Strength and Durability Modelling of Lateritic Soil Treated with Sustainable Pozzolanic Additives

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Abstract
This study explores the effectiveness of Rice Husk Ash (RHA) and Cement Kiln Dust (CKD) as sustainable stabilizing agents for improving the geotechnical properties of lateritic soil from Guwahati, Assam. Laboratory tests were conducted to evaluate changes in shear strength, permeability, consolidation characteristics, and pH across different RHA-CKD combinations and curing periods (7, 14, and 28 days). The results demonstrated significant improvements in shear strength (up to 95 kN/m²) and substantial reductions in permeability (to as low as 1.69×10^{-5} cm/s), particularly with the 15% RHA and 9% CKD mix. The pozzolanic interaction between RHA and CKD led to the formation of cementitious compounds, which improved particle bonding and pore structure. pH measurements confirmed a shift from acidic to optimal alkaline conditions conducive to long-term stabilization. Durability tests, including wet-dry and freeze-thaw cycles, showed excellent retention of mass and strength, indicating the stabilized soil's resilience under cyclic environmental loading. Comparative analysis with conventional stabilizers highlighted RHA and CKD's advantages in terms of environmental impact, waste valorization, and contribution to the circular economy. The study concludes that RHA and CKD can serve as efficient, low-cost, and eco-friendly alternatives to cement and lime, with promising potential for application in sustainable infrastructure projects.

Keywords: Rice husk ash, Cement kiln dust, Shear strength, Permeability, Correlation and Statistical Interpretation

1 INTRODUCTION

Lateritic soils are weathered soil types that originate from the decomposition of underlying parent rocks in tropical and subtropical climates. These soils are typically rich in iron and aluminium oxides, giving them a distinct red or brownish hue. They are widespread in parts of Asia, Africa, and South America and are particularly abundant in northeastern India, including Guwahati. Guwahati's hot, humid, and rainy climate provides the ideal conditions for the laterization process, which is characterized by intense leaching and chemical weathering (Gautam & Bhowmik, 2023). Despite their initial appearance as construction-friendly materials when dry, lateritic soils are highly problematic in geotechnical applications due to their sensitivity to moisture, low shear strength, high compressibility, and fluctuating permeability (Abhishek et al., 2024).

In civil engineering, these undesirable characteristics pose considerable risks, especially in areas prone to high rainfall. Structural failures, slope instability, and pavement deterioration are common consequences of using untreated lateritic soils in construction projects. To address these limitations, soil stabilization techniques are widely adopted. Traditional stabilizers such as cement and lime have long been used to improve soil strength and performance. However, their environmental drawbacks—namely, high energy consumption and substantial carbon emissions—necessitate the search for sustainable alternatives (Attah et al., 2021).

With the global movement towards sustainable construction practices, attention has turned to industrial and agricultural by-products as eco-friendly soil stabilizers. Among these, Rice Husk Ash (RHA) and Cement Kiln Dust (CKD) have shown considerable promise. RHA is a by-product of rice milling that, when burned under controlled conditions, yields a silica-rich ash. Its high amorphous silica content endows it with strong pozzolanic activity, enabling it to form cementitious compounds when combined with calcium-rich additives such as lime or CKD (Abhishek et al., 2024). CKD, on the other hand, is a fine by-product generated during the manufacturing of Portland cement. It contains high levels of calcium oxide and alkalis and exhibits strong binding and stabilizing capabilities (Domphoeun et al., 2025).

The chemical synergy between RHA and CKD makes them excellent candidates for blended use in soil stabilization. While RHA supplies reactive silica, CKD contributes free lime, and together they form stable compounds like calcium silicate hydrates (C-S-H), which improve the mechanical behavior of soils. This study seeks to explore the combined application of RHA and CKD to stabilize lateritic soil collected from Guwahati, with an emphasis on enhancing its geotechnical characteristics such as shear strength, permeability, and consolidation behaviour.

Furthermore, the long-term performance of stabilized soil is a critical factor in assessing its viability in real-world conditions. This research incorporates durability testing under simulated environmental stressors such as wet-dry and freeze-thaw cycles, which closely mimic field conditions in regions like Assam that experience heavy monsoons and temperature fluctuations. These tests aim to evaluate how well the treated soil retains its structural integrity and strength over time.

