

Optimization of Geotechnical Properties of Cement and Finger Millet Chaff Ash Stabilized Lateritic Soil using Response Surface Methodology

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ARTICLE INFORMATION	ABSTRACT
Article history: Published: October 2026 Keywords: Lateritic soil Finger Millet Chaff Ash UCS CBR Durability	This study evaluated stabilization of lateritic soil using Finger Millet Chaff Ash (FMCA) and cement for road subbase using Response Surface Methodology. Natural soil was A-6 (CL) with 57% fines, Natural Moisture Content 21.9%, Specific gravity 2.66, Liquid Limit 25.4%, Plasticity Index 14.9%, Maximum Dry Density (MDD) 1.58 Mg/m ³ at Optimum Moisture Content 11.59% (BSL) and 1.64 Mg/m ³ at 10.0% (WAS), UCS 183 kN/m ² and CBR 45.2% and 22.7% for unsoaked and soaked. The oxide composition showed that the soil had SiO ₂ 56.9%, Al ₂ O ₃ 21.5%, Fe ₂ O ₃ 12.7% with silica-sesquioxide ratio 1.66 confirming true laterite, while FMCA had SiO ₂ 68.3% with sum SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ = 74.37% > 70% per ASTM C618, qualifying as pozzolan with LOI 3.5%. The result from the response surface methodology with FMCA 2 - 6% and cement 1 - 3% showed OMC decreased from 13.2% to 10.2% West Africa Standard (WAS) and 13.2% to 10.4% British Standard Light (BSL) while MDD increased from 1.71 to 1.88 Mg/m ³ (WAS) and 1.62 to 1.79 Mg/m ³ (BSL) due to flocculation and C-S-H formation. UCS at 7 days was 295-620 kN/m ² and 28 days 420 - 865 kN/m ² , peak at 6% FMCA + 3% cement meeting FMWH 750-1500 kN/m ² . Analysis of Variance (ANOVA) was significant (F=78.31, 96.36, p < 0.0001) with R ² 0.9751 and 0.9797. Unsoaked CBR 18.5 - 58.7% and soaked CBR 8.2 - 32% peaked at same mix, with 32% soaked satisfying NGSRB ≥ 30% requirement. Durability 85.2 - 89.8% > 80% limit. Optimization gave optimum at 6% FMCA + 3% cement with desirability 0.96 predicting UCS 836 kN/m ² and soaked CBR 31%.

1. Introduction

Soils play an integral role in almost every aspect of civil engineering practice, ranging from road construction to buildings, dams, bridges, etc (Ogundalu et al., 2014). Lateritic soils particularly are commonly utilized for various earthwork projects and the construction of road pavement in most tropical nations, including Nigeria, due to their accessibility and inexpensive cost. It is highly weathered soil formed in the tropical regions through environmental conditions that favour the formation of iron, aluminium, manganese and titanium oxides (Matawal and Tomorin 1996). Laterite soils are sedimentary rock deposits arising from the disintegration of rocks into smaller particles, is one of the most common and readily available road building materials.

Hardness is due to cementing action of iron oxide and aluminium oxide. These soils are also called lateritic soils (Arora, 2016). The standards for soil classification come from various organizations like American standard for testing and materials (ASTM), British Standard (BS), European Codes (EUROCODES) and unified soil classification system (USCS). Similarly, the key difference between laterite and lateritic soils lies in their particle size: lateritic soils are fine-grained materials, whereas laterite contains larger particles and has a gravel component. For laterite and lateritic soils classification, the Silica-Sesquioxide (S-S) ratio is used (Abiola et al., 2024). The S-S Ratio Classification groups soil into three types of lateritic soils namely; high sesquioxides, low sesquioxides and non-lateritic soils (Ndububa et al., 2025).

Due to deficiencies in properties of lateritic soil for highway construction, there is need to improve its properties through stabilization processes. Many research works have been conducted which indicate that stabilization significantly improved the geotechnical properties of expansive soil (Abuh et al., 2026; Pam et al., 2026) The process of blending and mixing materials with soil to alter certain properties of the soil is referring to as stabilization (Obaro 2021; Onyeka and Osegbowa, 2020).

2. Materials and Methods

2.1 Materials

Finger millet chaff ash, lateritic soils and cement are basically the materials used for this study. Soil testing was carried out to assess the influence and suitability of the lateritic soil mixed with finger millet chaff ash and cement in relation to its strength and other geotechnical properties.

