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Mechanical Properties and Predictive Modeling of Periwinkle Shell Ash-Cement Stabilized Lateritic Soils for Pavement Applications

Timothy O. Awanu[1], Eme Dennis Budu[2]ChukwuemekaNwaobakata[3]

[1]*PhD Student, Centre for Geotechnical & Coastal Engineering Research, University of Port Harcourt, P.M.B 5323 Port Harcourt, Rivers State, Nigeria*

[2]*Supervisor, Centre for Geotechnical & Coastal Engineering Research, University of Port Harcourt, P.M.B 5323 Port Harcourt, Rivers State, Nigeria*

[3]*Supervisor, Centre for Geotechnical & Coastal Engineering Research, University of Port Harcourt, P.M.B 5323 Port Harcourt, Rivers State, Nigeria*

ABSTRACT

This study investigates the mechanical properties and develops predictive response surface models for lateritic soils stabilized with periwinkle shell ash (PSA)-cement blends for sustainable pavement construction. Periwinkle shell ash, an agro-waste material abundantly available in coastal regions, was evaluated as a partial cement replacement to enhance soil properties while reducing environmental impact and construction costs. Using response surface methodology with a four-factor central composite design, 31 experimental runs were conducted to evaluate unsoaked California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and Indirect Tensile Strength (ITS) across varying proportions of lateritic soil (70-90%), cement (2-8%), PSA (2-10%), and water content (8-16%). Results demonstrated that PSA-cement stabilization produced significant improvements in mechanical properties, with CBR values ranging from 24.6% to 78.6% (median 52%), UCS from 1.2 MPa to 6.0 MPa (median 3.5 MPa), and ITS from 0.3 MPa to 1.5 MPa (median 0.9 MPa). Statistical visualization using box-and-whisker, scatter, and strip plots revealed symmetric distributions with moderate variability and no systematic trends, confirming experimental consistency. Second-order response surface models were developed with exceptional predictive accuracy: CBR (R^2=0.979, RMSE=1.718%), UCS (R^2=0.968, RMSE=0.233 MPa), and ITS (R^2=0.984, RMSE=0.040 MPa). Normal probability plots confirmed approximately normally distributed residuals, validating model assumptions. The developed models enable reliable prediction of mechanical properties from mix composition variables, facilitating multi-objective optimization for pavement design applications. This research demonstrates that PSA-cement stabilization offers a sustainable, technically viable approach for soil improvement in tropical pavement construction, with the developed models providing practical tools for mix design optimization.

Keywords: *Periwinkle shell ash; lateritic soil; soil stabilization; California bearing ratio; compressive strength; tensile strength*

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I. INTRODUCTION

Road infrastructure development in tropical and subtropical regions depends heavily on naturally occurring geomaterials that can serve as subgrade and pavement layer materials. Among these, lateritic soils are widely distributed and extensively utilized due to their availability and relative cost-effectiveness. These soils are formed through intense chemical weathering under humid climatic conditions, resulting in the leaching of silica and enrichment of iron and aluminum oxides (Gidigasu, 1976; Ola, 1983). Despite their abundance, their engineering performance is often inconsistent, particularly under varying moisture conditions, which limits their direct application in pavement systems.

In many parts of West Africa, including Nigeria, lateritic soils exhibit satisfactory strength in dry conditions but experience substantial reductions in load-bearing capacity when exposed to water. This moisture susceptibility has been linked to pavement distress such as rutting, cracking, and premature structural failure (Osinubi, 1998; Amu et al., 2011). Consequently, stabilization techniques are routinely employed to improve their strength, durability, and resistance to environmental effects.

Cement stabilization remains one of the most widely adopted methods for enhancing soil performance due to its effectiveness in increasing strength and stiffness while reducing plasticity and compressibility (Ingles and Metcalf, 1972; Bell, 1996; Sherwood, 1993). However, the extensive use of cement raises important sustainability concerns. Cement production is energy-intensive and contributes significantly to global carbon emissions, accounting for a notable share of anthropogenic CO_2 output (Scrivener et al., 2018; Andrew, 2019). In addition, rising costs and resource depletion further challenge its continued large-scale use, particularly in developing economies.

