Characterization of Granite Sludge Dust and Zeolite for Stabilizing Lateritic Road Soils

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ABSTRACT

Lateritic soils are widely used in Nigerian road construction, but their high plasticity, moisture sensitivity, and low strength often lead to pavement failures. This study investigates the characterization and stabilization of lateritic soil with granite sludge dust obtained from a marble company and commercially available zeolite as sustainable alternatives to conventional stabilizers. Lateritic soil, zeolite, and granite sludge were characterized, and blended mixtures with varying proportions were tested for compaction, California Bearing Ratio (CBR), and unconfined compressive strength (UCS). The characterization results showed the soil as highly plastic clay (CH, A-7-6), granite sludge as a granular material with 24.6 percent fines, and zeolite as an extremely fine powder with a specific gravity of 2.78. Furthermore, chemical analysis confirmed that all three materials are predominantly siliceous, with quartz as the dominant crystalline phase and silica contents of 46.24 percent (soil), 58.66 percent (granite sludge), and 69 percent (zeolite). The stabilized mixtures reduced plasticity, increased maximum dry density, lowered optimum moisture content, and significantly improved strength, with soaked CBR rising from below 10 percent to above 35 percent and UCS increasing from 180 kN/m² to over 450 kN/m². The findings enhance engineering performance of lateritic soils, making them suitable for subgrade and sub-base applications in Nigerian road construction.

Keywords: Lateritic soil, granite sludge, zeolite, soil stabilization, road construction, compaction, strength properties

INTRODUCTION

The growing emphasis on sustainable construction practices has prompted exploration into the use of industrial by-products such as granite sludge and zeolite, both of which exhibit pozzolanic properties and can react with lime or alkali to form cementitious compounds. Their potential application in stabilizing lateritic soils—commonly used in road base and subbase layers in Nigeria and other subtropical regions—offers a cost-effective and environmentally friendly alternative to conventional stabilizers. Lateritic soils, while abundant and locally accessible, often suffer from high porosity, moisture sensitivity, and clay content, leading to reduced strength and premature road failures under wet conditions. Rainwater infiltration weakens the subgrade foundation, diminishing bearing capacity and accelerating deterioration of pavements (Umar et al., 2025; Ali et al., 2025). These challenges highlight the necessity of stabilization techniques that improve volume stability, strength, permeability, and durability.

Traditionally, cement and lime have been the primary stabilizers in geotechnical engineering. However, their high production costs, environmental footprint, and health risks during handling necessitate alternatives (Mohammed et al., 2020). Industrial and agricultural wastes with pozzolanic potential are increasingly recognized as viable substitutes, aligning wit h global efforts to reduce greenhouse gas emissions and promote sustainable infrastructure (Kolo et al., 2019).

Granite sludge, a fine-grained by-product of granite cutting and polishing, has historically posed disposal challenges due to its environmental impact. Recent studies, however, demonstrate its potential as a resource for soil stabilization and construction applications, shifting perspectives from waste management to resource utilization (Akintola et al., 2021). Similarly, zeolite, a naturally occurring aluminosilicate with high cation-exchange capacity, has been shown to enhance soil strength and durability when used as a stabilizer. Its low cost, abundance, and eco-friendly properties make it particularly attractive for developing regions (Umar et al., 2025; Ali et al., 2025).

Zeolite's ion-exchange and sorption properties also contribute to environmental remediation, while its pozzolanic reactivity enables the formation of cementitious compounds when combined with lime or other activators (Misaelides, 2011; Wen et al., 2016). Recent experimental studies confirm that zeolite-based stabilizers significantly improve the geomechanical behavior of expansive and soft soils, offering a sustainable alternative to cement (Ali et al., 2025).

Although prior research has examined granite sludge and zeolite individually, or in binary combinations with cement, the synergistic effects of combining granite sludge and zeolite for lateritic soil stabilization remain underexplored. Investigating this combination could provide a breakthrough in achieving cost-effective, durable, and sustainable road construction practices in Nigeria, reducing reliance on conventional cementitious materials.

