

Engineering Performance of a Ternary Stabilization System for Lateritic Road Subbase Construction in Tropical Nigeria

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Abstract

The inadequacy of natural lateritic soils for highway pavement subbase construction in tropical West Africa necessitates effective and affordable stabilization solutions. This study presents the first systematic investigation of a ternary waste-based stabilization system comprising Rice Husk Ash (RHA), Granulated Steel Slag (GSS), and Calcium Carbide Residue (CCR) to improve lateritic soil from Offa, Kwara State, Nigeria. Six mix proportions (Mixes A–F) were designed at incremental RHA:GSS:CCR ratios of 0:0:0, 3:2:2, 6:4:4, 9:6:6, 12:8:8, and 15:10:10 percent by dry mass of soil. The experimental program evaluated Atterberg limits, specific gravity, compaction characteristics (OMC and MDD), California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS) after 7 and 28 days of curing. The ternary system substantially improved the engineering properties of the lateritic soil. The Plasticity Index was reduced from 19% (natural laterite) to 10% at the optimum proportion (Mix F). The maximum dry density occurred in Mix B (1570.36 kg/m³) and generally decreased with increasing stabilizer content, reaching a minimum value of 1355.87 kg/m³ at Mix F. CBR peaked at Mix E (73.44%), representing a 13.7% improvement. In contrast, UCS peaked at Mix E (609.11 kPa), representing a 67.9% improvement, both substantially exceeding the Federal Ministry of Works and Housing (FMWH) minimum specifications of 30% and 200 kPa, respectively. Mix E is identified as the optimum formulation. The RHA-GSS-CCR ternary system offers a technically effective alternative for constructing lateritic road sub-bases in tropical environments.

Keywords: Lateritic Soil, Soil Stabilization, Stabilizers, Index Properties, Strength Properties.

Introduction

Road infrastructure constitutes the backbone of Nigeria's economy, handling an estimated 90% of all surface freight and passenger transport (Oluremi *et al.*, 2012). Despite this critical role, the condition of rural roads in Nigeria remains poor, with most failures attributable to inadequate strength and moisture susceptibility of the naturally occurring lateritic soils used as subgrade and sub-base materials (Ademila, 2017; Aginam *et al.*, 2015). Lateritic soils are the dominant surface deposit across tropical West Africa, covering approximately 35% of Nigeria's land area (Amadi *et al.*, 2015). While they offer accessibility and economic advantage as construction fill, most lateritic soils exhibit Plasticity Indices exceeding 20%, California Bearing Ratio (CBR) values below 30%, and significant volume change under moisture fluctuation, making them unsuitable as sub-base materials without treatment (Amu *et al.*, 2011; Makusa, 2012). Chemical stabilization using Ordinary Portland Cement (OPC) and lime remains the standard engineering response to these limitations (Makusa, 2012). However, the prohibitive and increasingly volatile cost of cement in Nigeria, rising from ₦3,000 per 50 kg bag in 2015 to over ₦9,500 per bag in 2024, renders cement stabilization economically unviable for rural road programs, particularly at the sub-national level where funding is constrained (Federal Ministry of Works and Housing, 2016).

Furthermore, OPC production accounts for approximately 8% of global anthropogenic CO₂ emissions (IPCC, 2006), a figure that runs counter to Nigeria's sustainability commitments. Industrial and agricultural wastes offer a promising alternative. Rice Husk Ash (RHA), produced by controlled calcination of rice husk at 500–650°C, is rich in amorphous reactive silica (Nguyen *et al.*, 2011; Liu *et al.*, 2019). Granulated Steel Slag (GSS) is a latent hydraulic material requiring alkaline activation (Yadu and Tripathi, 2013).

Calcium Carbide Residue (CCR), generated during acetylene gas production from calcium carbide and water, is predominantly composed of calcium hydroxide ($\text{Ca}(\text{OH})_2$) (Horpibulsuk *et al.*, 2012). CCR serves as an alkaline activator, providing the high-pH environment necessary for pozzolanic reactions while contributing calcium ions to cementitious gel formation. Prior studies have confirmed the individual effectiveness of RHA (Ayodele *et al.*, 2022; Azunna *et al.*, 2020), GSS (Oluwasola *et al.*, 2020; Yadu and Tripathi, 2013), and CCR (Horpibulsuk *et al.*, 2015; Horpibulsuk *et al.*, 2013) as soil stabilizers. However, no study has investigated the ternary RHA–GSS–CCR combination, leaving the synergistic geochemical interaction between these three complementary materials uncharacterized. This study fills that gap by presenting the first comprehensive experimental evaluation of the ternary system across six dosage levels, supported by geotechnical performance evaluation, and validated against Federal Ministry of Works and Housing (FMWH) specifications for sub-base construction.

