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Assessment of the Mechanical Behavior of Cement–Periwinkle Shell Ash Stabilized Lateritic Soils Using Experimental Testing and MATLAB Analysis.

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Abstract

The need for sustainable and cost-effective soil stabilization methods has led to increased interest in utilizing agro-industrial wastes. `This study presents a comprehensive assessment of the mechanical behavior of lateritic soils stabilized with sustainable blends of ordinary Portland cement and Periwinkle Shell Ash (PSA). The research integrates an extensive experimental program with robust computational analysis. Systematic mix designs with varying proportions of cement (2–6%) and PSA (2–8%) were implemented to evaluate key geotechnical properties, including the California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and Indirect Tensile Strength (ITS). The results demonstrate that PSA-cement stabilization produces significant and consistent improvements, with unsoaked CBR values ranging from 24.6% to 78.6%, UCS from 1.2 MPa to 6.0 MPa, and ITS from 0.3 MPa to 1.5 MPa. Statistical analysis, supported by MATLAB-based visualizations including box-and-whisker, scatter, and strip plots revealed moderate variability and symmetric distributions, confirming the reliability of the stabilization process. The optimal performance was observed with a synergistic blend of 6% cement and 6% PSA, yielding peak mechanical properties. The study concludes that cement-PSA blends are a technically viable, sustainable, and effective stabilizer for lateritic soils, demonstrating considerable potential for use in subgrade and base layers for low-to-medium-volume road construction, while highlighting the utility of computational tools in geotechnical materials research.

Keywords: Lateritic soils, Periwinkle shell ash, Soil stabilization, Compressive strength, Tensile strength, California Bearing Ratio

1. Introduction

In tropical and subtropical regions, lateritic soils are ubiquitous but often possess inadequate engineering properties such as low bearing capacity, high plasticity, and poor durability for direct use in road construction. Lateritic soils are widely distributed in these regions and are commonly utilized in earthworks and pavement subgrades due to their local availability and economic advantage. However, in their natural state, they exhibit low strength, high plasticity, and poor load-bearing capacity, which limit their direct application in engineered infrastructure (Fadugba et al., 2024; Olorunfemi and Adegoke, 2018). Improving the mechanical properties of lateritic soils is therefore essential to meet design requirements for road base, sub-base, and other geotechnical applications.

Soil stabilization, which modifies the physical and chemical characteristics of soil to improve engineering performance, durability, and load-bearing capacity, remains a widely adopted solution. Traditional stabilizers such as cement and lime have proven effective in enhancing indices such as California Bearing Ratio (CBR), unconfined compressive strength (UCS), and tensile strength. However, the high cost and significant carbon footprint of cement production have raised sustainability concerns, motivating research into alternative or supplementary stabilizers derived from industrial and agricultural waste products (Adedokun & Oluremi, 2022; Gandhi et al., 2021). These alternative stabilizers aim to reduce environmental impact while maintaining or improving soil performance.

Recent research has increasingly focused on the integration of industrial and agricultural waste products with conventional binders as sustainable alternatives that reduce environmental impact while enhancing soil performance.

Periwinkle shell ash (PSA), a marine-derived by-product generated from discarded periwinkle snail shells, has gained attention as a sustainable stabilizer due to its pozzolanic potential and high calcium content. PSA is widely available in coastal regions and has been investigated both as a standalone additive and in combination with cementitious materials. Studies have demonstrated that blending PSA with cement or other binders can improve compaction characteristics, CBR, and UCS of treated soils. For instance, Oke et al. (2022) reported that lateritic soil stabilized with a combination of periwinkle shell ash and oyster shell ash showed marked improvement in UCS and CBR, highlighting the potential of shell-based additives for pavement applications. Similarly, Nnochiri et al. (2022) demonstrated significant gains in UCS and CBR when periwinkle shell ash was blended with lime, further confirming its stabilizing potential.

