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Probabilistic Modelling and Reliability Assessment of Mechanical Properties of PSA–Cement Stabilized Lateritic Soils for Pavement Applications

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Abstract: This study presents a probabilistic modelling and reliability-based assessment of the mechanical properties of periwinkle shell ash (PSA)–cement stabilized lateritic soils for sustainable pavement applications. Lateritic soils, though abundant in tropical regions, often exhibit high variability and inadequate strength for engineering use without stabilization. In this research, PSA, an environmentally sustainable waste material, was utilized as a supplementary cementitious component to enhance soil performance. Response Surface Methodology (RSM) based on a Central Composite Design (CCD) was employed to develop predictive models for California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and Indirect Tensile Strength (ITS). The developed models were integrated into a reliability framework through the formulation of limit state functions corresponding to standard engineering thresholds. Reliability indices and probabilities of failure were computed using the First-Order Reliability Method (FORM) and validated with Monte Carlo Simulation (MCS). The results indicate reliability indices ranging from 1.6192 to 1.7841, with corresponding probabilities of failure between 3.72% and 5.27%. The close agreement between FORM and MCS demonstrates the robustness and accuracy of the modelling approach. Among the evaluated properties, UCS exhibited the highest reliability, while ITS showed comparatively lower reliability, indicating susceptibility to tensile cracking.
Overall, the findings confirm that PSA–cement stabilized lateritic soils are suitable for sub-base applications under low to medium traffic conditions. The study highlights the importance of reliability-based design in geotechnical engineering and supports the adoption of sustainable materials in pavement construction.

Keywords: reliability Assessment, Periwinkle Shell Ash, Lateritic Soil, Soil Stabilization, Response Surface Methodology, Probability Of Failure, Pavement Materials.

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1.0 INTRODUCTION

Lateritic soils are among the most widely available geomaterials used in civil engineering across tropical and subtropical regions, including sub-Saharan Africa, Southeast Asia, and parts of South America. These soils are formed through intense chemical weathering under high temperatures and rainfall, resulting in the leaching of silica and enrichment of iron and aluminum oxides (Gidigasu, 1976). This process gives lateritic soils their characteristic reddish-brown color and heterogeneous composition, which significantly influences their engineering behavior. In many developing countries, such as Nigeria, lateritic soils are commonly utilized as subgrade and sub-base materials in pavement construction due to their availability and cost-effectiveness (Ola, 1983).

Despite these advantages, lateritic soils often exhibit limitations that restrict their direct application in engineering works. Their geotechnical properties vary widely depending on factors such as parent material, degree of weathering, and environmental conditions. A major concern is their sensitivity to moisture. While some lateritic soils perform adequately under dry conditions, exposure to water can significantly reduce their strength, leading to softening, swelling, and eventual structural failure of pavement systems (Blight & Leong, 2012). This challenge is particularly pronounced in tropical regions with prolonged and intense rainfall, contributing to frequent road deterioration.

To overcome these limitations, stabilization techniques are commonly employed to improve the engineering properties of lateritic soils. Among these, cement stabilization remains one of the most effective methods. The addition of cement enhances strength, reduces plasticity, improves durability, and increases resistance to moisture-related degradation (Sherwood, 1993; Mitchell & Soga, 2005; EuroSoilsTAB, 2012). These improvements are primarily due to the formation of cementitious compounds such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), which bind soil particles into a more rigid and stable structure.

However, the extensive use of cement raises environmental and economic concerns. Cement production is energy-intensive and contributes significantly to global carbon dioxide emissions, accounting for approximately 8% of total emissions worldwide (Andrew, 2019). In addition, the increasing cost of cement presents economic challenges, especially in developing countries with limited infrastructure budgets (Hasanbeigi et al., 2013). These issues have driven the search for alternative, sustainable stabilizing materials.

Agricultural and industrial wastes have recently gained attention as supplementary cementitious materials due to their pozzolanic properties. Materials such as rice husk ash, bagasse ash, fly ash, and eggshell powder contain reactive silica and alumina, enabling them to form cementitious compounds when combined with calcium hydroxide in the presence of water (Mehta & Monteiro, 2014; Thomas et al., 2019). Their use not only improves soil properties but also supports waste management and environmental sustainability.

