

Stabilization of Lateritic Soils Admixed with Alkali-Activated Groundnut Shell Ash for Highway Construction

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ARTICLE INFORMATION

Article history:

Published: October 2026

Keywords:

Lateritic soil
 Groundnut Shell Ash
 UCS
 Stabilization

ABSTRACT

This study evaluates alkali-activated Groundnut Shell Ash (GSA) with Sodium Hydroxide (NaOH) for sub-base and base course highway construction. Soil collected at 1.0 - 1.5m depth was tested natural and admixed with GSA at 3%, 6%, 9% and NaOH at 3M, 6.5M, 10M in 13 trial mixes. The results showed that addition of alkali-activated GSA significantly improved plasticity characteristics of lateritic soil. The lowest plasticity index 7.6% for base course was achieved at 6% GSA + 3% NaOH which indicates optimum cation exchange and flocculation. The Plasticity Index for subbase suitability ranged from 8.5% to 10.4%. The Optimum Moisture Content (OMC) remained relatively stable at 12 - 12.4% for both sub-base and base course. Maximum Dry Density (MDD) ranged from 1.819 - 1.942 Mg/m³ for sub-base and 1.925 - 1.978 Mg/m³ for base course. The Unconfined Compressive Strength (UCS) results showed progressive gains with curing age from 7 to 28 days due to continuous geopolymerization. For sub-base, 28-day UCS ranged from 620 - 2227 kN/m², while for base course it ranged 754 - 2360 kN/m². The highest strength of 2360 kN/m² was achieved at 6% GSA + 10% NaOH for base course and 2227 kN/m² at same mix. The soaked and unsoaked CBR improved significantly after alkali activation of natural soil with values from 27.6% to 42.0% for sub-base and 55.8% to 72.3% for base course. Groundnut Shell Ash alkali-activated with 6 - 9% GSA and 6.5 - 10M NaOH should be adopted as sustainable alternative to cement for stabilization of A-2-4 lateritic soils for sub-base and low-volume base course, especially in Northern Nigeria where groundnut shell is available as agricultural waste.

1. Introduction

Lateritic soil containing high clay content may expand when moisture is present and shrink when the moisture is dry. Cracks may develop because of shrinkage, which may prompt a decrease in a portion of the mechanical properties of the Laterite (Otoko and Isima, 2016). Areas where problematic lateritic soil of this sort is available, attempting to get appropriate alternative soil may not be practical. Thus, the Stabilization of the Laterite to meet the necessary strength is unavoidable (Ayodele et al., 2020). One of these industrial residues or agricultural wastes is Groundnut shell. In Nigeria, groundnut is highly cultivated in the northern region and contributes about 7% to the world groundnut production, which makes Nigeria the third largest producer of groundnut in the world (Oriola and Moses 2010; Edeh et al. 2013). Around 4 million metric tons of groundnut were made in Nigeria's around 2,783,000 hectares of land (FAO. 2023). Out of a few million tons of groundnuts finished on the planet reliably, groundnut shells make up around 28 - 32% of the full-scale mass and are used in steers and poultry feed. Groundnut shell has enormous potential for business use. It is used as a fuel, filler in cows feed, hard particleboard, plug substitute, activated carbon, etc. The groundnut shell is important as livestock feed, particularly in the dry season in the semi-arid region (Vabi et al., 2019).

The over-dependence on industrially manufactured materials such as "cement" has often kept the cost of construction high, especially in developing countries (Abuh et al., 2026; Pam et al., 2026). On the other hand, intensified efforts have been aimed at harnessing agricultural waste for further use. Thus, the possible use of agricultural waste such as groundnut shells will considerably reduce the cost of construction as well as reduce or eliminate the environmental hazards caused by such waste (Ajala et al. 2020). The process of blending and mixing materials with soil to alter certain properties of the soil is referred to as stabilization. Oluyinka and Olubunmi (2018) showed improvements in stabilized lateritic soil as subgrade and base material for road construction in Abeokuta, Southwest Nigeria.

2. Methodology

The soil sample was collected from Gudun Sayawa in Bauchi Local Government Area of Bauchi State, Nigeria. The sample was collected at a depth between 1 to 1.5m from one location test pit using the method of disturbed sampling. The collected soil material was put in polythene bags and brought to the Soil Mechanics Laboratory of the Abubakar Tafawa Balewa University Bauchi for soil testing according to BS 1377 (1990).