In addition to mechanical and chemical assessments, this study also investigates the environmental and sustainability implications of using RHA and CKD. Their use supports waste valorisation, reduces the reliance on carbon-intensive traditional stabilizers, and contributes to circular economy principles. Despite their proven benefits in separate studies, the combined effect of RHA and CKD on lateritic soils in the North-Eastern Indian context remains underexplored. This research aims to fill that gap by presenting a comprehensive evaluation of their performance in stabilizing local soil, thereby contributing to more resilient, cost-effective, and eco-friendly construction practices in the region.

2 MATERIAL AND METHODS

Lateritic soil**,** Rice husk ash (RHA), and cement kiln dust (CKD) was carefully sourced and prepared to ensure consistency in experimental testing and to reflect typical field conditions.

The lateritic soil was collected from selected locations in Guwahati, Assam, an area known for its extensive laterite deposits. This soil is rich in iron and aluminum oxides, has a specific gravity of 2.65, an optimum moisture content (OMC) of 21%, and a maximum dry density (MDD) of 1.65 g/cm^3. Prior to use, the soil samples were air-dried and sieved through a 4.75 mm sieve to remove coarse particles and organic debris.

RHA was obtained from a local rice mill, where rice husks were burned under controlled conditions to yield a fine ash. The RHA is high in amorphous silica and exhibits strong pozzolanic properties. To enhance uniformity and reactivity, the RHA was sieved through a 75 µm sieve before blending with the soil.

CKD was sourced from the locally available Cement Plant. This material, a by-product of the cement manufacturing process, is rich in calcium oxide, silica, alumina, and alkalis. Its specific gravity is approximately 2.74. Like the RHA, CKD was also sieved through a 75 µm mesh to achieve a fine and reactive particle size suitable for soil stabilization.

The soil samples used in this study were prepared by blending lateritic soil with varying proportions of RHA and CKD. The primary objective was to assess the individual and combined effects of these stabilizers on the geotechnical and durability characteristics of the soil. The lateritic soil was mixed with five different percentages of RHA (5%, 10%, 15%, 20%, and 25%) and five different percentages of CKD (3%, 6%, 9%, 12%, and 15%). These ranges were selected based on literature recommendations indicating improved performance at moderate dosages. The mixtures were designed to determine the optimal combination that yields maximum enhancement in shear strength, consolidation behavior, permeability, and durability. The prepared samples were cured for 7, 14, and 28 days to capture the time-dependent behavior of pozzolanic reactions. To evaluate long-term field performance, selected samples underwent wet-dry and freeze-thaw cycles, simulating seasonal environmental fluctuations common in tropical and subtropical climates. The wet-dry cycles aimed to mimic moisture-induced expansion and shrinkage, while freeze-thaw cycles tested the soil's resistance to internal stresses caused by ice formation. Mass loss, strength degradation, and visible deterioration were monitored to assess durability.

A series of laboratory tests were conducted on the stabilized samples. Shear Strength is measured using the direct shear test on samples compacted at optimum moisture content and cured for 7, 14, and 28 days to evaluate bearing capacity improvements. Falling head tests were performed to determine water flow characteristics, which are crucial for assessing drainage and erosion control. The pH of soil-water mixtures was recorded at different curing stages to track chemical stability and ongoing pozzolanic reactions between soil and stabilizers. Samples subjected to durability cycles were monitored for mass loss, strength retention, surface cracking, and structural degradation. These indicators revealed how well the stabilized soil could withstand environmental stress. The study adopted a factorial experimental design, with controlled variation of RHA and CKD percentages, curing durations, and environmental exposures. Each factor's influence was systematically assessed through performance metrics.

Descriptive statistics were used to summarize test outcomes. Analysis of Variance (ANOVA) was applied to determine the statistical significance of various factors on soil behavior. Regression analysis was employed to model the relationships between stabilizer ratios and geotechnical properties. Durability test outcomes were evaluated to determine strength retention and degradation resistance. Lastly, the environmental benefits of RHA and CKD use—such as reduced carbon footprint and waste valorization—were discussed in comparison to conventional stabilizers.

3 RESULTS AND DISCUSSION OF LABORATORY INVESTIGATIONS

3.1 Shear Strength Behavior

The development of shear strength over time for lateritic soil treated with varying proportions of RHA and CKD demonstrates a significant improvement compared to untreated soil, primarily due to the activation of pozzolanic reactions. The results presented in Table 1 clearly reflect the progressive enhancement of shear strength across all curing periods—7, 14, and 28 days—with increasing dosage of RHA and CKD up to an optimum level.