RELATED STUDIES

Lateritic soils are highly weathered tropical soils rich in iron and aluminum oxides, typically formed under conditions of high temperature and humidity. These soils are characterized by their reddish to brownish color, variable texture, and the presence of clay minerals (such as kaolinite montmorillonite and elite), making them abundant in many parts of Africa, Asia, and South America (Etim *et al*., 2022; Wahab et al., 2021). These soils are widely utilized as construction and pavement materials in tropical regions due to their natural abundance and relatively low cost. In many developing countries, including Nigeria, lateritic soil serves as a primary material for road subgrades, sub-bases, and low-cost building foundations. However, the engineering performance of lateritic soils is often constrained by inadequate compressive strength, high plasticity, and sensitivity to moisture variations, which limit their direct application in load-bearing structures.

These inherent weaknesses pose significant challenges to the durability and long-term performance of structures built with or on lateritic soils. The instability of these soils often results in premature pavement failure, foundation settlement, and increased maintenance costs, hindering the development of sustainable and resilient infrastructure (Phummiphan *et al*., 2016). Consequently, there is a critical need for effective and economical soil improvement techniques to enhance the engineering properties of these problematic soils.

Stabilization of soil with various types of admixtures, to meet these challenges, has become a widely accepted technique of ground improvement. The stabilization technique includes mixing and blending of soil with other materials to enhance the geotechnical properties including strength, stiffness and durability of the soil (Firoozi et al., 2017). Cement and lime are the major conventional admixtures used in construction industry (Mohammed *et al.,* 2020). However, the relative high cost of cement production, the negative environmental effect associated with its production (including significant greenhouse gas emissions), coupled with its health-related issues when handling it in the field, has made sourcing for alternative materials imperative. The urgency to address climate change further emphasizes the need for sustainable construction practices, including the exploration of lower-impact cementitious materials. This has prompted researches into possible use of industrial by-products (such as Granite Sludge) that have cementitious and pozzolanic potentials, which were initially regarded as waste, but have recently been known to have economic importance as stabilizing agents (Mohammed *et al.,* 2020; Kolo *et al.,* 2019).

Granite sludge, a fine-grained material produced during the cutting, sawing, and polishing of granite. While granite itself is a valuable construction material, the resulting sludge often poses a disposal challenge. Traditionally, granite sludge has been landfilled, raising concerns about its potential environmental impact on soil and water resources (Lozano-Lunar *et al.,* 2020; Mashaly *et al.,* 2018). Despite its environmental and economic benefits, granite sludge on its own is often insufficient to achieve the level of strength, durability, and long-term performance required for effective lateritic soil stabilization, largely due to its relatively low pozzolanic reactivity and limited capacity to form adequate cementitious bonds within the soil matrix. Consequently, there is a need to complement granite sludge with a more reactive pozzolanic material such as zeolite, whose aluminosilicate composition, higher reactivity, and ion-exchange characteristics can enhance the stabilization mechanism.

Zeolite has also been used as pozzolana to enhance the strength in stabilized soils. Zeolites are a family of naturally occurring or synthetic microporous, crystalline aluminosilicate materials. in recent years, zeolite materials have been widely used as soil stabilization additives. Zeolite is a pozzolanic material and can be found in large volumes in nature, so that it is economically advantageous compared to cement and lime (Harianto and Utami, 2021). zeolites offer an advantage as a low-cost material, the availability in big quantities in many (even economically weak) parts of the world, the good mechanical and thermal properties and the combination of high sorption capacity with the ability to modestly adjust the pH of the soil or the aqueous system. In addition, the natural zeolites, do not introduce additional pollution in the environment (Misaelides, 2011; Wen *et al.,* 2016).

In recent years, experimental investigations have been complemented by modelling approaches to better understand and predict soil behavior under varying material compositions and loading conditions (Mojtahedi et al., 2023; Abbey et al., 2017; Thapa and Ghani, 2024). Modelling techniques provide a valuable framework for estimating compressive strength, optimizing mix proportions, and reducing extensive laboratory testing. Despite existing studies on lateritic soil stabilization, limited research has focused on the integrated experimental and modelling evaluation of compressive strength when granite sludge and zeolite are used in combination. Therefore, this research aims to experimentally assess and model the compressive strength characteristics of lateritic soil admixed with granite sludge and zeolite, with a view to establishing reliable predictive relationships and enhancing the effective utilization of these materials in geotechnical and pavement engineering applications.

