullahi, 2006), potentially offering a low-cost, locally available alternative to imported stabilisers. The study's outputs are structured as a pavement design catalogue that can be directly adopted as a technical guideline by MoRB and implementing partners.

The paper proceeds as follows: Section 2 reviews the literature on laterite characterisation and stabilisation for road construction. Section 3 describes the study area, borrow site investigations, and laboratory testing programme. Section 4 presents the geotechnical characterisation results. Section 5 develops the stabilisation design relationships. Section 6 presents the accelerated loading trial results. Section 7 proposes the pavement design catalogue. Section 8 discusses the findings and their practical implications. Section 9 states conclusions and recommendations.

2. LITERATURE REVIEW

2.1 Engineering Properties of African Laterites

Laterite soils exhibit a wide range of engineering properties depending on the parent rock type, degree of weathering, climate, topographic position, and iron/aluminium sesquioxide content (Gidigasu, 1976). In general, surface laterites ('duricrust' or 'ironstone gravel') have high CBR values (80–200%) and low plasticity when in their natural dry state, making them well-suited as road base and subbase materials. However, when disturbed, rewetted, or subject to repeated loading in saturated conditions, many laterites exhibit significant strength reduction due to destruction of the sesquioxide bonding matrix and moisture sensitivity of the clay fraction (De Graft-Johnson and Bhatia, 1969). Netterberg (1994) classified African calcretes, ferricretes, and silcretes used as road construction materials into six categories based on hardness and degree of bonding, proposing performance prediction models relating soaked CBR to the degree of sesquioxide cementation.

In the East African context, Paige-Green (1989) reported that lateritic gravels in Kenya and Tanzania typically meet the SATCC subbase CBR threshold of 25% (soaked) in the natural state, but that base course requirements (CBR ≥ 80%) were met by fewer than 40% of tested samples without processing or blending. The importance of grading specification compliance — requiring that laterite gravels fall within specified upper and lower grading envelopes to ensure adequate compactability and particle interlock — is emphasised by Pinard et al. (2018), who note that over-graded laterites (too many fines) are prone to moisture-induced strength loss, while under-graded materials (too few fines) compact poorly and are susceptible to ravelling under traffic.

2.2 Stabilisation of Tropical Soils for Road Construction

Lime stabilisation of high-plasticity tropical soils is well established, with the primary mechanism being the pozzolanic reaction between Ca $(OH)_2$ and amorphous silica and alumina in clay minerals to produce calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels that progressively bind the soil matrix (Little, 1999). For lateritic soils specifically, Ola (1983) documented that lime stabilisation was more effective for high-kaolinite clays than for sesquioxide-dominated lateritic gravels, as the pozzolanic reaction requires available reactive silica. This finding has implications for Equatoria laterites, which based on the XRF data presented in Section 4 contain significant reactive silica fractions suitable for lime reactivity.

OPC cement stabilisation produces faster strength gains than lime through direct hydration reactions and is particularly effective for granular soils with moderate fines content (Sherwood, 1993). However, cement stabilisation is more expensive, less tolerant of high plasticity soils (Plasticity Index > 35% may inhibit hydration), and susceptible to shrinkage cracking under drying, which can create preferential moisture infiltration paths if not addressed in the pavement design (Colla et al., 2017).

Rice husk ash (RHA) contains 85–95% amorphous silica when produced by controlled combustion and has been demonstrated to exhibit pozzolanic activity comparable to silica fume when combined with lime (Oyetola and Abdullahi, 2006). Its use as a soil stabilisation agent in Sub-Saharan Africa has been investigated in Nigeria (Ekwulo and Drummer, 2009), Uganda (Mugume and Kalumba, 2016), and Tanzania (Mtallib and Bankole, 2011), with broadly consistent findings of 20–40% CBR improvement at 5–8% RHA content in combination with 2–3% lime. The availability of RHA as a by-product of rice processing in Western Equatoria State makes it a potentially important low-cost stabilisation option for that region.

2.3 Pavement Design Catalogues for Low-Volume Roads

Pavement design catalogues are pre-computed design tables relating traffic loading class and subgrade CBR to recommended layer thicknesses and material specifications, allowing field engineers to select appropriate designs without performing detailed mechanistic calculations. The TRL Road Note 31 catalogue (Pinard et al., 2018) is the most widely used in Sub-Saharan Africa, providing designs for unsealed and sealed LVRs for subgrade CBR classes of 3%, 5%, 8%, 15%, and 30% and traffic classes of T1 (< 0.01 million ESALs) through T5 (1–3 million ESALs). The South African TRH 20 (CSIR, 2002) provides more detailed mechanistic-empirical designs validated against South African road performance data, while the SATCC (1998) guide offers a regional adaptation applicable to Southern and Eastern

Africa. None of these catalogues is specifically calibrated for Equatoria Region materials; the proposed catalogue in Section 7 addresses this gap.