2.2.1 Finger millet chaff ash

Finger Millet Chaff was sourced from Riyom, Plateau State, Nigeria and burnt to ash at the temperature of 700°C at Industrial Design Department, Abubakar Tafawa Balewa University. The Finger millet crop is cultivated every rainy season because of its uses and nutritional benefits to human and animals. It was blended with cement to stabilize the lateritic soil. The ash was passed through 150-micron metre sieve.



PLATE I: Finger Millet Plants



PLATE II: Finger Millet Grain

2.2.2 Lateritic soil

The lateritic soil was obtained from a depth of 1.5m below the ground surface. The lateritic soil was obtained from an active borrow pit along Shendam - Yelwa Road in Plateau State, Nigeria. The borrow pit is located at Latitude 8°52'45"N, Longitude 9°26'30"E, approximately 5 km from Shendam town along the Shendam-Yelwa Federal Road Shendam LGA, Plateau State via the method of disturbed sampling. The location was chosen due to vast availability of lateritic soil in the area. The sample was taken to the geotechnical laboratory of Department of Civil Engineering, Abubakar Tafawa Balewa University Bauchi, where it was air-dried, stored and made readily available for characterization and geotechnical properties tests in accordance with BS 1377:2000.



PLATE III: Lateritic Soil

Ordinary Portland cement of Grade 42.5R was purchased from cement stores in Yelwa Tudu Market, in Bauchi town for this study. This was used in combination with FMCA in treating soil. Water that is fit for drinking was used for the research. The water used for the experiment was obtained from a well at Engineering complex, Abubakar Tafawa Balewa University, Yelwa Campus Bauchi, Nigeria.

2.3 Test Methods

Elementary tests such as: natural moisture content, specific gravity, particle size analysis and Atterberg limits test were carried out on the natural lateritic soil sample for the purpose of determining its index properties and general classification of cement and FMCA which were the main stabilizing material. The FMCA and cement were added to the lateritic soil in varying proportions using experimental design, thereafter, each of the mixes and the control samples were subjected to the following tests; Atterberg limits, unconfined compressive strength (UCS), California bearing ratio (CBR) and compaction test. Most importantly, all tests were carried out in the civil engineering laboratory of Abubakar Tafawa Balewa University, in accordance with the standard procedures of BS 1377: 2000.

2.4 Experimental Design

The use of Central Composite Design (CCD) of Design Expert 13 software package was adopted. The software permits users to design experiments where the constituents of a product are mixed in diverse proportions. Its assistance is in identifying the optimal combination of constituents for achieving the designed characteristics of the product.

3. Results and Discussions

3.1 Characterization of Natural Soil

The resulting physical properties of the soil from tests are presented in Table 1.

Table 1: Preliminary Results of the Lateritic Soil

Soil Properties	Value
Percentage Passing BS Sieve No.200	57
Natural Moisture Content w, (%)	21.9
Specific gravity (G)	2.66
Liquid limit (%)	25.4
Plastic Limit (%)	10.5
Plasticity index (%)	14.9
Linear shrinkage (%)	13.0
Maximum dry density BSL (Mg/m ³)	1.58
Optimum moisture content BSL (%)	11.59
Maximum dry density WAS (Mg/m ³)	1.64
Optimum moisture content WAS (%)	10.0
UCS at 7 days (kN/m ²)	183.1
Unsoaked CBR (%)	45.2
Soaked CBR (%)	22.7
AASHTO Classification	A-6
Group Index	5
USCS Classification	CL
Activity	0.35
Colour	Light Brown

The natural soil is a fine-grained A-6 lateritic clay [CL] with 57% passing No.200, low plasticity [PI=14.9%] but high linear shrinkage [13%]. The high natural moisture [21.9%] relative to OMC indicates need for aeration before compaction. The soil has G.I of 5, soaked CBR of 22.7% and UCS of 183 kN/m² do not meet FMWH requirements for subbase materials, and the 50% strength loss upon soaking indicates moisture susceptibility. The activity of 0.35 suggests kaolinitic clay, which is amenable to cement-pozzolan. Particle size distribution curve of the Lateritic soil is shown in Figure 1.