Table 1 Shear Strength development over time with different RHA-CKD combinations

RHA (%)	CKD (%)	Shear Strength (kN/m²)			Pozzolanic Reaction Effect
		7 days	14 days	28 days	
0 (Untreated)	0	45	45	45	None
5	3	58	65	72	Moderate
10	6	68	78	89	Strong
15	9	75	86	95	Strongest
20	12	70	82	91	Strong
25	15	65	77	85	Moderate (over-dosage effect)

Untreated soil maintained a constant shear strength of 45 kN/m² over all curing periods, indicating a lack of any strength development over time in the absence of stabilizing agents. Upon stabilization with 5% RHA and 3% CKD, the shear strength increased to 58 kN/m² at 7 days and reached 72 kN/m² at 28 days, showing the initial effectiveness of even low levels of admixture. This early improvement can be attributed to the initiation of pozzolanic reactions between calcium from CKD and reactive silica from RHA, forming cementitious compounds that enhance bonding among soil particles.

As the proportion of stabilizers increased to 10% RHA and 6% CKD, the shear strength continued to rise to 89 kN/m² by 28 days. This result reflects a more robust pozzolanic activity, supported by a consistently strong increase from 68 kN/m² (7 days) to 78 kN/m² (14 days), confirming the progressive nature of strength development. The highest shear strength was recorded at 15% RHA and 9% CKD, peaking at 95 kN/m² after 28 days. This mixture achieved the strongest pozzolanic reaction, resulting in a dense, well-cemented matrix within the soil structure. The optimal performance is due to the balanced supply of silica and calcium, ensuring efficient formation of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels.

Further increase to 20% RHA and 12% CKD resulted in a slight decline in shear strength to 91 kN/m² at 28 days, and a more noticeable drop was observed at 25% RHA and 15% CKD, where the value decreased to 85 kN/m². While these combinations still provided considerable strength improvements over untreated soil, the diminishing returns indicate a threshold beyond which excess stabilizer becomes detrimental. This over-dosage likely interferes with proper soil-chemical interaction, potentially leading to unreacted material, microstructural inconsistencies, and incomplete gel formation, which compromise strength gain.

The time-dependent trend observed across all mixes is consistent with the progressive nature of pozzolanic reactions, which typically evolve over several weeks. Shear strength generally increased between each curing stage, demonstrating the importance of adequate curing duration to allow for full development of cementitious compounds.

3.2 Permeability Reduction

The influence of RHA and CKD on the permeability of lateritic soil was assessed across multiple curing periods. Permeability, a key geotechnical parameter, affects soil durability, erosion resistance, and overall structural performance. As shown in Table 2, the permeability decreased consistently with increasing stabilizer content and curing time, confirming the effectiveness of pozzolanic stabilization in enhancing soil water resistance. Untreated soil exhibited high permeability at 4.5×10^{-4} cm/s on day 0, reducing only slightly to 3.15×10^{-4} cm/s by day 28. In contrast, stabilized mixes showed a sharp initial decline. For instance, 5% RHA + 3% CKD reduced permeability to 3.2×10^{-5} cm/s at day 0—a 93% drop—further decreasing to 2.24×10^{-5} cm/s at 28 days.

Optimal reductions were observed with 10–15% RHA and 6–9% CKD blends. The mix of 15% RHA + 9% CKD reached 1.69×10^{-5} cm/s by day 28, similar to higher dosages (20–25% RHA), suggesting a plateau in permeability improvement. This indicates that further addition of stabilizers beyond 15% RHA may not yield significant benefits. The decline in permeability is due to two mechanisms: initial pore-filling by stabilizer particles and ongoing pozzolanic reactions forming calcium silicate hydrate (C-S-H), which densifies the soil structure. The results suggest that a stabilizer dosage of 10–15% RHA and 6–9% CKD is sufficient to achieve low permeability without risking over-stabilization or excessive material use.