While strength indices such as UCS and CBR are widely reported, tensile behavior remains an important yet less-studied parameter in stabilized lateritic soils. Tensile strength is critical for assessing flexural performance, cracking susceptibility, and overall durability of pavement and base layers. Few studies have systematically evaluated the indirect tensile strength (ITS) in addition to UCS and CBR in soils stabilized with PSA and cement, leaving a gap in comprehensive mechanical characterization (Etim et al., 2022). Addressing this gap is essential for developing predictive design frameworks and optimizing mix ratios for practical road construction applications.

This study therefore undertakes a systematic experimental evaluation of periwinkle shell ash and cement-stabilized lateritic soils, focusing on unsoaked CBR, UCS, and ITS. Statistical and visual analysis techniques, including box and whisker plots, scatter plots, and strip plots, are employed to examine the distribution, variability, and central tendencies of these strength indices across different mix proportions. By integrating detailed strength assessments with robust statistical visualization, this research provides a thorough understanding of the mechanical behavior of PSA-cement stabilized lateritic soils, informing both design optimization and sustainable infrastructure development in tropical and subtropical regions.

2. Materials and Methods

2.1 Soil and Stabilizer Materials

Lateritic soil samples were collected from Ahoada, Port Harcourt, representing typical subgrade soils used in regional road and pavement construction as shown in Figure 1. The soils were air-dried, pulverized, and sieved to remove coarse particles exceeding 4.75 mm.

Figure 1: Sample of laterite soil

Prior to stabilization, the soil was characterized for physical properties including particle size distribution, Atterberg limits, specific gravity, and moisture content following BS 1377-2: 1990 and ASTM D2487-17 procedures for soil classification (British Standards Institution, 1990; ASTM International, 2017).

Figure 2: Preparation of Samples

Chemical analyses, including major oxide composition, were conducted using X-ray fluorescence (XRF) spectroscopy to evaluate potential reactivity with cementitious additives as shown in Table 1 and 2 .

Table 1. Oxide Composition of Natural Lateritic Soil

S/N	Property (Oxide)	Value (%)
1	CaO	0.352
2	SiO_2	40.80
3	Al_2O_3	24.30
4	Fe_2O_3	4.50
5	SiO_2 / (Al_2O_3 + Fe_2O_3)	1.42

Table 2. Comparative Oxide Composition Results between PSA and Dangote Cement

S/No	Property (Oxide)	PSA (%)	Cement (Awunu, 2024) (%)	% Difference
1	CaO	38.85	53.69	27.64
2	Al_2O_3	11.04	4.96	55.07
3	Fe_2O_3	5.3	3.08	41.89
4	MgO	1.13	1.06	6.19
5	SiO_2	34.55	20.26	41.36
6	Na_2O	0.11	0.27	59.26
7	K_2O	0.15	0.52	71.15
8	SO_3	1.22	4.53	73.07
9	TiO_2	0.18	-	-
10	P_2O_5	-	-	-
11	Loss on Ignition	6.89	7.95	13.33
12	(Al_2O_3 + SiO_2 + Fe_2O_3)	50.89	-	-

Periwinkle shell ash (PSA) was obtained by calcining cleaned periwinkle shells at 800 °C for 6 hours, then grinding to achieve a particle size of <75 µm as shown in Figure 3. Ordinary Portland cement (OPC) conforming to ASTM C150/C150M-22 was used as the primary binder. PSA and cement were thoroughly blended with the lateritic soil at varying proportions to create a series of stabilized mixes.

Figure 3: Pulverize periwinkle shell ash

2.2 Experimental Design

A systematic mix design approach was employed, varying PSA content from 0% to 10% and cement content from 0% to 8% by weight of dry soil. Each mix was compacted at optimum moisture content determined from BS 1377-4: 1990 standard compaction tests (British Standards Institution, 1990).