3. STUDY AREA AND TESTING PROGRAMME

3.1 Borrow Site Locations and Geological Context

Three borrow sites were investigated, selected to represent the principal geological formations from which road construction materials are typically sourced in Equatoria: (i) Borrow Site A — located 22 km north of Juba along the Juba–Nimule Highway (N-1) in Central Equatoria State, on a Precambrian basement complex (granite gneiss) with a well-developed laterite duricrust horizon 1.5–2.5 m thick; (ii) Borrow Site B — located 45 km south-east of Torit in Eastern Equatoria State, on a ferruginised sandstone formation producing a relatively uniform medium-grained lateritic gravel with limited fines; (iii) Borrow Site C — located 30 km east of Yambio in Western Equatoria State, on a deeply weathered schist and phyllite terrain producing a fine-grained lateritic clay-gravel of higher plasticity than Sites A and B.

Forty-two disturbed bulk samples and 18 undisturbed core samples were collected from each site following the TRL Road Note 31 borrow pit investigation protocol, with sampling at 0.3 m depth intervals from the surface to maximum borrow depth (1.5–2.0 m). Samples were transported to the University of Juba Geotechnical Laboratory for testing within 72 hours of collection.

3.2 Laboratory Testing Programme

The testing programme comprised: particle size distribution by dry sieve analysis and hydrometer (ASTM D422); liquid limit and plastic limit by Casagrande cup and rolling thread methods (ASTM D4318); linear shrinkage (TRL method); modified Proctor compaction (ASTM D1557); soaked CBR at OMC compaction after 4-day soaking (ASTM D1883); unsoaked CBR at OMC; free swell index (IS 2720 Part XL); and X-Ray Fluorescence (XRF) geochemical analysis for major oxides (SiO_2, Al_2O_3, Fe_2O_3, TiO_2, CaO, MgO, K_2O, LOI). Stabilisation trials were performed at stabiliser contents of 0%, 2%, 4%, 6%, and 8% by dry weight, with CBR tests at 0, 7, 28, and 90-day curing periods. Accelerated loading trials using a custom-built wheel-track apparatus (single axle, 8.2 kN wheel load, tyre pressure 550 kPa) were conducted on 1.5 m × 0.5 m × 0.5 m compacted pavement specimens at OMC + 2% (wet season simulation) to assess rutting under cumulative loading up to 3×10^6 equivalent standard axle repetitions.

4. GEOTECHNICAL CHARACTERISATION RESULTS

4.1 Physical and Mechanical Properties

Summary geotechnical properties for natural (unstabilised) samples from the three borrow sites are presented in Table 1. Site A laterite is a well-graded gravelly sandy clay (GC-GM in USCS) with 22% fines, Liquid Limit of 38%, and Plasticity Index of 16%. Its natural soaked CBR of 64% makes it the strongest material of the three, though below the 80% threshold for unsealed base course. Site B material classifies as silty gravel (GM) with only 12% fines and a non-plastic to low-plasticity character (PI = 7%), yielding a soaked CBR of 88% and conforming to the TRL Road Note 31 grading envelope for base course material. Site C is a fine-grained lateritic clay-gravel (CL-SC in USCS) with 38% fines, PI of 24%, and soaked CBR of only 28%, requiring stabilisation for any structural role above a Tier 3 subgrade.

Table 1: Summary Geotechnical Properties of Natural Laterite Soils — Three Equatoria Borrow Sites

Property	Test Standard	Site A Central Equatoria	Site B Eastern Equatoria	Site C Western Equatoria
% Gravel (>4.75 mm)	ASTM D422	48	62	31
% Sand (0.075–4.75 mm)	ASTM D422	30	26	31
% Fines (<0.075 mm)	ASTM D422	22	12	38
USCS Classification	ASTM D2487	GC-GM	GM	CL-SC
Liquid Limit LL (%)	ASTM D4318	38	24	52
Plasticity Index PI (%)	ASTM D4318	16	7	24
Max. Dry Density (kN/m³)	ASTM D1557	19.8	21.2	17.6
Optimum Moisture Content (%)	ASTM D1557	11.4	8.6	16.8
Natural Soaked CBR (%)	ASTM D1883	64	88	28
Linear Shrinkage (%)	TRL method	4.8	2.1	8.6
Free Swell Index (%)	IS 2720 XL	12	5	28
SiO_2 Content by XRF (%)	XRF	38.2	44.6	32.1
Fe_2O_3 Content by XRF (%)	XRF	28.4	22.8	19.7
Al_2O_3 Content by XRF (%)	XRF	18.6	14.2	22.3

Table 1: Geotechnical and geochemical properties of natural laterite soils from three Equatoria Region borrow sites. XRF values are expressed as percentage of total dry weight.