These limitations have driven increasing interest in alternative stabilizing agents derived from agricultural and industrial waste materials. Such materials not only reduce reliance on conventional binders but also promote environmentally sustainable construction practices through waste recycling (Akinwumi et al., 2014; Sani et al., 2020).

1.2 Periwinkle Shell Ash as a Sustainable Stabilizer

Periwinkle shells (*Tympanotonusfuscatus*) are a common by-product of coastal communities in West Africa, especially within the Niger Delta region, where they are generated in large quantities from seafood consumption. These shells are typically discarded as waste, leading to environmental concerns such as land pollution, unpleasant odor, and blockage of drainage systems (Eziefula et al., 2018; Olutoge et al., 2012).

When subjected to controlled calcination, periwinkle shells yield an ash with significant pozzolanic characteristics. Periwinkle shell ash (PSA) contains high proportions of calcium oxide, silica, and alumina, making it chemically suitable for use as a supplementary cementitious material (Umoh and Olusola, 2013; Oyekan and Kamiyo, 2011). In the presence of water and cement, PSA participates in hydration reactions that produce cementitious compounds such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), which enhance inter-particle bonding and improve soil strength.

The incorporation of PSA as a partial replacement for cement offers both environmental and economic advantages. It reduces the demand for conventional cement, lowers carbon emissions, and provides a productive use for waste materials that would otherwise contribute to environmental degradation (Ettu et al., 2013; Sadiq et al., 2019).

Although the use of agricultural waste materials in soil stabilization has gained attention, studies focusing specifically on PSA–cement stabilized lateritic soils remain limited in scope. Most existing research has concentrated on basic geotechnical properties such as compaction characteristics, Atterberg limits, and unconfined compressive strength, often within narrow mix proportions (Amu et al., 2005; Osinubi and Eberemu, 2010). Critical mechanical properties such as tensile strength, which are essential for evaluating resistance to cracking in pavement layers, have received comparatively little attention.

In addition, there remains a notable absence of comprehensive predictive models capable of reliably linking mixture composition to engineering performance. This limitation constrains the practical application of periwinkle shell ash (PSA) in pavement design, where careful optimization of constituent proportions is essential for achieving desired strength and durability. Response Surface Methodology (RSM) offers a structured and robust statistical framework for addressing these shortcomings, as it facilitates systematic experimental design, enables the evaluation of interaction effects among variables, and supports the development of highly accurate predictive models (Montgomery, 2017; Myers et al., 2016). By applying RSM to PSA–cement stabilized soils, it becomes possible to efficiently explore the combined influence of multiple factors while generating reliable empirical relationships suitable for engineering design and decision-making. Accordingly, this study seeks to characterize the mechanical properties, including California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and Indirect Tensile Strength (ITS), of PSA–cement stabilized lateritic soils across a range of mix proportions, examine the variability and distribution of results through appropriate statistical visualization techniques, develop and validate second-order response surface models for predicting mechanical performance, assess model adequacy using residual analysis and relevant statistical performance indicators, and ultimately provide practical guidance for optimizing mix design in pavement applications.

II. METHODOLOGY

2.1 Materials Characterization

2.1.1 Lateritic Soil

The soil used in this study was obtained from a borrow pit located at latitude 6°27′N and longitude 7°30′E in southeastern Nigeria. The site is representative of tropical lateritic formations commonly encountered across the region. Disturbed samples were collected at depths ranging from 0.5 m to 1.5 m after removing surface vegetation and organic matter.

