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Performance of Stabilised Lateritic Soil with Citric Acid Cross Linked Cassava Starch Biopolymer for Rural Highway Infrastructure

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ABSTRACT: This study investigated the geotechnical and pavement performance of lateritic subgrade soil stabilized with citric acid cross-linked cassava starch (CLSS) biopolymer for rural highway infrastructure. Ten mix designations (S1-S10) were formulated by varying CLSS content (0-15% by dry weight of soil) and citric acid cross-linking concentration (5%, 7.5%, 10% by weight of starch). Laboratory test was carried out in accordance with BS 1377:1990 - involving Atterberg limits, Modified Proctor compaction, Unconfined Compressive Strength (UCS) at 7, 14, and 28 days curing. Also, California Bearing Ratio (soaked and un-soaked), and durability test were done under six wetting-drying (W-D) cycles. The results show that the optimum mix, S9 (15% CLSS, 7.5% citric acid cross-linking), reduced the Plasticity Index from 18.3% to 7.1% (a 61.2% reduction), the Free Swell Index from 42% to 14% (a 66.7% reduction), and swell from 2.4% to 0.3% (an 87.5% reduction). The 28-day UCS improved from 260 kPa (S1) to 1,480 kPa at S9, a 469.2% improvement, whilst soaked CBR increased from 9% to 103% (a 1,044.4% improvement). S9 retained 89.0% of its initial UCS after six W-D cycles with a mass loss of only 2.93%. These findings establish CLSS as a technically viable, environmentally sustainable, and good locally sourced stabilizer for lateritic subgrade soils in tropical rural highway construction.

KEYWORDS: Lateritic soil, Citric acid cross-linked cassava starch (CLSS), Biopolymer, rural highway, Laboratory test.

INTRODUCTION

Lateritic soils, ubiquitous in the tropical regions of Sub-Saharan Africa including Nigeria, constitute the primary subgrade material in rural highway construction owing to their widespread availability and relatively low procurement cost (Gidigasu, 1976). The high plasticity indices, low shear strength, and significant compressibility of lateritic soils predispose them to a range of pavement distresses including rutting, cracking, and differential settlement under the combined effects of heavy traffic loading and seasonal moisture fluctuations Osinubi *et al.* (2016). According to Oluwatuyi *et al.*, (2020); lateritic soils could lose as much as 30% of their shear strength under prolonged cyclic wetting and drying. Traditional soil stabilization methods, principally Portland cement and hydrated lime, have been widely employed to ameliorate the engineering deficiencies of lateritic soils. However, their widespread adoption in rural infrastructure projects in developing economies is severely constrained by environmental impact and economic cost. The manufacture of Portland cement releases approximately 0.9 tonnes of carbon dioxide per tonne produced, accounting for 7-8% of total anthropogenic CO2 emissions worldwide (Fenglai *et al.*, 2018). The procurement cost of cement in rural Nigerian communities represents a significant budgetary burden (Bhattacharyya *et al.*, 2021). These twin constraints have stimulated international research interest in alternative, sustainable stabilization approaches.

Biopolymers have emerged as a promising class of geotechnical stabilizers offering environmental sustainability and engineering performance. Their soil stabilization mechanism relies on the formation of a gel-like matrix within the soil pore network, which enhances inter-particle cohesion, reduces permeability, and improves resistance to moisture-induced deterioration (Chang *et al.*, 2016; Latifi *et al.*, 2017). Among the biopolymers investigated, cassava starch is particularly relevant in Nigeria, where production exceeds 60 million tonnes annually (Food and Agriculture Organization, 2023). The high amylose content of cassava starch facilitates formation of a viscous, cohesive gel upon hydration, which has been shown to bind soil particles and reduce void ratios (Razanajatovo *et al.*, 2020).

A critical limitation of unmodified cassava starch is its susceptibility to hydrolytic degradation upon prolonged moisture exposure. Cross-linking with citric acid (a bio-derived tricarboxylic acid) addresses this limitation by forming a three-dimensional ester-linked network between starch chains, conferring enhanced mechanical rigidity, chemical resistance, and reduced water absorption (Reddy *et al.*, 2015). This study aims to evaluate the geotechnical and pavement performance of lateritic subgrade soil stabilized with citric acid cross-linked cassava starch (CLCS) biopolymer to determine the optimal CLCS dosage and cross-linking concentration through a comprehensive laboratory testing programme.

Rural highways in tropical regions of Nigeria rely on lateritic soils as subgrade materials, yet their engineering deficiencies, including high plasticity indices (commonly exceeding 15%), low CBR values (below 10% in soaked conditions), and pronounced moisture susceptibility, leading to accelerated pavement deterioration and high maintenance costs. This study aim at evaluating the geotechnical and pavement performance of lateritic subgrade soil stabilized with a citric acid cross-linked cassava starch biopolymer for rural highway infrastructure in tropical regions of Nigeria.