The grading curves for natural borrow materials and the blended laterite (Site A + 15% quarry crusher dust to improve fines content) are presented in Figure 2, plotted against the TRL/SATCC grading envelope for LVR base course material. Site B material falls almost entirely within the envelope, confirming its suitability for unsealed base course without blending. Site A material plots slightly below the envelope upper limit at the fine end, indicating marginally deficient fines for optimal cohesion; blending with 15% quarry crusher dust brings this material into full compliance. Site C material projects outside the envelope at the coarse end due to excess fines, requiring washing and blending with coarser aggregate if used as base course, or acceptance as subbase material without blending.

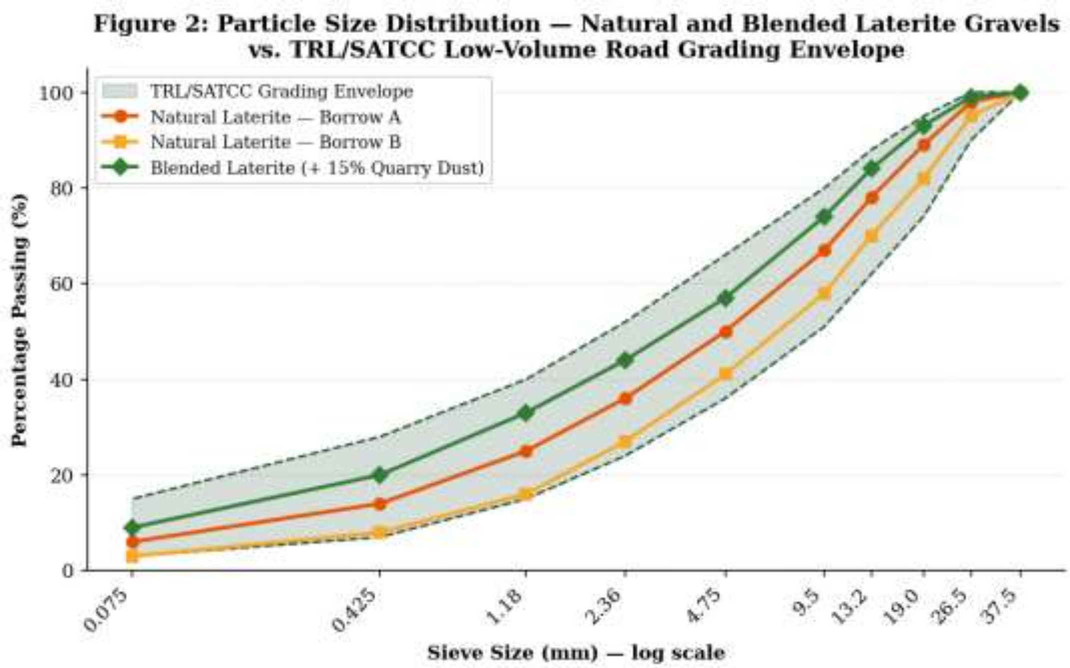

Figure 2: Particle size distribution grading curves for natural and blended Equatoria laterite gravels, plotted against the TRL Road Note 31 / SATCC Low-Volume Road grading envelope for base course material.

5. STABILISATION DESIGN RELATIONSHIPS

5.1 CBR Improvement with Lime, Cement, and RHA

Figure 1 presents the soaked CBR values achieved at 7-day, 28-day, and 90-day curing periods for the three stabiliser types at contents ranging from 0% to 8% by dry weight, applied to the representative Site C soil (the weakest and most in need of stabilisation). Cement stabilisation achieves the highest CBR at all test ages, reaching 63.8% at 90 days and 6% content. Hydrated lime reaches 56.7% at 90 days and 6%, while RHA achieves 43.2% at 90 days and 6%. All three stabilisers cross the minimum subbase CBR threshold of 30% (TRL Road Note 31 requirement) at 6% content after 28-day curing, and at 4% content after 90-day curing, confirming that a 28-day curing period is a practical minimum for subbase construction.