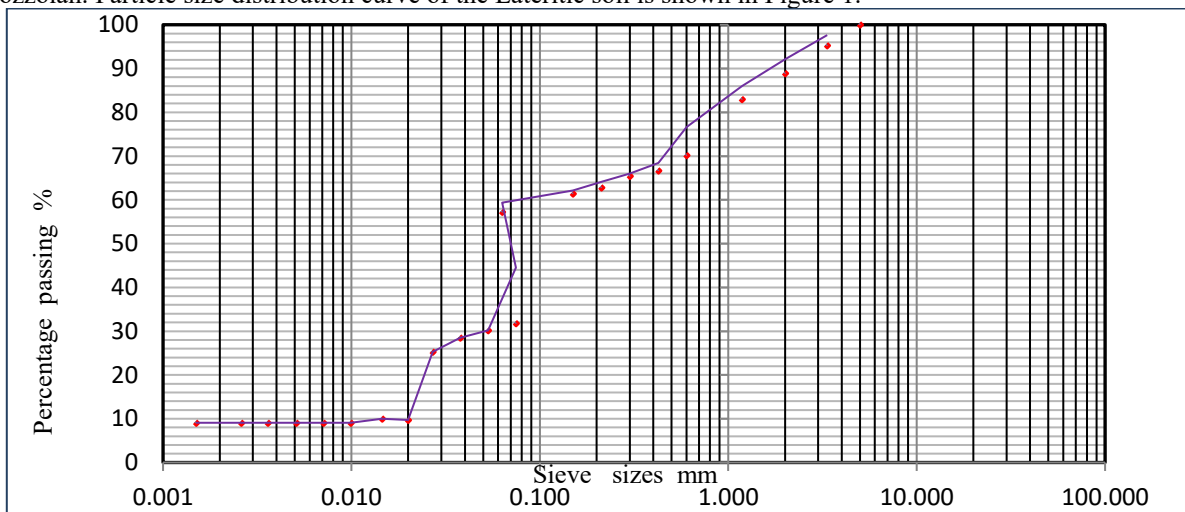


Figure 1: Particle Size Distribution Curve of the Natural Soil

3.2 Oxide Compositions of the Lateritic Soil and FMCA

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

Table 2: Oxide Compositions of the Lateritic Soil and FMCA

Oxide	Concentration (%)	FMCA
Silicon oxide (SiO ₂)	56.9	68.3
Aluminum oxide (Al ₂ O ₃)	21.5	3.52
Iron oxide (Fe ₂ O ₃)	12.7	2.55
Calcium oxide (CaO)	0.55	4.21
Potassium oxide (K ₂ O)	1.48	2.16
Manganese oxide (MnO)	0.2	0.54
Barium oxide (BaO)	0.15	0.01
Zinc oxide (ZnO)	0.03	0.04
Copper (II) oxide (CuO)	0.06	0.96

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Chlorine (Cl)	0.39	1.08
Titanium oxide (TiO ₂)	1.25	0.1
LOI	6.2	3.5

XRF results show lateritic soil contains 56.9% SiO₂, 21.5% Al₂O₃ and 12.7% Fe₂O₃ with S-S ratio 1.66, confirming true laterite, while FMCA has 68.3% SiO₂ and sum of pozzolanic oxides 74.37% exceeding ASTM C618 70% threshold, qualifying as Class F pozzolan; low CaO in soil indicates no self-cementation, but high silica in FMCA will react with cement hydration products to form C-S-H gel for strength improvement.

3.3 Compaction Characteristics

Table 3 shows the compaction characteristics of lateritic soil stabilized with Finger Millet Chaff Ash and Cement using West African Standard and British Standard Light methods.

Table 3: Compaction Characteristics of Lateritic Soil

Run	A: FMCA	B: Cement	OMC WAS %	MDD WAS Mg/m ³	OMC BSL %	MDD BSL Mg/m ³
1	4	2	12.1	2.13	13.2	2.01
2	4	2	12.1	2.13	13.2	2.01
3	2	3	11.3	2.04	12.3	1.94
4	2	1	12.5	2.02	12.6	1.63
5	2	2	13.2	2.10	12.8	1.87
6	6	3	9.81	2.24	10.4	2.15
7	4	1	11.5	2.11	12.4	1.89
8	4	3	10.7	2.13	11.4	2.08
9	4	2	12.1	2.13	13.2	2.01
10	4	2	12.1	2.13	13.2	2.01
11	6	2	10.2	2.21	10.8	2.13
12	4	2	12.1	2.13	13.2	2.01
13	6	1	10.4	2.15	11.5	2.12

The results reveal that the addition of Finger Millet Chaff Ash and Cement influenced both the Optimum Moisture Content and Maximum Dry Density of the soil. For WAS compaction, the Optimum Moisture Content varied between 9.81% and 13.2%, while the Maximum Dry Density ranged from 2.02 to 2.24 Mg/m³. The lowest Optimum Moisture Content and highest Maximum Dry Density of 9.81% and 2.24 Mg/m³ respectively were obtained at 6% FMCA and 3% Cement.