LITERATURE REVIEW

Several scholars have explored biopolymer geotechnical applications, xanthan gum efficacy for clay stabilization and demonstrated economic benefits for Konkan lateritic soils in the literature. These studies offer valuable insights into diverse methodologies for stabilizations of lateritic subgrade soils. Chang, *et al.* (2016) worked on introduction of microbial biopolymers in soil treatment for future environmentally-friendly and sustainable geotechnical engineering. They established the conceptual framework for biopolymer geotechnical applications. Latifi *et al.* (2017) worked on improvement of problematic soils with biopolymer—An environmentally friendly soil stabilizer. The study confirmed xanthan gum efficacy for clay stabilization. Amadi and Oke (2018) worked on Strength characteristics of lateritic soils stabilized with biopolymers. The study provided the durability and Nigerian CBR precedents. Rashid, *et al.,* (2019) worked on Shear strength improvement of lateritic soil stabilized by biopolymer-based stabilizer. The study provided FESEM-corroborated evidence of biopolymer network formation in lateritic soils. Razanajatovo *et al.* (2020) worked on Effect of cassava (*Manihot esculenta* Crantz: Euphorbiaceae) starch on the stabilization of Malagasy lateritic soil. The study provided the highest-precedent cassava starch UCS data. . Im *et al.* (2021) and Ashok Kumar *et al.* (2022) explored Effects of malonic acid cross-linked starch for soil strength improvement and Efficacy of cross-linking of biopolymers in soil stabilization respectively. They both confirmed cross-linked biopolymer efficacy for other soil types. Walter *et al.* (2023) worked on exploring the potential of locally sourced biopolymers to stabilize lateritic earthen construction. The study reinforced the case for cassava starch for iron-rich lateritic soils. . Banne *et al.* (2025) worked on Experimental study on the stabilization of laterite soil with chitosan biopolymer for subgrade applications. The study showed exceptional CBR improvements with chitosan, including 108.81% un-soaked and 142.83% soaked CBR increase. However, these reviewed studies identify some research gaps: The systematic evaluation of CLCS across multiple dosages and cross-linking concentrations for Nigerian lateritic soils was not addressed. Durability assessment under cyclic wetting-drying was not reported for CLCS-treated lateritic soils and finally, soaked CBR performance under the worst-case moisture condition relevant to tropical pavement design was not reported for CLCS-treated lateritic soils. This study addressed all these gaps through a comprehensive and controlled laboratory tests.

MATERIALS AND METHODS

The experiment was conducted at the Geotechnical Engineering Laboratory of Landmark University, Omu-Aran, Kwara State, Nigeria. Weak lateritic soil was sourced from a borrow pit in Ikole-Ekiti, Ekiti State, within the Precambrian basement complex formation of southwestern Nigeria. Bulk samples were obtained from 0.5-1.5 m depth following topsoil removal, in accordance with BS 1377-1:1990. Cassava starch was procured from a local cassava processing industry in Ado-Ekiti and verified to contain amylose content exceeding 20% through iodometric spectrophotometric analysis. Food-grade citric acid (anhydrous, 99% purity) was procured from a certified chemical supplier. Distilled water was employed throughout all procedures to ensure consistency. CLCS was prepared according to specification of Reddy *et al.* (2015), adapted for geotechnical laboratory conditions. A starch slurry (100 g/L, 10% w/v in distilled water) was prepared. Citric acid was added at three concentrations: 5%, 7.5%, and 10% by weight of the dry starch. The pH was adjusted to 3.5-4.0 using 1 M sodium hydroxide solution to promote ester bond formation. Each slurry batch was heated to 120 degrees C in a temperature-controlled oven for two hours to facilitate cross-linking through esterification. The resulting gel was dried at 60 degrees C for 24 hours, ground using an agate mortar and pestle, sieved through a No. 200 BS sieve (0.075 mm aperture), and stored in sealed airtight containers. Ten mix designations were adopted as presented in Table1, incorporating three CLCS dosage levels (5%, 10%, 15% by dry weight of soil) combined with three citric acid cross-linking concentrations (5%, 7.5%, 10% by weight of starch), together with an untreated control (S1). Each mix was tested in triplicate.

Laboratory Tests

All tests were conducted in accordance with BS 1377:1990 using calibrated equipment. Atterberg limits, linear shrinkage, free swell index, and specific gravity tests were performed following BS 1377-2:1990 directives. Modified Proctor compaction tests were conducted according to Clause 3.5 of BS 1377-4:1990, using a 1,000 cm^3 mould and 4.5 kg rammer with a minimum of five test points per mix. UCS tests were performed at strain rate 1.0 mm/min according to Clause 7 of BS 1377-7:1990, for 7, 14, and 28 days curing. Also, using the same Clause 7; CBR tests were performed, specimens were submerged for 96 hours with a 4.5 kg surcharge and swell measured at 24-hour intervals. Durability tests was done following a procedure from ASTM D559: six cycles of immersion in distilled water for 48 hours were carried out by oven drying the samples at 40 degrees C for 48 hours. UCS was determined on separate specimens after each cycle and mass loss was calculated. Table 1 shows the design mix proportion for laboratory tests.

Table 1: Design Mix Proportions for Laboratory Tests

Sample ID	Lateritic Soil (%)	CLCS (%)	Citric Acid Conc. (% of starch)	Curing (days)
S1	100	0	0	7, 14, 28
S2	95	5	5	7, 14, 28
S3	95	5	7.5	7, 14, 28
S4	95	5	10	7, 14, 28

S5	90	10	5	7, 14, 28
S6	90	10	7.5	7, 14, 28
S7	90	10	10	7, 14, 28
S8	85	15	5	7, 14, 28
S9	85	15	7.5	7, 14, 28
S10	85	15	10	7, 14, 28

Note: S1 = untreated control. CLCS content expressed as percentage of dry soil weight. Water content adjusted to OMC for each mix during compaction.