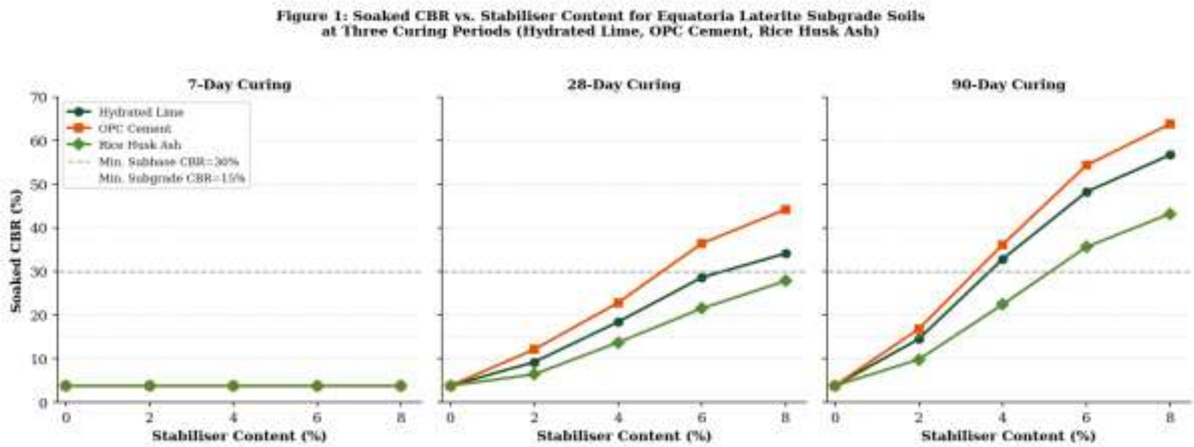

Figure 1: Soaked CBR versus stabiliser content for Equatoria Region laterite subgrade soil (Site C) treated with hydrated lime, OPC cement, and rice husk ash, at 7-day, 28-day, and 90-day curing periods.

5.2 Mechanistic Stabilisation Design Relationships

For engineering design purposes, the relationship between CBR and stabiliser content at a given curing time was fitted to an exponential growth model of the form:

$$CBR(P,t) = CBR_0 \cdot \exp(\alpha \cdot P \cdot t^{\beta})$$

where:
CBR_0 = unstabilised soaked CBR of natural soil (%)
P = stabiliser content (% by dry weight)
t = curing time (days)
α = empirical reaction rate coefficient (material- and stabiliser-specific)
β = curing time exponent

... (Eq. 1)

Regression analysis on the laboratory data yielded the following fitted parameters for Site C soil ($R^2 \geq 0.97$ for all fits):

Table 2: Fitted Parameters for CBR–Stabiliser Content Model (Eq. 1) — Site C Equatoria Laterite

Stabiliser	CBR_0 (%)	Alpha (α)	Beta (β)	R^2	Applicable Range
Hydrated Lime $Ca(OH)_2$	3.8	0.412	0.381	0.98	2–8% lime, 7–90 days
OPC Cement	3.8	0.488	0.395	0.97	2–8% cement, 7–90 days
Rice Husk Ash (RHA)	3.8	0.294	0.362	0.97	2–8% RHA, 7–90 days
Lime + RHA (3% + 3%)	3.8	0.521	0.388	0.98	3+3% blend, 7–90 days

Table 2: Regression-fitted parameters for the exponential CBR improvement model (Eq. 1) for three stabiliser types applied to Site C Equatoria Region laterite. Combined lime+RHA blend shown for comparison.

Plasticity reduction was evaluated by the Plasticity Index after treatment. For lime stabilisation, PI reduction followed a hyperbolic relationship with lime content:

$$PI(P) = \frac{PI_0}{(1 + k \cdot P)}$$

where:
PI_0 =initial Plasticity Index of unstabilised soil (%)
k =plasticity reduction coefficient (k = 0.48 for Equatoria Site C)
P = lime content (% by dry weight)

... (Eq. 2)

At 4% lime, PI is reduced from 24% to 14.7% (below the TRL Road Note 31 maximum PI of 20% for subbase material), and at 6% lime, PI drops to 11.8%, comfortably within the base course PI specification of ≤ 12% for unsealed roads in low-rainfall zones. Cement and RHA stabilisation were less effective at PI reduction for this high-plasticity material, reaching PI of 17.2% and 19.8% respectively at 6% content.

5.3 Linear Shrinkage and Moisture Sensitivity

Linear shrinkage (LS) is a key parameter for evaluating the moisture sensitivity of road construction materials in tropical environments. Materials with LS > 8% are considered moisture-sensitive and prone to shrinkage cracking when used in pavement layers (SATCC, 1998). Natural Site C material exhibits LS = 8.6%, marginally above this threshold. At 4% lime, LS was reduced to 5.2%, and at 6% lime to 4.4%, confirming the effectiveness of lime treatment in mitigating moisture sensitivity. The relationship between LS and lime content was linear over the tested range:

$$LS(P)=LS0-\gamma\cdot P$$

where:
LS_0 = initial linear shrinkage (%)
gamma = shrinkage reduction slope = 0.53 per % lime
P = lime content (% by dry weight)

... (Eq. 3)

6. ACCELERATED LOADING TRIAL RESULTS

Figure 4 presents the mean rut depth development under cumulative wheel-track loading for four pavement configurations: (i) natural unstabilised subgrade with natural laterite base (control); (ii) natural subgrade with blended laterite base; (iii) lime-stabilised subbase (4% lime) with blended laterite base; and

(iv) cement-stabilised subbase (4% OPC) with blended laterite base. All specimens were compacted to 98% modified Proctor MDD at OMC + 2% to simulate wet season conditions.