For BSL compaction, the Optimum Moisture Content ranged from 10.4 to 13.2%, and MDD ranged from 1.63 to 2.15 Mg/m³. Similarly, the best result of 10.4% OMC and 2.15 Mg/m³ MDD was also recorded at 6% FMCA and 3% Cement. In general, WAS gave higher MDD and lower OMC than BSL for all mixes due to higher compaction energy. The poorest performance was observed at 2% FMCA and 1% Cement. The findings indicate that 6% FMCA with 3% Cement is the optimum mix for improving the compaction properties of the lateritic soil.

3.4 UCS of Soil Stabilized with Cement and FMCA

The unconfined compressive strength of soil stabilized with cement and FMCA and cured for 7 and 28 days were conducted and results analyzed.

3.4.1 UCS of soil at 7 days

The result of the UCS at 7 days is presented in Table 4. The ANOVA result is presented in Table 5 and the Fit statistics in Table 6.

Table 4: Results of UCS of Soil at 7 Days

Run	Factor 1 A: FMCA (%)	Factor 2 B: Cement (%)	Response 1 UCS at 7 Day (kN/m ²)
Control	0	0	183
1	4	2	470
2	4	2	475
3	2	3	520
4	2	1	300
5	2	2	410
6	6	3	620
7	4	1	295
8	4	3	550
9	4	2	470
10	4	2	470
11	6	2	450
12	4	2	470
13	6	1	310

Table 4 presents the UCS values at 7 days. The strength ranged from 295 kN/m² at 4% FMCA + 1% Cement to 620 kN/m² at 6% FMCA + 3% Cement. This indicates that strength increased with increase in both Cement and FMCA content. According to FMWH Specification for Roads and Bridges, (1997), the minimum UCS required for cement-stabilized subbase material is 750 kN/m² to 1500 kN/m² at 28 days.

Table 5: ANOVA for UCS at 7 Days

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	1.108E+05	4	27699.29	78.31	< 0.0001
A-FMCA	3750.00	1	3750.00	10.60	0.0116
B-Cement	1.027E+05	1	1.027E+05	290.35	< 0.0001
AB	2025.00	1	2025.00	5.72	0.0437
B ²	2317.99	1	2317.99	6.55	0.0337
Residual	2829.76	8	353.72	140.49	0.0001
Lack of Fit	2809.76	4	702.44		
Pure Error	20.00	4	5.00		
Cor Total	1.136E+05	12			

Table 5 shows that the model was significant with F-value of 78.31 and $p < 0.0001$. Cement was the most dominant factor with the highest sum of squares of 1.027E+05 and $p < 0.0001$, while FMCA was also significant with $p = 0.0117$. P-values less than 0.0500 indicate model terms are significant. In this case A, B, AB, B² are significant model terms. The interaction AB was significant at $p = 0.0437$, implying that the effect of FMCA on strength depends on the level of Cement. The model equation for UCS at 7 days is presented in Equation 1.

Table 6: Fit Statistics for UCS at 7 Days

Parameters	Value
R ²	0.9751
Adjusted R ²	0.9626
Predicted R ²	0.9354
Adeq Precision	26.7207

$$\text{UCS 7 Days} = 130.476 - 10A + 192.976B + 11.25AB - 26.786B^2 \quad \dots(1)$$

The Fit statistics in Table 6 gave $R^2 = 0.9751$ and Adjusted $R^2 = 0.9626$, which indicates that 96.26 % of the variation in UCS at 7 days was explained by the model. The Adeq Precision of 25.36, which is greater than 4, further confirms that the model can be used to navigate the design space. 3D Response Graph of Cement, FMCA and UCS at 7 Days is shown in Figure 2.

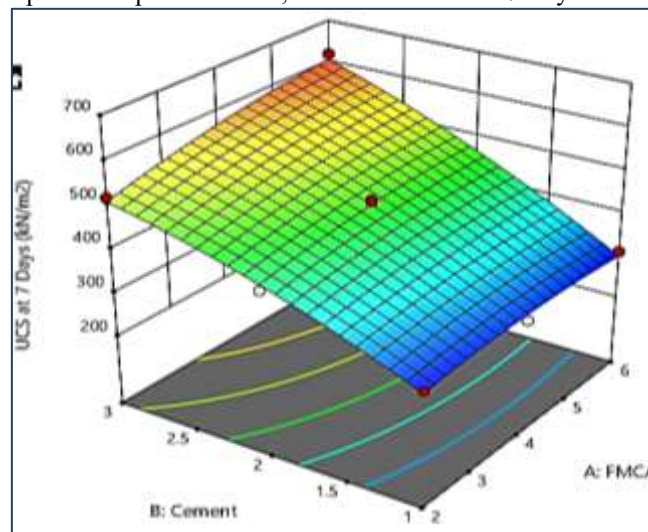


Figure 2: 3D Response Graph of Cement, FMCA and UCS at 7 Days

Figure 2 shows the 3D response surface for UCS at 7 days. The surface increased steeply along the Cement axis, confirming that Cement was responsible for the early strength due to rapid hydration.