RESULTS AND DISCUSSION

The following are the various results obtained from the experiment carried out:

Index Properties of CLCS-Stabilised Lateritic Soil

The index properties of all ten mixes of CLCS-Stabilized Lateritic Soil are presented in Table 2. Complementarily, figure 1 illustrates the trends in plasticity reduction.

Table 2: Index Properties of CLCS-Stabilized Lateritic Soil Mixes

Mix	LL (%)	PL (%)	PI (%)	LS (%)	FSI (%)
S1	45.2	26.9	18.3	11.7	42
S2	44.1	27.1	17.0	10.8	38
S3	43.0	27.4	15.6	10.0	34
S4	41.9	27.8	14.1	9.2	30
S5	40.7	28.2	12.5	8.4	26
S6	39.6	28.6	11.0	7.7	22
S7	38.8	29.0	9.8	7.1	19
S8	38.2	29.5	8.7	6.5	16
S9	37.8	30.7	7.1	6.0	14
S10	38.1	30.4	7.7	6.3	15

Source: Author's Laboratory Results (2026)

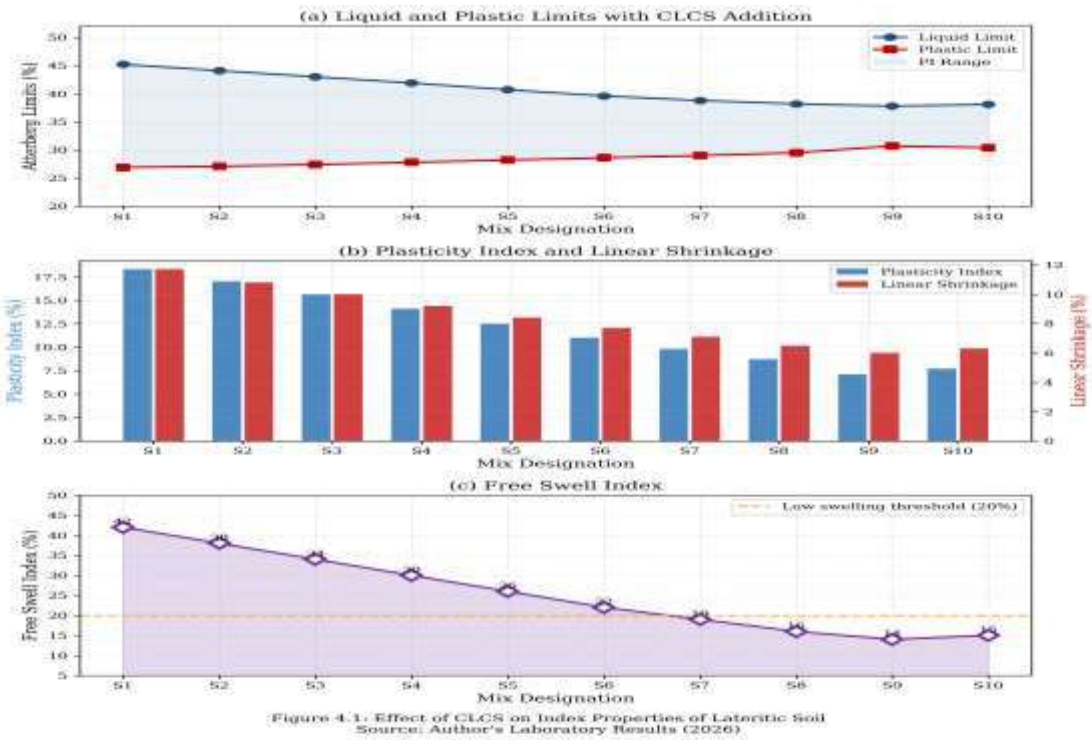

Figure 1: Effect of CLCS on Index Properties of Lateritic Soil Source: Author's Laboratory Results (2026)

According to table 2, the liquid limit decreased progressively from 45.2% for S1 to 37.8% at S9, whilst the plastic limit increased from 26.9% to 30.7%, producing a substantial reduction in plasticity index from 18.3% to 7.1% (a 61.2% decrease of direct practical significance), moving the stabilised soil from A-7-6 to a substantially improved AASHTO classification. It can be seen from Figure 1 that Linear shrinkage reduced from 11.7% to 6.0% at S9 (a 48.7% reduction), and the free swell index was reduced from 42% to 14% at S9 (a 66.7% reduction), below the 20% threshold indicative of low swelling potential. The optimum cross-linking concentration of 7.5% (S9) achieved superior plasticity reduction compared to both 5% (S8) and 10% (S10) concentrations at 15% CLCS content, consistent with findings of Kahraman *et al.* (2015) who reported optimal cross-linking performance at intermediate reagent concentrations.

Compaction Characteristics

The Modified Proctor compaction characteristics of all mixes are summarized in Table 3, with compaction curves and MDD-OMC trends presented in Figure 2.