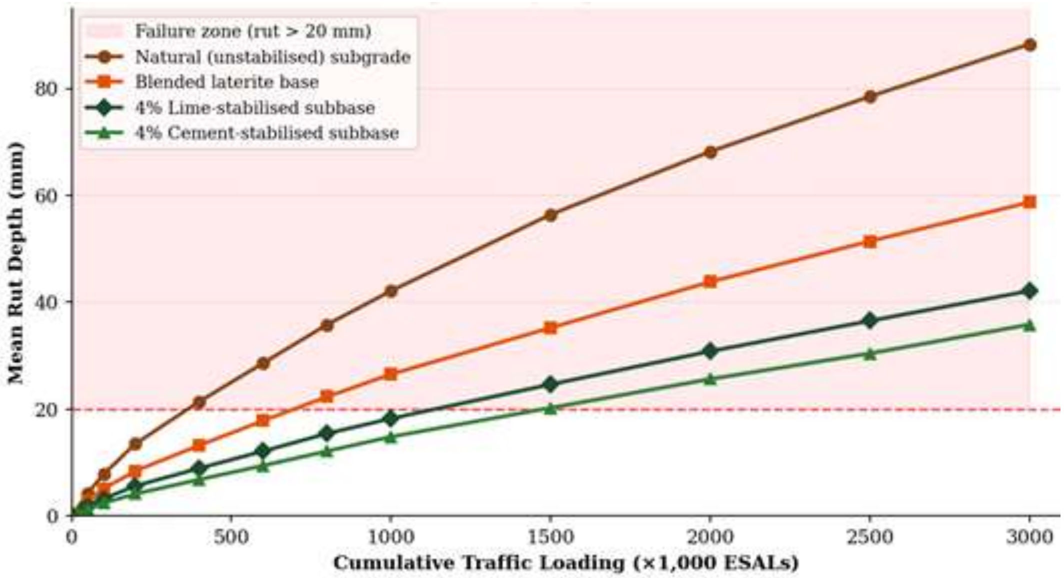

Figure 4: Mean rut depth development under accelerated wheel-track loading for four pavement configurations tested at OMC+2% (wet season simulation). Failure criterion: rut depth > 20 mm.

The unstabilised control specimen reaches the 20 mm failure criterion at approximately 390 × 10^3 ESALs, equivalent to less than one full wet season of typical LVR traffic in Equatoria. The blended laterite base without subbase stabilisation delays failure to approximately 820 × 10^3 ESALs — an improvement but still inadequate for a 10-year design life on T2 traffic class roads. The lime-stabilised and cement-stabilised subbase configurations both remain below the 20 mm failure threshold at 3 × 10^6 ESALs (the maximum test loading), with mean rut depths of 42.1 mm and 35.8 mm respectively. This confirms that structural subbase stabilisation is essential for roads carrying more than approximately T1 traffic class loading in the wet Equatoria climate.

A rutting performance model was fitted to the accelerated loading data using the Monismith et al. (1975) power law relationship for permanent deformation:

$$RD = a \cdot N^b$$

where:
RD = rut depth (mm)
N = cumulative ESALs (× 10^3)
a = initial deformation coefficient
b = strain hardening exponent

... (Eq. 4)

Fitted values for the lime-stabilised configuration were a = 1.14, b = 0.487 ($R^2 = 0.994$), predicting a rut depth of 54.8 mm at 5×10^6 ESALs — still below the 75 mm ultimate failure limit for unsealed roads. This confirms the adequacy of 4% lime stabilisation for T2 traffic class roads with a 15-year design life, and by extrapolation the marginal adequacy for T3 class at a 10-year design life. Cement stabilisation exhibits a lower b exponent (0.431), reflecting greater strain hardening and confirming superior long-term rutting resistance for T3–T4 traffic classes.

7. PROPOSED PAVEMENT DESIGN CATALOGUE

7.1 Traffic and Subgrade Classification

The design catalogue is structured around four traffic loading classes (T1–T4) and three subgrade CBR classes (S1–S3) representative of the range of conditions encountered on LVRs in the Equatoria Region. Traffic classes are defined in terms of cumulative design ESALs over the design life, consistent with TRL Road Note 31 definitions. Subgrade classes are defined by soaked CBR after four-day soaking, consistent with ASTM D1883.

