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Investigation of the Impact of Lime and Nano-Silica on the California Bearing Ratio of Treated Lateritic Soil

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ABSTRACT

This study assessed the effect of lime and nano-silica additives on the engineering behavior of lateritic soil from Iyamho, Edo State, Nigeria, with emphasis on index properties, compaction, and California Bearing Ratio (CBR) performance. Laboratory tests were conducted in line with ASTM standards, and a Taguchi L25 orthogonal array experimental design was adopted to optimize additive proportions while reducing experimental runs. The results revealed that stabilization reduced the plasticity index from 7.72% to 3.42%, signifying improved workability and reduced shrink–swell potential. Compaction tests showed an increase in optimum moisture content (from 13.25% to 15.25%) and a decrease in maximum dry density (from 1.90 g/cm³ to 1.75–1.78 g/cm³), reflecting higher water demand and partial replacement of soil particles. The CBR values declined from 15.15% in untreated soil to 5.15–6.15% in treated samples, although partial recovery (14.06%) was observed at 10% additive content. Regression modeling indicated a negative linear relationship (R^2 = 51.36%) between additive content and short-term CBR, while Taguchi optimization identified the best performance at 80–85% soil, 2.5–5% lime, and 0–2.5% nano-silica, yielding CBR values above 17%.The study concludes that moderate lime contents (2.5–5%) combined with minimal nano-silica provide the most effective balance between soil strength and workability, making this approach a cost-efficient and sustainable solution for pavement subgrade improvement in tropical environments.

1 INTRODUCTION

Soil stabilization is a critical strategy in geotechnical engineering for improving the performance of weak soils, particularly in infrastructure projects such as highways, airfields, and retaining structures. Lime has emerged as a widely adopted stabilizer due to its capacity to enhance strength, reduce plasticity and swelling potential, and improve long-term durability (Amu et al., 2021; Behnood, 2020).

However, lateritic soils commonly found in tropical regions such as Nigeria pose significant challenges for engineering applications because of their high clay content, variable mineralogy, low natural strength, and pronounced moisture sensitivity, which often result in settlement and premature pavement failure (Omotayo et al., 2023). Although lime stabilization improves the engineering behavior of lateritic soils, its effectiveness is inconsistent across regions and depends on dosage and soil composition, with optimal performance typically achieved at around 6% lime (Ogundipe&Adekanmi, 2019; Hezmi et al., 2019).

Stabilization more broadly involves modifying soil properties mechanically or chemically to achieve improved strength, permeability, and durability, thereby supporting sustainable infrastructure development (Amar &Shahin, 2021; ASTM, 2014). Beyond technical benefits, stabilization has economic importance in developing countries, where high costs of conventional construction materials necessitate cost-effective alternatives (Madu, 2017; Sickler, 2021).

The mechanism of lime stabilization includes immediate cation exchange and flocculation, which enhance workability, and long-term pozzolanic reactions that generate cementitious compounds such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), which significantly improve soil stiffness and strength (Okeke et al., 2021). Recent research further highlights the potential of combining lime with supplementary stabilizers, including agricultural ashes and nano-materials, to maximize soil improvement (Amu et al., 2021; Omotayo et al., 2023).

This study examines the combined effect of lime and nano-silica on the California Bearing Ratio (CBR) of lateritic soil. Given that CBR remains a fundamental parameter in the design and evaluation of pavement subgrades, the research aims to provide practical insights into cost-effective and sustainable stabilization strategies for lateritic soils in tropical regions.

4. MATERIALSAND METHODS

Materials

i. **Lateritic Soil**: The lateritic soil used in this study was obtained from Iyamho, Etsako West Local Government Area of Edo State, Nigeria, at an average depth of 1.2 m. Six representative samples were collected, placed in sealed sample bags, and transported to the laboratory for testing. Lateritic soils are typical residual soils of tropical regions and are characterized by high clay content and variable weathering. The collected samples were air-dried, pulverized, and sieved to remove oversized particles before stabilization.

ii. **Lime**: Commercially available hydrated lime, purchased from the local market, was used as a stabilizing agent. Lime was selected due to its proven pozzolanic reactivity and widespread application in geotechnical soil improvement.

iii. **Nano-Silica**: Nano-silica powder was also procured from the market and employed as a supplementary stabilizer. Its high surface area and reactive silica content were expected to enhance soil densification and the development of cementitious compounds when combined with lime.