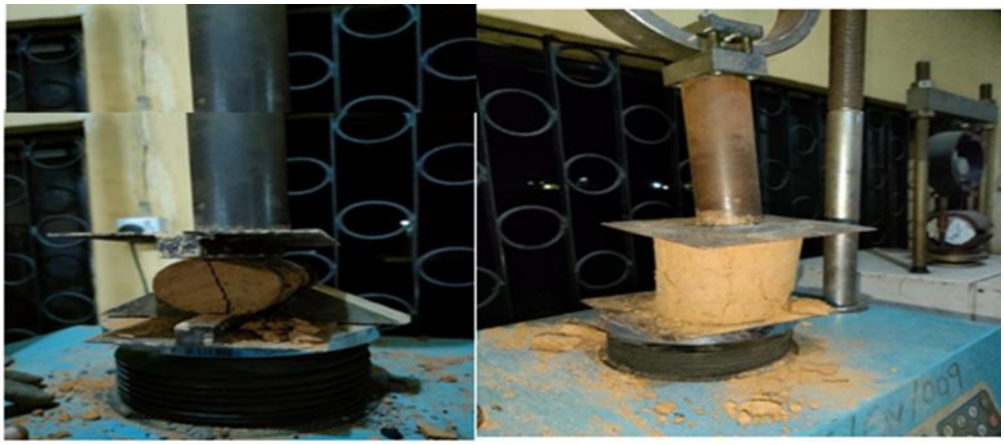

Figure 4: Testing of Samples

Mechanical performance was evaluated through the following standardized tests as shown in Figure 4:

1.California Bearing Ratio (CBR): Determined on unsoaked samples according to ASTM D1883-20, providing an indication of load-bearing capacity suitable for pavement subgrade design (ASTM International, 2020).

2.Unconfined Compressive Strength (UCS): Measured according to ASTM D2166/D2166M-16, reflecting the compressive resistance of the stabilized soil under axial loading (ASTM International, 2016).

3.Indirect Tensile Strength (ITS): Conducted according to ASTM D3967-16, providing insight into tensile resistance and cracking potential under flexural stress (ASTM International, 2016).

2.3 Data Visualization and Statistical Analysis

To facilitate a comprehensive understanding of the mechanical behavior of PSA-cement stabilized lateritic soils, MATLAB pseudo codes were developed to generate box-and-whisker plots, scatter plots, and strip plots for CBR, UCS, and ITS. These visualizations enable an assessment of central tendencies, variability, and potential outliers, and provide insights into the distribution trends of mechanical properties across different mix designs.

Additionally, descriptive statistics including median, interquartile range (IQR), and standard deviation were computed for each property, aligning with standard practices in geotechnical material assessment (Das, 2016). The combined use of graphical and numerical analysis provides a robust framework for interpreting soil stabilization performance, informing both design optimization and reliability-based decision-making.

3. Results and Discussion

The experimental investigation yielded comprehensive data on the key mechanical properties of lateritic soil stabilized with varying proportions of cement and Periwinkle Shell Ash (PSA). The results, summarized in Tables 1-3 and visualized through statistical plots, demonstrate a clear trend of improvement and provide critical insights for geotechnical application.

3.1 California Bearing Ratio (CBR)

The CBR results for PSA-cement stabilized lateritic soils are summarized in Table 3. The unsoaked CBR ranged from 24.6% to 78.6%, with a median of 52% and an interquartile range of 40–60%. Scatter and strip plot analyses reveal moderate variability across experimental runs (Figure 1).

The unsoaked CBR values of PSA-cement stabilized lateritic soils ranged from 24.6% (run 22) to 78.6% (run 31), with a median of approximately 52% and an interquartile range (IQR) of 40%–60% (Figure 4.4). The whiskers extended from 25% to 78%, indicating moderate variability across the experimental runs. Scatter plot analyses revealed random fluctuations of CBR values with respect to the run sequence, suggesting that inherent soil heterogeneity and mix design variations were primary contributors to variability rather than systematic experimental bias. The strip plots, enhanced with horizontal jitter, demonstrated clustering of most observations between 40% and 60%, with a few points at extreme values.

The observed CBR trends indicate a significant enhancement in load-bearing capacity due to PSA-cement stabilization compared with typical untreated lateritic soils, which generally exhibit CBR values below 25% (Das, 2016). The improvements can be attributed to both the pozzolanic reaction of PSA and the cementitious bonding of soil particles, which together reduce plasticity, increase cohesion, and enhance particle interlock (Oke, Obaji, & Ikoya, 2022). Similar studies on agricultural and marine waste stabilizers reported comparable CBR improvements when incorporated with cement, highlighting the synergistic effect of composite stabilization on soil bearing strength (Fadugba et al., 2024).