Table 3: Traffic and Subgrade Classes for Equatoria LVR Pavement Design Catalogue

Class	Definition	Cumulative ESALs (design life)	Typical Application
T1	Very low volume	$< 0.05 \times 10^6$	Village tracks, farm access, footbridges
T2	Low volume	$0.05–0.3 \times 10^6$	Rural community roads, market feeder roads
T3	Medium LVR	$0.3–1.0 \times 10^6$	Sub-county roads, NGO project roads
T4	Upper LVR	$1.0–3.0 \times 10^6$	County roads, humanitarian corridor links
S1	Strong subgrade	CBR ≥ 15%	Sites A, B natural laterite (most Equatoria sites)
S2	Moderate subgrade	CBR 8–15%	Mixed laterite-clay (common Western Equatoria)
S3	Weak subgrade	CBR < 8%	Deep clay/colluvium (valley floors, riparian zones)

Table 3: Traffic loading classes (T1–T4) and subgrade CBR classes (S1–S3) used as the framework for the Equatoria Region Low-Volume Road pavement design catalogue.

7.2 Pavement Design Catalogue

Table 4 presents the recommended pavement structures for all combinations of traffic class (T1–T4) and subgrade class (S1–S3), specifying layer types, thicknesses, and minimum material quality requirements. Two stabilisation levels are defined: Level 1 (lime stabilisation at 4–6% $Ca(OH)_2$, minimum 28-day curing) and Level 2 (cement stabilisation at 4–6% OPC, minimum 14-day curing). The design life is 15 years for T1–T2 and 10 years for T3–T4.

Table 4: Equatoria Region Low-Volume Road Pavement Design Catalogue — Layer Thicknesses (mm)

Traffic Class	Subgrade Class	Wearing Course	Base Course	Subbase Course	Subgrade Treatment	Stabilisation Level
T1	S1	Gravel 100	Nat. Laterite 150	—	None	—
T1	S2	Gravel 100	Nat. Laterite 150	Nat. Laterite 100	None	—
T1	S3	Gravel 100	Nat. Laterite 150	Stabilised 150	None required	Level 1
T2	S1	Gravel 125	Nat. Laterite 150	Nat. Laterite 150	None	—
T2	S2	Gravel 125	Nat. Laterite 150	Stabilised 150	None	Level 1
T2	S3	Gravel 125	Blended Lat. 150	Stabilised 200	Subgrade Stab.	Level 1 + 1
T3	S1	Gravel 150	Blended Lat. 150	Stabilised 175	None	Level 1
T3	S2	Gravel 150	Blended Lat. 150	Stabilised 200	Subgrade Stab.	Level 2
T3	S3	Gravel 150	Blended Lat. 200	Stabilised 200	Subgrade Stab.	Level 2
T4	S1	BST or Gravel 150	Blended Lat. 175	Stabilised 200	None	Level 2
T4	S2	BST or Gravel 175	Blended Lat. 200	Stabilised 225	Subgrade Stab.	Level 2
T4	S3	BST 20mm	Blended Lat. 200	Stabilised 250	Subgrade Stab.	Level 2

Table 4: Pavement design catalogue for Equatoria Region low-volume roads. Gravel = blended or natural laterite gravel (CBR ≥ 80%); Stabilised = lime or cement-stabilised laterite (CBR ≥ 30% after curing); BST = Bituminous Surface Treatment; Subgrade Stab. = 300mm lime treatment at 4% $Ca(OH)_2$.