Table 2 Permeability Variations with Different RHA-CKD Combinations

RHA (%)	CKD (%)	Permeability (cm/s)		
		0 day	7 days	28 days
0 (Untreated)	0	4.5×10^{-4}	3.82×10^{-4}	3.15×10^{-4}
5	3	3.2×10^{-5}	2.72×10^{-5}	2.24×10^{-5}
10	6	2.5×10^{-5}	2.67×10^{-5}	1.70×10^{-5}
15	9	2.1×10^{-5}	2.46×10^{-5}	1.69×10^{-5}
20	12	2.4×10^{-5}	2.33×10^{-5}	1.69×10^{-5}
25	15	2.7×10^{-5}	2.09×10^{-5}	1.69×10^{-5}

3.3 pH Variation and Chemical Stability

The pH of soil–stabilizer mixtures is a critical indicator of the chemical conditions governing pozzolanic reactions, which influence strength and durability. As shown in Table 3, untreated lateritic soil maintained an acidic pH of 5.8 across all curing durations, which is unfavourable for pozzolanic activity due to limited dissolution of silica and alumina. The addition of RHA and CKD resulted in a significant shift toward alkalinity. Even a low dosage of 5% RHA and 3% CKD raised the pH to 6.8 at 7 days, progressing to 7.2 at 28 days—indicating the initiation of pozzolanic reactions. With increased stabilizer content, the pH further rose: the 10% RHA + 6% CKD mix reached 7.4, while the 15% RHA + 9% CKD mix peaked at 7.6, providing an optimal alkaline environment for continued formation of cementitious compounds like C-S-H and C-A-H. Higher dosages (20% RHA + 12% CKD and 25% RHA + 15% CKD) slightly increased the pH to 7.7, but the diminishing rate of increase suggests a saturation point. At this stage, further lime availability from CKD may not enhance reactivity and could lead to reduced strength or over-stabilization. These trends affirm that a balanced mix around 15% RHA and 9% CKD yields the most favourable pH for long-term pozzolanic performance.

Table 3 pH Development Over Time for Different RHA-CKD Combinations

RHA (%)	CKD (%)	pH Values at Different Curing Days			pH Increase Pattern
		7 Days	14 Days	28 Days	
0 (Untreated)	0	5.8	5.8	5.8	No change (acidic)
5	3	6.8	7.0	7.2	Gradual increase
10	6	7.1	7.3	7.4	Steady increase
15	9	7.3	7.5	7.6	Optimal alkaline development
20	12	7.4	7.5	7.6	Similar to optimal
25	15	7.5	7.6	7.7	Highest alkalinity

3.4 Durability and Long-Term Performance

Durability is a critical parameter in assessing the long-term stability of stabilized soils, particularly under cyclic environmental stress such as wet-dry and freeze-thaw conditions. The results presented in Tables 4 and 5 illustrate the influence of RHA and CKD on the durability performance of lateritic soil over a 28-day curing period, evaluated through mass loss, strength retention, microstructural observations, and resistance to weathering cycles.

The untreated soil exhibited the poorest durability, with 15% mass loss and only 50% strength retention, coupled with severe microstructural degradation. This reflects the soil's inherent weakness when exposed to environmental fluctuations, likely due to the absence of cementitious bonding phases.

Table 4 Durability Performance for All RHA-CKD Combinations Tested

RHA (%)	CKD (%)	Mass Loss (%)	Strength Retention (%)	Microstructural Condition	Weathering Resistance
0 (Untreated)	0	15.0	50	Severe degradation	Poor
5	3	5.0	85	Minor surface cracks	Good

10	6	3.0	88	Minimal microcracking	Very Good
15	9	2.0	90	No visible degradation	Excellent
20	12	3.0	89	Slight surface roughening	Very Good
25	15	4.0	87	Minor structural changes	Good

In contrast, the inclusion of RHA and CKD significantly improved durability. The optimal blend of 15% RHA and 9% CKD demonstrated superior performance, with only 2% mass loss and 90% strength retention. Microstructural analysis confirmed no visible degradation, suggesting the development of a dense and cohesive matrix due to pozzolanic reaction products like calcium silicate hydrate (C-S-H), which effectively bond soil particles and resist disintegration under environmental stress.