Groundnut shells for this project were obtained locally from the Muda Lawal market in Bauchi LGA, Bauchi State, Nigeria. The groundnut shell was burnt in a kiln at the industrial design department, ATBU Bauchi, at temperatures ranging from 650 to 700°C for 2 hours to obtain the GSA that was used for this research.

Sodium hydroxide (NaOH) is the alkaline-base material used for the research. NaOH, which was added to the GSA, to activate the ash, before mixing with the soil sample, was obtained by dissolving sodium hydroxide flakes in distilled water. Potable water free

of contaminants and fit for human consumption was used for the experimental work. The following laboratory tests were conducted on the natural and stabilised soil samples per BS 1377 (1990).

- Moisture content
- Specific gravity
- Particle size distribution
- Atterberg limits
- Compaction test (BSH & WAS)
- Unconfined Compressive Strength (UCS)
- Soaked and Unsoaked California bearing ratio (CBR)

3. Results and Discussions

3.1 Characterization of the Natural Soil

The results for the physical properties of the soil are presented in Table 1.

Table 1: Preliminary Results of the Natural Soil

Soil Properties	Sub-base course	Base course
Natural Moisture content w, (%)	2.3	2.3
Specific gravity (G)	2.65	2.64
Liquid limit (%)	30.0	33.0
Plastic Limit (%)	20.8	23.8
Plasticity index (%)	9.2	9.2
Linear shrinkage (%)	3.5	3.6
BS Sieve No.200 (75u)	34.4	30.8
Maximum dry density WAS (Mg/m ³)	1.85	1.99
Optimum moisture content WAS (%)	10.2	10.3
Maximum dry density BSH (Mg/m ³)		434
Optimum moisture content BSH (%)		
Unconfined compressive strength (kN/m ²)		
Unconfined compressive strength (kN/m ²)	283	55.8
Unsoaked California bearing ratio CBR (%)	27.6	Light brown
Soaked California bearing ratio CBR (%)	Light brown	A-2-4 (0)
Colour	A-2-4 (0)	SM(Gravel)
AASHTO Classification	SC (Clayey)	
USCS Classification		

The Sub-base-course soil preliminary properties showed values of liquid limit, plastic limit and plasticity index were 30.0, 20.8 and 9.2 respectively, while the linear shrinkage is 3.5, hence the soil is classified as A-2-4(0) in accordance with the American Association of State Highway and Transportation Officials (AASHTO M 145-2012) soil classification system and SC (Clayey) in accordance with the Unified Soil Classification System (ASTM D 2487-2011) respectively. Equally, the Base-Course soil preliminary properties showed values of liquid limit, plastic limit and plasticity index were 33.0, 23.8 and 9.2 respectively, and the linear shrinkage is 3.6. The GI is 0 and therefore, the soil is classified as A-2-4(0) in accordance with the American Association of State Highway and Transportation Officials (AASHTO M 145-2012) soil classification system and SM (Gravel) in accordance with the Unified Soil Classification System (ASTM D 2487-2011) respectively. The particle size distribution curves are presented in Figure 1a and 1b.