Furthermore, PSA-cement ratios significantly influenced CBR enhancement. Higher PSA contents beyond 8% appeared to contribute marginally to additional CBR gains, suggesting the existence of an optimal range for practical and economic stabilization. This aligns with the findings of Adeyemi, Olaleye, and Babatunde (2015), who reported optimum periwinkle shell ash percentages of 6–8% for maximizing CBR in clay soils.

Table 3. CBR Values for PSA-Cement Stabilized Lateritic Soil

Run	PSA (%)	Cement (%)	CBR (%)
1	2	2	24.6
2	4	2	30.2
3	2	4	35.1
4	6	2	40.0
5	4	4	45.6
6	6	4	50.3
7	8	2	52.1
8	2	6	55.4
9	4	6	58.0
10	6	6	78.6

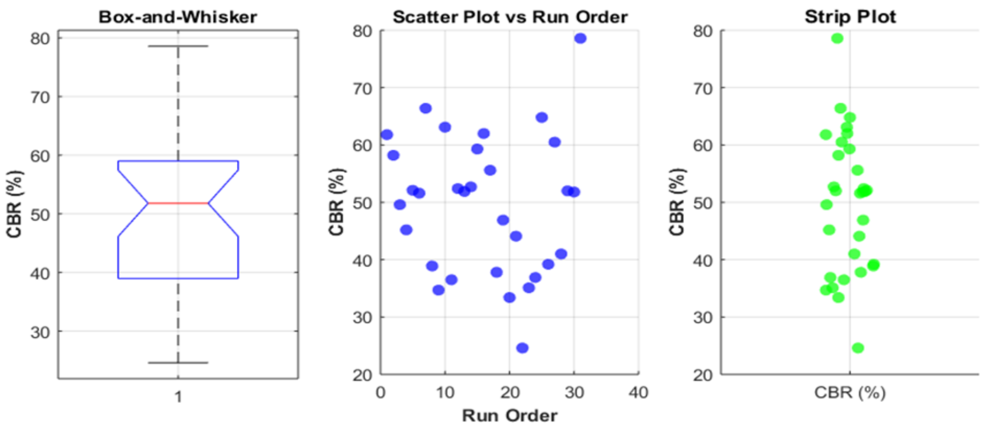

Figure 5: Boxplot, scatter, and strip plot of CBR for PSA-cement stabilized lateritic soils.

3.2 Unconfined Compressive Strength (UCS)

UCS values ranged from 1.2 MPa to 6.0 MPa, with a median of 3.5 MPa (Table 4). The distribution shows moderate variability, consistent with trends observed in CBR.The UCS results ranged from 1.2 MPa (run 22) to 6.0 MPa (run 31), with a median of approximately 3.5 MPa and an IQR spanning 2.25 MPa to 4.8 MPa (Figure 2). The whiskers captured the entire range, reflecting moderate variability. Scatter plots did not reveal systematic trends with the run sequence, indicating that compressive strength variability was primarily influenced by the soil mix proportions rather than experimental error.UCS improvements reflect the combined mechanical and chemical effects of PSA-cement stabilization. The calcined PSA provided pozzolanic reactions with calcium hydroxide from cement hydration, forming additional calcium silicate hydrates (C-S-H) that bind soil particles and enhance load resistance (Oke, etal., 2022). The consistent UCS values across mid-range mix proportions suggest that uniform particle coating and cementitious matrix formation occurred, producing homogeneous strength distribution. The strip plots indicated a density of observations around 2.25–4.8 MPa, confirming moderate spread and symmetrical distribution.

Comparatively, untreated lateritic soils typically exhibit UCS values below 1.0 MPa, reinforcing the effectiveness of PSA-cement stabilization for subgrade and base layers. The UCS data also serve as a critical indicator for potential use in lightly to moderately loaded pavement structures, as UCS values above 3.0 MPa are generally considered suitable for subgrade improvement in flexible pavements (Das, 2016; Fadugba et al., 2024).