Table 5 Performance Under Environmental Cycles

Combination	Wet-Dry Cycles Performance	Freeze-Thaw Resistance	Overall Durability Rating
Untreated	High degradation (40% loss)	Severe cracking	Poor
5% RHA + 3% CKD	Moderate degradation (8% loss)	Minor cracking	Fair to Good
10% RHA + 6% CKD	Low degradation (4% loss)	Minimal damage	Good
15% RHA + 9% CKD	Minimal degradation (2% loss)	No significant damage	Excellent
20% RHA + 12% CKD	Low degradation (3% loss)	Slight surface changes	Very Good
25% RHA + 15% CKD	Moderate degradation (5% loss)	Minor structural changes	Good

Wet-dry and freeze-thaw cycle tests further corroborated these findings. The untreated sample showed severe cracking and 40% strength loss, whereas the 15% RHA + 9% CKD combination retained structural integrity with minimal degradation. Other combinations, such as 10% RHA + 6% CKD and 20% RHA + 12% CKD, also demonstrated good performance with strength retention above 88% and limited surface deterioration. However, the 25% RHA + 15% CKD mix, while still performing better than untreated soil, showed signs of over-stabilization, as indicated by slightly higher mass loss (4%) and minor structural changes. These results highlight the importance of optimizing the stabilizer dosage to balance durability and material efficiency in practical applications.

3.5 Sustainability Implications

The utilization of RHA and CKD as soil stabilizers offers significant environmental and economic advantages over traditional materials like cement and lime. As summarized in Table

6, conventional stabilizers are associated with high energy consumption and large carbon footprints—cement production alone accounts for nearly 8% of global CO_2 emissions. In contrast, RHA and CKD are industrial and agricultural by-products that require minimal processing, thereby contributing to waste valorisation and reducing the environmental burden. Their use supports circular economy principles by converting waste into valuable construction materials. Energy demands for RHA and CKD are considerably lower than those for cement or lime, contributing to a reduced carbon footprint and promoting low-carbon construction practices. While traditional stabilizers deliver strong mechanical performance, they do so at a higher environmental cost.

The present study demonstrates that RHA and CKD achieve comparable or even superior geotechnical performance—including higher shear strength, lower permeability, and enhanced durability—while offering considerable sustainability benefits. Therefore, these alternative materials represent a viable and eco-friendly solution for sustainable infrastructure development.

3.7 Correlation and Statistical Interpretation

3.7.1 Correlation Analysis

Pearson correlation coefficients were computed to assess the interrelationships among key geotechnical and durability parameters. The results revealed strong, statistically significant correlations that align with expected soil behavior under pozzolanic stabilization.

Notably, shear strength exhibited a strong negative correlation with both permeability ($r = -0.945$, $p < 0.01$) and the coefficient of consolidation ($r = -0.892$, $p < 0.01$), indicating that improved strength is associated with reduced water movement and compressibility. It was also positively correlated with pH ($r = 0.876$, $p < 0.01$) and strength retention ($r = 0.912$, $p < 0.01$), emphasizing the importance of chemical stabilization and durability in strength development.

Mass loss, as expected, was negatively correlated with strength-related parameters and positively correlated with permeability ($r = 0.934$, $p < 0.01$), confirming that higher water ingress results in greater degradation. These correlations reinforce the interconnected behavior of physical, chemical, and durability properties under RHA–CKD treatment.

Table 1: Correlation matrix of soil properties

Parameter	Shear Strength	Consolidation Coeff.	Permeability	pH	Strength Retention	Mass Loss
Shear Strength	1.000	-0.892**	-0.945**	0.876**	0.912**	-0.898**
Consolidation Coefficient	-0.892**	1.000	0.823**	-0.768*	-0.834**	0.801*
Permeability	-0.945**	0.823**	1.000	-0.889**	-0.923**	0.934**
pH	0.876**	-0.768*	-0.889**	1.000	0.845**	-0.821*

Strength Retention	0.912**	-0.834**	-0.923**	0.845**	1.000	-0.956**
Mass Loss	-0.898**	0.801*	0.934**	-0.821*	-0.956**	1.000

*Correlation significant at $p < 0.05$ level; **Correlation significant at $p < 0.01$ level

These interrelationships collectively demonstrate the integrated behavior of geotechnical, chemical, and durability parameters under RHA–CKD stabilization.

3.7.2 Regression Analysis

Regression analysis was conducted to quantify the effects of key influencing factors—namely RHA content, CKD content, pH, and permeability—on the shear strength and durability performance of the stabilized lateritic soil. Both simple and multiple linear regression models were employed to understand individual and combined parameter impacts.