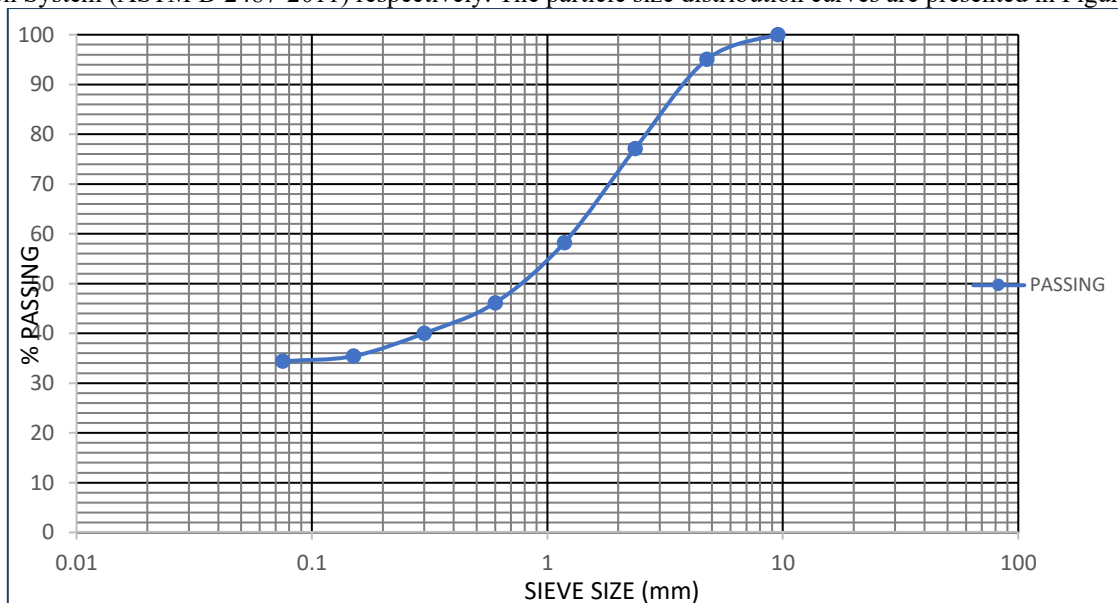


Figure 1a: Particle Size Distribution Curve of the Natural Soil (Sub-Base Course)

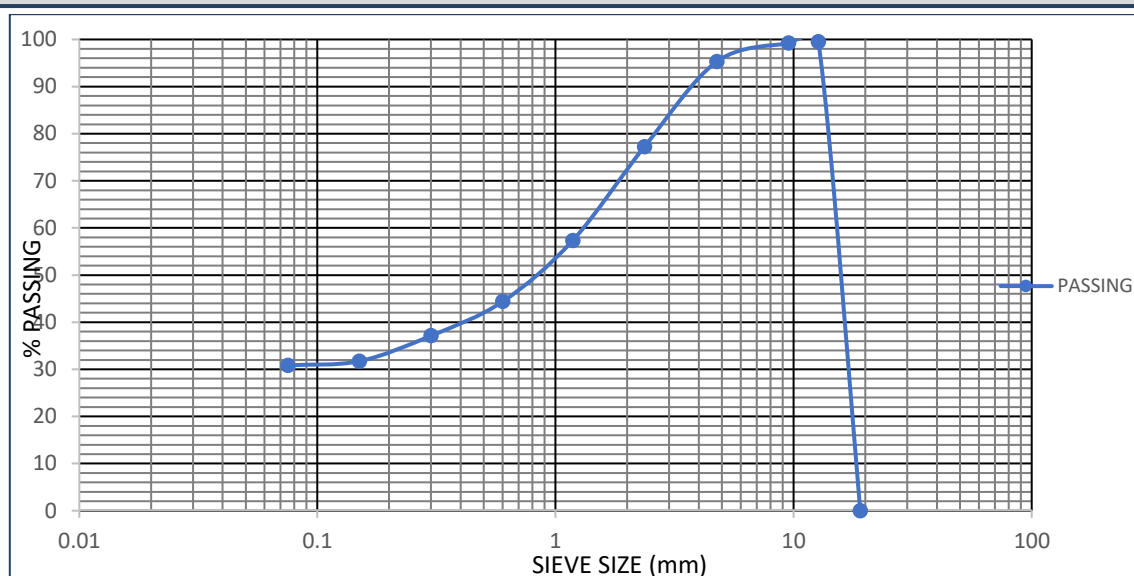


Figure 1b: Particle Size Distribution Curve of the Natural Soil (Base Course)

In Figure 1a and 1b illustrated that the particle size distribution curves for both sub-base and base course soils were presented in Figures 1a and 1b. It was shown that the soils were well-graded with approximately 65-70% sand and gravel and 30-34% fines passing 75 microns. It was confirmed that the S-shaped curves supported the A-2-4 classification. It was concluded that the gradation was suitable for stabilization with ash.

3.2 Chemical Compositions of the Natural Soil

The oxide composition for the natural or untreated soil sample obtained from the XRF analysis is presented in Table 2.