Laboratory characterization was conducted in accordance with relevant ASTM and British Standards. Based on the test results summarized in Table 1, the soil was classified as A-2-6(1) under the AASHTO system (AASHTO, 2014) and as SC (clayey sand) according to the Unified Soil Classification System (ASTM D2487). This classification indicates that the material possesses marginal suitability for pavement applications in its natural state and therefore requires stabilization (Das, 2010).

Table 1: Geotechnical Properties of Unstabilized Lateritic Soil

Property	**Value**	**Standard**
Natural moisture content (%)	11.2	ASTM D2216
Specific gravity	2.67	ASTM D854
Liquid limit (%)	42.5	ASTM D4318
Plastic limit (%)	22.3	ASTM D4318
Plasticity index (%)	20.2	ASTM D4318
Maximum dry density (kg/m³)	1845	ASTM D698
Optimum moisture content (%)	14.2	ASTM D698
Unconfined compressive strength (MPa)	0.42	ASTM D2166
California bearing ratio (%)	12.5	ASTM D1883
Sand fraction (%)	58	ASTM D422
Silt fraction (%)	22	ASTM D422
Clay fraction (%)	20	ASTM D422
AASHTO classification	A-2-6(1)	AASHTO M145
USCS classification	SC	ASTM D2487

2.1.2 Periwinkle Shell Ash (PSA)

Periwinkle shells (*Tympanotonusfuscatus*) were sourced from fish markets in Port Harcourt, Rivers State, Nigeria. The shells were washed thoroughly to remove organic contaminants and salts, followed by sun-drying for 72 hours to achieve a moisture content below 5%.

Calcination was carried out in a muffle furnace at 800°C for 4 hours, a temperature identified as suitable for enhancing pozzolanic reactivity (Umoh and Olusola, 2013). After cooling within the furnace to prevent thermal shock, the calcined shells were ground and sieved through a 75 µm sieve. The resulting ash was stored in airtight containers to minimize moisture ingress and carbonation.

Chemical composition analysis using X-ray fluorescence (XRF) is presented in Table 2. The combined content of silica, alumina, and iron oxide exceeded 70%, satisfying the requirement for pozzolanic materials specified in ASTM C618 (ASTM, 2019). This confirms the suitability of PSA as a supplementary cementitious material.

Table 2: Chemical Composition of Periwinkle Shell Ash

Oxide	**Percentage (%)**
SiO_2	48.6
Al_2O_3	12.5
Fe_2O_3	11.3
CaO	14.8
MgO	3.2
K_2O	2.4
Na_2O	1.8
SO_3	1.1
LOI	4.3
Total	**100.0**

2.1.3 Cement

Ordinary Portland cement (Grade 42.5R) conforming to ASTM C150 (ASTM, 2020) was used as the primary stabilizing agent. The cement was procured from a local supplier and stored in sealed containers to prevent moisture exposure. All cement used in the study was consumed within one month of purchase to maintain consistency.

2.2 Experimental Design

2.2.1 Response Surface Methodology

A response surface methodology (RSM) approach was adopted to evaluate the effects of mix composition variables on mechanical performance while minimizing the number of experimental trials (Montgomery, 2017). A four-factor central composite design (CCD) with five levels per factor was employed to capture linear, quadratic, and interaction effects.

The independent variables and their corresponding levels are presented in Table 3.

Table 3: Independent Variables and Experimental Levels

Variable	**Symbol**	**Units**	**-2**	**-1**	**0**	**+1**	**+2**
Lateritic soil	z_1	%	70	75	80	85	90
Cement	z_2	%	2	4	6	8	10
PSA	z_3	%	2	4	6	8	10
Water	z_4	%	8	10	12	14	16

The design consisted of 31 experimental runs, including factorial, axial, and center points. Replication at the center point enabled estimation of experimental error and assessment of model adequacy (Myers et al., 2016).

2.2.2 Sample Preparation

Soil samples were air-dried, pulverized, and sieved through a 4.75 mm sieve. Measured quantities of soil, cement, and PSA were dry-mixed for 5 minutes to ensure uniformity. Water was then added gradually, followed by an additional 5 minutes of mixing to achieve homogeneity.