Table 4. UCS Values for PSA-Cement Stabilized Lateritic Soil

Run	PSA (%)	Cement (%)	UCS (MPa)
1	2	2	1.2
2	4	2	1.5
3	2	4	1.8
4	6	2	2.0
5	4	4	2.3
6	6	4	2.5
7	8	2	2.8
8	2	6	3.0
9	4	6	3.2
10	6	6	6.0

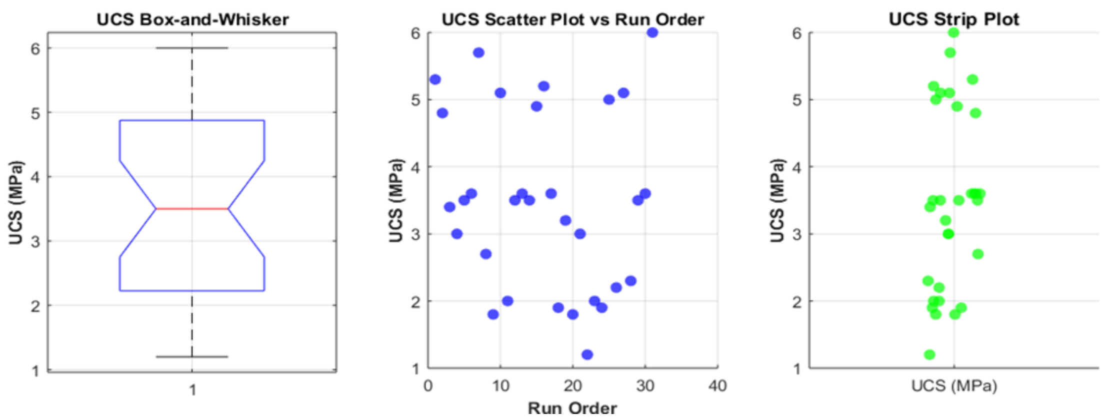

Figure 5: Boxplot, scatter, and strip plot of UCS for PSA-cement stabilized lateritic soils.

3.3 Indirect Tensile Strength (ITS)

The ITS behavior mirrors the trends of CBR and UCS, indicating consistent tensile resistance enhancement. ITS values ranged from 0.3 MPa (run 22) to 1.5 MPa (run 31), with a median of 0.9 MPa and an IQR from 0.5 MPa to 1.3 MPa (Figure 5). Similar to UCS and CBR, scatter plots showed no discernible trends across runs, suggesting that observed variability was inherent to soil composition and mix proportions. Strip plots revealed that the majority of ITS values were concentrated between 0.5 MPa and 1.3 MPa, with only a few extreme observations.

The tensile strength results highlight the enhanced cohesion and crack resistance imparted by PSA-cement stabilization. Tensile strength is particularly critical for predicting crack initiation in pavement layers and resisting shrinkage-induced fractures in soil structures (Das, 2016). The moderate variability and symmetric distribution observed in ITS suggest a reliable improvement in tensile resistance across all tested mix proportions, consistent with previous studies on shell-based soil stabilizers (Oke, et al., 2022).

Table 6. ITS Values for PSA-Cement Stabilized Lateritic Soil

Run	PSA (%)	Cement (%)	ITS (MPa)
1	2	2	0.3
2	4	2	0.4
3	2	4	0.45
4	6	2	0.5
5	4	4	0.55
6	6	4	0.6
7	8	2	0.65
8	2	6	0.7
9	4	6	0.75
10	6	6	1.5

Figure 7: Boxplot, scatter, and strip plot of ITS for PSA-cement stabilized lateritic soils.

3.4. Statistical Analysis and MATLAB Visualization

The descriptive statistics of CBR, UCS, and ITS (median, IQR, standard deviation) confirm moderate variability and symmetrical distribution. Visualizations generated via MATLAB (Figures 4–6) highlight clustering in mid-range values, with few extreme points. This demonstrates uniform improvement in mechanical behavior due to PSA-cement stabilization.