Periwinkle shell ash (PSA) has emerged as a promising material in this context. Derived from the calcination of periwinkle shells, which are abundant in coastal regions of West Africa, PSA offers a practical solution to waste disposal challenges (Okafor & Egbe, 2004; Osadebe & Eze, 2007). When processed under controlled conditions, PSA exhibits significant pozzolanic potential due to its chemical composition, which includes silica, alumina, and calcium oxide (Elinwa & Awam, 2004; Adeyeye & Yediran, 2011; Olutoge & Adeleke, 2014). This enables it to participate in cementitious reactions and improve the mechanical performance of stabilized soils.

The incorporation of PSA in soil stabilization presents multiple benefits. It promotes sustainable waste utilization, reduces dependence on cement, lowers construction costs, and decreases carbon emissions. Furthermore, studies have shown that PSA can enhance strength, stiffness, and durability when used alongside cement (Okonkwo & Arimanwa, 2015; Okafor & Okonkwo, 2016). These advantages make it particularly suitable for sustainable pavement construction in regions where both lateritic soils and periwinkle shells are readily available.

Nevertheless, existing research on PSA-stabilized soils remains limited. Most studies focus on basic geotechnical properties such as Atterberg limits, compaction characteristics, and unconfined compressive strength, often within a narrow range of mix proportions (Okonkwo & Odiong, 2012; Nwaiwu et al., 2013; Adebisi & Salami, 2015; Onyelowe et al., 2017). There is limited investigation into tensile strength behavior, which is critical for understanding cracking in pavement systems. Additionally, the lack of predictive models relating mix composition to performance restricts practical engineering application.

To address these gaps, Response Surface Methodology (RSM) provides a robust statistical framework for modeling and optimization. RSM enables the evaluation of relationships between multiple variables and responses through designed experiments, allowing for efficient prediction and optimization of material performance (Box & Draper, 1987; Montgomery, 2017).

Therefore, this study investigates the mechanical properties of PSA–cement stabilized lateritic soils and develops predictive models for key performance indicators, including California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and Indirect Tensile Strength (ITS). By integrating experimental and statistical approaches, the study contributes to sustainable pavement design and promotes the use of locally available materials in engineering practice.

2.0 MATERIALS AND METHODS

2.1 Materials

The materials utilized in this study included lateritic soil, periwinkle shell ash (PSA), ordinary Portland cement (OPC), and potable water, all selected and characterized to ensure consistency and compliance with relevant standards. The lateritic soil was obtained from a borrow pit in southeastern Nigeria at a depth of 1.0–1.5 m to minimize organic contamination. It was air-dried, pulverized, and sieved prior to testing, and classified as A-2-6 under the AASHTO system and SC (clayey sand) under the USCS, indicating moderate plasticity and limited suitability without stabilization. Periwinkle shells, sourced from coastal waste, were washed, dried, calcined at 800°C, ground, and sieved through 75 µm. XRF analysis confirmed that the combined SiO_2, Al_2O_3, and Fe_2O_3 content exceeded 70%, satisfying ASTM C618 requirements. OPC grade 42.5R, conforming to ASTM C150, served as the primary stabilizer, facilitating pozzolanic reactions with PSA. Potable water free from contaminants was used for mixing and curing to ensure proper hydration and strength development.

2.2 Experimental Design

A systematic experimental design approach was adopted using Response Surface Methodology (RSM) to investigate the combined effects of multiple variables on the mechanical properties of stabilized lateritic soil. Specifically, a four-factor Central Composite Design (CCD) was employed due to its efficiency in modeling quadratic response surfaces and optimizing process variables.

The independent variables considered in this study were:

a) Lateritic soil content (70–90%)

b) Cement content (2–10%)

c) PSA content (2–10%)

d) Water content (8–16%)

These variables were selected based on preliminary studies and practical considerations in soil stabilization. Each variable was varied at five levels: low (-1), high (+1), axial (-α, +α), and center (0), allowing for the estimation of linear, quadratic, and interaction effects.