Table 3: Compaction Characteristics of Untreated and CLCS-Stabilized Lateritic Soil

Mix	Mean MDD (Mg/m3)	SD	CV (%)	Mean OMC (%)	SD	CV (%)
S1	1.819	0.009	0.50	14.00	0.20	1.43
S2	1.808	0.014	0.78	14.43	0.35	2.43
S3	1.802	0.011	0.58	14.83	0.35	2.37
S4	1.790	0.018	1.01	15.23	0.35	2.31
S5	1.780	0.008	0.42	15.73	0.40	2.57
S6	1.761	0.016	0.91	16.10	0.40	2.48
S7	1.745	0.008	0.47	16.53	0.25	1.52
S8	1.735	0.007	0.40	16.87	0.25	1.49
S9	1.726	0.017	0.96	17.23	0.40	2.35
S10	1.705	0.015	0.85	17.70	0.36	2.04

Source: Author's Laboratory Results (2026)

From table 3 and figure 2, CLCS addition produced a progressive decrease in MDD from 1.819 Mg/m3 (S1) to 1.705 Mg/m3 (S10), a reduction of 0.114 Mg/m3 (6.3%), and a corresponding increase in OMC from 14.0% to 17.7% (a 26.4% increase). These trends reflect the lower specific gravity of the biopolymer phase (approximately 1.45-1.50 g/cm3 vs. approximately 2.68 g/cm^3 for soil mineral particles) and the hygroscopic nature of the starch biopolymer. The CV values below 1.1% for MDD across all triplicate groups confirm excellent reproducibility of specimen preparation.

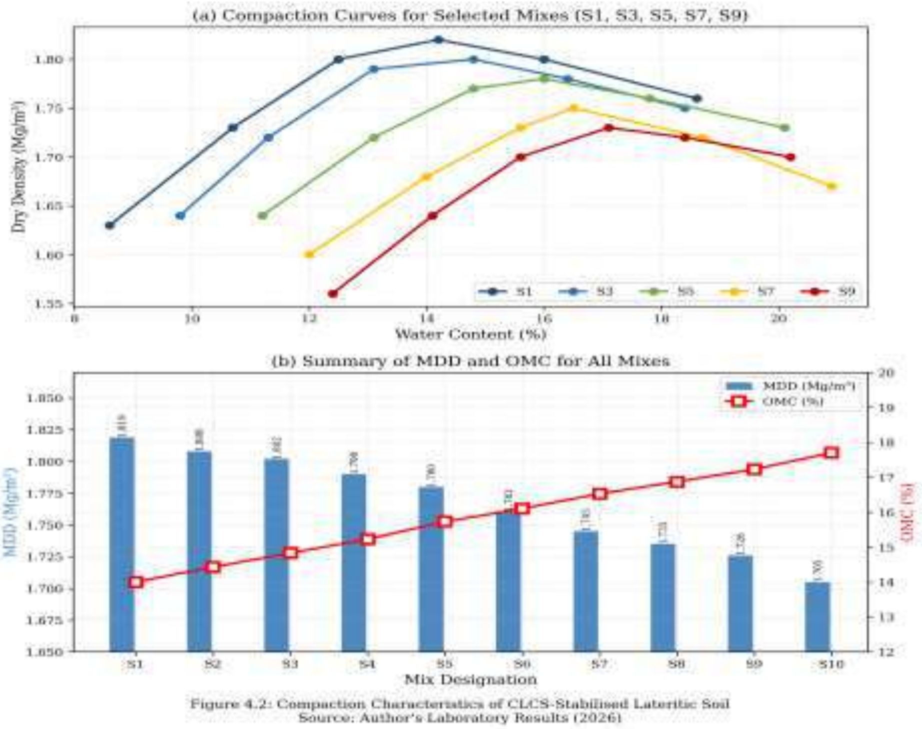

Figure 2: Compaction Characteristics of CLCS-Stabilized Lateritic Soil Source: Author's Laboratory Results (2026)

Unconfined Compressive Strength

The unconfined compressive strength results for all mixes at 7, 14, and 28 days of curing are presented in Tables 4 and 5. Also, figure 3 presents UCS development with mix designation and curing age.

Table 4: UCS Results for All Mixes at 7, 14, and 28 Days Curing (kPa)

Mix	7D Mean	7D SD	14D Mean	14D SD	28D Mean	28D SD	CV 28D (%)
S1	185	7.94	220	8.54	260	12.53	4.82
S2	238	10.58	287	13.53	352	16.52	4.69
S3	292	10.15	381	13.75	478	19.52	4.08
S4	378	14.18	465	17.06	602	26.01	4.32
S5	452	15.72	586	21.38	768	24.64	3.21
S6	572	16.37	718	23.58	918	33.51	3.65
S7	685	16.52	852	23.90	1,125	38.69	3.44
S8	818	21.63	1,018	30.20	1,245	35.00	2.81
S9	925	24.88	1,160	32.74	1,480	41.24	2.79
S10	878	24.02	1,092	28.83	1,360	52.00	3.82

Table 5: Percentage UCS Improvement over Control at 28 Days

Mix	28D UCS (kPa)	Improvement over S1 (%)	kPa increment from previous
S1	260	–	–
S2	352	35.4	+92
S3	478	83.8	+126
S4	602	131.7	+124
S5	768	195.4	+166
S6	918	253.1	+150
S7	1,125	332.7	+207
S8	1,245	378.8	+120
S9	1,480	469.2	+235
S10	1,360	423.1	−90 (regression)

Source: Author's Laboratory Results (2026)