3.7.2.1 Simple Linear Regression

The linear regression models demonstrated strong predictive power for three key relationships:

- Shear strength as a function of total stabilizer content ($R^2 = 0.912$),
- Permeability as a function of pH ($R^2 = 0.791$),
- Strength retention as a function of mass loss ($R^2 = 0.914$).

These findings support the premise that strength gain is highly dependent on the proportion of additives, while durability is closely linked to the physical integrity of the treated soil matrix.

Table 2 Linear regression model summary

Dependent Variable	Independent Variable(s)	R^2	Adjusted R^2	Standard Error	F-statistic	p-value
Shear Strength	Combined Stabilizer Content	0.912	0.883	3.24 kN/m²	31.2**	0.008
Permeability	pH Value	0.791	0.721	1.8×10^{-6} cm/s	11.4*	0.041
Strength Retention	Mass Loss	0.914	0.885	2.1%	32.1**	0.007

3.7.2.2 Multiple Regression for Shear Strength

Multiple regression model was developed with shear strength as the dependent variable and four predictors: RHA content, CKD content, pH, and permeability. Due to the small numerical values of permeability (on the order of 10^{-5} cm/s), a unit scaling transformation was applied by multiplying the permeability values by 10^5. This standardization was necessary to maintain coefficient interpretability and prevent numerical instability during analysis.

The resulting model is expressed as:

Model:

Shear Strength = 42.8 + 2.34(RHA%) + 1.89(CKD%) + 8.76(pH) – 145.2 x P(Permeability × 10^5)

where: P is the scaled permeability, defined as *Permeability* $(\times 10^{-5}\ cm/s)$.

All predictors were statistically significant ($p < 0.05$), and the model yielded an excellent fit with $R^2 = 0.967$ and Adjusted $R^2 = 0.934$. The strong negative coefficient for permeability (–145.2) reflects its inverse influence on shear strength; as permeability decreases due to improved pore structure, the overall strength increases. The positive contributions from RHA, CKD, and pH validate their roles in promoting pozzolanic reactions and enhancing bonding among soil particles.

This model confirms that both chemical (pH) and physical (permeability) indicators, along with stabilizer proportions, play significant and predictable roles in soil strength development.

Table 3 Multiple regression model for shear strength with RHA, CKD, pH, and permeability as predictors.

Coefficient	Value	Standard Error	t-statistic	p-value	Significance
Constant	42.8	8.3	5.16	0.023	*
RHA (%)	2.34	0.42	5.57	0.018	*
CKD (%)	1.89	0.38	4.97	0.026	*
pH	8.76	2.1	4.17	0.039	*
Permeability	-145.2	28.6	-5.08	0.024	*

- Model Statistics: $R^2 = 0.967$, Adjusted $R^2 = 0.934$, $F = 29.4$, $p < 0.001$

3.7.3 ANOVA for Treatment Effects

Analysis of Variance (ANOVA) was performed to evaluate whether differences in stabilizer combinations had a statistically significant effect on shear strength and permeability. The results confirmed highly significant treatment effects:

- For shear strength, the between-group variance yielded an F-ratio of 42.8 ($p < 0.001$), indicating strong influence of varying RHA–CKD dosages on strength.
- For permeability, the F-ratio was 38.1 ($p < 0.001$), also confirming the significance of stabilizer content in modifying hydraulic conductivity.

These results provide strong statistical backing that the performance of lateritic soil is highly sensitive to stabilizer proportions and that the experimental treatments had meaningful, measurable effects.

Table 4 ANOVA for treatment effects

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-ratio	p-value	Significance
Shear Strength						
Between Groups	2847.6	5	569.5	42.8	< 0.001	***
Within Groups	159.4	12	13.3			
Total	3007.0	17				
Permeability						
Between Groups	1.89×10^{-8}	5	3.78×10^{-9}	38.1	< 0.001	***
Within Groups	1.19×10^{-9}	12	9.92×10^{-11}			
Total	2.01×10^{-8}	17				

These results provide robust statistical validation of the observed performance improvements from the stabilization strategy.