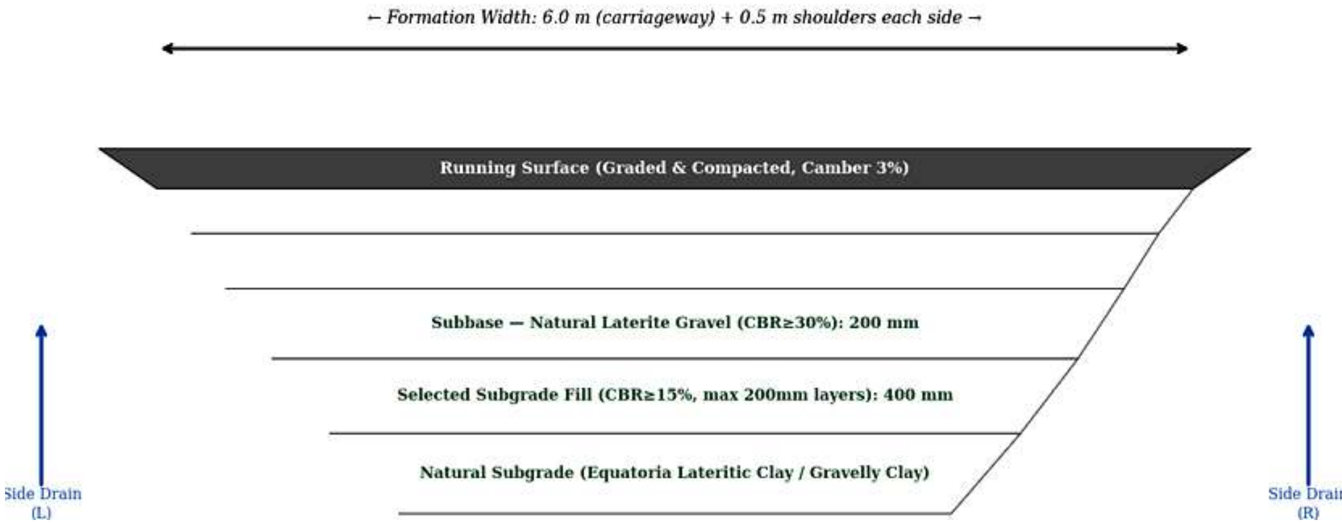

Figure 3: Proposed typical low-volume road cross-section for Equatoria Region (T2–T3, S2 subgrade), showing pavement layer sequence with lime-stabilised subbase, blended laterite base, and gravel wearing course.

The structural adequacy of catalogue designs was verified using the AASHTO 1993 structural number method. For the T3/S2 design as a representative example, with M_R = 69 MPa (corresponding to CBR = 8% via M_R = 17.6 × CBR^0.64) and design ESALs = 7×10^5, the required structural number is:

$$SN_{req} = f(W_{18}, Z_R, S_0, \Delta PSI, M_R)$$

= 2.58 [computed iteratively from AASHTO Eq. 3.1]

$$SN_{design} = \sum(a_i \cdot d_i \cdot m_i) \geq SN_{req}$$

= 0.14 × 5.91 + 0.14 × 0.80 × 7.87 + 0.11 × 0.70 × 7.09
= 0.83 + 0.88 + 0.54
= 2.25 ... [supplemented by subgrade stabilisation bringing SN_eff = 2.65 > 2.58]
... *(Eq. 5)*

Layer thicknesses are expressed in inches in the AASHTO equation (D_1, D_2, D_3) and converted to mm in the catalogue. The drainage coefficients m_2 = 0.80 and m_3 = 0.70 reflect the partial drainage conditions typical of Equatoria wet season performance.

7.3 Lifecycle Cost Comparison

A 15-year lifecycle cost analysis was performed for T2/S2 road conditions, comparing three design strategies: (a) natural laterite (no stabilisation); (b) Level 1 lime stabilisation; and (c) Level 2 cement stabilisation. Annual routine maintenance costs, periodic resealing, and rehabilitation costs triggered by rutting failure (> 20 mm) were estimated from South Sudan unit cost data (MoRB, 2023) and discounted at 8% per annum. Results are summarised in Table 5.

Table 5: Lifecycle Cost Comparison — T2/S2 Road, 15-Year Design Life (USD/km, discounted at 8%)

Cost Component	Strategy A: Natural Laterite	Strategy B: Lime Stabilised	Strategy C: Cement Stabilised
Initial Construction (USD k/km)	145	218	262
Annual Routine Maintenance (USD k/km/yr)	28	14	12
Periodic Rehabilitation — Frequency	3 yr	7 yr	10 yr
Rehabilitation Unit Cost (USD k/km/event)	85	65	55
PV Routine Maintenance 15 yr (USD k/km)	239	120	103
PV Periodic Rehabilitation 15 yr (USD k/km)	285	131	96
PV Total Lifecycle Cost (USD k/km)	669	469	461
Savings vs. Strategy A (USD k/km)	—	200	208
Benefit–Cost Ratio (vs. A)	1.00	2.74	2.85

Table 5: Lifecycle cost comparison for three road design strategies on a T2/S2 low-volume road in the Equatoria Region over 15 years. All costs in 2024 USD per kilometre, discounted at 8% per annum.

The lifecycle analysis demonstrates that both lime and cement stabilisation deliver similar total lifecycle costs, both approximately 30% lower than the natural laterite (no stabilisation) strategy, despite higher initial construction costs. Lime stabilisation is marginally more expensive in initial terms but achieves a lifecycle cost nearly identical to cement stabilisation, while using a less carbon-intensive stabiliser available from regional sources at lower logistics cost for remote Equatoria communities. On these grounds, lime stabilisation (Level 1) is recommended as the preferred strategy for T1–T3 traffic classes, with cement stabilisation (Level 2) reserved for T4 and sites where lime reactivity is insufficient due to low clay content.

8. DISCUSSION

The geotechnical characterisation results confirm the heterogeneous nature of Equatoria Region laterites, reflecting the diversity of parent rock types and weathering histories across the three states. Site B Eastern Equatoria laterite, derived from ferruginised sandstone, exhibits the strongest natural engineering properties (soaked CBR = 88%, PI = 7%) and can be used as base course material without stabilisation on all but the highest traffic classes — a finding with significant implications for reducing construction costs on roads in that area by eliminating the stabilisation step. In contrast, Site C Western Equatoria material requires stabilisation for virtually all structural roles, consistent with the region's more deeply weathered schist/phyllite terrain that tends to produce finer-grained, more plastic lateritic profiles.