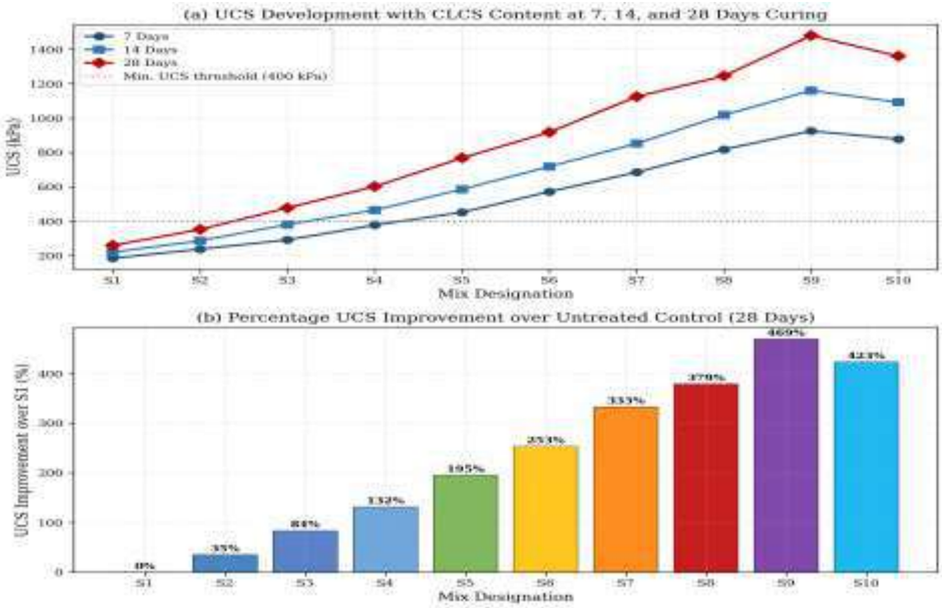

Figure 3: UCS of CLCS-Stabilized Lateritic Soil; Source: Author's Laboratory Results (2026)

Tables 4 and 5 and figure 3 show a demonstration of a highly significant and progressive improvement in compressive strength with increase in CLCS content and with advanced curing age across all mix designations. The optimum mix S9 (15% CLCS, 7.5% citric acid cross-linking) achieved a 28-day UCS of 1,480 kPa, representing a 469.2% improvement over the untreated control value of 260 kPa. This is a transformative improvement that moves the stabilized soil from a condition of inadequate subgrade strength to one substantially exceeding the minimum UCS requirement of 400 kPa commonly specified for lightly trafficked rural road subgrades in tropical pavement design guidelines.

The dose-response relationship between CLCS content and UCS exhibits a clear optimum at S9 within the 15% CLCS group. Comparing S8 (1,245 kPa), S9 (1,480 kPa), and S10 (1,360 kPa) confirms that citric acid cross-linking concentration critically influences strength development. At 5% cross-linking (S8), the biopolymer network density may be insufficient to maximize the binding effect. At 10% cross-linking (S10), over-cross-linking may produce a more brittle, less deformable matrix, reducing peak UCS relative to S9. This optimum at intermediate cross-linking concentration is consistent with the starch chemistry findings of Kahraman *et al.* (2015).

The curing age effect is pronounced across all mixes. For S9, UCS increased from 925 kPa at 7 days to 1,160 kPa at 14 days and 1,480 kPa at 28 days, representing a 25.4% gain from 7 to 14 days and a further 27.6% gain from 14 to 28 days. This progressive strength development is consistent with continued ester bond formation and biopolymer network densification over time, analogous to pozzolanic curing in lime-stabilized soils but proceeding through different chemical mechanisms. The continued significant gain between 14 and 28 days suggests that full biopolymer curing had not been achieved at 14 days, and that extended curing periods might yield further improvement.

Comparison with the prior literature confirms the significance of these findings. Razanajatovo *et al.* (2020) reported a UCS of 5,480 kPa for Malagasy lateritic soil stabilized with 15% unmodified cassava starch under dry curing conditions. The substantially lower values obtained in the present study under moist curing conditions are considered more representative of field performance in a humid tropical environment. Ayeldeen *et al.* (2017) reported a 25% UCS improvement for citric acid cross-linked starch on collapsible soils at much lower biopolymer dosages, confirming that higher dosages yield proportionally greater improvements. The failure strain data confirm that CLCS treatment reduced the failure strain from 2.82% for S1 to 2.02% for S9 at 28 days, indicating a transition towards a stiffer failure mode consistent with biopolymer network stiffening, a characteristic of chemically stabilized soils that does not represent an engineering limitation for subgrade applications.

California Bearing Ratio Characteristics

The soaked and unsoaked CBR results, swell measurements, and CBR retention data are presented in Tables 6 and 7. Also, Figure 4 illustrates the CBR performance trends.