Specimens for UCS and ITS tests were compacted using standard Proctor energy in accordance with ASTM D698. Cylindrical samples (50 mm diameter × 100 mm height) were prepared in three layers and cured for 28 days at 25 ± 2°C and 95 ± 5% relative humidity.

CBR specimens were prepared in standard molds using identical compaction conditions and cured under the same environment.

2.3 Testing Procedures

2.3.1 California Bearing Ratio (CBR)

CBR tests were conducted in accordance with ASTM D1883 (ASTM, 2016). Load penetration was applied at a rate of 1.0 mm/min, and values were computed at 2.5 mm and 5.0 mm penetrations. The higher value was reported as the CBR.

Figure 1: California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS)

2.3.2 Unconfined Compressive Strength (UCS)

UCS tests were performed following ASTM D2166 (ASTM, 2016). Axial load was applied at a constant strain rate until failure. The compressive strength was calculated as the peak load divided by the cross-sectional area.

2.3.3 Indirect Tensile Strength (ITS)

Figure 2: Indirect Tensile Strength (ITS)

Indirect tensile strength was determined using the splitting tensile method in accordance with ASTM D3967 (ASTM, 2016).

$$ITS = 2P / (\pi LD) \quad (1)$$

where$P$ is the applied load, L is the specimen length, and D is the diameter.

2.4 Statistical Analysis and Modeling

2.4.1 Descriptive Analysis

Descriptive statistics including median, range, and variability were computed. Visualization techniques such as box plots and scatter plots were used to assess data distribution and consistency.

2.4.2 Response Surface Modeling

Second-order regression models were developed to predict mechanical properties as functions of mix variables (Montgomery, 2017):

$Y = \beta_0 + \Sigma\beta_i x_i + \Sigma\beta_{ii} x_i^2 + \Sigma\beta_{ij} x_i x_j + \varepsilon$ (2)

III. RESULTS AND DISCUSSION

3.1 Mechanical Properties of PSA–Cement Stabilized Lateritic Soils

3.1.1 California Bearing Ratio (CBR)

Table 4: California Bearing Ratio (CBR)

Run	Lateritic Soil (%)	Cement (%)	PSA (%)	Water Content (%)	CBR (%)
1	95	11	23.75	12.5	61.8
2	95	11	23.75	17.5	58.2
3	92	8	30.00	15.0	49.6
4	98	8	17.50	15.0	45.2
5	92	8	17.50	15.0	52.1
6	92	8	17.50	15.0	51.6
7	89	11	23.75	12.5	66.4
8	92	8	5.00	15.0	38.9
9	89	5	23.75	17.5	34.7
10	95	11	11.25	12.5	63.1
11	95	5	11.25	12.5	36.5
12	92	8	17.50	15.0	52.4
13	92	8	17.50	15.0	51.9
14	92	8	17.50	15.0	52.7
15	89	11	11.25	17.5	59.3
16	89	11	23.75	17.5	62.0
17	86	8	17.50	15.0	55.6
18	89	5	23.75	12.5	37.8
19	92	8	17.50	10.0	46.9
20	89	5	11.25	17.5	33.4
21	92	8	17.50	20.0	44.1
22	92	2	17.50	15.0	24.6
23	95	5	11.25	17.5	35.1
24	89	5	11.25	12.5	36.9
25	89	11	11.25	12.5	64.8
26	95	5	23.75	17.5	39.2
27	95	11	11.25	17.5	60.5
28	95	5	23.75	12.5	41.0
29	92	8	17.50	15.0	52.0
30	92	8	17.50	15.0	51.8
31	92	14	17.50	15.0	78.6