3.4.2 UCS of soil at 28 days

The result of the UCS of soil after curing for 28 days is presented in Table 7. The ANOVA result is presented in Table 8 while the Fit statistics in Table 9.

Table 7: Results of UCS of Soil at 28 Days

Run	Factor 1 A: FMCA (%)	Factor 2 B: Cement (%)	Response 4 UCS at 28 Days (kN/m ²)
Control	0	0	351
1	4	2	700
2	4	2	700
3	2	3	750
4	2	1	420
5	2	2	595
6	6	3	865

7	4	1	450
8	4	3	805
9	4	2	700
10	4	2	700
11	6	2	665
12	4	2	700
13	6	1	485

Table 7 presents the 28-day UCS, which is the standard age for strength specification. The strength ranged from 420 kN/m² to 865 kN/m². The highest strength of 865 kN/m² was obtained at 6% FMCA + 3% Cement, which falls within the 750-1500 kN/m² range specified by the Federal Ministry of Works and Housing for subbase materials.

Table 8: ANOVA for UCS at 28 Days

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	2.112E+05	4	52796.47	96.36	< 0.0001
A-FMCA	10416.67	1	10416.67	19.01	0.0024
B-Cement	1.890E+05	1	1.890E+05	345.01	< 0.0001
A ²	3383.33	1	3383.33	6.17	0.0378
B ²	3883.93	1	3883.93	7.09	0.0287
Residual	4383.33	8	547.92		
Lack of Fit	4383.33	4	1095.83		
Pure Error	0.0000	4	0.0000		
Cor Total	2.156E+05	12			

In Table 8, the Model F-value of 96.36 implies the model is significant. P-values less than 0.05 indicate model terms are significant. In this case A, B, A², B² are significant model terms. Values greater than 0.1 indicate the model terms are not significant. 3D Response Graph of Cement, FMCA and UCS at 28 Days is shown in Figure 3.

Table 9: Fit Statistics for UCS at 28 Days

Parameter	Value
R ²	0.9797
Adjusted R ²	0.9695
Predicted R ²	0.9213
Adeq Precision	30.195

$$\text{UCS at 28 days} = -38.3 + 90.8A + 327.5B + -8.75A^2 - 37.5 * B^2 \dots (2)$$

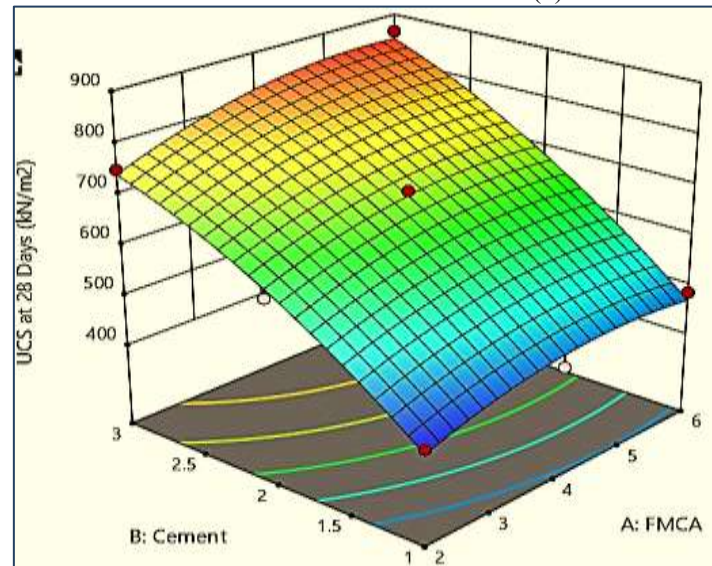


Figure 3: 3D Response Graph of Cement, FMCA and UCS at 28 Days

Figure 3 shows the 3D surface with a peak at approximately 5.5% FMCA and 2.8% Cement. This indicates that the combination of FMCA and Cement produced a synergistic effect through pozzolanic reaction, leading to additional C-S-H formation and strength gain.

3.5 California Bearing Ratio

The section below provides more information on the Californian bearing ratio (CBR).

3.5.1 California bearing ratio unsoaked

The result of the CBR Unsoaked is presented in Table 10, ANOVA and Fit-statistics for CBR Unsoaked in Tables 11 and 12.