MATERIALS AND METHODS

3.1 Materials

Materials that will be used for this research are lateritic soil, cement, Granite sludge and Zeolite. The lateritic soil sample will be obtained from a borrow pit at Talba Farm opposite the Federal University of Technology Minna, Niger State Nigeria by disturbed sampling method in accordance to BS 1377:1 (2016) standard procedure for sample collection. The granite sludge will be obtained from Giovanni Marbles and Granite Limited Asaba, Delta State. While the Kaolin used in the production of Zeolite was obtained from Lokoja, Kogi State.

(a) Zeolite (b) Granite Sludge dust (c) Lateritic Soil

Plate I: Sample of Material Used

3.2 Methods

Laboratory tests carried out on the lateritic soil samples and mixture in accordance with BS 1377 (2016) and BS 1924 (2019). The tests carried out includes: Natural moisture content, Specific gravity, mechanical sieve analysis, Atterberg limits (liquid limit and plastic limit), compaction, CBR and UCS tests. The variation of the soil and the stabilizers used are presented in Table 1.

Table 1: Proportion of the Materials Used

Mix ID	Granite Sludge (%)	Zeolite (%)	Laterite (%)
M1	20	10	70
M2	20	15	65
M3	20	20	60
M4	25	10	65
M5	25	15	60
M6	25	20	55
M7	30	10	60
M8	30	15	55
M9	30	20	50

RESULTS AND DISCUSSION

4.1 Characterization of Materials Used

From an engineering perspective, a PI value exceeding 17% is generally indicative of high swelling potential and compressibility (FMWH, 2016). Consequently, the natural soil falls short of the standard requirements for stable subgrade or base course materials in road construction, confirming the necessity for stabilization to mitigate its sensitivity to moisture and volume changes.

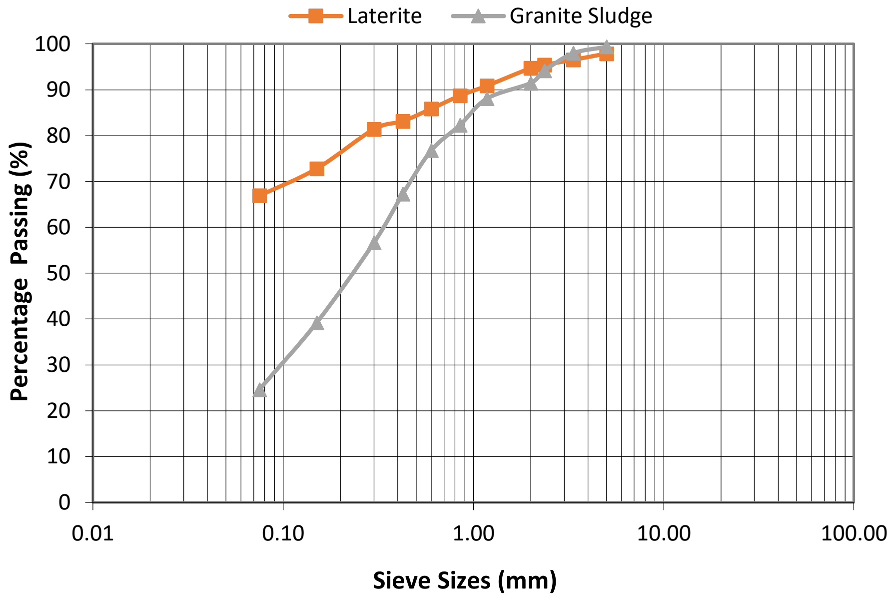

Figure 1: Particle Size Distribution Curve for Lateritic Soil and Granite Sludge

Table 4.1: Physical Properties of the Materials used

Basic characteristics	Laterite	Granite Sludge	Zeolite
% larger No.200 sieve (>0.075 mm)	33.1	75.4	-
% passing No.200 sieve (<0.075 mm) (%)	66.9	24.6	100
Liquid limit (%)	62	22	-
Plastic limit (%)	30.95	-	-
Plasticity index (%)	31.05	22	-
Linear shrinkage (%)	13.24	-	-
Specific gravity	2.53	2.63	2.78
Soil class	CH		
Colour	Reddish	Grey	White