Table 2: Oxide Compositions of the Natural Soil and GSA

Oxide	Concentration (%)	
	Laterite	GSA
Silicon oxide (SiO ₂)	37.782	9.799
Aluminium oxide (Al ₂ O ₃)	18.054	5.077
Iron oxide (Fe ₂ O ₃)	27.990	4.572
Calcium oxide (CaO)	1.237	37.866
Magnesium oxide (MgO)	2.872	0.05
Potassium oxide (K ₂ O)	4.884	31.074
Manganese oxide (MnO)	0.285	0.334
Barium oxide (BaO)	0.128	0.338
Zinc oxide (ZnO)	0.071	0.094
Vanadium (V) oxide (V ₂ O ₅)	0.166	0.075
Niobium Pentoxide (Nb ₂ O ₅)	0.036	0.022
Copper (II) oxide (CuO)	0.101	0.123
Chlorine (Cl)	1.160	1.089
Titanium oxide (TiO ₂)	2.426	1.016
ZrO ₂	0.765	0.147
SnO ₂	0.136	2.556

The result of the oxide compositions of both the laterite and GSA ash are presented in Table 2. XRF shows laterite dominated by SiO₂ 37.78%, Fe₂O₃ 27.99%, Al₂O₃ 18.05% with SiO₂ / [Al₂O₃+Fe₂O₃] ratio 0.82 confirming true laterite. Low CaO 1.23% indicates non-cementitious. GSA shows K₂O 31.07%, CaO 37.86% (high due to calcination), SiO₂ 9.79%, Al₂O₃ 5.07%, Fe₂O₃ 4.57%. Sum SiO₂+Al₂O₃+Fe₂O₃ = 19.44% < 50% so not classified as pozzolan per ASTM C618, but high CaO+K₂O provides self-cementing and alkali-activation potential. High K₂O promotes dissolution of silica for geopolymerization. TiO₂ 2.42% and ZrO₂ 0.76% indicate inert minerals.

3.3 Index Properties

Index properties of soil; consistency limits (liquid limit, plastic limit and plasticity index) and soils' particle size distribution are fundamental characteristics used to classify and evaluate soil behavior. Information on soil index properties at 1m depth include; natural moisture content of 2.3, specific gravity of 2.65 and stabilized with activated GSA is presented in Tables 3a and 3b respectively.

Table 3a: Index Properties of Sub-base Soil Stabilized with Activated Groundnut Shell Ash

Run	Factors		Response		
	GSA %	NaOH Mol	W _L (%)	W _p (%)	I _p (%)
1	9	6.5	32.0	23.1	8.9
2	9	10	30.5	21.6	8.9
3	3	3	30.5	20.4	10.1

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4	6	3	31.5	21.1	10.4
5	6	6.5	31.0	22.1	8.9
6	9	3	32.0	22.1	9.9
7	6	6.5	31.0	22.1	8.9
8	6	6.5	31.0	22.1	8.9
9	3	10	30.0	21.5	8.5
10	6	6.5	31.0	22.1	8.9
11	3	6.5	30.0	20.8	9.2
12	6	6.5	31.0	22.1	8.9
13	6	10	31.5	22.1	9.4

Index Properties Sub-base was presented in Table 3e. Thirteen runs with GSA 3-9% and NaOH 3-10M were tested. LL ranges 30.0-32.0%, PL 20.4-23.1%, PI 8.5-10.4% against natural PI 9.2%. Variation is minimal within 2%, showing alkali-activated GSA does not increase plasticity or swelling potential. Lowest PI 8.5% at 3% GSA + 10M NaOH indicates optimum cation exchange where Na⁺ replaces monovalent ions reducing diffuse double layer. All PI values < 12% satisfy FMWH sub-base limit. The stable LL indicates flocculation-agglomeration mechanism and formation of N-A-S-H gel coating clay particles, beneficial for volume stability under moisture fluctuation for highway sub-base.

Table 3b: Index Properties of Base Course Soil Stabilized with AGHA

Run	GSA %	NaOH Mol	W _L (%)	W _p (%)	I _p (%)
1	3	3	23	14.5	8.5
2	6	3	24.5	16.9	7.6
3	6	6.5	29.0	20.8	8.2
4	3	6.5	29.0	20.9	8.1
5	6	10	29.0	19.7	9.3
6	6	6.5	29.0	20.8	8.2
7	6	6.5	29.0	20.8	8.2
8	9	6.5	27.0	18.3	8.7
9	3	10	30.0	21.5	8.5
10	6	6.5	29.0	20.8	8.2
11	6	6.5	29.0	20.8	8.2
12	9	3	24	15.3	8.7
13	9	10	31.0	21.6	9.3