Methods

Sample Preparation

The air-dried lateritic soil was thoroughly mixed with lime and nano-silica at varying percentages of 0%, 2.5%, 5%, 7.5%, and 10% by dry weight. Homogenization was carefully carried out to ensure even distribution of additives across all specimens.

a. Materials and Equipment

Compaction Characteristics

Standard Proctor Compaction Tests were performed to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of both untreated and treated soils. Each sample was compacted in three layers under controlled effort, and moisture–density relationships were plotted to identify OMC and MDD values.

Strength Test

The California Bearing Ratio (CBR) test was carried out in line with ASTM D1883 to assess the bearing capacity of subgrade soils. Specimens were compacted at OMC, cured appropriately, and subjected to penetration by a standard plunger at a rate of 1.25 mm/min. CBR values were determined at 2.5 mm and 5 mm penetrations, with the higher value adopted for analysis.

b. Experimental Procedure

Experimental Design

A Taguchi L25 (5^2) orthogonal array experimental design was adopted to optimize lime–nano-silica combinations. This design reduced the required experiments from 625 to 25 while allowing interactions between factors to be captured efficiently. Each trial consisted of soil samples stabilized with a specific lime–nano-silica ratio, compacted using the Standard Proctor Test, and evaluated for geotechnical properties. Signal-to-Noise (S/N) ratios were computed for performance evaluation: *"larger is better"* for density and strength, and *"smaller is better"* for plasticity and compressibility. The optimal mix was confirmed through validation testing.

Index Property Tests

i. **Particle Size Distribution:** Sieve analysis was carried out following ASTM C136 to determine soil gradation and classify its engineering behavior. The results provided a basis for predicting compaction and strength performance.

ii. **Moisture Content:** Natural water content was measured in accordance with ASTM D2216 by oven-drying samples to constant mass. This parameter is critical in understanding soil workability and stability.

iii. **Specific Gravity:** The pycnometer method was used to determine the specific gravity of soil solids, which is useful for calculating density-related properties. It also gives insight into the soil's mineralogical composition.

iv. **Atterberg Limits:** Liquid limit, plastic limit, and plasticity index were determined in line with ASTM D4318 to assess soil consistency and plasticity characteristics. These values indicate the soil's behavior under varying moisture conditions.

Data Analysis and Modeling

Regression analysis was used to predict the relationship between additive content and CBR. The derived linear model, shows a negative correlation, with R^2 = 51.36%, indicating moderate explanatory power. While not fully predictive, the model provides a useful framework for assessing the influence of lime and nano-silica on lateritic soil strength.

3. RESULTS AND DISCUSSION

Results

The results of the experimental program are presented and discussed in this section. Analyses cover the optimization of lime–nano-silica additions, index properties, compaction characteristics and strength performance of the treated lateritic soil.

3.1 Experimental Results

Design of Experiment

The Taguchi L25 design matrix provided insights into the effects of lime and nano-silica on soil strength, with CBR as the response and SNRA1 values as performance indicators (Table 1). The analysis revealed that the optimal zone for peak CBR (>17%) occurred when soil content was between 80–85%, lime content 2.5–5%, nano-silica 0–2.5%, and factor ratio 27.5–31.7. This indicates that moderate stabilizer dosages yield superior soil strength, while higher proportions produce diminishing returns.

Table 1: Design of Experiment

Soil	Lime	Nano	Factor ratio	SNRA1	Response/ (CBR)
100	0.0	0.0	33.3	30.4576	15.1500
100	2.5	2.5	35.0	30.8814	5.1500
100	5.0	5.0	36.7	31.2854	5.9500
100	7.5	7.5	38.3	31.6715	6.1500
100	10.0	10.0	40.0	32.0412	14.0612
95	0.0	2.5	32.5	30.2377	16.8964
95	2.5	5.0	34.2	30.6721	16.2135
95	5.0	7.5	35.8	31.0857	15.5632
95	7.5	10.0	37.5	31.4806	14.9425
95	10.0	0.0	35.0	30.8814	15.8845
90	0.0	5.0	31.7	30.0120	17.2511
90	2.5	7.5	33.3	30.4576	16.5507
90	5.0	10.0	35.0	30.8814	15.8845
90	7.5	0.0	32.5	30.2377	16.8964
90	10.0	2.5	34.2	30.6721	16.2135
85	0.0	7.5	30.8	29.7804	17.6152
85	2.5	10.0	32.5	30.2377	16.8964
85	5.0	0.0	30.0	29.5424	17.9893
85	7.5	2.5	31.7	30.0120	17.2511
85	10.0	5.0	33.3	30.4576	16.5507
80	0.0	10.0	30.0	29.5424	17.9893
80	2.5	0.0	27.5	28.7867	19.1774
80	5.0	2.5	29.2	29.2977	18.3740
80	7.5	5.0	30.8	29.7804	17.6152
80	10.0	7.5	32.5	30.2377	16.8964