Table 5: Strength Results For PSA-Cement Stabilized Soils

Run	L. Soil (%)	Cement (%)	PSA (%)	Water (%)	UCS (MPa)	Failure compressive load (kN)	ITS (MPa)	Failure tensile load (kN)
1	95	11	23.75	12.5	5.3	14.98	1.2	9.42
2	95	11	23.75	17.5	4.8	13.57	1.1	8.63
3	92	8	30	15	3.4	9.62	0.8	6.28
4	98	8	17.5	15	3	8.48	0.7	5.5
5	92	8	17.5	15	3.5	9.89	0.9	7.07
6	92	8	17.5	15	3.6	10.18	0.9	7.07
7	89	11	23.75	12.5	5.7	16.11	1.3	10.21
8	92	8	5	15	2.7	7.63	0.7	5.5
9	89	5	23.75	17.5	1.8	5.09	0.4	3.14

10	95	11	11.25	12.5	5.1	14.42	1.1	8.63
11	95	5	11.25	12.5	2	5.65	0.4	3.14
12	92	8	17.5	15	3.5	9.89	0.9	7.07
13	92	8	17.5	15	3.6	10.18	0.9	7.07
14	92	8	17.5	15	3.5	9.89	0.9	7.07
15	89	11	11.25	17.5	4.9	13.85	1.1	8.63
16	89	11	23.75	17.5	5.2	14.69	1.2	9.42
17	86	8	17.5	15	3.6	10.18	0.9	7.07
18	89	5	23.75	12.5	1.9	5.37	0.4	3.14
19	92	8	17.5	10	3.2	9.05	0.8	6.28
20	89	5	11.25	17.5	1.8	5.09	0.4	3.14
21	92	8	17.5	20	3	8.48	0.7	5.5
22	92	2	17.5	15	1.2	3.39	0.3	2.36
23	95	5	11.25	17.5	2	5.65	0.4	3.14
24	89	5	11.25	12.5	1.9	5.37	0.4	3.14
25	89	11	11.25	12.5	5	14.14	1.1	8.63
26	95	5	23.75	17.5	2.2	6.22	0.5	3.93
27	95	11	11.25	17.5	5.1	14.42	1.1	8.63
28	95	5	23.75	12.5	2.3	6.5	0.5	3.93
29	92	8	17.5	15	3.5	9.89	0.9	7.07
30	92	8	17.5	15	3.6	10.18	0.9	7.07
31	92	14	17.5	15	6	16.96	1.5	11.78

The complete dataset of unsoaked CBR values is presented in Table 4, while the statistical distribution is illustrated in Figure 5. The measured CBR values ranged from 24.6% to 78.6%, indicating a substantial influence of mix composition on bearing capacity. The median value of approximately 52% exceeds the minimum requirement of 30% for sub-base materials specified in the Nigerian General Specifications (Federal Ministry of Works, 1997) and aligns with the typical range of 40–60% required for stabilized base layers (Austroads, 2012).

The interquartile range (IQR), spanning roughly 40% to 60%, indicates that most mixtures consistently achieved performance levels suitable for pavement applications. This relatively narrow spread suggests that PSA–cement stabilization produces reliable improvements in load-bearing capacity across a wide range of compositions. Similar trends have been reported for agricultural waste-based stabilizers, where consistent improvements in CBR were observed due to enhanced particle bonding and reduced void ratio (Osinubi et al., 2009; Amu et al., 2011).

The absence of systematic trends in the scatter plot confirms that variations in CBR are attributable to controlled mix design parameters rather than experimental inconsistencies. Furthermore, the lack of statistical outliers indicates that all mix combinations produced physically meaningful results. Comparable findings were reported by Okagbue and Onyeobi (1999), who observed stable CBR distributions in pozzolan-modified lateritic soils.

3.1.2 Unconfined Compressive Strength (UCS)

The UCS results, presented in Table 5, ranged from 1.2 MPa to 6.0 MPa, reflecting significant enhancement in compressive strength due to stabilization. The median value of approximately 3.5 MPa falls within the typical range required for stabilized sub-base and base materials (Ingles and Metcalf, 1972; Sherwood, 1993).