The natural lateritic soil is classified as CH (high plasticity clay), with 66.9% fines, a Liquid Limit of 62%, and a Plasticity Index of 31.05%, indicating high swelling and compressibility. This makes it unsuitable as a stable subgrade or base material without stabilization. By contrast, Granite Sludge (GS) is a granular material with only 24.6% fines, higher specific gravity (2.63 vs. 2.53), and potential to improve soil gradation and density. Zeolite, an extremely fine powder with the highest specific gravity (2.78), acts as a micro-filler and enhances chemical reactivity. Together, GS and Zeolite provide a complementary stabilization mechanism: GS improves gradation and reduces plasticity, while Zeolite fills voids and boosts reactivity, making the lateritic soil more suitable for road construction.

4.1.1 Oxide composition

All three materials—Lateritic Soil, Granite Sludge, and Zeolite—are predominantly siliceous, with SiO_2 as the main constituent. Zeolite has the highest silica content (69.12%), followed by Granite Sludge (58.66%) and Lateritic Soil (46.24%). Al_2O_3 is the second major oxide, with Lateritic Soil richest at 28.27%, compared to 16.95% in Granite Sludge and 10.79% in Zeolite. Lateritic Soil also contains significant Fe_2O_3 (18.04%), typical of its reddish hue, while Granite Sludge shows none and Zeolite only 4.2%. Granite Sludge records the highest CaO (4.44%) and Na_2O (5.39%), reflecting its parent rock composition, whereas Zeolite has relatively low levels of these oxides. Loss on Ignition (LOI) is greatest in Granite Sludge (8.17%), moderate in Zeolite (4.5–7.0%), and lowest in Lateritic Soil (2.35%), indicating higher stability of the latter. Importantly, the combined oxides ($SiO_2 + Al_2O_3 + Fe_2O_3$) exceed the ASTM C618 pozzolanic threshold of 70% in all cases: Lateritic Soil (92.55%), Zeolite (84.11%), and Granite Sludge (75.61%). This confirms their strong potential as supplementary cementitious materials or stabilizers in soil engineering.

Table 2: Oxide Composition of Materials Used

Oxide	Lateritic Soil (%)	Granite Sludge (%)	Zeolite (%)
Calcium oxide (CaO)	0.31	4.44	0.84
Silicon dioxide (SiO_2)	46.24	58.66	69.12
Magnesium oxide (MgO)	1.1	3.18	0.65
Potassium oxide (K_2O)	2.43	3.21	1.09
Sodium oxide (Na_2O)	0.83	5.39	0.73
Aluminum oxide (Al_2O_3)	28.27	16.95	10.79
Ferric oxide (Fe_2O_3)	18.04	-	4.2
Sulfur trioxide (SO_3)	0.43	-	0.04
LOI	2.35	8.17	4.5-7.0

4.2 Effect of Stabilizers on Consistency Limits of Soil Mixtures

Figure 4.3 shows that adding Granite Sludge (GS) and Zeolite (Z) consistently reduced the consistency limits of lateritic soil. The untreated soil had the highest plasticity (LL = 62%, PI = 31.05%), but with increasing stabilizer content, values dropped sharply. At 50% Laterite, 30% GS, and 20% Zeolite, the Liquid Limit fell to ~30% and the Plasticity Index to 12%. This improvement results from two mechanisms: GS acts as a granular filler, diluting clay minerals and reducing water absorption, while Zeolite promotes cation exchange, flocculating clay particles into silt-like clusters with lower affinity for water. From a pavement design standpoint, reducing PI from >30% to 12–15% is critical. The stabilized mixes meet FMWH (2016) and AASHTO T90 specifications for sub-base and base materials, confirming enhanced workability, stability, and suitability for road construction.