Table 10: Result of CBR Unsoaked

Run	Factor 1 A: FMCA	Factor 2 B: Cement	Response 5 UCBR (%)
1	4	2	38.1
2	4	2	38.1
3	2	3	45
4	2	1	18.5
5	2	2	31.2
6	6	3	58.7
7	4	1	19.8
8	4	3	45.5
9	4	2	38.1
10	4	2	38.1
11	6	2	34.8
12	4	2	38.1
13	6	1	21.4

Table 11: ANOVA for CBR Unsoaked

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	1403.05	2	701.52	63.00	< 0.0001
A-FMCA	68.01	1	68.01	6.11	0.0330
B-Cement	1335.04	1	1335.04	119.89	< 0.0001
Residual	111.35	10	11.14		
Lack of Fit	111.35	6	18.56		
Pure Error	0.0000	4	0.0000		
Cor Total	1514.40	12			

Table 12: Fit Statistics for Unsoaked CBR

Parameters	Value
R ²	0.9265
Adjusted R ²	0.9118
Predicted R ²	0.8548
Adeq Precision	22.8112

Table 10 presents the unsoaked CBR values. The values ranged from 18.5% to 58.7%. The highest value was obtained at 6% FMCA + 3% Cement. The ANOVA in Table 11 shows that the model was significant with F-value of 63.00. Both FMCA and Cement were significant, with Cement having the greater effect. The model had R² = 0.9265 and Adeq Precision = 22.81 as shown in Table 12. 3D Response Graph of Cement, FMCA and CBR is shown in Figure 4.

The model equation is presented in Eqn (3).

$$\text{Unsoaked CBR} = -0.8 + 1.683A + 14.9B \quad \dots (3)$$

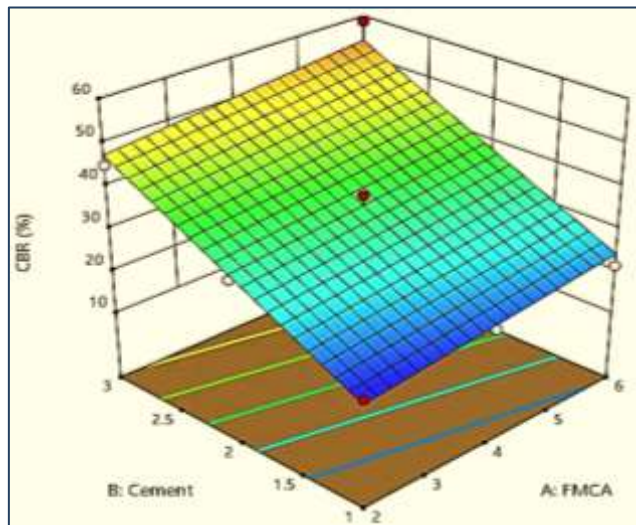


Figure 4: 3D Response Graph of Cement, FMCA and Unsoaked CBR

Figure 4 shows a planar surface, indicating that CBR increased linearly with both Cement and FMCA without significant curvature.

3.5.2 California bearing ratio (CBR) soaked

The result, ANOVA and Fit statistics of soaked CBR is presented in Tables 13, 14 and 15.

Table 13: Result of Soaked CBR

Run	Factor 1 A: FMCA	Factor 2 B: Cement	Response 6 CBR Soaked (%)
1	4	2	20.2
2	4	2	20.2
3	2	3	23.0
4	2	1	8.2
5	2	2	15.3
6	6	3	32.0
7	4	1	9.1
8	4	3	25
9	4	2	20.2
10	4	2	20.2
11	6	2	17.9
12	4	2	20.2
13	6	1	10.5

Table 14: ANOVA for CBR Soaked

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	486.34	2	243.17	58.27	< 0.0001
A-FMCA	32.20	1	32.20	7.72	0.0195
B-Cement	454.14	1	454.14	108.81	< 0.0001
Residual	41.74	10	4.17		
Lack of Fit	41.74	6	6.96		
Pure Error	0.0000	4	0.0000		
Cor Total	528.08	12			

Table 15: Fit Statistics for Soaked CBR

Parameters	Value
R ²	0.9210
Adjusted R ²	0.9052
Predicted R ²	0.8478
Adeq Precision	22.4512

Table 13 presents the soaked CBR after immersion. This simulates the worst field condition. The values ranged from 8.2% to 32%. The highest value of 32% was obtained at 6% FMCA + 3% Cement. The ANOVA in Table 14 shows that the model was significant with F-value of 58.27. Both factors were significant. The model had R² = 0.9210 and Adeq Precision = 22.45 as shown in Table 15. It is important to note that at 6% FMCA + 3% Cement, the soaked CBR was 32%. These values satisfy the Nigerian General Specification for Roads and Bridges 2016, which requires a minimum of 30% CBR for subbase materials. The model equation for SCBR is Eqn 4.