Materials and Methods

Materials and Preparation

Lateritic soil was collected from the Federal Polytechnic Offa borrow pit ($8^{\circ}07'57''$ N, $4^{\circ}42'27''$ E), Kwara State, at depths of 1.5 - 2.0 m. RHA was obtained from Hillcrest Agro-Allied Limited, Amberi, Kwara State, produced by calcination at approximately 600°C , and sieved to pass $75\text{ }\mu\text{m}$ (BS No. 200). GSS was sourced from KAM Integrated Steel Co., Ltd, Jimba-Oja, Kwara State, in its as-produced granulated form from the Electric Arc Furnace process. CCR was collected from automobile panel-beating workshops in Offa, oven-dried at 100°C for 24 hours, and sieved to pass $425\text{ }\mu\text{m}$ (BS No. 40). All materials were sourced within Kwara State, consistent with Nigeria's local content development policy. The raw laterite sample, Rice Husk Ash, Granulated Steel Slag, and Calcium Carbide Residue are shown in Figure 1(a), (b), (c), and (d), respectively.



(a): Raw Laterite



(b): RHA



(c): GSS



(d): CCR

Figure 1: Materials used in the study

Mix Design

Six mixes (A–F) were prepared as shown in Table 1. Mix A (100% laterite) served as the control. Stabilizer proportions were increased incrementally: RHA from 0 - 15%, GSS from 0–10%, and CCR from 0–10% by dry mass of soil, maintaining a consistent 3:2:2 RHA:GSS:CCR ratio.

Table 1: Mix proportions for ternary RHA–GSS–CCR stabilization of lateritic soil

Mix	Laterite (%)	RHA (%)	GSS (%)	CCR (%)	Total adds. (%)
A	100	0	0	0	0
B	93	3	2	2	7
C	86	6	4	4	14
D	79	9	6	6	21
E	72	12	8	8	28
F	65	15	10	10	35

Laboratory Testing Program

Atterberg limits (Liquid Limit, Plastic Limit, Plasticity Index, Linear Shrinkage) were determined in accordance with ASTM D4318 (2017). Standard Proctor compaction tests were conducted in accordance with BS 1377 (1990) to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). Soaked California Bearing Ratio (CBR) tests were performed in accordance with BS 1377 (1990): specimens were compacted at OMC, cured for 6 days under moisture-retaining covers, and soaked for 24 hours in accordance with the FMWH (1997, 2016) specifications for sub-base materials. Unconfined Compressive Strength (UCS) tests were conducted in accordance with ASTM D2166 (2006) on cylindrical specimens measuring approximately 38 mm in diameter and 88 mm in initial height. Particle-size analysis of the treated soil showed that 62.80% passed the 6.30 mm sieve, while 37.20% was retained at 6.30 mm and larger. Consequently, the full gradation did not completely satisfy the approximate 6:1 specimen-diameter-to-maximum-particle-size criterion for the 38 mm diameter specimens. This limitation was considered in interpreting the UCS results, which were used principally for comparative assessment of the relative strength development of the different stabilization mixes, compacted at the OMC, sealed, and cured for 7 and 28 days at ambient temperature. All tests were performed in triplicate; mean values are reported. Specification thresholds applied were: minimum sub-base CBR $\geq 30\%$ and stabilized sub-base UCS ≥ 200 kPa (FMWH, 1997, 2016).