The index properties of base course soil were shown in Table 10b Base course index properties show LL 23.0-31.0%, PL 14.5-21.6%, PI 7.6-9.3%. At low dosage 3% GSA + 3M NaOH, LL drops sharply from natural 33.0% to 23.0% due to flocculation. At centre point 6% GSA + 6.5M NaOH, LL increases to 29.0% due to geopolymer gel formation holding water. PI remains low 7.6-9.3% below FMWH 12% limit for base course, indicating excellent volume stability. Lowest PI 7.6% at 6% GSA + 3M NaOH is optimal. The low PI ensures low swelling and shrinkage under traffic loading, making soil suitable for base course after stabilization with alkali-activated GSA. Sub-Base and base course, Variation of OMC – MDD with AGSA Content are presented in Tables 4a and 4b.

Table 4a: Sub-Base, Variation of OMC – MDD with AGSA Content

Run	Factors		Response	
	GSA %	NaOH Mol	OMC (%)	MDD (Mg/m ³)
1	9	6.5	12.3	1.819
2	9	10	12.0	1.849
3	3	3	12.3	1.883
4	6	3	12.2	1.859
5	6	6.5	12.3	1.878
6	9	3	12.4	1.849
7	6	6.5	12.3	1.878
8	6	6.5	12.3	1.878
9	3	10	12.4	1.923
10	6	6.5	12.3	1.878
11	3	6.5	12.2	1.942
12	6	6.5	12.3	1.878
13	6	10	12.3	1.896

Compaction shows OMC 12.0-12.4% with narrow 0.4% variation, slightly higher than natural 10.2% due to water demand of GSA and NaOH dissolution. MDD ranges 1.819-1.942 Mg/m³ against natural 1.85 Mg/m³. Highest MDD 1.942 Mg/m³ at 3% GSA + 6.5M NaOH indicates filler effect where fine ash fills voids. Lowest MDD 1.819 Mg/m³ at 9% GSA + 6.5M NaOH due to low specific gravity of GSA [2.15] vs soil [2.65] and porous nature. All MDD exceed 1.70 Mg/m³ minimum for sub-base. The stable OMC is advantageous for field compaction control while density reduction at high GSA is compensated by strength gain.

Table 4b: Base Course, Variation of OMC – MDD with AGSA Content

Run	Factors		Response	
	GSA %	NaOH Mol	OMC (%)	MDD (Mg/m ³)
1	3	3	12.3	1.957
2	6	3	12.3	1.963
3	6	6.5	12.2	1.934
4	3	6.5	12.3	1.935
5	6	10	12.2	1.950
6	6	6.5	12.2	1.934
7	6	6.5	12.2	1.934
8	9	6.5	12.0	1.934
9	3	10	12.4	1.971
10	6	6.5	12.2	1.934
11	6	6.5	12.2	1.934
12	9	3	12.3	1.978
13	9	10	12.4	1.925

Base course compaction shows OMC 12 - 12.4% vs natural 10.3%, slight increase due to ash water absorption. MDD ranges 1.925 - 1.978 Mg/m³ vs natural 1.99 Mg/m³, with 0.8% maximum reduction. Peak MDD 1.978 Mg/m³ at 9% GSA + 3M NaOH shows best packing from filler effect of fine GSA particles. Lowest MDD 1.925 Mg/m³ at 9% GSA + 10M NaOH still exceeds 1.90 Mg/m³ threshold for base course. The higher MDD than sub-base average [1.948 vs 1.880 Mg/m³] reflects better gradation. Compaction characteristics confirm all mixes are compactable to high density required for load distribution in base course.

3.4 Stabilization Results of Soil Admixed with GSA and NaOH

The experimental results of all the works are presented in Tables 5a and 5b.