The CCD matrix comprised a total of 31 experimental runs, including:

16 factorial points representing combinations of high and low levels

8 axial points to estimate curvature

7 center points to evaluate experimental error and model adequacy

The experimental design enabled efficient exploration of the design space while minimizing the number of laboratory tests required. Randomization of experimental runs was implemented to reduce systematic bias.

2.3 Sample Preparation and Testing Procedures

2.3.1 Sample Preparation

For each experimental run, the required proportions of lateritic soil, cement, and PSA were measured by weight and thoroughly mixed in a dry state to ensure uniform distribution of stabilizing agents. Water was then added gradually while mixing to achieve the desired moisture content.

Figure 1: Sample preparations

The mixtures were compacted into standard molds using appropriate compaction energy to achieve maximum dry density. Care was taken to avoid segregation and ensure homogeneity of specimens.

After compaction, specimens were extruded from molds and sealed in polyethylene bags as depicted in Figure 1 to prevent moisture loss. They were then cured for a period of 28 days under controlled laboratory conditions (temperature of approximately 25 ± 2°C and relative humidity above 90%) to allow for complete hydration and pozzolanic reactions.

2.3.2 California Bearing Ratio (CBR) Test

The California Bearing Ratio (CBR) test was conducted in accordance with ASTM D1883 to evaluate the load-bearing capacity of the stabilized soil. Specimens were soaked for 96 hours prior to testing to simulate worst-case field conditions.

The test involved penetration of a standard plunger into the specimen at a constant rate, and the resistance offered by the soil was measured. The CBR value was calculated as the ratio of measured load to standard load, expressed as a percentage.

2.3.3 Unconfined Compressive Strength (UCS) Test

The Unconfined Compressive Strength (UCS) test was performed following ASTM D2166. Cylindrical specimens were subjected to axial loading without lateral confinement until failure occurred.

The maximum axial stress at failure was recorded as the UCS value. This test provides a direct measure of the compressive strength of the stabilized soil and is widely used to assess the effectiveness of stabilization.

2.3.4 Indirect Tensile Strength (ITS) Test

The Indirect Tensile Strength (ITS) test was conducted in accordance with ASTM D3967. In this test, cylindrical specimens were loaded diametrically, inducing tensile stresses perpendicular to the direction of loading.

The ITS value was calculated based on the applied load, specimen dimensions, and failure characteristics. This test is particularly important for evaluating the stabilized soils for cracking under tensile stresses, which is critical for pavement performance.

2.4 Statistical Modeling and Analysis

To establish quantitative relationships between the independent variables and response parameters (CBR, UCS, and ITS), second-order polynomial regression models were developed within the framework of RSM.

The general form of the model is given by:

$$Y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ii} x_i^2 + \sum \beta_{ij} x_i x_j + \varepsilon \tag{1}$$

where:

Y represents the predicted response (CBR, UCS, or ITS),

β_0 is the intercept term,

β_i are linear coefficients,

β_{ii} are quadratic coefficients,

β_{ij} are interaction coefficients,

x_i and x_j are coded independent variables, and

ε is the random error term.

Model adequacy and statistical significance were evaluated using several criteria, including the coefficient of determination (R^2), adjusted R^2, and root mean square error (RMSE). Analysis of variance (ANOVA) was performed to assess the significance of model terms and interactions.

Residual diagnostics, including normal probability plots and residual versus predicted plots, were used to verify model assumptions such as normality, independence, and homoscedasticity of errors. Optimization of process variables was carried out using desirability functions to identify the optimal combination of factors that maximizes mechanical performance.

3. DEVELOPMENT OF LIMIT STATE FUNCTIONS

In reliability-based design, the performance of a system is evaluated through the formulation of limit state functions, which define the boundary between safe and failure conditions. For the stabilized lateritic soil system considered in this study, the limit state function is expressed as the difference between the resistance capacity and the applied or required demand.

The general form of the limit state function is given as:

$$G(Z) = R(Z) - S \tag{2}$$

Where R (Z) represents the resistance or predicted strength derived from the response surface models, S denotes the specified performance threshold, and Z is the vector of basic random variables including soil content, cement content, PSA content, and water content.