The untreated soil recorded a baseline CBR of 15.15%. At additive levels of 2.5–7.5% lime and nano-silica, CBR values dropped to 5.15–6.15%, but partial recovery was noted at 10% additives with 14.06%. The highest strength (19.18%) occurred at 80% soil, 2.5% lime, and 0% nano-silica, confirming lime's effectiveness at low dosages. Taguchi analysis highlighted the optimal range as 80–85% soil, 2.5–5% lime, and 0–2.5% nano-silica, beyond which performance gains diminished.

Index Properties of Soil

Particle size distribution (PSD):

The particle size distribution (PSD) curve (Figure 1) and (Table 2) showed Cu = 20 and Cc = 0.8, partially satisfying AASHTO gradation requirements (Cu > 4, 1 < Cc < 3). The soil was classified as coarse sand under BS 1377:2018 and as medium coarse sand by ASTM C136. This gradation suggests favorable compaction behavior.

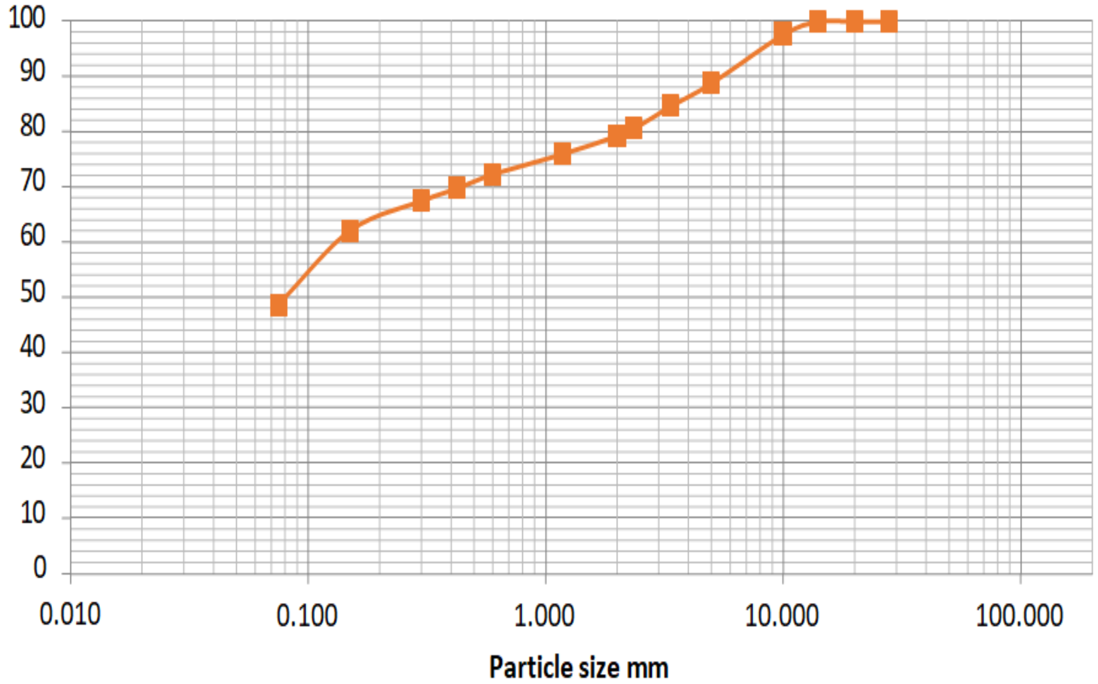


Figure 1: Particle Size Distribution Curve of Lateritic Soil

Specific Gravity Results

Specific gravity indicates the relative density of soil solids compared to water and is essential for assessing soil composition, compaction, and load response. Its variation with additives reflects whether stabilization alters the soil's inherent mineral properties.