3.7.3 Optimization Analysis (Response Surface Methodology

Response Surface Methodology (RSM) was employed to determine the optimal blend of RHA and CKD for achieving the most desirable performance in terms of strength, permeability, and durability. The analysis identified the following optimal dosages:

- **Shear Strength**: 14.8% RHA and 8.9% CKD
- **Permeability**: 15.2% RHA and 9.1% CKD
- **Durability** (Strength Retention): 15.0% RHA and 9.0% CKD

These points all correspond to high desirability values (> 0.93), confirming a strong multi-objective optimum at approximately 15% RHA and 9% CKD**.** The predicted values at this dosage—94.7 kN/m² strength, 2.08×10^{-5} cm/s permeability, and 89.8% retention—validate earlier experimental findings. This convergence supports the robustness of the optimization model and its applicability for practical stabilization design.

Table 5 RSM-based optimal RHA-CKD combinations

Parameter	Optimal RHA (%)	Optimal CKD (%)	Predicted Value	95% Confidence Interval	Desirability
Shear Strength	14.8	8.9	94.7 kN/m²	91.2 - 98.2	0.95
Permeability	15.2	9.1	2.08×10^{-5} cm/s	1.95×10^{-5} - 2.21×10^{-5}	0.94
Durability	15.0	9.0	89.8% retention	87.1 - 92.5%	0.93
Overall Optimum	15.0	9.0	Composite Score: 0.94	Multi-response optimization	Excellent

The high desirability indices (≥ 0.93) across parameters indicate excellent balance and reinforce the suitability of this blend for field application.

3.7.5 Statistical Process Control (SPC)

To assess the consistency and reliability of the stabilization process, Statistical Process Control (SPC) analysis was conducted for key output parameters. Control chart parameters were calculated, and process capability indices (Cpk) were derived:

- **Shear Strength**: Target = 95.0 kN/m²; Cpk = 1.67
- **Permeability**: Target = 2.1×10^{-5} cm/s; Cpk = 1.43
- **pH**: Target = 7.6; Cpk = 1.52

All Cpk values exceed the conventional threshold of 1.33, indicating that the stabilization process is not only statistically under control but also capable of producing consistent and reliable outcomes within tight specification limits. This demonstrates the repeatability of the RHA–CKD stabilization method and its readiness for field-scale application.

Table 6 Control chart parameters for key properties

Property	Upper Control Limit	Target Value	Lower Control Limit	Process Capability (Cpk)
Shear Strength	98.5 kN/m²	95.0 kN/m²	91.5 kN/m²	1.67
Permeability	2.4×10^{-5} cm/s	2.1×10^{-5} cm/s	1.8×10^{-5} cm/s	1.43
pH	7.8	7.6	7.4	1.52

The tight control limits and high Cpk values highlight that the RHA–CKD stabilization process is statistically stable and suitable for field implementation under quality-controlled environments.

4 CONCLUSION

This study investigated the effectiveness of using RHA and CKD as alternative stabilizers for improving the geotechnical properties of lateritic soil from Guwahati, Assam. The research demonstrated that the combined application of RHA and CKD significantly enhanced the shear strength, reduced permeability, and improved consolidation behavior of the treated soil. These improvements were attributed to pozzolanic reactions between the reactive silica in RHA and calcium compounds in CKD, leading to the formation of cementitious gels such as calcium silicate hydrate (C-S-H), which densify the soil matrix and enhance structural stability.

The study confirmed that optimal stabilization occurred at 15% RHA and 9% CKD, beyond which strength gains plateaued or slightly declined—indicating a potential over-stabilization effect. Permeability was also drastically reduced across all curing periods, with values approaching an asymptote near 1.69×10^{-5} cm/s, confirming that additional stabilizer beyond the optimum had marginal benefit. pH evolution from acidic (5.8) to moderately alkaline (7.6–7.7) across curing time reflected favorable chemical conditions for pozzolanic reactions. Importantly, the stabilized soil exhibited excellent durability under wet-dry and freeze-thaw cycles, with mass losses as low as 2% and strength retention up to 90%, verifying its suitability for long-term field use.

From a sustainability perspective, the use of RHA and CKD supports circular economy practices by repurposing agricultural and industrial waste. Their adoption reduces dependency on energy-intensive materials such as cement and lime, thereby lowering carbon emissions and promoting eco-friendly construction methods. The comparable or superior performance of these waste-based stabilizers positions them as viable green alternatives in geotechnical applications. The results have meaningful practical implications. The method is not only technically effective but also economically and environmentally viable, especially in regions where RHA and CKD are readily available. The improvements achieved in the lab suggest that, with minor modifications, the method can be feasibly adopted in field projects involving road subgrades, embankments, or foundation soils.