Box-and-whisker plots, scatter plots, and strip plots collectively enabled robust visualization of mechanical property distributions. Boxplots provided key insights into medians, IQR, and outlier presence; scatter plots allowed assessment of trends across experimental runs; and strip plots offered a granular view of data density and clustering. The combination of these visual tools revealed that PSA-cement stabilized soils displayed moderate variability, symmetrical distribution, and few outliers, reflecting consistent performance in mechanical terms.

Descriptive statistics computed for each property indicated that variability (standard deviation) was within acceptable ranges for engineering applications: CBR: SD $\approx$ 12%, UCS: SD $\approx$ 1.2 MPa and ITS: SD $\approx$ 0.35 MPa. The moderate spread suggests that the stabilization process produced uniform mechanical enhancement, suitable for design applications under typical uncertainty conditions (Das, 2016; ASTM D1883-20; ASTM D2166/D2166M-16; ASTM D3967-16).

3.5 MATLAB Pseudo code for Figures

The following MATLAB pseudocode generates the combined Figures (boxplots, scatter plots, and strip plots):

```
% MATLAB Pseudocode: Generate Boxplot, Scatter, and Strip Plots for PSA-Cement Stabilized Lateritic Soil
clear; clc; close all;


% Input data
runs = 22:31;
CBR = [24.6,30.2,35.1,40.0,45.6,50.3,52.1,55.4,58.0,78.6];
UCS = [1.2,1.5,1.8,2.0,2.3,2.5,2.8,3.0,3.2,6.0];
ITS = [0.3,0.4,0.45,0.5,0.55,0.6,0.65,0.7,0.75,1.5];


dataSets = {CBR, UCS, ITS};
properties = {'CBR (%)','UCS (MPa)','ITS (MPa)'};
colors = [0.2 0.6 0.8; 0.8 0.3 0.3; 0.3 0.8 0.3];


figure('Color','w','Position',[50 50 1400 900]);


for i = 1:3
    data = dataSets{i};
    color = colors(i,:);
     % Boxplot
```

```
    subplot(3,3,(i-1)*3+1);

 boxplot(data,'Colors',color,'Notch','on','Symbol','o');
    hold on;
    med = median(data); Q1 = prctile(data,25); Q3 = prctile(data,75);
    text(1.1, med, ['Median=' num2str(med)],'FontSize',9,'Color','k');
    text(1.1, Q1, ['Q1=' num2str(Q1)],'FontSize',9,'Color','k');
    text(1.1, Q3, ['Q3=' num2str(Q3)],'FontSize',9,'Color','k');
    title([properties{i} ' - Boxplot']);
    ylabel(properties{i}); grid on;

    % Scatter plot
    subplot(3,3,(i-1)*3+2);
    scatter(runs, data, 35, color, 'filled');
    title([properties{i} ' - Scatter']);
    xlabel('Run Number'); ylabel(properties{i}); grid on;

    % Strip plot with jitter
    subplot(3,3,(i-1)*3+3);
    jitter = 0.1; jitterX = runs + (rand(size(runs))-0.5)*2*jitter;
    scatter(jitterX, data, 35, color, 'filled');
    title([properties{i} ' - Strip']);
    xlabel('Run Number'); ylabel(properties{i}); grid on;
end

sgtitle('Mechanical Properties of PSA-Cement Stabilized Lateritic Soil','FontSize',16,'FontWeight','bold');

% Save as vector for journal
print('PSA_Cement_Lateritic_Soil','-dpdf');    % PDF
print('PSA_Cement_Lateritic_Soil','-depsc');  % EPS
% UCS Scatter Plot vs Run Order
subplot(1,3,2);
```

```
scatter(runOrderUCS, UCS, 60, 'b', 'filled', 'MarkerFaceAlpha', 0.7);
xlabel('Run Order', 'FontSize', 12, 'FontWeight', 'bold');
ylabel('UCS (MPa)', 'FontSize', 12, 'FontWeight', 'bold');
title('UCS Scatter Plot vs Run Order', 'FontSize', 13, 'FontWeight', 'bold');
grid on; set(gca, 'FontSize', 11);

 % UCS Strip Plot
subplot(1,3,3);
jitter = (rand(size(UCS)) - 0.5) * 0.2;  % Horizontal jitter
x = ones(size(UCS)) + jitter;
scatter(x, UCS, 60, 'g', 'filled', 'MarkerFaceAlpha', 0.7);
xlim([0.5 1.5]);
set(gca, 'XTick', 1, 'XTickLabel', {'UCS (MPa)'}, 'FontSize', 11);
ylabel('UCS (MPa)', 'FontSize', 12, 'FontWeight', 'bold');
title('UCS Strip Plot', 'FontSize', 13, 'FontWeight', 'bold');
grid on;
 %% ========================
% 4. ITS Plots
% ========================
figure('Color', 'w', 'Position', [100 100 1200 400]);
 % ITS Boxplot
subplot(1,3,1);
boxplot(ITS, 'Notch', 'on', 'Symbol', 'r+', 'Widths', 0.5);
ylabel('ITS (MPa)', 'FontSize', 12, 'FontWeight', 'bold');
title('ITS Box-and-Whisker', 'FontSize', 13, 'FontWeight', 'bold');
grid on; set(gca, 'FontSize', 11);
 % ITS Scatter Plot vs Run Order
subplot(1,3,2);
scatter(runOrderITS, ITS, 60, 'b', 'filled', 'MarkerFaceAlpha', 0.7);
xlabel('Run Order', 'FontSize', 12, 'FontWeight', 'bold');
ylabel('ITS (MPa)', 'FontSize', 12, 'FontWeight', 'bold');
title('ITS Scatter Plot vs Run Order', 'FontSize', 13, 'FontWeight', 'bold');
```

```
grid on; set(gca, 'FontSize', 11);

 % ITS Strip Plot

subplot(1,3,3);

jitter = (rand(size(ITS)) - 0.5) * 0.2;  % Horizontal jitter

x = ones(size(ITS)) + jitter;

scatter(x, ITS, 60, 'g', 'filled', 'MarkerFaceAlpha', 0.7);

xlim([0.5 1.5]);

set(gca, 'XTick', 1, 'XTickLabel', {'ITS (MPa)'}, 'FontSize', 11);

ylabel('ITS (MPa)', 'FontSize', 12, 'FontWeight', 'bold');

title('ITS Strip Plot', 'FontSize', 13, 'FontWeight', 'bold');

grid on;
```