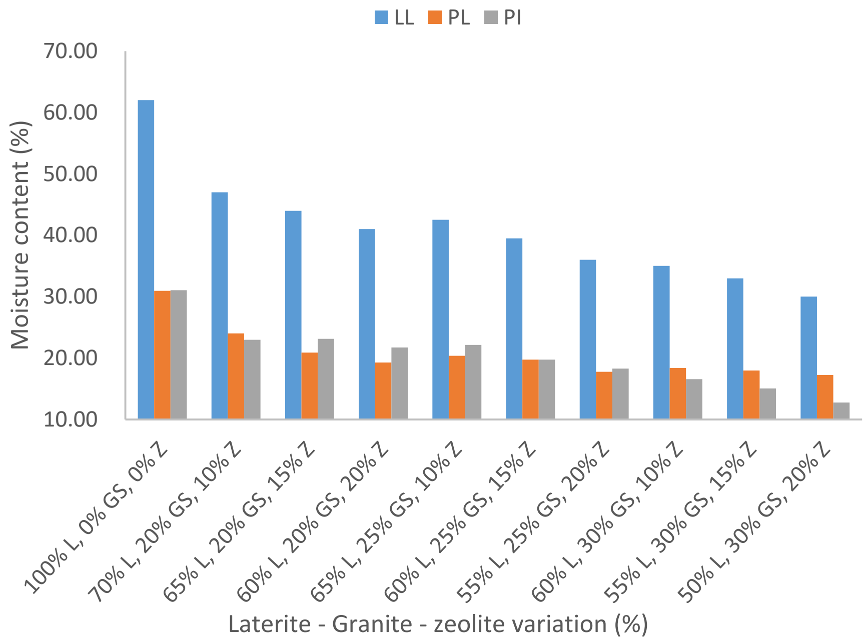

Figure 3: Variation of Consistency Limits of Soil Mixtures and Soil-Admixture Content

4.3 Effect of Stabilizers on Compaction Parameters of the Soil-Mixture

The natural soil recorded a Maximum Dry Density (MDD) of 1.62 g/cm³, which increased to 1.83 g/cm³ with 50% Laterite, 30% Granite Sludge (GS), and 20% Zeolite. This improvement results from replacing lighter soil particles with denser GS and Zeolite, and from enhanced particle packing—GS forming a granular skeleton and Zeolite filling voids to create a compact matrix. Conversely, the Optimum Moisture Content (OMC) decreased from 16.8% to 10.5%, due to reduced clay content and cation exchange that flocculated clay particles, lowering water demand for compaction. These trends, i.e. higher MDD and lower OMC are highly favourable for pavement design, indicating improved bearing capacity, reduced settlement, and compliance with strength requirements (CBR and UCS), making the stabilized soil suitable for road construction.