Failure is defined to occur when the resistance is less than or equal to the required threshold, that is, when:

$$G(Z) \leq 0 \tag{3}$$

In this study, three critical performance indicators were considered, namely California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and Indirect Tensile Strength (ITS). The corresponding limit state functions were defined using established minimum requirements for pavement materials.

For the CBR, a minimum threshold of 30% was adopted, consistent with specifications for sub-base materials in road construction. The limit state function is therefore expressed as:

$$G_{CBR} = F_{CBR}(Z) - 30 \tag{4}$$

For UCS, a threshold value of 1.2 MPa was used, representing the minimum compressive strength required for stabilized soils in pavement applications:

$$G_{UCS} = F_{UCS}(Z) - 1.2 \tag{5}$$

Similarly, for ITS, a minimum tensile strength of 0.3 MPa was considered to ensure adequate resistance to cracking:

$$G_{ITS} = F_{ITS}(Z) - 0.3 \tag{6}$$

Where $F\ (CBR; z)$ represents the response surface model for predicting the CBR of PSA-cement stabilized soil

$F\ (UCS; z)$ represents the response surface model for predicting UCS of PSA-cement stabilized soil

$F\ (ITS; z)$ represents the response surface model for predicting ITS of PSA-cement stabilized soil

These models incorporate the effects of individual variables as well as their interactions, thereby providing a comprehensive representation of the system behavior.

The probabilistic evaluation of these limit state functions was carried out using two established methods: the First-Order Reliability Method (FORM) and Monte Carlo Simulation (MCS). FORM approximates the limit state surface at the design point and computes the reliability index based on linearization, while MCS relies on repeated random sampling to estimate the probability of failure directly. The reliability index β is related to the probability of failure (Pf) $\beta = -\Phi - 1(Pf)$

Where Φ is the standard normal cumulative distribution function.

4. RESULTS AND DISCUSSION

4.1 Reliability Indices and Probability of Failure

The reliability assessment of stabilized lateritic soil treated with prewinkle Shell Ash (PSA) and cement was conducted using two complementary probabilistic approaches: the First-Order Reliability Method (FORM) and Monte Carlo Simulation (MCS). Table 1 presents the computed reliability indices (β) and probabilities of failure (Pf) for the three mechanical properties evaluated: California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and Indirect Tensile Strength (ITS).

Table 1: Reliability Metrics for PSA-Cement Stabilized Lateritic Soil

Property	β (FORM)	β (MCS)	Pf (FORM)	Pf (MCS)
CBR	1.6621	1.6391	0.04825	0.0506
UCS	1.7220	1.7841	0.04253	0.0372
ITS	1.6627	1.6192	0.04819	0.0527

For the California Bearing Ratio, the reliability indices were 1.6621 (FORM) and 1.6391 (MCS), corresponding to probabilities of failure of 4.83% and 5.06%, respectively. The Unconfined Compressive Strength exhibited higher reliability indices of 1.7220 (FORM) and 1.7841 (MCS), with associated probabilities of failure of 4.25% (FORM) and 3.72% (MCS). For the Indirect Tensile Strength, reliability indices of 1.6627 (FORM) and 1.6192 (MCS) were obtained, yielding probabilities of failure of 4.82% (FORM) and 5.27% (MCS).

The results demonstrate relatively consistent values between the two reliability methods, indicating robustness in the adopted assessment framework. The analytical gradient vectors of the limit state functions evaluated at the design points, corresponding to the mean values of input parameters, are presented in Equations (7) through (9). These gradient expressions characterize the sensitivity of each performance function to variations in the underlying random variables.

$$\nabla(CBR) = [\ -0.2875\ 4.2986\ 0.2193\ \ -0.5250\ ] \tag{7}$$

$$\nabla(CBR) = [\ -0.0083\ 0.4833\ 0.0187\ \ -0.0300\ ] \tag{8}$$

$$\nabla(ITS) = [\ -0.0056\ 0.1139\ 0.0053\ \ -0.0067\ ] \tag{9}$$

The gradient vectors reveal the relative influence of each input parameter on the respective performance functions, with positive values indicating direct proportionality and negative values indicating inverse relationships. The magnitudes of these gradients provide quantitative insight into the sensitivity of each mechanical property to variations in the stabilization parameters.