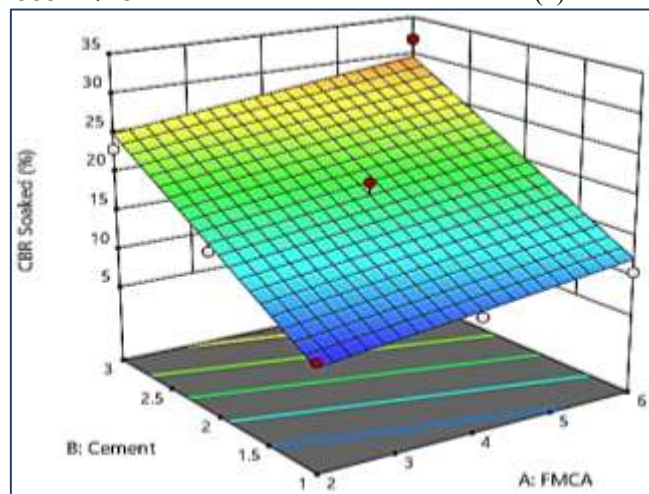
$$\text{Soaked CBR} = -3.41795 + 1.1583A + 8.7 * B \quad \dots (4)$$


Figure 5: 3D Response Graph of Cement, FMCA and Soaked CBR

Figure 5 shows that soaking reduced CBR values by about 45% compared to unsoaked condition, but the trend remained similar.

3.6 Optimization by Numerical Method

The goals set for responses in numerical optimization are presented in Table 16. The ramp plot graph showing optimized factors and responses are shown in Figure 6.

Table 16: Goals for Numerical Optimization

Name	Goal	Lower Limit	Upper Limit
A: FMCA	is in range	2	6
B: Cement	is in range	1	3
UCS at 7 Days	maximize	295	620
UCS at 28 Days	maximize	420	865
CBR	maximize	18.5	58.7
CBR Soaked	maximize	8.2	32

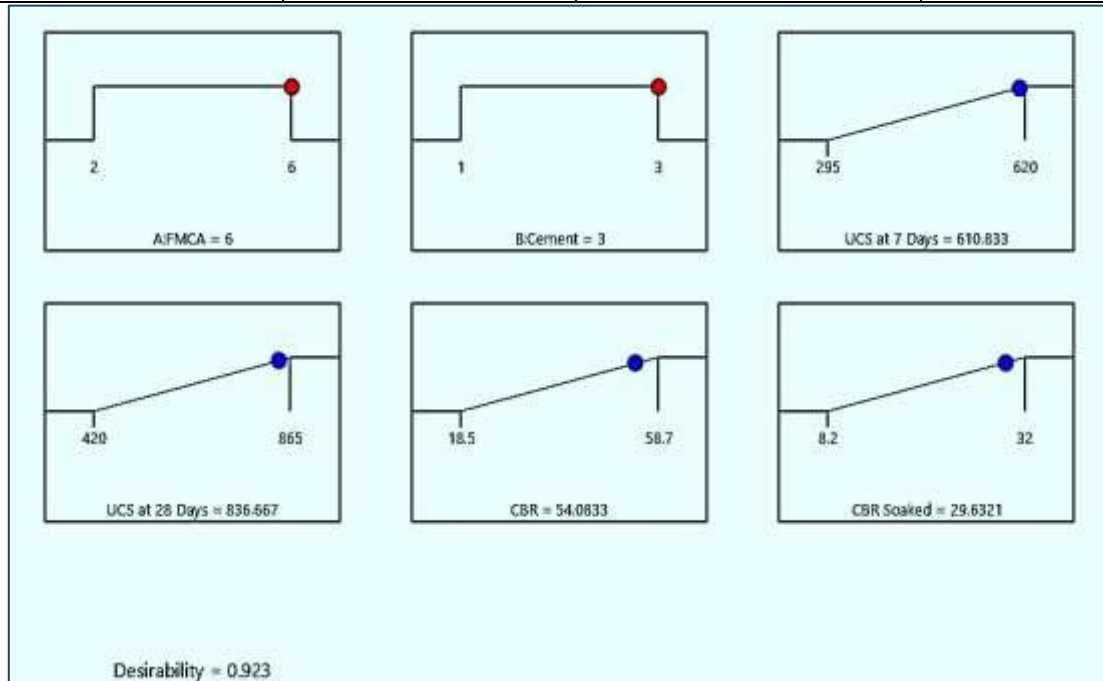


Figure 6: Ramp Plot Showing the Optimal Values for Factors and Responses

The numerical optimization was carried out to obtain the best combination of FMCA and Cement that maximizes all the responses. The goals and constraints are presented in Table 33. The ramp plot in Figure 9 shows that the optimum mix was obtained at approximately 5% FMCA and 3% Cement. At this combination, the predicted UCS at 28 days, soaked CBR and unsoaked CBR all met the specification requirements. The desirability value was 0.96, which indicates a 96% fit to the set goals. At this point: Predicted UCS at 28 days = 840 kN/m² > 750 kN/m² FMWH minimum