Table 6: CBR Results (Unsoaked and Soaked) for All Mixes

Mix	Unsoaked CBR (%)	Soaked CBR (%)	Swell after 96 h (%)
S1	18	9	2.4
S2	23	14	2.1
S3	32	20.7	1.8
S4	41	29.7	1.5
S5	53	42	1.1
S6	67	56.7	0.9
S7	81	73	0.7
S8	94	87	0.5
S9	110	103	0.3
S10	102	94.7	0.4

Source: Author's Laboratory Results (2026)

Table 7: CBR Retention and Swell Data after Soaking

Mix	Unsoaked CBR (%)	Soaked CBR (%)	Retention (%)	Improvement vs S1 Soaked (%)
S1	18	9	50.0	–
S2	23	14	60.9	55.6
S3	32	20.7	64.6	129.6
S4	41	29.7	72.4	229.6
S5	53	42	79.2	366.7
S6	67	56.7	84.6	529.6
S7	81	73	90.1	711.1

S8	94	87	92.6	866.7
S9	110	103	93.6	1,044.4
S10	102	94.7	92.8	951.9

Source: Author's Laboratory Results (2026)

From tables 6 and 7, the CBR results corroborate and amplify the UCS findings. The optimum mix S9 achieved an unsoaked CBR of 110% and a soaked CBR of 103%, compared to 18% and 9% respectively for S1. The soaked CBR improvement of 1,044.4% is particularly noteworthy, as soaked CBR is the parameter universally employed in tropical pavement design for determining subgrade strength under worst-case moisture conditions. A soaked CBR of 103% at S9 far exceeds the threshold of 30% typically required for a good subgrade material in Nigerian Federal Highway design practice and approaches the specification threshold for sub-base quality material (CBR >= 80%). This implies that CLCS-stabilized lateritic soil at the optimum dosage could potentially eliminate the need for a discrete sub-base layer in lightly trafficked pavement structures, yielding significant construction cost savings.

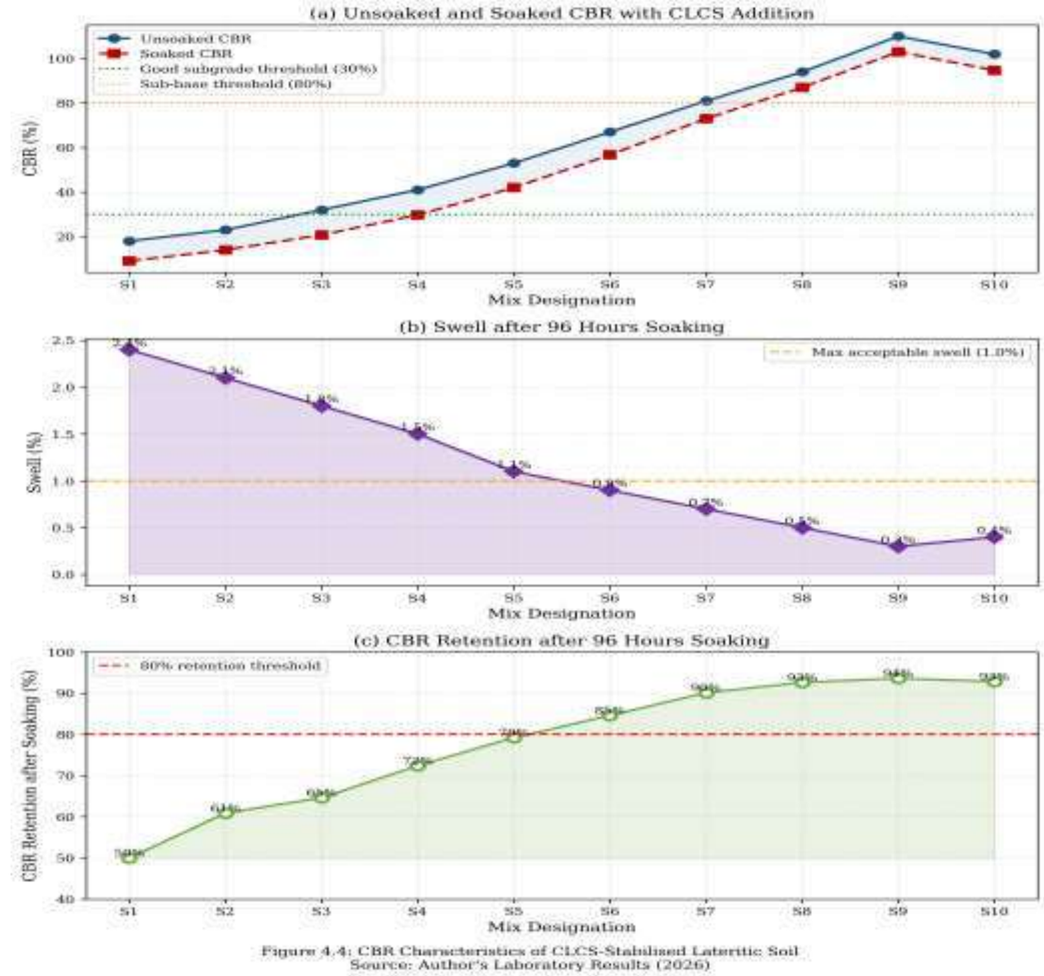

Figure 4: CBR Characteristics of CLCS-Stabilized Lateritic Soil Source: Author's Laboratory Results (2026)

Figure 4 reveals that the CBR retention data provide a direct measure of moisture resistance. The untreated soil retained only 50.0% of its unsoaked CBR after 96 hours of soaking, confirming high moisture sensitivity. CLCS treatment progressively improved CBR retention to 93.6% at S9, representing near-complete preservation of bearing capacity upon saturation. This improvement is mechanistically attributed to the cross-linked biopolymer network filling inter-particle pore spaces, reducing hydraulic conductivity and limiting water ingress that would otherwise disrupt inter-particle bonding. From figure 4, it could be deduced that the swell data further confirm the beneficial effect: swell after 96 hours of soaking was reduced from 2.4% for S1 to 0.3% at S9, a reduction of 87.5%. Mixes S5 through S9 all achieved swell values below the 1.0% threshold commonly specified as the maximum acceptable for pavement subgrade materials.