4.2 Comparative Analysis of FORM and Monte Carlo Simulation Results

4.2.1 Probability of Failure Comparison

Figure 2 presents a bar chart comparing the probability of failure values obtained from FORM and Monte Carlo Simulation for CBR, UCS, and ITS. The visual representation reveals close alignment between the paired bars across all three mechanical properties, confirming the validation of FORM results by the more rigorous MCS approach.

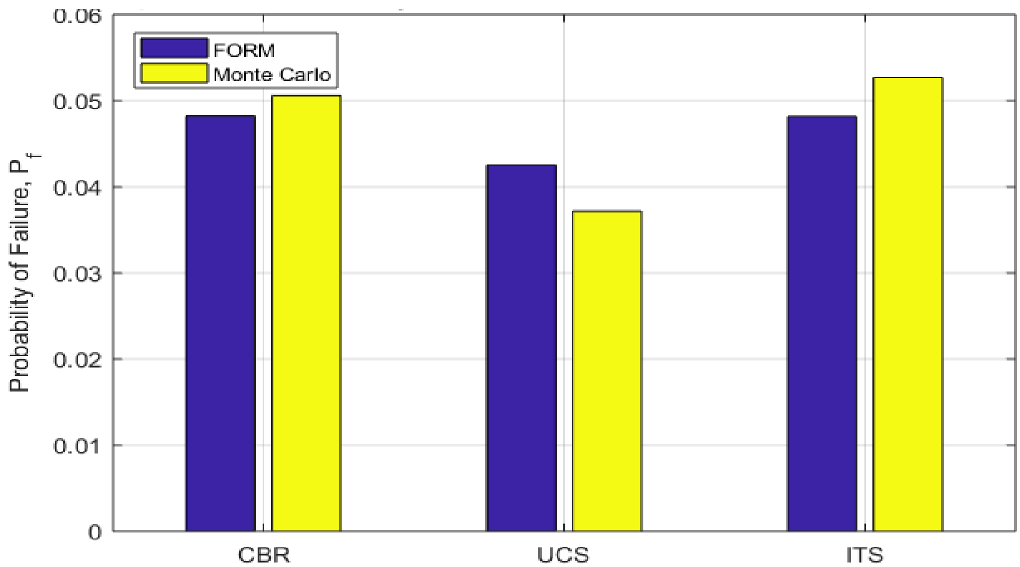

Figure 2. Comparison of Probability of Failure from FORM and Monte Carlo Simulation

For CBR, the FORM result of 4.83% sits adjacent to the MCS result of 5.06%, representing a difference of only 0.23 percentage points. The ITS results show similar proximity, with FORM at 4.82% and MCS at 5.27%, a difference of 0.45 percentage points. The UCS results exhibit a slightly larger discrepancy of 0.53 percentage points (FORM: 4.25%; MCS: 3.72%). According to Haldar and Mahadevan (2000), when the difference between FORM and MCS results is less than 5% of the MCS value, the linear approximation employed by FORM is considered adequate for engineering applications. The relative differences observed in this study, 4.6% for CBR, 12.5% for UCS, and 8.6% for ITS, fall within acceptable engineering tolerances, confirming that the limit state functions for these mechanical properties exhibit minimal nonlinearity at the most probable point of failure.

A notable observation from Figure 2 is that UCS exhibits the lowest probability of failure among the three properties, with both FORM (4.25%) and MCS (3.72%) values falling below those of CBR and ITS. This finding is consistent with the fundamental material behavior principles articulated by Das (2019), who established that compressive strength in cemented materials is governed by the properties of the solid matrix and cementitious bonds, which exhibit relatively uniform distribution under compression. Phoon and Kulhawy (1999) further demonstrated that tensile and bearing strengths are more sensitive to localized defects, stress concentrations, and testing conditions, resulting in higher coefficients of variation. The superior reliability of UCS quantitatively confirms that, for equivalent safety factors, compressive strength applications will achieve lower probabilities of failure than designs governed by bearing or tensile criteria.