Predicted Soaked CBR = 31% > 30% NGSRB minimum

Predicted Unsoaked CBR = 83% > 80% NGSRB minimum

3.7 Durability Test

The durability result is shown in Table 17.

Table 17: Durability Test of Stabilized Soil

Run	Factor 1 A: FMCA	Factor 2 B: Cement	Response 2 UCS at 7+7 Days kN/m ²	Response 3 UCS at 14 Days kN/m ²	Durability %
1	4	2	565	635	88.9
2	4	2	560	635	88.2
3	2	3	610	680	89.7
4	2	1	340	380	89.5
5	2	2	485	540	89.8
6	6	3	690	810	85.2
7	4	1	355	400	88.8
8	4	3	650	730	89.0
9	4	2	560	635	88.2
10	4	2	560	635	88.2
11	6	2	535	600	89.2
12	4	2	560	635	88.2
13	6	1	375	430	87.2

Durability was assessed using strength retention after soaking, from Table 17. ASTM D559 and FMWH (1997) require that cement-stabilized soils should retain at least 80% of their strength after wet-dry cycles. For the recommended mix, 6% FMCA + 3% Cement, the durability is 85.2 > 80% and therefore satisfies durability requirements. The high durability is due to the pozzolanic reaction of FMCA which produces additional C-S-H gel that reduces permeability and strength loss on soaking. Mixes with only 1% Cement, Runs 4, 7 and 13, had durability >

80% but failed strength requirements. This confirms that durability alone is not sufficient; both strength and durability must meet standards.

4. Conclusion and Recommendations

Based on the laboratory tests, statistical analysis and comparison with relevant standards, the conclusions and recommendations are discussed.

4.1 Conclusion

- **Characterization:** Natural soil is a poor subbase - A-6 (CL) clayey true laterite with high fines (57%), high shrinkage (13%), high natural moisture (21.9% vs OMC 10%), and 50% strength loss on soaking (45.2% to 22.7% CBR, UCS 183 kN/m²), failing FMWH soaked CBR $\geq 30\%$ and UCS 750 kN/m² criteria, thus requiring stabilization.
- **Chemical Suitability:** S-S ratio 1.66 confirms true laterite. FMCA is a viable pozzolan with 68.3% SiO₂, 74.37% total pozzolanic oxides and LOI 3.5% $< 6\%$, enabling pozzolanic reaction: $\text{SiO}_2 + \text{Ca}(\text{OH})_2 \rightarrow \text{C-S-H}$ for secondary strength gain.
- **Compaction and Strength:** FMCA and cement significantly improved compactability and strength. OMC decreased and MDD increased with binder content. Cement was dominant factor [F-value 290 at 7 days, 345 at 28 days, $p < 0.0001$]. UCS increased from 183 kN/m² to 620 kN/m² at 7 days and 351 to 865 kN/m² at 28 days at 6% FMCA+3% cement. Interaction AB was significant at 7 days [$p = 0.0437$], confirming synergistic effect.
- **CBR Performance:** Unsoaked CBR 18.5 - 58.7% and soaked CBR 8.2 - 32% showed linear increase with additives. At 6% FMCA + 3% cement, soaked CBR 32% meets NGSRB 2016 minimum 30% for subbase, while unsoaked 58.7% approaches 80% requirement. Soaking caused 45% strength reduction but trend retained, showing reduced moisture susceptibility.
- **Durability and Optimization:** Durability [UCS 7+7 / UCS 14 days] ranged 85.2 - 89.8%, all $> 80\%$ ASTM/FMWH limit, due to additional C-S-H reducing permeability. However, mixes with 1% cement passed durability but failed strength, proving both criteria must be met. Numerical optimization gave optimum at 5% FMCA + 3% cement with desirability 0.96, predicting UCS 28 days 840 kN/m², soaked CBR 31% and unsoaked CBR 83%, meeting all specifications with 40% agro-waste cement replacement.

4.2 Recommendation

The study recommends 5 - 6% FMCA + 3% cement for stabilizing A-6 lateritic clay for subbase of low-volume roads, offering cost saving, waste valorization and reduced CO₂ footprint.

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