Table 5a: Summary of Experimental Design for Sub-base (GSA and NaOH)

Run	GSA (%)	NaOH	W _L (%)	W _P (%)	I _P (%)	OMC (%)	MDD Mg/m ³	UCS 7 Days kN/m ²	UCS14 Days kN/m ²	UCS 28 Days kN/m ²	CBR %
1	9	6.5	32.0	23.1	8.9	12.3	1.819	920	988	1684	42.0
2	9	10	30.5	21.6	8.9	12.0	1.849	804	812	1497	40.0
3	3	3	30.5	20.4	10.1	12.3	1.883	269	336	620	30.5
4	6	3	31.5	21.1	10.4	12.2	1.859	342	438	1429	32.4
5	6	6.5	31.0	22.1	8.9	12.3	1.878	567	672	1458	37.9
6	9	3	32.0	22.1	9.9	12.4	1.849	452	516	1838	34.3
7	6	6.5	31.0	22.1	8.9	12.3	1.878	567	672	1458	37.9
8	6	6.5	31.0	22.1	8.9	12.3	1.878	567	672	1458	37.9
9	3	10	30.0	21.5	8.5	12.4	1.923	718	872	1904	30.1
10	6	6.5	31.0	22.1	8.9	12.3	1.878	567	672	1458	37.9
11	3	6.5	30.0	20.8	9.2	12.2	1.942	422	521	1396	35.6
12	6	6.5	31.0	22.1	8.9	12.3	1.878	567	672	1458	37.9
13	6	10	31.5	22.1	9.4	12.3	1.896	1055	1288	2227	32.0

Table 5a presents the experimental results of lateritic soil admixed with Groundnut Shell Ash at 3 - 9% and Sodium Hydroxide as alkali activator at 3 - 10% for subbase application. The Atterberg limits results show significant improvement in plasticity characteristics. The Liquid Limit ranged from 30.0% to 32.0% with an average of 30.8%, while Plastic Limit ranged from 20.4% to 23.1%. The Plasticity Index which is the most critical parameter for subbase suitability ranged from 8.5% to 10.4%. All IP values are below 12% maximum specified by Federal Ministry of Works and Housing (FMWH) for subbase materials, indicating that alkali-activated GSA effectively reduced plasticity through cation exchange and flocculation-agglomeration mechanism. The lowest IP of 8.5% was obtained at Run 9 [3% GSA + 10% NaOH] and Run 5 [6% GSA + 6.5% NaOH at 8.9%], showing that high alkali concentration promotes dissolution of silica from GSA for pozzolanic reaction. This reduction in plasticity is attributed to the replacement of univalent ions in clay with Ca²⁺ and Na⁺ from GSA and NaOH, leading to reduction in diffuse double layer thickness. Compaction characteristics show Optimum Moisture Content (OMC) ranging from 12% to 12.4% with very narrow variation of 0.4%, indicating that GSA - NaOH has minimal effect on water demand, which is advantageous for field compaction control. Maximum Dry Density (MDD) ranged from 1.819 Mg/m³ to 1.942 Mg/m³. The highest MDD of 1.942 Mg/m³ was achieved at Run 11 (3% GSA + 6.5% NaOH) while the lowest at Run 1 (9% GSA + 6.5% NaOH), suggesting that excessive GSA content beyond 6% reduces density due to low specific gravity of ash (2.15) compared to soil (2.66) and increased voids. However, all MDD values exceed 1.7 Mg/m³ minimum for subbase, confirming suitability.

Unconfined Compressive Strength at 7 days ranged from 269 kN/m² to 1055 kN/m², at 14 days from 336 to 1288 kN/m², and at 28 days from 620 to 2227 kN/m². This shows progressive strength gain with curing due to alkali activation forming N-A-S-H and C-A-S-H gels. 6% GSA + 10% NaOH gave the highest 7-day and 14-day strength of 1055 and 1288 kN/m² respectively, while 28-day peak was 2227 kN/m² at same mix, exceeding FMWH requirement of 750 - 1500 kN/m² for cement stabilized subbase by 48%, proving that alkali-activated GSA can completely replace cement. Even the lowest mix 3% GSA + 3% NaOH with 620 kN/m² at 28

days is close to minimum, indicating that any combination above 3% is practicable. The strength gain ratio from 7 to 28 days is 1.83 to 2.3 times, higher than conventional cement stabilization, due to continuous geopolymerization.

CBR values ranged from 30.1% to 42.0%. All values exceed 30% minimum for subbase per Nigerian General Specification for Roads and Bridges (2016). Highest CBR of 42.0% was at 9% GSA + 6.5% NaOH, showing that higher GSA content favors bearing capacity due to frictional resistance of ash particles. The lowest CBR of 30.1% at Run 9 still passes specification, demonstrating robustness of the stabilization system. The correlation between UCS and CBR is strong, confirming both measure same cementation effect.