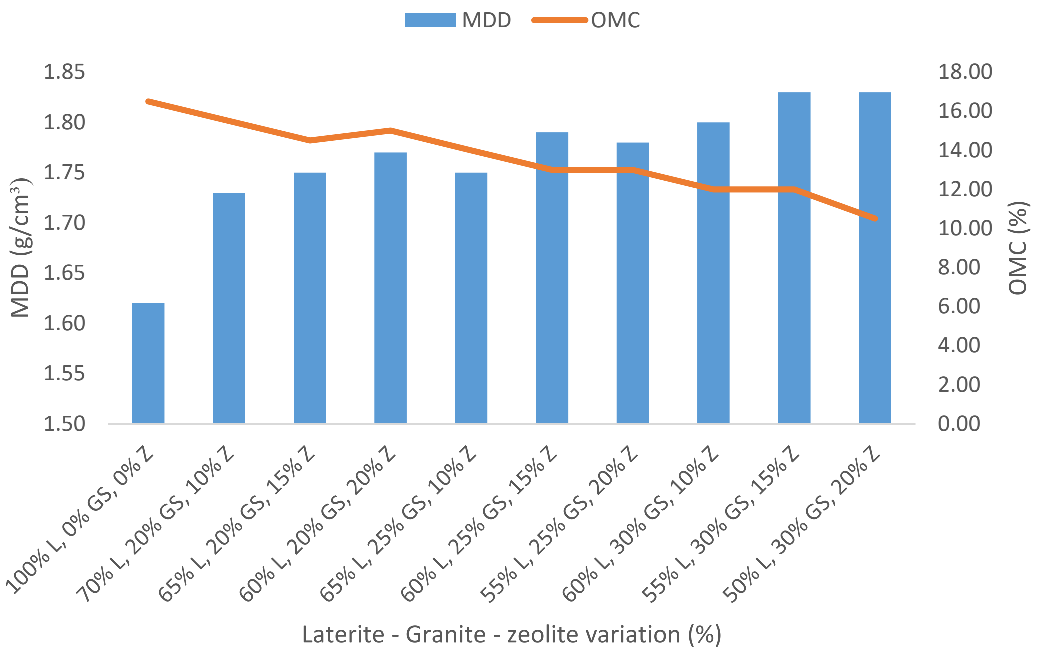

Figure 4.4: Variation of MDD and OMC of the Soil Mixtures and Soil-Admixture Content

4.4 Effect of Stabilizers on Strength Properties of the Soil-Mixture

4.1.1 California bearing ration (CBR) value

Figure 4.5 highlights the impact of granite sludge (GS) and zeolite (Z) on the California Bearing Ratio (CBR) of lateritic soil. The untreated soil showed poor performance, with unsoaked CBR at 18% and soaked CBR at only 4%. With stabilizer addition, CBR values increased progressively. For instance, at 70L–20GS–10Z, unsoaked and soaked CBR rose to 22% and 6%, while at 65L–20GS–15Z, values reached 28% and 9%. The optimum mix (60L–20GS–20Z) achieved the highest improvement, with an unsoaked CBR of 52%, reflecting enhanced particle packing and pozzolanic bonding.

Higher GS contents also yielded notable gains. At 55L–25GS–20Z, CBR values were 35% (unsoaked) and 15% (soaked), while at 50L–30GS–20Z, they reached 42% and 16%, showing improved moisture resistance. Although soaked CBR values remained lower than unsoaked, the increase from 4% in natural soil to over 15% in stabilized mixes demonstrates the effectiveness of GS and Z in strengthening lateritic soil. Overall, the results confirm that an optimum GS–Z blend significantly enhances bearing capacity and durability, making the soil suitable for road construction.