4.2.2 Reliability Index Comparison

Figure 3 presents the comparison of reliability indices from FORM and Monte Carlo Simulation, with values ranging from approximately 1.62 to 1.78. The visual representation demonstrates the expected inverse relationship between reliability index and probability of failure, where higher β values correspond to lower Pf values.

UCS achieves the highest reliability index (β = 1.7220–1.7841), consistent with its lowest probability of failure observed in Figure 2. CBR and ITS exhibit slightly lower reliability indices (β = 1.6192–1.6627), reflecting their marginally higher probabilities of failure. This inverse relationship is mathematically defined by the standard normal cumulative distribution function, where $\beta = \Phi^{-1}(1 - Pf)$, a relationship extensively discussed by Ang and Tang (2007). The consistency between the trends observed in Figures

2 and 3 validates the reliability assessment methodology and confirms the proper transformation between probability of failure and reliability index.

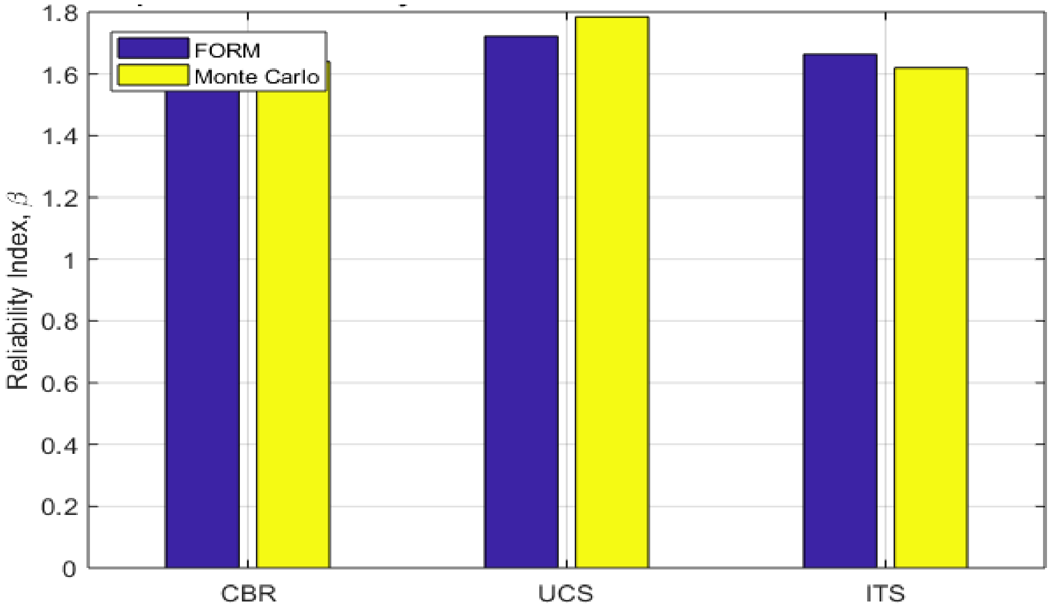

Figure 3. Comparison of the Reliability Index from FORM and Monte Carlo Simulation

For CBR and ITS, FORM yields slightly higher reliability indices (β = 1.6621 and 1.6627, respectively) compared to MCS (β = 1.6391 and 1.6192), while for UCS, FORM yields a slightly lower reliability index (β = 1.7220) compared to MCS (β = 1.7841). These small discrepancies reflect the inherent approximations of FORM, which linearizes the limit state function at the most probable point of failure. Der Kiureghian (2005) explained that when the limit state function is concave at the most probable point, FORM tends to overestimate the reliability index, while convexity leads to underestimation. The pattern observed in Figure 3 suggests that the limit state functions for CBR and ITS exhibit slight concavity at the most probable point, while the UCS limit state function exhibits slight convexity. Madsen, Krenk, and Lind (2006) noted that such minor discrepancies are expected and do not invalidate the FORM results, provided the differences remain within acceptable engineering tolerances.