Table 5b: Summary of Experimental Design for Base course (GSA and NaOH)

Run	GSA (%)	NaOH %	W _L (%)	W _P (%)	I _p (%)	OMC (%)	MDD Mg/m ³	UCS 7 Days kN/m ²	UCS14 Days kN/m ²	UCS 28 Days kN/m ²	CBR %
1	3	3	23	14.5	8.5	12.3	1.957	512	453	754	54.9
2	6	3	24.5	16.9	7.6	12.3	1.963	580	553	890	64.5
3	6	6.5	29.0	20.8	8.2	12.2	1.934	650	710	1447	68.4
4	3	6.5	29.0	20.9	8.1	12.3	1.935	600	721	1212	62.2
5	6	10	29.0	19.7	9.3	12.2	1.950	950	1405	2360	68.8
6	6	6.5	29.0	20.8	8.2	12.2	1.934	650	710	1447	68.4
7	6	6.5	29.0	20.8	8.2	12.2	1.934	650	710	1447	68.4
8	9	6.5	27.0	18.3	8.7	12.0	1.934	910	1600	2190	70.0
9	3	10	30.0	21.5	8.5	12.4	1.971	878	1033	1988	63.1
10	6	6.5	29.0	20.8	8.2	12.2	1.934	650	710	1447	68.4
11	6	6.5	29.0	20.8	8.2	12.2	1.934	650	710	1447	68.4
12	9	3	24	15.3	8.7	12.3	1.978	568	626	926	68.6
13	9	10	31.0	21.6	9.3	12.4	1.925	1210	907	2100	72.3

Table 5b presents results for base course application using same binder system but with different soil or compaction energy, targeting higher strength requirement of base course (CBR $\geq$ 80% ideal, $\geq$ 60% minimum for low volume roads, UCS $\geq$ 1500 kN/m². Atterberg limits for base course show WL ranging 23% to 31%, WP 14.5% to 21.6%, IP 7.6% to 9.3%. Compared to Table 5a subbase, IP values are lower (average 8.4% vs 9.1%), indicating better plasticity control for base course which demands IP $\leq$ 10% for base. The lowest IP of 7.6% was at 6% GSA + 3% NaOH, while highest 9.3% at Runs 5 and 13 with high NaOH 10%. This suggests that for base course, moderate alkali (3 - 6.5%) is more effective than high alkali which may cause dispersion at high pH. All IP values satisfy FMWH base course limit of 12%, with 70% of runs below 8.5% indicating excellent volume stability and low swelling potential, critical for base under traffic loading almost identical to subbase table, proving binder does not alter water demand significantly. MDD ranges 1.925 to 1.978 Mg/m³, higher than subbase average 1.880 Mg/m³. Peak MDD 1.978 Mg/m³ at Run 12 (9% GSA + 3% NaOH) indicates that combination of high ash and low alkali gives best packing density due to filler effect of fine ash particles filling voids. Lowest MDD 1.925 Mg/m³ at Run 13 with high binder content still exceeds 1.9 Mg/m³ threshold for base, showing all mixes are compactable to high density required for load distribution.

Strength development is superior to subbase table. UCS at 7 days 512 - 1210 kN/m², at 14 days 453 - 1600 kN/m², at 28 days 754 - 2360 kN/m². Average 28-day strength is 1498 kN/m² compared to 1489 kN/m² for subbase, but peak is higher at 2360 kN/m² for base vs 2227 kN/m² for subbase. Run 5 (6% GSA + 10% NaOH) achieved highest 28-day strength of 2360 kN/m² which exceeds 1500-3000 kN/m² requirement for cement stabilized base course and qualifies as heavy-duty base. Even at 7 days, 3 mixes exceed 878 kN/m², showing rapid early strength gain due to alkali activation which is crucial for early traffic opening. The strength gain pattern shows that high NaOH [10%] consistently produces higher strength at all ages: average 28-day strength for NaOH 10% runs [Runs 5,9,13] is 2149 kN/m² vs 1026 kN/m² for NaOH 3% runs (Runs 1,2,12), proving NaOH concentration is dominant factor.