Table 2: Specific Gravity of Untreated and Treated Soil

Condition	Specific Gravity (Gs)
Untreated Soil	2.55
2.5% Lime + Nano-Silica	2.51
5.0% Lime + Nano-Silica	2.50
7.5% Lime + Nano-Silica	2.51

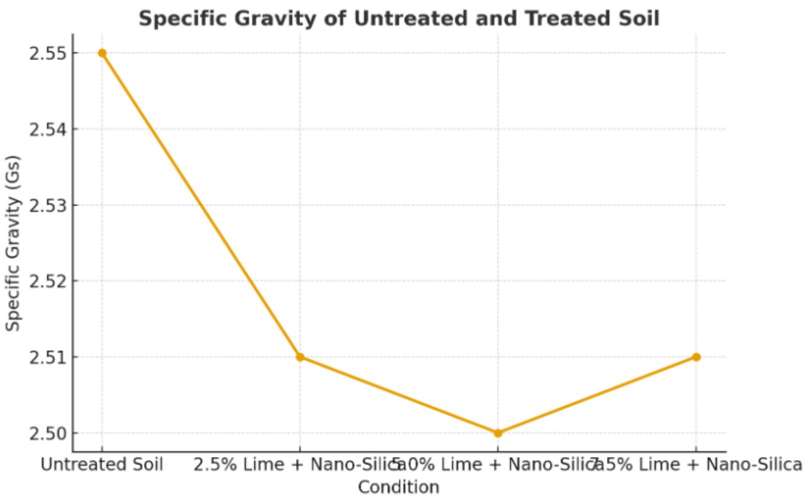


Figure 1: *Specific Gravity of Untreated and Treated Soil*

From Table 2 and Figure 1, the untreated soil had a specific gravity of 2.55, slightly below the typical 2.60–2.70 range, implying minor lightweight minerals or organics. Stabilized samples recorded 2.50–2.51, showing only marginal reduction. This consistency indicates that lime and nano-silica primarily modify soil structure and compaction rather than altering mineral density.

Atterberg Limits Results

The Atterberg limits liquid limit (LL), plastic limit (PL), and plasticity index (PI)—are widely used to assess the consistency, plasticity, and workability of fine-grained soils. These indices provide vital information on the soil's moisture sensitivity and its likely behavior under varying environmental conditions.

Table 3: Atterberg Limits of Untreated and Treated Soil

Property	Untreated Soil (%)	Treated Soil (%)
Liquid Limit (LL)	20.58	20.08
Plastic Limit (PL)	12.86	16.68
Plasticity Index (PI)	7.72	3.42