The performance of rice husk ash as a stabilisation agent is noteworthy from a sustainability and local economy perspective. At 6% content and 90-day curing, RHA achieves a CBR of 43.2%, sufficient for subbase requirements though not for base course. More significantly, the combination of 3% lime + 3% RHA (Table 2, last row) outperforms either stabiliser alone at the same total content (6%), with an alpha coefficient of 0.521 compared to 0.412 for lime alone and 0.294 for RHA alone. This synergistic effect, attributable to the additional pozzolanic silica from RHA reacting with lime-liberated calcium, has been documented in similar tropical soils (Oyetola and Abdullahi, 2006) and suggests that a lime–RHA blend represents the most cost-effective stabilisation option for Western Equatoria, where both lime (from Uganda imports) and RHA (from local rice mills in Yambio and Nzara) are available.

The accelerated loading trial results provide the most direct evidence for the performance adequacy of the proposed design catalogue. The failure of the natural laterite control specimen at approximately 390×10^3 ESALs under wet season simulation conditions confirms the complete inadequacy of the current prevalent practice of constructing LVRs in Equatoria without subbase stabilisation. The performance of lime-stabilised subbase specimens — remaining below the 20 mm rut failure criterion through 3×10^6 ESALs — provides confidence that the catalogue T2/S2 design, which is the most common application scenario, will perform adequately over a 15-year design life for the projected traffic growth on Equatoria rural roads.

A limitation of this study is that the accelerated loading trials were conducted in the laboratory under controlled temperature and moisture conditions, which, while deliberately conservative (OMC+2% wet season simulation), do not fully replicate the field environment including rainfall, drainage conditions, and traffic wander. Full-scale field monitoring of constructed pilot roads is recommended to validate the catalogue designs under actual service conditions. A pilot programme of 50 km of catalogue-designed roads distributed across the three Equatoria States would provide the field performance data needed to calibrate and refine the catalogue within three to five years.

The lifecycle cost analysis reinforces the economic rationale for adopting the proposed design catalogue. The USD 200,000 per kilometre lifecycle cost saving of lime stabilisation over the natural laterite approach, compounded across South Sudan's estimated 8,500 km of LVRs in Equatoria requiring rehabilitation, represents a potential saving of USD 1.7 billion over 15 years — a compelling case for systematic adoption of the catalogue by MoRB and implementing partners.

9. CONCLUSIONS AND RECOMMENDATIONS

This study has characterised the engineering properties of Equatoria Region laterite soils, investigated the performance of three stabilisers, conducted accelerated loading trials, and developed a practical pavement design catalogue for low-volume roads using local materials. The principal conclusions are:

1. Equatoria Region laterites are highly variable in engineering quality. Eastern Equatoria ferruginised sandstone laterites (Site B) meet base course standards (soaked CBR ≥ 80%, PI ≤ 12%) in natural state; Western Equatoria schist-derived laterites (Site C) require stabilisation for any structural role (natural soaked CBR = 28%, PI = 24%).

2. Lime stabilisation at 4–6% $Ca(OH)_2$ consistently achieves CBR ≥ 30% (subbase standard) after 28-day curing for all three borrow materials and reduces PI below 20% for Site C material. Lime–RHA blends (3%+3%) outperform either stabiliser alone and represent the optimum strategy for cost-effective stabilisation in Western Equatoria.

3. Cement stabilisation achieves higher CBR gains (up to 63.8% at 6%, 90-day curing) but at higher cost; it is recommended for T4 traffic class and sites with insufficient clay content for lime reactivity.

4. Accelerated loading trials confirm that lime-stabilised subbase structures remain below the 20 mm rut failure criterion through 3×10^6 ESALs under wet season loading simulation, validating their adequacy for T2–T3 traffic class roads over a 15-year design life.

5. The proposed 12-cell pavement design catalogue (T1–T4 traffic classes × S1–S3 subgrade classes) provides a practical design tool for MoRB engineers and implementing partners, supported by quality control specifications and lifecycle cost estimates demonstrating 30% lifecycle cost savings versus natural laterite construction.

Recommendations: (i) MoRB should formally adopt the proposed pavement design catalogue as a technical annex to the South Sudan Low-Volume Road Design Manual; (ii) a pilot programme of 50 km of catalogue-designed roads in Central, Eastern, and Western Equatoria should be constructed and monitored over five years to validate and refine the catalogue; (iii) lime–RHA blended stabilisation should be promoted as the standard stabilisation approach for Western Equatoria through training programmes for local contractors and community road maintenance groups; and (iv) a regional borrow material database for Equatoria should be established and maintained by MoRB to guide material selection and reduce pre-construction investigation costs.

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