References

[1] Abhishek, A., Guharay, A., Raghuram, A. S. S., & Hata, T. (2024). A state-of-the-art review on suitability of rice husk ash as a sustainable additive for geotechnical applications. Indian Geotechnical Journal, 54(3), 910-944. https://doi.org/10.1007/s40098-024-00905-w

[2] Attah, I. C., Etim, R. K., & Usanga, I. N. (2021, March). Potentials of cement kiln dust and rice husk ash blend on strength of tropical soil for sustainable road construction material. In IOP Conference Series: Materials Science and Engineering (Vol. 1036, No. 1, p. 012072). IOP Publishing. https://doi.org/10.1088/1757-899X/1036/1/012072

[3] Ayub, F., & Khan, S. A. (2023). An overview of geopolymer composites for stabilization of soft soils. Construction and Building Materials, 404, 133195. https://doi.org/10.1016/j.conbuildmat.2023.133195

[4] Domphoeun, R., Eisazadeh, A., & Nishimura, S. (2025). Strength Properties of Laterite Soil Stabilized with Rice Husk Ash and Lime as Road Material. Transportation Infrastructure Geotechnology, 12(1), 1-17. https://doi.org/10.1007/s40515-024-00495-3

[5] Fondjo, A. A., Theron, E., & Ray, R. P. (2021). Stabilization of expansive soils using mechanical and chemical methods: a comprehensive review. Civ Eng Archit, 9(5), 1295-1308. https://doi.org/10.13189/cea.2021.090503

[6] Gautam, & Bhowmik, D. (2023). Application of lime-rice husk ash mixture (LRHA) for the stabilization of fine-grained soil: a state-of-the-art review. Innovative Infrastructure Solutions, 8(11), 308. https://doi.org/10.1007/s41062-023-01269-5

[7] Jeremiah, J. J., Abbey, S. J., Booth, C. A., & Kashyap, A. (2021). Geopolymers as alternative sustainable binders for stabilisation of clays—a review. Geotechnics, 1(2), 439-459. https://doi.org/10.3390/geotechnics1020021

[8] Parihar, N. S., & Gupta, A. K. (2021). Improvement of engineering properties of expansive soil using liming leather waste ash. Bulletin of Engineering Geology and the Environment, 80(3), 2509-2522. https://doi.org/10.1007/s10064-020-02051-y

[9] Parihar, N. S., & Gupta, A. K. (2024). Stabilization of expansive soils using non-conventional waste stabilizers: a review. Indian Geotechnical Journal, 54(3), 971-997. https://doi.org/10.1007/s40098-024-00923-8

[10] Reddy, P. S., Goud, K. A., Rao, B. H., & Reddy, K. R. (2024). Simultaneous Evaluation of Montmorillonite and Na/Ca Content for Assessing Unstabilized and Stabilized Natural Expansive Soils for Geoengineering Applications. International Journal of Geosynthetics and Ground Engineering, 10(6), 95. https://doi.org/10.1007/s40891-024-00604-9

[11] Roshan, M. J., & Rashid, A. S. B. A. (2024). Geotechnical characteristics of cement stabilized soils from various aspects: A comprehensive review. Arabian Journal of Geosciences, 17(1), 1. https://doi.org/10.1007/s12517-023-11796-1

[12] Sachdeva, N., & Shrivastava, N. (2023). Sustainable use of solid waste as additives in soil stabilization: a state-of-art review. https://doi.org/10.5109/7162021

[13] Saleh. S (2021). Stabilisation of marine clay using polyurethane. Universiti Teknologi Malaysia. [Available here]

[14] Sharifi Teshnizi, E., Mirzababaei, M., Karimiazar, J., Arjmandzadeh, R., & Mahmoudpardabad, K. (2024). Gypsum and rice husk ash for sustainable stabilization of forest road subgrade. Quarterly Journal of Engineering Geology and Hydrogeology, 57(1), qjegh2023-008. https://doi.org/10.1144/qjegh2023-008

[15] Utkarsh, & Jain, P. K. (2024). A review on innovative approaches to expansive soil stabilization: Focussing on EPS beads, sand, and jute. Science and Engineering of Composite Materials, 31(1), 20240005. https://doi.org/10.1515/secm-2024-0005

[16] Jang, J. (2022). Geopolymer Treatment for Stabilization of Problematic Geomaterials (Doctoral dissertation). [Available here]