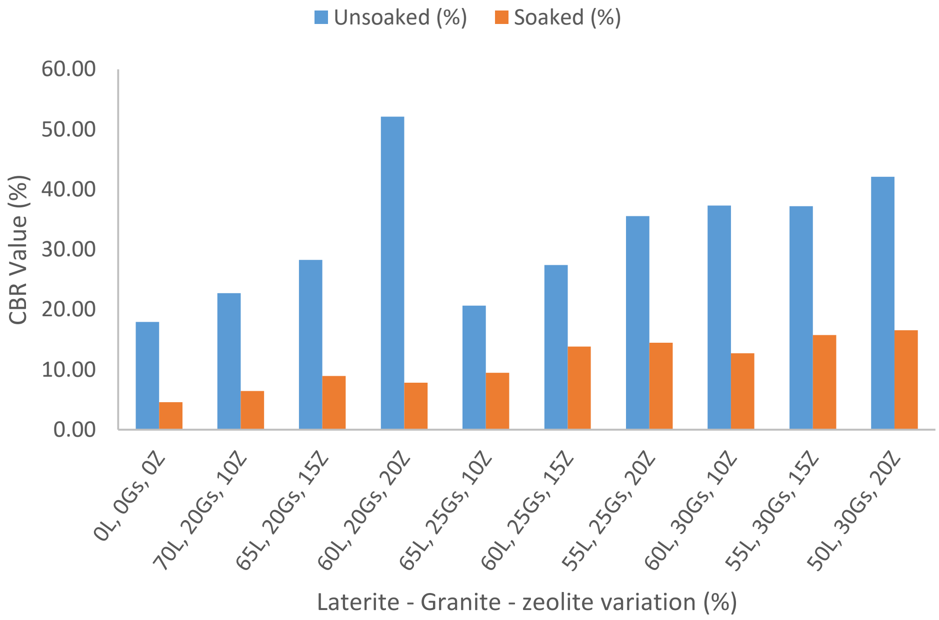

Figure 5: Variation of CBR Value of the Soil Mixtures and Soil-Admixture Content

4.1.2 Unconfined compressive strength (UCS)

Figure 6 shows that the unconfined compressive strength (UCS) of natural lateritic soil was low (~100 kN/m² at both 7 and 28 days), reflecting weak bonding. The inclusion of granite sludge (GS) and zeolite (Z) progressively increased UCS across all mixes, with strength gains more pronounced at higher stabilizer contents. For example, UCS rose to 130/170 kN/m² (7/28 days) at 70L–20GS–10Z, and further to 180/320 kN/m² at 65L–20GS–15Z.

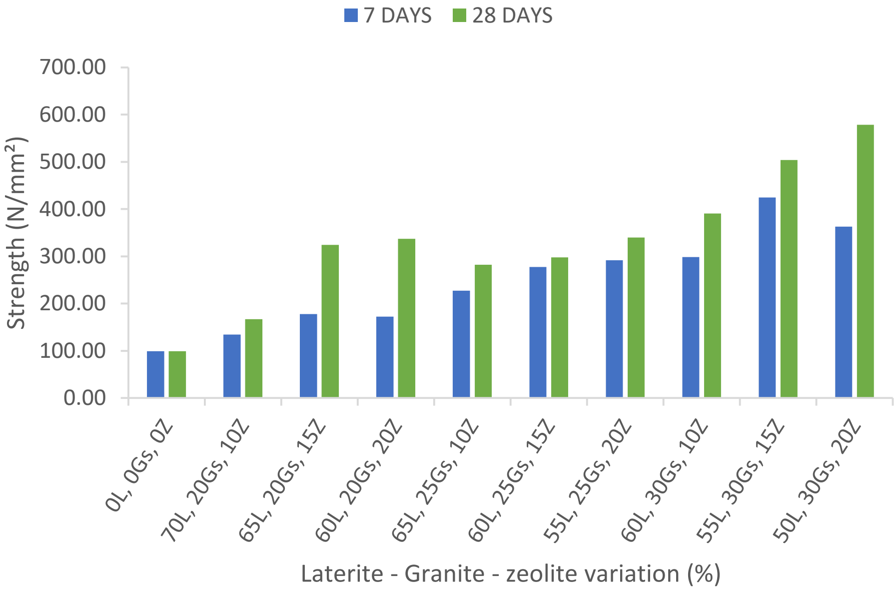

Figure 6: Variation of UCS and Soil-Admixture Content of the Soil Mixtures

Curing age had a clear effect, with 28-day strengths consistently exceeding 7-day values. At higher GS levels, improvements were substantial: 55L–25GS–20Z reached 290/340 kN/m², while the optimum mix (50L–30GS–20Z) achieved the highest UCS of 360/580 kN/m². These results confirm that strength development is time-dependent and driven by particle packing from GS and pozzolanic reactions of Z with soil alumino-silicates, forming cementitious compounds that enhance soil stability.

5.0 CONCLUSION AND RECOMMENDATIONS

The incorporation of Granite Sludge (GS) and Zeolite (Z) into lateritic soil markedly improved its engineering properties. Plasticity was significantly reduced, with the Plasticity Index dropping from 31.05% to 12% at the optimal mix (50L–30GS–20Z), minimizing swelling potential. Compaction characteristics improved as the Maximum Dry Density increased from 1.62 to 1.83 g/cm³, while the Optimum Moisture Content decreased from 16.8% to 10.5%, indicating enhanced workability. Strength indices also showed substantial gains: the CBR rose from 18% to 52%, and the UCS increased from 100 kN/m² in the natural soil to 360 kN/m² at 7 days and 580 kN/m² at 28 days, with the highest strength achieved at the 50L–30GS–20Z mix. Given these improvements, the use of Granite Sludge and Zeolite as stabilizers is recommended for upgrading lateritic soils in pavement construction. The optimal blend of 50% Laterite, 30% GS, and 20% Zeolite provides the best balance of reduced plasticity, higher density, and enhanced strength, making it suitable for sub-base and base course applications in line with standard specifications.

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