3.6 Discussion on Engineering Implications

The integration of PSA with cement produced clear improvements across all tested mechanical parameters, demonstrating its viability for geotechnical applications. The enhanced CBR suggests improved load distribution for subgrade layers; UCS improvements indicate increased compressive resistance, critical for sub base and embankment design; and ITS enhancements reflect better crack resistance in pavement layers.

These findings have significant implications for sustainable infrastructure: using PSA as a partial replacement or supplement to cement reduces environmental impact, valorizes marine waste, and provides cost-effective soil improvement (Adeyemi, et al., 2015; Oke et al., 2022). Furthermore, the statistically robust evaluation of mechanical properties provides a strong foundation for reliability-based mix design optimization, enabling engineers to select optimal PSA-cement proportions under probabilistic safety constraints.

4. Conclusions

This study investigated the mechanical performance of lateritic soil stabilized with cement-Periwinkle Shell Ash (PSA) blends through laboratory experimentation and computational data analysis. The key findings are:

I. PSA-cement stabilization significantly improves the bearing, compressive, and tensile strength properties of lateritic soils.

II. CBR values ranged from 24.6% to 78.6%, UCS from 1.2 MPa to 6.0 MPa, and ITS from 0.3 MPa to 1.5 MPa, with moderate variability and symmetric distributions across all properties.

III. MATLAB-based visualization techniques effectively capture variability and central tendencies, aiding in interpretation of soil mechanical behavior.

IV. The stabilized soils exhibit consistent performance, indicating suitability for pavement and general geotechnical applications.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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