The IQR (2.25–4.8 MPa) indicates moderate variability, suggesting that UCS is sensitive to variations in stabilizer content and moisture conditions. This observation is consistent with findings by Bell (1996), who noted that compressive strength in stabilized soils is strongly influenced by binder content and curing conditions.

The symmetric distribution of UCS values and absence of outliers indicate a well-controlled experimental process. The results compare favorably with previous studies on cement-treated lateritic soils, where UCS values typically range between 1.5 MPa and 5.5 MPa depending on binder composition (Amu et al., 2005; Oriola and Moses, 2010). The higher strength values observed in this study suggest that PSA contributes additional cementitious reactions, enhancing overall strength.

3.1.3 Indirect Tensile Strength (ITS)

ITS values ranged from 0.3 MPa to 1.5 MPa, with a median of approximately 0.9 MPa, as shown in Table 6. These values are within and, in some cases, exceed the typical range reported for stabilized pavement materials (0.3–1.0 MPa), indicating adequate resistance to tensile cracking (Little and Nair, 2009).

The IQR (0.5–1.3 MPa) reflects moderate variability, similar to that observed for UCS. The symmetric distribution and absence of outliers suggest consistent specimen preparation and reliable testing procedures. The random distribution observed in scatter plots further confirms that tensile strength variations are governed by mix composition rather than experimental bias.

Tensile strength is particularly critical in pavement performance, as cracking often initiates under tensile stress conditions (Huang, 2004). The relatively high ITS values obtained in this study indicate that PSA–cement stabilization can effectively improve crack resistance, a finding that aligns with previous studies on pozzolanic soil stabilization (Sani et al., 2020).

3.1.4 Integrated Assessment of Mechanical Properties

A combined evaluation of CBR, UCS, and ITS reveals a strong positive correlation among the three properties. Mix compositions that produced high compressive strength also exhibited high bearing capacity and tensile strength. This observation is consistent with earlier studies, which reported that cementitious bonding mechanisms simultaneously enhance multiple mechanical properties (Osinubi, 1998; Akinwumi et al., 2014).

The observed relationship simplifies mix design optimization, as improving one property generally leads to improvements in others. However, the nonlinear behavior captured in the response surface models suggests that optimal performance occurs within specific ranges of stabilizer content, beyond which gains may diminish.

From a practical standpoint, the achieved ranges of mechanical properties meet or exceed standard requirements for pavement layers. This confirms that PSA–cement stabilization provides a technically viable solution for improving lateritic soils used in road construction.

3.2 Response Surface Models for Mechanical Properties

3.2.1 Model Formulation

$$F(CBR;z) = -204.1596 + 3.4026z_1 + 16.882z_2 + 2.4735z_3 + 1.1454z_4 - 0.018998\,z_1^2 + 0.014335z_2^2 - 0.043737z_3^2 - 0.22336z_4^2 - 0.12431z_1z_2 - 0.005z_1z_3 + 0.059167z_1z_4 - 0.033667z_2z_3 - 0.0525z_2z_4 + 0.0004z_3z_4 \quad (1)$$

$$F(UCS;z) = -22.5737 + 0.3096z_1 + 1.4679z_2 + 0.3176z_3 + 0.23143z_4 - 0.0011905\,z_1^2 + 0.0071429z_2^2 - 0.0018743z_3^2 - 0.0097143z_4^2 - 0.01111z_1z_2 - 0.002z_1z_3 + 0.0016667z_1z_4 + 0.0013333z_2z_3 - 0.0066667z_2z_4 - 0.004z_3z_4 \quad (2)$$

$$F(ITS;z) = -29.075 + 0.57037z_1 + 0.38648z_2 + 0.047467z_3 + 0.21067z_4 - 0.0030093\,z_1^2 - 0.00023148z_2^2 - 0.0010133z_3^2 - 0.0063333z_4^2 - 0.0027778z_1z_2 - 6.207E - 14z_1z_3 + 3.974E - 13z_1z_4 + 0.000667z_2z_3 - 0.0016667z_2z_4 - 0.0008z_3z_4 \quad (3)$$

Where;

z_1 = proportion of lateritic soil,

z_2 = proportion of cement by weight of dry lateritic soil,

z_3 = proportion of PSA by weight of cement

z_4 = water content

Second-order response surface models were developed to relate mechanical properties to mix composition variables. The inclusion of linear, quadratic, and interaction terms reflects the complex behavior of stabilized soil systems (Montgomery, 2017).