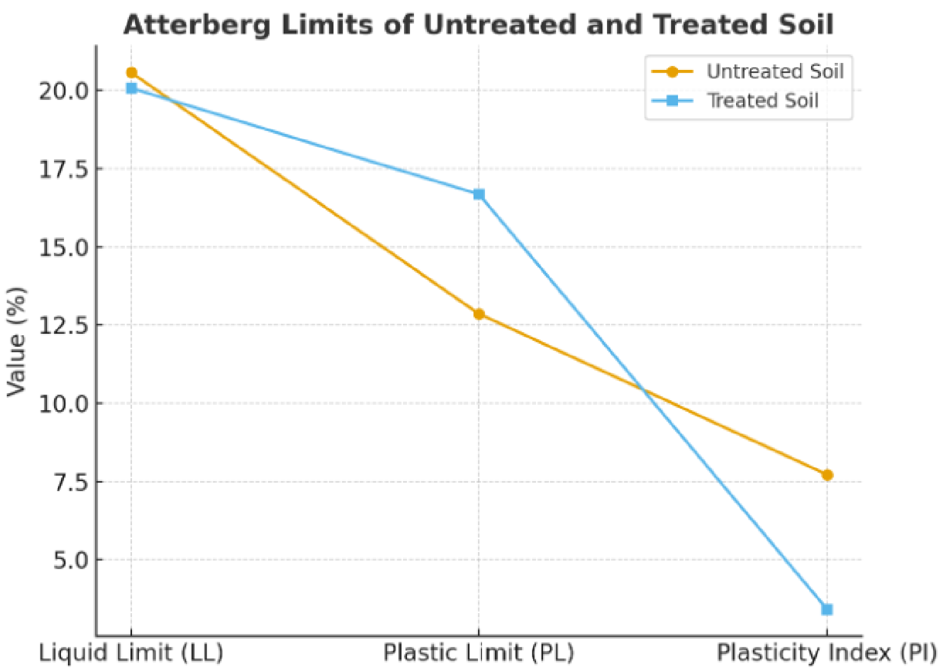


Figure 2: Atterberg Limits of Untreated and Treated Soil

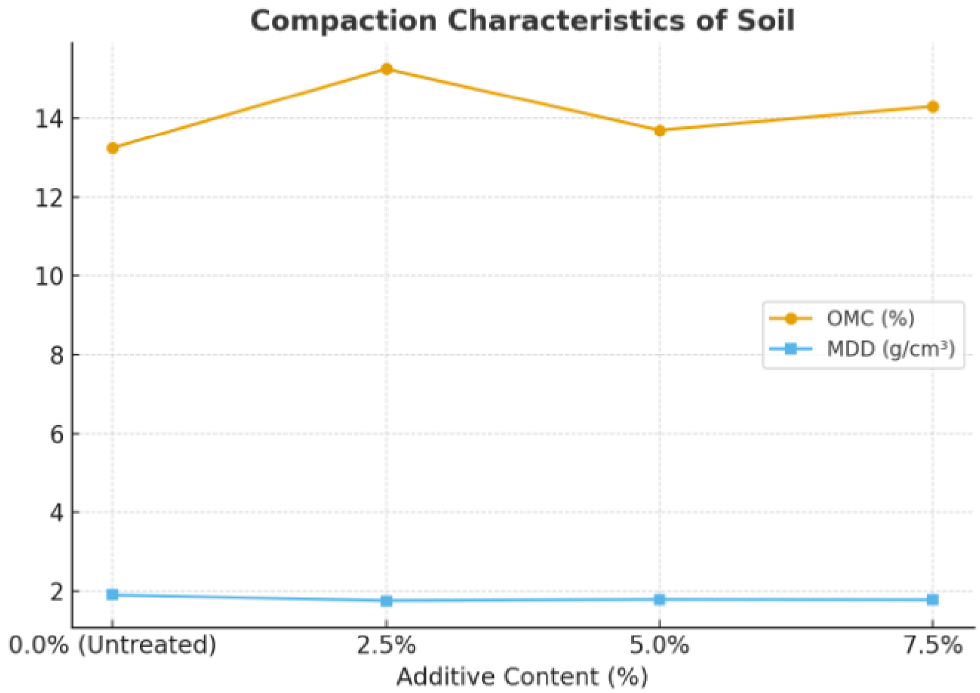
Table 3 and figure 2 explains that treatment with lime and nano-silica produced notable changes in plasticity characteristics. The **liquid limit** slightly decreased from **20.58% to 20.08%**, indicating reduced water affinity due to particle flocculation. Meanwhile, the **plastic limit** increased significantly from **12.86% to 16.68%**, implying enhanced soil stiffness and greater resistance to deformation. Consequently, the **plasticity index** declined sharply from **7.72% to 3.42%**, signifying reduced plasticity and lower shrink–swell potential. These results demonstrate that lime and nano-silica stabilization effectively improves soil workability, stability, and suitability for subgrade and foundation applications.

Standard Proctor Compaction Test Results

Compaction tests assessed the effect of lime and nano-silica on lateritic soil using OMC and MDD.

Table 4: Compaction Characteristics of Untreated and Treated Lateritic Soil

Sample Condition	Additive Content (%)	OMC (%)	MDD (g/cm³)
Untreated Soil	0.0	13.25	1.90
Treated Soil (2.5% mix)	2.5	15.25	1.75
Treated Soil (5.0% mix)	5.0	13.70	1.78
Treated Soil (7.5% mix)	7.5	14.30	1.77



Figures 3: Compaction Characteristics of Soil

Table 4 and figure 3show that untreated soil had an MDD of 1.90 g/cm³ at 13.25% OMC. With lime and nano-silica, OMC varied between 13.70–15.25%, while MDD ranged from 1.75–1.78 g/cm³. The optimum improvement occurred at 5.0% additive, confirming enhanced compaction from better particle packing and cementitious bonding.