Results and Discussion

Index Properties

Table 2 presents the Atterberg limits for all six mixes. The liquid limit (LL) declined monotonically from 41% (Mix A) to 27% (Mix F), a 34% reduction at the maximum stabilizer dosage. The Plasticity Index (PI) decreased progressively from 19% (Mix A) to 10% (Mix F), confirming that CCR-driven Ca^{2+} cation exchange effectively reduces clay double-layer thickness and plasticity. Linear shrinkage improved from 6.50% (Mix A) to 2.86% (Mix F), indicating a reduced moisture susceptibility during drying, a critical property for pavement layers exposed to seasonal moisture variation in tropical Nigeria. The specific gravity varied non-monotonically across the stabilized mixes, ranging from 1.43 in Mix D to 2.60 in Mix B. Since RHA, GSS, and CCR were incorporated simultaneously at a fixed 3:2:2 ratio, the variation cannot be attributed to any single stabilizer. Rather, it reflects the combined influence of the constituent solids, with no linear relationship between specific gravity and increasing stabilizer content. The values demonstrate that the proportion and type of stabilizer strongly influence the specific gravity of stabilized mixes. Under AASHTO classification, the natural laterite (Mix A) is categorized as A-7-6, a high-plasticity soil poorly suited for sub-base use. All stabilized mixes (B–F) reclassify to A-6, confirming a significant improvement

in geotechnical suitability. Figure 2 indicates a progressive reduction in plasticity with increasing stabilizer content, while the changes in linear shrinkage across all six mixes are presented in Figure 3.

Table 2: Atterberg limits, specific gravity, and linear shrinkage for all mixes

Mix	LL (%)	PL (%)	PI (%)	LS (%)	Gs	AASHTO
A	41	22	19	93.50	2.03	A-7-6
B	39	23	16	95.57	2.60	A-6
C	36	22	14	95.64	1.63	A-6
D	34	21	13	96.36	1.43	A-6
E	30	18	12	97.00	2.26	A-6
F	27	17	10	97.14	1.98	A-6