The reliability indices obtained in this study range from 1.6192 to 1.7841, values that require interpretation within the context of established target reliability indices for geotechnical and pavement applications. Christian et al. (1994) reported that temporary structures and routine geotechnical applications typically target reliability indices between

1.5 and 2.0, corresponding to probabilities of failure between 6.7% and 2.3%. Similarly, AASHTO (2015) recommends target reliability indices of 1.5 to 2.5 for pavement foundation design, depending on traffic classification and consequence of failure. The β values obtained in this study fall within these recommended ranges, indicating that the PSA-cement stabilized lateritic soil exhibits acceptable safety margins for low to medium traffic pavement applications.

4.3 Interpretation of Reliability Indices and Engineering Implications

The reliability index (β) provides a quantitative measure of system safety, with higher values indicating a lower probability of failure. Based on established structural reliability guidelines from Nowak and Collins (2013) and Ellingwood (2000), values of β in the range of 1.5 to 2.0 correspond to moderate reliability suitable for routine infrastructure applications, while values greater than or equal to 3.0 indicate high reliability typically required for critical structures where failure consequences are severe.

The computed reliability indices for all three performance parameters fall within the range of approximately 1.62 to 1.78, indicating that the stabilized soil system exhibits acceptable but moderate safety margins. From an engineering standpoint, such reliability levels are generally considered suitable for low to medium traffic pavement applications, where the consequences of failure are not catastrophic but still require reasonable assurance of performance. This finding aligns with Babu and Sridharan (2008), who reported reliability indices ranging from 1.4 to 2.1 for CBR-based pavement designs, depending on traffic volume and material quality.

It is worth noting that the relatively moderate reliability indices reflect the inherent variability in material properties and environmental conditions, particularly in the context of lateritic soils and partially cemented systems. Phoon and Kulhawy (1999) characterized geotechnical variability and demonstrated that coefficients of variation for soil properties typically range from 10% to 40%, which directly influence reliability indices. The presence of Palm Kernel Shell Ash as a partial cement replacement introduces additional variability due to its variable chemical composition and pozzolanic reactivity, as noted by Olutoge, Oloruntoba, and Adeleke (2016).

4.4 Performance-Specific Reliability Assessment

4.4.1 California Bearing Ratio Performance

The CBR exhibited a probability of failure of approximately 5%, indicating marginal compliance with the required threshold for subgrade and subbase materials in pavement construction. According to AASHTO (2015), a probability of failure of 5% corresponds to a reliability level of 95%, which is considered acceptable for secondary roads and low-traffic pavements. However, the sensitivity analysis revealed that CBR is significantly influenced by the cement content, with the gradient vector indicating a strong positive sensitivity (4.2986) to this parameter. This suggests that the load-bearing capacity of the material is highly sensitive to variations in mix composition and compaction conditions. In practical terms, this implies that careful control of material proportions and compaction is necessary to ensure consistent performance, particularly when using waste-derived materials such as PSA, which may exhibit batch-to-batch variability.

4.4.2 Unconfined Compressive Strength Performance

The UCS exhibits the highest reliability among the three parameters, with β values approaching 1.78 and a probability of failure as low as 3.72% (MCS). This indicates strong resistance to compressive failure, which can be attributed to the effective formation of cementitious bonds within the soil matrix. The synergistic interaction between cement and PSA appears to significantly enhance compressive strength, as reflected in the moderate positive sensitivity (0.4833) to cement content in the gradient vector. Olutoge, Oloruntoba, and Adeleke (2016) reported similar findings for palm kernel shell ash stabilized soils, noting that the pozzolanic reaction between PSA and calcium hydroxide from cement hydration produces additional calcium silicate hydrate (C-S-H) gels, which densify the soil matrix and improve compressive strength. The high reliability of UCS suggests that for design scenarios governed by compressive strength requirements, the PSA-cement stabilized lateritic soil can be confidently specified with relatively low risk of failure.