California Bearing Ratio (CBR) Performance

The CBR results show that untreated lateritic soil had varying resistance between layers. The top layer initially sustained higher loads but weakened beyond 7.5 mm penetration, while the bottom layer showed steady densification. Calculated CBR values ranged from 8.9% to 22.5%, with a design CBR of 15.15% adopted for the untreated soil (Table 5).

Table 5: CBR Values for Untreated and Treated Lateritic Soil

Condition / Penetration	2.5 mm	5.0 mm	7.5 mm	10 mm	12.5 mm	Accepted CBR (%)
Untreated (Top)	9.85	10.00	–	–	–	15.15
Untreated (Bottom)	15.15	14.50	–	–	–	15.15
Treated (2.5% mix)	–	–	5.15	–	–	5.15
Treated (5.0% mix)	–	–	5.95	–	–	5.95
Treated (7.5% mix)	–	–	6.15	–	–	6.15

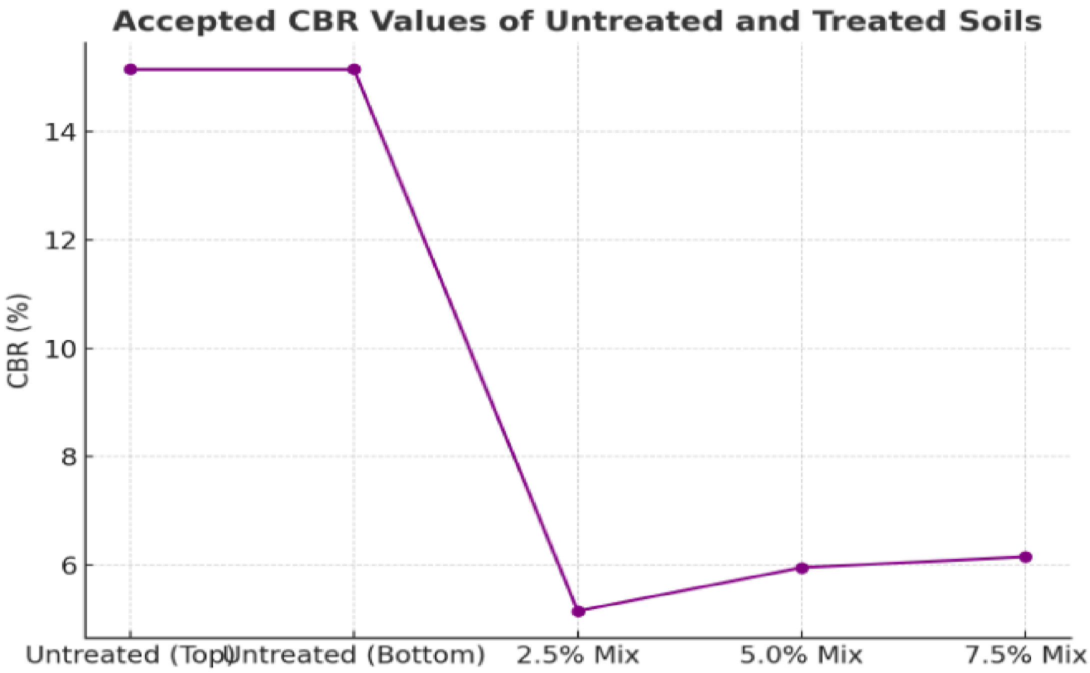


Figure 4: Accepted CBR Values of unt#reated and Treated Soil

Table 5 and Figure 4indicates that the untreated soil exhibited higher strength, with an accepted CBR of 15.15%, reflecting good load-bearing capacity. Conversely, the lime–nano-silica treated samples recorded lower values (5.15–6.15%), suggesting that while stabilization altered soil structure, immediate strength was reduced, likely requiring longer curing for full cementitious benefits.

Regression Analysis

A regression model was developed to examine the effect of lime–nano-silica content on CBR performance:

The model indicates a **negative linear relationship**, with CBR decreasing by approximately 1.048 units per 1% increase in additive content. The coefficient of determination (**R^2 = 51.36%**) suggests moderate predictive strength, while the **p-value (0.07)** implies marginal statistical significance. This result indicates that excessive additive content may reduce short-term CBR values, likely due to delayed pozzolanic reactions or incomplete lime–nano interaction.