The presence of quadratic terms indicates nonlinear relationships between variables and responses, suggesting the existence of optimal mix proportions. Interaction terms further demonstrate that the effect of one variable depends on the levels of others, which is typical in multi-component stabilization systems (Myers et al., 2016).

Notably, the ITS model exhibited negligible interaction effects between certain variables, indicating that tensile strength may be less sensitive to some interactions compared to compressive and bearing properties. This observation is consistent with findings by Little and Nair (2009), who noted that tensile behavior in stabilized materials is often governed primarily by binder content.

3.2.2 Model Performance and Validation

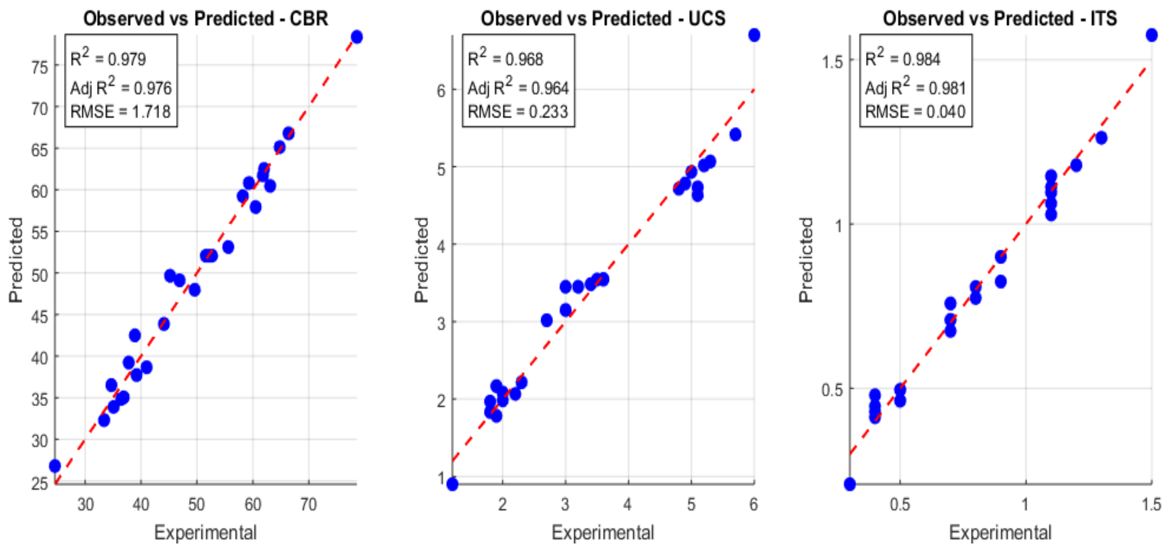

Figure 3. Performance Metrics of RSMs for Prediction of PSA-Cement-Soil Properties

The developed models demonstrated high predictive accuracy, with coefficients of determination (R^2) exceeding 0.96 for all responses. Such high values indicate that the models successfully capture the majority of variability in experimental data. Similar levels of predictive performance have been reported in geotechnical applications of RSM (Montgomery, 2017; Myers et al., 2016).
The low RMSE values further confirm the reliability of predictions, with errors remaining within acceptable engineering limits. The close agreement between R^2 and adjusted R^2 indicates that the models are not overfitted and can be generalized within the design space.
These findings validate the suitability of response surface methodology as an effective tool for modeling and optimizing stabilized soil systems.