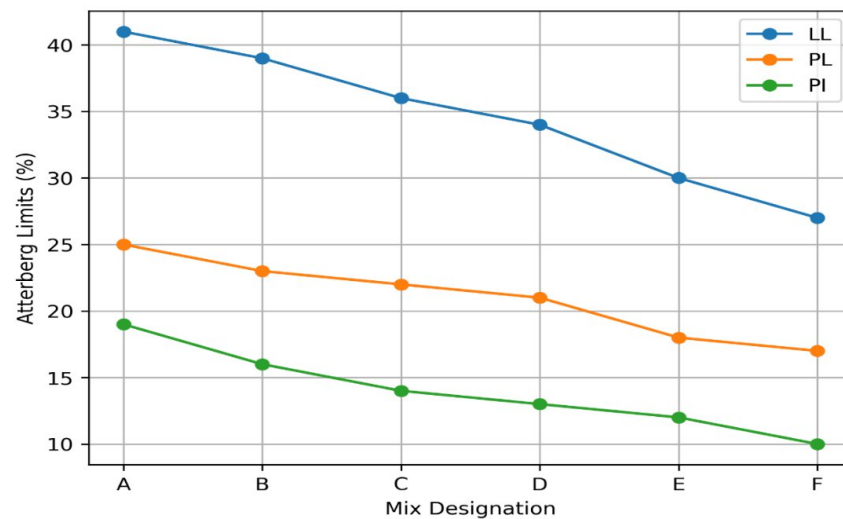


Figure 2: Effect of RHA, GSS, and CCR on Atterberg Limits of lateritic soil

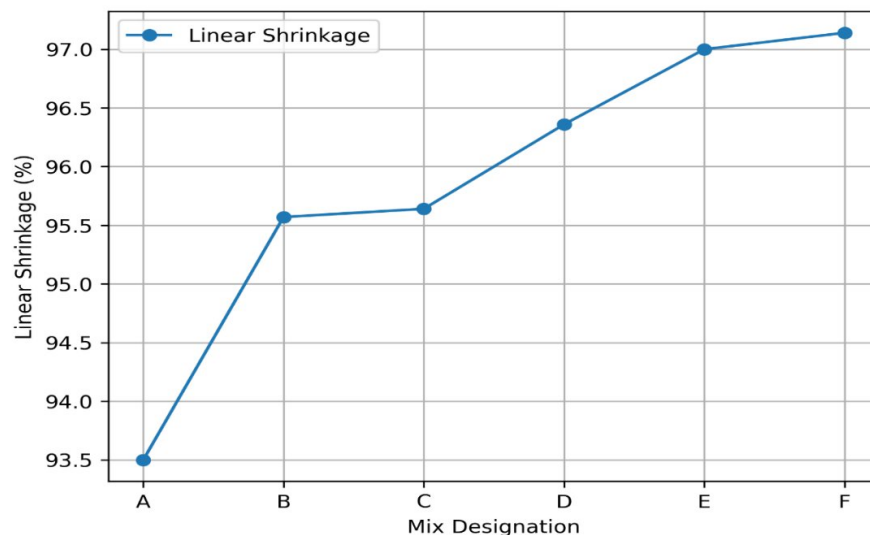


Figure 3: Linear Shrinkage of lateritic soil across all mixes

Compaction Characteristics

Table 3 presents the compaction results for all mixes. OMC decreased from 12% (Mix A) to 8% (Mixes E and F), reflecting the progressive consumption of mixing water by pozzolanic hydration reactions, a favourable outcome for field construction in Nigeria's humid tropical climate, where excess moisture during compaction is a common problem (Bandyopadhyay *et al.*, 2016). MDD peaked at Mix B (1570.36 kg/m³), then declined to Mix E (1477.77 kg/m³), reaching a minimum at Mix F (1355.87 kg/m³), as the low-density RHA fraction dominated the mixture. These trends are consistent with findings reported for CCR–fly-ash-stabilized soils (Horpibulsuk *et al.*, 2013). Figure 4 illustrates the variation of dry density with moisture content for all mixes.

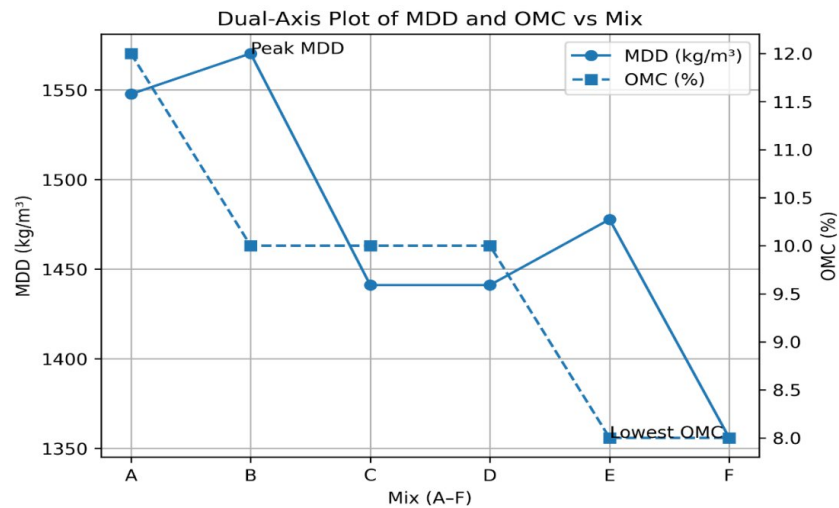


Figure 4: Compaction characteristics (OMC and MDD) for all mixes

California Bearing Ratio

Table 3 presents the CBR and UCS results for all mixes. The CBR results follow a bimodal pattern, declining from 64.61% (Mix A) to 57.15% (Mix B), then recovering progressively through Mixes C (58.72%) and D (60.88%), and peaking at Mix E (73.44%). Mix F showed a slight reduction to 67.36%. All mixes exceed the FMWH (1997/2016) minimum soaked CBR of 30% for subbase material, confirming the fundamental suitability of the lateritic soil and providing a substantial safety margin at Mix E. The initial decline at Mix B is attributed to dilution of the laterite skeleton before sufficient pozzolanic gel has formed. The strength behavior is presented in Figure 5.

Table 3: Compaction, CBR, and UCS results for all mixes

Mix	OMC (%)	MDD (kg/m ³)	CBR (%)	ΔCBR vs A	UCS (kPa)	ΔUCS vs A
A	12	1547.68	64.61	Baseline	362.79	Baseline
B	10	1570.36	57.15	−11.5%	603.38	+66.3%
C	10	1441.12	58.72	−9.1%	510.97	+40.8%
D	10	1441.12	60.88	−5.8%	434.59	+19.8%
E	8	1477.77	73.44	+13.7% ★	609.11	+67.9% ★
F	8	1355.87	67.36	+4.3%	537.70	+48.2%