Table 6: Regression Model Results

Additive (%)	CBR (%)	Fitted Value
0.0	15.15	12.03
2.5	5.15	9.41
5.0	5.95	6.79
7.5	6.15	4.17

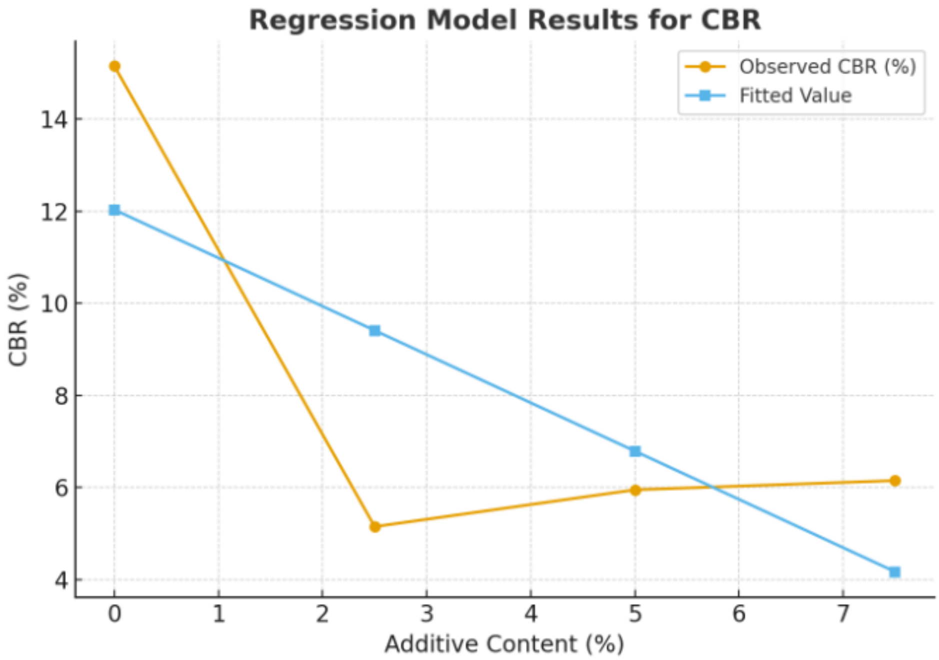


Figure 7: *Regression Model Results for CBR*

Table 8 shows the effect of additive content on soil CBR. The untreated soil (0%) had the highest CBR (15.15%), but adding 2.5% additive sharply reduced it to 5.15%. Further increases to 5.0% and 7.5% slightly improved CBR to 5.95% and 6.15%, suggesting a minor stabilizing effect at higher additive levels. The fitted values indicate an overall declining trend in strength with increasing additive, highlighting the need for careful optimization to balance soil modification with load-bearing performance.

4. CONCLUSION

This study investigated the effects of lime–nano-silica additives on the geotechnical properties and strength performance of lateritic soil with the aim of enhancing its suitability for pavement subgrade applications. The findings provide insight into how additive dosage influences soil plasticity, compaction behavior, and load-bearing capacity, while also highlighting the role of regression and Taguchi optimization in determining performance trends. The key outcomes are summarized as follows:

i. Stabilization with lime and nano-silica significantly reduced the plasticity index of the lateritic soil from 7.72% to 3.42%, indicating improved workability and reduced shrink–swell potential.
ii. Compaction results showed an increase in optimum moisture content (from 13.25% to 15.25%) and a reduction in maximum dry density (from 1.90 g/cm³ to 1.75–1.78 g/cm³), suggesting higher water demand and partial replacement of soil particles with additives.
iii. CBR values decreased from 15.15% in the untreated soil to between 5.15% and 6.15% in treated soils, although partial strength recovery (14.06%) was achieved at 10% additive content.
iv. Regression analysis revealed a negative linear relationship (R^2 = 51.36%) between additive dosage and short-term CBR, highlighting the sensitivity of strength performance to additive levels.
v. Taguchi optimization identified the best performance at 80–85% soil, 2.5–5% lime, and 0–2.5% nano-silica, which produced CBR values above 17%, demonstrating the potential for achieving improved subgrade stability when additives are applied at controlled dosages.

Abbreviations

CBR	California Bearing Ratio
OMC	Optimum Moisture Content
MDD	Maximum Dry density
PSD	Particle Size Distribution
SI	International System of Units
XRD	X-Ray Diffraction

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