Comparison with the prior literature contextualises these results. Banne *et al.* (2025) reported unsoaked and soaked CBR improvements of 108.81% and 142.83% for Konkan lateritic soil treated with 0.3% chitosan, achievements of comparable relative magnitude but at a much lower biopolymer dosage. The higher CLCS dosage required in the present study may reflect differences in biopolymer-soil affinity specific to Nigerian lateritic soils. Amadi and Oke (2018) reported a 30% CBR improvement for Nigerian lateritic soils treated with biopolymers at lower dosages, substantially below the improvements recorded here. Chang *et al.* (2016) attributed moisture resistance improvements in xanthan gum-treated soils to biopolymer coating of particle surfaces that reduced hydrophilicity; the same mechanism is operative in CLCS-treated specimens.

Durability Characteristics

The durability of the untreated and CLCS-stabilized specimens under six wetting-drying cycles is assessed through UCS degradation, mass loss, and a Durability Performance Index. Results are presented in Tables 8 and 9. In commemoration of the result, Figure 5 illustrates durability performance index.

Table 8: UCS Degradation under Wetting-Drying Cycles (kPa)

Mix	Cycle 0	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6
S1	260	244	229	213	198	182	164
S2	352	336	319	301	282	262	239
S3	478	458	439	418	396	372	335
S4	602	583	562	540	512	484	458
S5	768	752	733	708	675	637	607
S6	918	899	878	850	812	777	744
S7	1,125	1,104	1,080	1,050	1,015	982	956
S8	1,245	1,220	1,198	1,170	1,138	1,105	1,071
S9	1,480	1,462	1,443	1,416	1,386	1,352	1,317
S10	1,360	1,338	1,310	1,280	1,238	1,192	1,156

Source: Author's Laboratory Results (2026)

Table 9: Strength Retention, Mass Loss, and Durability Performance Index (DPI)

Mix	Initial UCS (kPa)	Final UCS (kPa)	Retention (%)	Mass Loss (%)	DPI
S1	260	164	63.1	13.47	4.68
S2	352	239	67.9	11.90	5.71
S3	478	335	70.1	10.40	6.74
S4	602	458	76.1	8.90	8.55
S5	768	607	79.0	7.20	10.98
S6	918	744	81.0	6.00	13.51
S7	1,125	956	85.0	4.90	17.34
S8	1,245	1,071	86.0	3.90	22.06
S9	1,480	1,317	89.0	2.93	30.34
S10	1,360	1,156	85.0	3.60	23.61

Source: Author's Laboratory Results (2026). DPI = Strength Retention (%) / Mass Loss (%).

According to tables 8 and 9, the durability test results confirm that CLCS treatment substantially improved the resistance of the lateritic soil to cyclic wetting-drying degradation. The untreated control (S1) retained only 63.1% of its initial 28-day UCS after six W-D cycles, declining from 260 kPa to 164 kPa, and suffered a mean mass loss of 13.47%. Visual inspection confirmed severe cracking and edge degradation, consistent with progressive loss of inter-particle cohesion upon repeated wetting and drying. In marked contrast, S9 retained 89.0% of its initial UCS (declining from 1,480 kPa to 1,317 kPa) and exhibited a mean mass loss of only 2.93%. The visual condition of S9 specimens after six cycles was recorded as intact with negligible deterioration, confirming the integrity of the cross-linked biopolymer matrix under repeated moisture stress.