★ Optimum mix

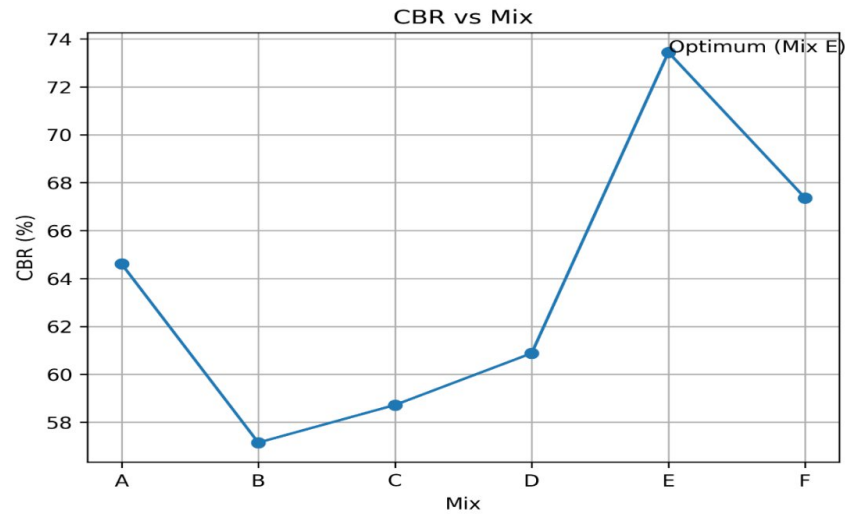


Figure 5: Soaked CBR values for all six mixes

Unconfined Compressive Strength

UCS results exhibited a pronounced bimodal pattern, consistent with CBR but with greater amplitude. Mix B achieved a strong secondary peak of 603.38 kPa (+66.3% over control), Mixes C and D recorded intermediate values, and Mix E produced the maximum UCS of 609.11 kPa (+67.9%). The observed strength gain may be associated with pozzolanic and hydraulic reactions reported in previous studies. Mix E's superiority is consolidated by its higher CBR and superior plasticity reduction. The UCS values for all six mixes are illustrated in Figure 6.

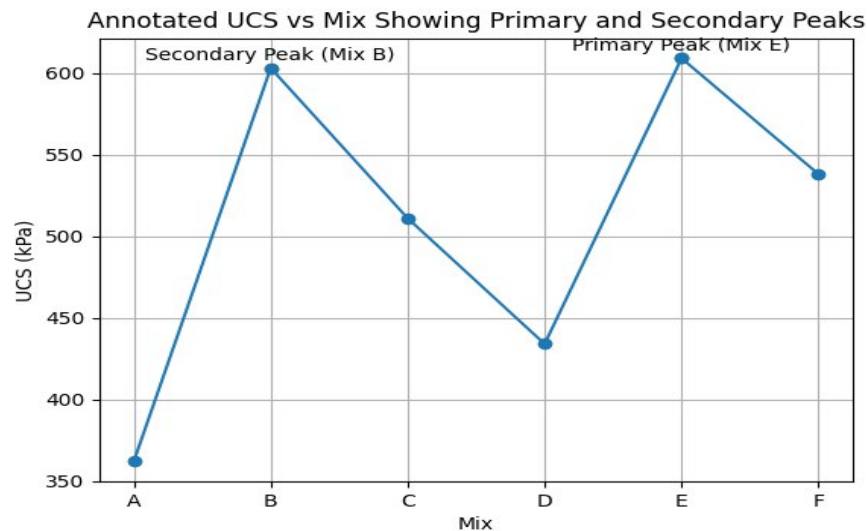


Figure 6: Unconfined Compressive Strength (UCS) for all six mixes

Conclusion

The effects of RHA, GSS and CCR as a combined stabilizer for a sustainable subbase road were investigated, and the following conclusions were drawn:

The ternary stabilization system progressively reduced the Plasticity Index from 19% to 10% and improved linear shrinkage from 93.50% to 97.14%, indicating a substantial reduction in swelling susceptibility.

The OMC decreases monotonically from 12% to 8%, reducing field compaction moisture requirements and construction risk in humid tropical climates. The MDD peaks at Mix B (1570.36 kg/m³) before declining

due to the increasing proportion of low-density RHA, reflecting the competing densification roles of GSS and RHA

Both CBR and UCS exhibited a bimodal response, with the primary optimum observed in Mix E, where CBR reached 73.44% (+13.70% over the control), which substantially exceeded the FMWH subbase minima.

UCS reached 609.11 kPa (+67.9% over the control), exceeding the Federal Ministry of Works and Housing specifications for road subbase materials.

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