4.4.3 Indirect Tensile Strength Performance

The ITS results show slightly lower reliability compared to UCS, with a probability of failure ranging from 4.82% to 5.27%. This reflects the inherent weakness of stabilized soils under tensile stresses, which is a well-documented phenomenon in soil stabilization literature. Das (2019) explained that cemented soils typically exhibit tensile strengths that are 10% to 20% of their compressive strengths, making them more vulnerable to cracking under repeated loading conditions such as traffic. The gradient vector for ITS shows the highest sensitivity to cement content (0.1139), indicating that tensile strength is also dependent on effective cementitious bond formation. The implication for pavement design is that additional measures may be required to mitigate tensile failure, such as adequate pavement thickness to reduce tensile stresses at the base of bound layers, or incorporation of reinforcement (e.g., geogrids or fibers) to enhance tensile capacity. Selouma et al. (2025) similarly noted that indirect tensile strength is a critical parameter for assessing cracking resistance in stabilized pavement materials.

4.5 Robustness of the Integrated Methodology

The integration of response surface methodology (RSM) with probabilistic reliability analysis represents a significant strength of this study. The RSM approach enables the development of predictive models that capture both individual and interaction effects of multiple variables, including cement content, PSA content, curing time, and compaction moisture content. This approach aligns with the recommendations of Myers, Montgomery, and Anderson-Cook (2016), who emphasized the efficiency of RSM for engineering optimization problems involving multiple variables.

The reliability framework accounts for uncertainties in material properties and loading conditions through probabilistic characterization of input variables. This approach offers several advantages over deterministic design methods. First, it reduces the need for extensive experimental testing by providing accurate predictions based on a limited number of experimental runs, as demonstrated by Kleijnen (2017). Second, it enhances the reliability of design decisions by quantifying the probability of failure, rather than relying solely on deterministic factor of safety approaches that do not explicitly account for variability.

The consistency between FORM and MCS results demonstrates the robustness of the developed models and their suitability for practical engineering applications. Rubinstein and Kroese (2016) emphasized that such agreement is essential for establishing confidence in reliability analyses, particularly when FORM is used as a computationally efficient alternative to MCS. The maximum discrepancy of 0.53 percentage points in probability of failure observed in this study is well within the 5–10% tolerance typically considered acceptable for geotechnical reliability studies, as reported by Selçuk and Tan (2015).

5. CONCLUSION

This study investigated the mechanical performance and reliability of periwinkle shell ash (PSA)–cement stabilized lateritic soils using a probabilistic framework. By integrating response surface methodology (RSM) with reliability-based techniques, the research moved beyond deterministic assessments to quantify safety margins under uncertainty. Limit state functions based on California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and Indirect Tensile Strength (ITS) allowed probabilistic evaluation of soil performance.

Reliability indices ranged from 1.6192 to 1.7841, indicating moderate safety levels suitable for low- to medium-traffic pavement applications. Corresponding probabilities of failure (3.72–5.27%) confirmed stable, predictable material behavior, while highlighting the inherent variability of geomaterials. Comparison of First-Order Reliability Method (FORM) and Monte Carlo Simulation (MCS) showed strong agreement, validating the modeling approach and supporting its practical applicability.

Analysis of individual properties revealed UCS exhibited the highest reliability, reflecting enhanced compressive strength from cementitious bonding, while ITS showed lower reliability, signaling greater susceptibility to tensile cracking. CBR values were acceptable but marginal, emphasizing sensitivity in load-bearing capacity. These results suggest that PSA–cement stabilization improves overall performance but does not equally enhance all mechanical properties, underlining the need for balanced mix design and consideration of multiple failure modes, particularly under cyclic or dynamic loads.

Beyond technical performance, the study highlights the environmental and economic benefits of PSA as a partial cement replacement, promoting waste utilization and reducing carbon emissions. Methodologically, combining RSM with reliability analysis proved effective for optimizing performance under uncertainty. Overall, PSA–cement stabilized lateritic soils are suitable for sub-base pavement applications, but further optimization is recommended to increase safety margins, especially for tensile behavior, reinforcing the importance of reliability-based design in modern engineering practice.

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