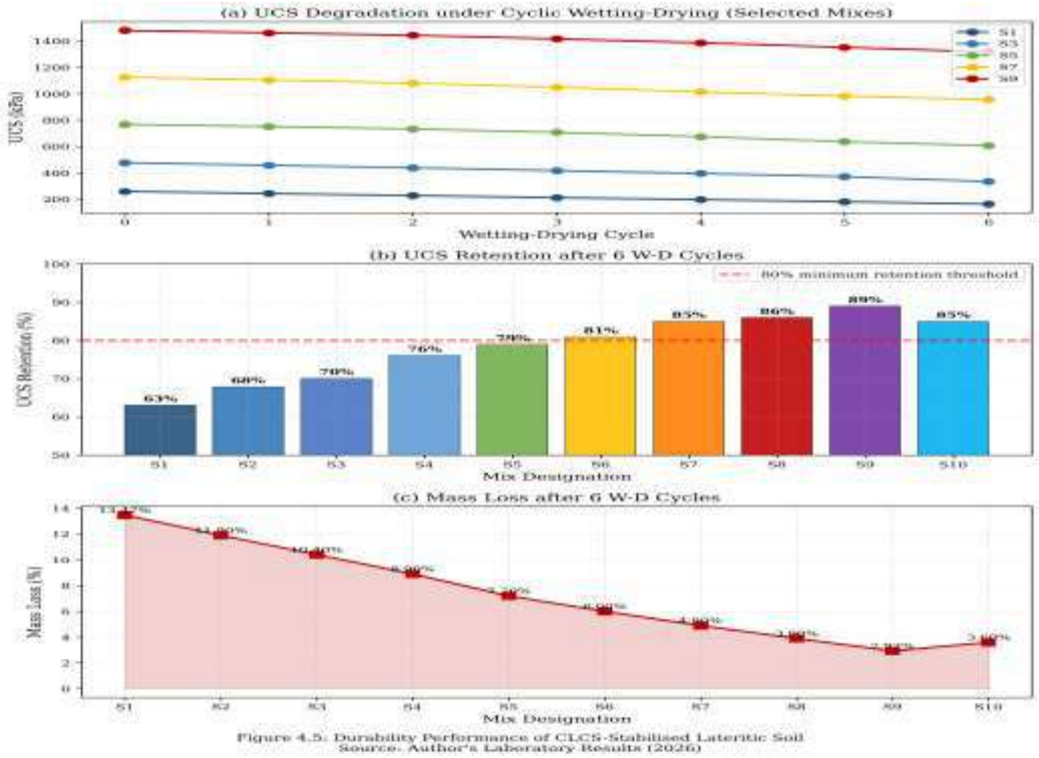

Figure 5: Durability of CLCS-Stabilised Lateritic Soil under Wetting-Drying Cycles Source: Author's Laboratory Results (2026)

From figure 5, the UCS degradation per cycle for S9 averaged approximately 27.2 kPa (1.84% of initial UCS per cycle), compared to 16.0 kPa per cycle for S1 (6.15% per cycle). This comparison illustrates that S9 not only retains a higher absolute UCS value but exhibits a substantially lower proportional rate of degradation. Critically, even after six W-D cycles, the residual UCS of S9 (1,317 kPa) exceeds the initial UCS of the untreated control (260 kPa) by more than five-fold, underlining the transformative and durable nature of CLCS stabilization.

The Durability Performance Index increased from 4.68 for S1 to 30.34 for S9, a 548% improvement. The DPI of S10 (23.61) fell below that of S9 (30.34), confirming the superiority of 7.5% citric acid cross-linking over both lower and higher concentrations at the 15% CLCS dosage. Reddy *et al.* (2015) reported 15-20% improved durability under wetting-drying cycles for citric acid cross-linked starch films; the present study recorded 89% strength retention for CLCS-stabilized lateritic soil, a substantially higher value, though the comparison is across different materials and conditions. The mass loss reduction from 13.47% (S1) to 2.93% (S9) demonstrates the effectiveness of CLCS in preserving specimen physical integrity under the mechanical abrasion and dissolution associated with W-D cycling, a finding that directly addresses the durability limitation previously identified as the primary obstacle to biopolymer stabilizer adoption in tropical highway applications.

CONCLUSION

The study established that the natural lateritic soil from Ikole-Ekiti is a poor subgrade material due to its high plasticity, swelling potential, and low soaked CBR. Treatment with CLCS significantly improved the soil's engineering properties, with the optimum mixture (S9) reducing plasticity and swelling while substantially increasing strength. At S9, the plasticity index decreased by 61.2%, free swell index by 66.7%**,** 28-day UCS increased by 469.2%**,** and soaked CBR increased from 9% to 103%**,** while swell reduced from 2.4% to 0.3%. The optimum 7.5% citric acid cross-linking concentration produced the best performance. The treatment also markedly improved durability under wetting–drying cycles, with S9 retaining 89% of its UCS after six cycles and showing much lower mass loss than the untreated soil. In all, the findings demonstrate that CLCS stabilized with 7.5% citric acid is an effective and durable treatment for improving poor lateritic subgrade soils, particularly under tropical climatic conditions.

Implications for Theory and Practice

Theoretically, this study contribute to the body of knowledge on the fact that a systematic and comprehensive dataset on the geotechnical performance of Nigerian lateritic soil stabilized with citric acid cross-linked cassava starch was established, spanning index properties, compaction, UCS at multiple curing ages, CBR, and W-D durability, thereby filling a critical gap in the tropical soil stabilisation literature. Practically, the insight gained on the durability of CLCS-stabilised lateritic soil under six wetting-drying cycles, demonstrating 89.0% UCS retention at the optimum mix and directly addressing the durability limitation previously identified as the primary obstacle to biopolymer stabiliser adoption in tropical highway applications can assist highway engineers' management strategies tailored to similar tropical regions.

Limitations of the study

Despite the valuable contributions, this study has several limitations. Performance of CLCS stabilization on tropical soil limits the generalizability of the findings. The laboratory findings under actual traffic and climatic conditions were not validated for long term performance. The long-term biodegradation behaviour of the CLCS biopolymer within the soil matrix under field conditions was not assessed for any maintenance or retreatment protocol or to establish temporal limitations of the stabilization effects.

Recommendations for Future Research

To address the identified gaps and build on the findings of this study, future research should consider the following:

i.) The performance of CLCS stabilisation should be evaluated for lateritic soils from different geological formations and regions across Nigeria to assess the generalizability of the optimum mix proportions established in this study to soils of varying mineralogical composition.

ii.) Field trials and pilot-scale pavement sections incorporating CLCS-stabilized subgrade layers should be constructed and monitored over a minimum period of two years to validate laboratory findings under actual traffic and climatic conditions, and to establish long-term performance data.

iii.) The long-term biodegradation behaviour of the CLCS biopolymer within the soil matrix under field conditions should be investigated through accelerated ageing tests, to establish the temporal limitations of the stabilization effect and the need for any maintenance or retreatment protocol.

Conflicts of Interest Declaration

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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