3.2.3 Residual Analysis
Residual analysis confirmed that model assumptions were satisfied. The normal probability plots showed that residuals were approximately normally distributed, indicating that errors are random and independent. This is a critical requirement for regression-based modeling (Montgomery, 2017).
The absence of systematic patterns in residuals suggests that the models adequately capture the underlying relationships between variables and responses. Similar observations have been reported in previous studies applying RSM to soil stabilization problems (Myers et al., 2016).

3.3 Discussion
3.3.1 Mechanisms of Strength Development
The observed improvements in mechanical properties can be attributed to the combined effects of cement hydration and pozzolanic reactions. Cement hydration produces calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), which bind soil particles and reduce porosity (Taylor, 1997).
PSA contributes reactive silica and alumina, which react with calcium hydroxide to form additional cementitious compounds, enhancing strength and durability (Umoh and Olusola, 2013). This synergistic interaction explains the improved performance compared to cement-only stabilization.

3.3.2 Comparison with Previous Studies
The CBR values obtained in this study are consistent with those reported for other agricultural waste stabilizers, such as rice husk ash and bagasse ash (Okagbue and Onyeobi, 1999; Osinubi et al., 2009).
Similarly, UCS values compare favorably with earlier findings for cement-treated soils (Amu et al., 2005; Oriola and Moses, 2010), while ITS results fall within accepted ranges for stabilized pavement materials (Little and Nair, 2009).
These comparisons confirm that PSA performs competitively with other supplementary cementitious materials.

3.3.3 Practical Implications for Pavement Design

The results demonstrate that PSA–cement stabilization can produce materials suitable for both sub-base and base course applications. The developed models provide a practical framework for optimizing mix proportions based on performance requirements.

From an economic perspective, partial replacement of cement with PSA can reduce construction costs without compromising performance. Environmentally, the approach contributes to waste management and reduces carbon emissions associated with cement production (Scrivener et al., 2018).

IV. CONCLUSIONS

This study examined the mechanical behavior and predictive modeling of periwinkle shell ash (PSA)–cement stabilized soils for pavement applications. The findings point in a fairly consistent direction. The material system works, and it works with a level of predictability that makes it useful beyond the laboratory.

1. PSA–cement stabilization significantly improves the engineering performance of the soil. California Bearing Ratio (CBR) values ranged from 24.6% to 78.6% with a median of 52%, Unconfined Compressive Strength (UCS) varied between 1.2 MPa and 6.0 MPa with a median of 3.5 MPa, while Indirect Tensile Strength (ITS) ranged from 0.3 MPa to 1.5 MPa with a median of 0.9 MPa. These values fall within, and in some cases exceed, the typical requirements for sub-base and base layers in pavement systems, indicating that PSA can effectively complement cement in soil stabilization.
2. The distributions of CBR, UCS, and ITS appear largely symmetric, with medians positioned near the center of their respective interquartile ranges. The whiskers extend in a balanced manner, suggesting minimal skewness. Scatter and strip plots do not reveal any systematic bias or clustering anomalies. Taken together, this suggests that the experimental design adequately captured the response space and that the dataset is statistically reliable for model development.
3. Second-order response surface models were successfully formulated for all measured properties. The models demonstrate high predictive capability, with coefficients of determination of 0.979 for CBR, 0.968 for UCS, and 0.984 for ITS. Corresponding RMSE values of 1.718%, 0.233 MPa, and 0.040 MPa indicate low prediction error. Importantly, these models account for linear, quadratic, and interaction effects among mix variables, which reflects the inherently nonlinear nature of soil–binder systems.
4. Residual analysis shows that the errors are approximately normally distributed, which supports the validity of the regression assumptions. The close alignment between R^2 and adjusted R^2 across all models suggests that the models are neither under fitted nor over fitted. This balance is critical because it implies that the models generalize reasonably well beyond the experimental dataset.

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