CBR values range 54.9% to 72.3% significantly higher than subbase table confirming base course soil has better inherent bearing capacity and responds better to stabilization. All CBR values exceed 50% minimum for subbase and 11 of 13 runs exceed 60% which is minimum for base course of low-volume roads per FMWH. Highest CBR 72.3% at Run 13 (9% GSA + 10% NaOH) and 70.0% at Run 8 (9% GSA + 6.5% NaOH) show that high GSA content 9% is beneficial for CBR due to increased frictional component and formation of dense geopolymer matrix. The lowest CBR 54.9% at Run 1 (3% GSA + 3% NaOH) still satisfies subbase requirement and indicates even minimum binder improves CBR by 80% over natural soil.

4. Conclusion and Recommendations

The stabilization of lateritic soils admixed with alkali-activated Groundnut Shell Ash and Sodium Hydroxide for highway construction was investigated and the following conclusions were drawn

4.1 Conclusion

- **Plasticity Improvement:** The addition of alkali-activated GSA significantly improved plasticity characteristics of lateritic soil. The Plasticity Index was reduced to 8.5% for sub-base and 7.6% for base course from natural soil value of 9.2%, with all mixes satisfying the Federal Ministry of Works and Housing requirement of less than 12% for sub-base and base materials. The lowest plasticity index of 7.6% was achieved at 6% GSA + 3% NaOH which indicates optimum cation exchange and flocculation.
- **Compaction Characteristics:** The OMC remained relatively stable at 12 - 12.4% for both sub-base and base course, indicating that alkali-activated GSA does not significantly increase water demand, which is advantageous for field compaction control. Maximum Dry Density ranged from 1.819 - 1.942 Mg/m³ for sub-base and 1.925 - 1.978 Mg/m³ for base course, all exceeding minimum

requirements. The decrease in MDD with increase in GSA content beyond 6% is due to lower specific gravity of ash and void creation, while peak MDD at 3 - 6% GSA indicates filler effect.

- **Strength Development:** The UCS results showed progressive gains with curing age from 7 to 28 days due to continuous geopolymerization. For sub-base, 28-day UCS ranged from 620 - 2227 kN/m², while for base course it ranged 754 - 2360 kN/m². The highest strength of 2360 kN/m² was achieved at 6% GSA + 10% NaOH for base course and 2227 kN/m² at same mix for sub-base, exceeding FMWH requirement of 750 - 1500 kN/m² for cement stabilized sub-base and approaching 1500-3000 kN/m² for base course. The strength gain ratio of 1.8 - 2.3 times from 7 to 28 days is higher than conventional cement stabilization, proving superiority of alkali activation in forming strong polymeric network.
- **Bearing Capacity:** The soaked and unsoaked CBR improved significantly after alkali activation of natural soil with values from 27.6% to 42.0% for sub-base and 55.8% to 72.3% for base course. All sub-base mixes exceeded 30% minimum for sub-base, while 85% of base course mixes exceeded 60% minimum for low-volume base course. The highest CBR of 72.3% at 9% GSA + 10% NaOH demonstrates that high GSA and high alkali combination produces dense matrix with high frictional resistance.
- **Sustainability:** Groundnut Shell Ash, an agro-waste with 56 - 68% silica content and pozzolanic activity index of 75%, when alkali-activated with NaOH, can completely replace cement in lateritic soil stabilization for highway construction, reducing CO₂ emission while solving waste disposal problem.

4.2 Recommendations

Based on the findings of this research, the following recommendations are made:

- **Implementation for Highway Projects:** The Federal Ministry of Works and Housing and State Ministries of Works should adopt alkali-activated Groundnut Shell Ash (6 - 9% GSA + 6.5-10% NaOH) as sustainable alternative to cement for stabilization of A-6 and A-7 lateritic soils for sub-base and low-volume base course construction, especially in groundnut producing areas of Northern Nigeria where GSA is abundantly available at zero cost.
- **Optimum Dosage:** For sub-base course, 6% GSA + 10% NaOH at OMC of 12.3% is recommended for maximum strength and durability. For base course of rural and low-volume roads [ADT < 500], 9% GSA + 10% NaOH is recommended to achieve CBR > 70%. For field application, GSA should be incinerated at 600-700°C for 2 hours and sieved through 75 microns to ensure high reactivity.

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