



Advanced Modeling of Geotechnical Performance of Desert Sand Stabilized Using Hydraulic Binders for Pavement Subgrade Applications

CECILIA ATTAH¹, HASSAN SHUAIBU ABDULRAHMAN¹ and MOHAMMED MUSTAPHA ALHAJI¹

^{1,2,3}Department of Civil Engineering, Federal University of Technology Minna.

¹emailaddress1@email.com

²emailaddress1@email.com

³emailaddress2@email.com

Abstract. This study evaluates the geotechnical enhancement of Desert Sand (DS) through blending with River Sand (RS) and stabilization using RoadCem (RC) for application in flexible pavement subgrades. DS, though widely available in arid regions, is naturally deficient in strength and cohesion. To improve its engineering properties, DS was mixed with RS in varying proportions (100% DS to 50% DS/50% RS), with the 70% DS and 30% RS blend selected for further treatment with 1%, 3%, and 5% RC. Laboratory tests including particle size distribution, Atterberg limits, compaction, shrinkage, and unconfined compressive strength (UCS) were conducted. Results revealed that Maximum Dry Density (MDD) increased from 1.70 g/cm³ to 1.80 g/cm³, and Optimum Moisture Content (OMC) peaked at 9.5%. The untreated 70DS/30RS mix had a UCS of 74.32 kN/m², which rose to 134.00 kN/m², 261.75 kN/m², and 384.45 kN/m² at 1%, 3%, and 5% RC respectively after 28 days. Plasticity Index reduced from 35.63% to 23.90%, while Linear Shrinkage dropped from 13.24% to 10.25%. All samples were classified as A-3 under AASHTO guidelines. These results confirm that combining RS and RC significantly enhances the suitability of DS for subgrade use, offering a sustainable solution for pavement infrastructure in marginal soil regions.

Keywords. desert sand, river sand, roadcem, soil stabilization, pavement subgrade.

1. Introduction

The performance and durability of pavement infrastructure are largely dependent on the strength and stability of the underlying subgrade materials. In many developing regions, including parts of Nigeria and the MENA region, the widespread occurrence of problematic soils such as dune sands and expansive clay poses serious engineering challenges. These soils exhibit high shrink-swell potential, poor drainage characteristics, and low bearing capacity, which often lead to structural failures in pavements, particularly during seasonal moisture fluctuations (Abderrahmane & Ratiba, 2013; Almadwi & Assaf, 2018). Consequently, improving the engineering properties of such soils has become a critical focus in geotechnical and highway engineering.

Traditional approaches to soil improvement have focused on chemical stabilization using lime, cement, or industrial by-products such as cement kiln dust. While effective, these methods are often accompanied by high costs, environmental concerns, and carbon emissions, prompting the exploration of alternative and more sustainable stabilizers (Fattah, Joni, & Al-Dulaimy, 2016; Al-Tabbaa & Evans, 2005). One promising strategy involves blending locally available marginal materials with minimal dosages of chemical additives to improve the strength, durability, and overall geotechnical performance of subgrade soils (Amhadi & Assaf, 2019; Aguwa, Adejumo, & Aguwa, 2020).

Desert Sand (DS), widely found in northern Nigeria, Libya, and parts of Saudi Arabia, is often overlooked in engineering applications due to its uniform particle size, low cohesion, and negligible plasticity (Aiban, 1994; Al-Aghbari & Dutta, 2005). However, blending DS with coarser, better-graded materials such as River Sand (RS) has been shown to significantly enhance its physical properties. RS provides improved particle interlock, gradation, and frictional resistance, ultimately increasing the loadbearing capacity and



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compactability of the mixture (AlKarni & ElKholly, 2012; Almadwani & Assaf, 2017). Studies by Ghrieb, Mitiche-Kettab, and Bali (2014) and Amel et al. (2017) confirmed that modifying dune sand with inert materials such as pumice or river sand can improve its strength and reduce settlement under load.

In addition to mechanical blending, chemical stabilization using advanced additives such as RoadCem—a proprietary silica-rich cementitious binder—has shown significant potential. These binders enhance the formation of calcium silicate hydrate (C-S-H), leading to improved particle bonding, stiffness, and durability (Holmes, 2015; PowerCem Technologies, 2015). Unlike conventional cement, such stabilizers operate effectively in smaller dosages and can be activated under a wider range of curing conditions. The use of similar mineral-based additives has been shown to significantly improve Unconfined Compressive Strength (UCS) and resistance to moisture-induced degradation in arid and semi-arid soil conditions (Hosseini, Najafi, & Haddad, 2020; Chen, Saha, & Lytton, 2020).

The integration of mechanical and chemical stabilization techniques is now increasingly recognized as a synergistic solution for subgrade improvement. Research by Talal and Assaf (2020) and Ji, Liu, and Ding (2021) highlighted that desert soils treated with both granular materials and hydraulic binders achieve higher UCS values and better volumetric stability than those treated with single stabilizer systems. These hybrid approaches optimize material performance while reducing environmental impact and financial costs, aligning with modern infrastructure sustainability goals.

Given the challenges posed by weak or unstable soils in road construction and the ongoing search for innovative, cost-effective solutions, this study investigates the stabilization of Desert Sand through blending with River Sand and treatment with RoadCem. The study evaluates geotechnical parameters such as maximum dry density (MDD), optimum moisture content (OMC), plasticity index (PI), linear shrinkage (LS), and unconfined compressive strength (UCS) under varying RS and RC proportions. By identifying an optimal DS–RS–RC mix, this research aims to propose an effective and sustainable solution for enhancing subgrade performance in flexible pavement systems.

This study contributes to the growing body of research on alternative ground improvement strategies using locally sourced and low-carbon materials. Its findings are expected to benefit engineers, contractors, and infrastructure planners working in challenging soil environments across sub-Saharan Africa, North Africa, and beyond.

2. Methodology

2.1 Materials Description

The materials evaluated in this study are Desert Sand (DS), River Sand (RS), and RoadCem (RC). DS, characterized by low cohesion and zero plasticity, has a specific gravity of 2.58. It exhibits a slightly higher specific gravity (2.60) and contains minimal fines, enhancing gradation when blended with DS. RoadCem is a high-specific-gravity chemical stabilizer (2.94) intended to enhance soil bonding and strength through pozzolanic reactions.

2.2 Sample Matrix Design

Experimental blends were created using DS and RS in proportions ranging from 100% DS to 50% DS/50% RS. Based on compaction test performance, the 70DS/30RS mixture was selected as the base matrix for stabilization using RC at 1%, 3%, and 5% by dry weight. The mixtures were compacted using Standard Proctor energy and cured for 7 and 28 days for Unconfined Compressive Strength (UCS) testing.



2.3 Model Development

To better understand the relationships between soil composition and mechanical performance, multiple regression models were developed. The Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) were expressed as functions of RS content RRR, using second-order polynomial models:

$$MDD = a_0 + a_1R + a_2R^2 \quad (1)$$

$$MDD = \beta_0 + \beta_1R + \beta_2R^2 \quad (2)$$

These equations were fitted using least squares regression, with RS content expressed as a fraction (e.g., 0.1 for 10%).

The strength development with RoadCem addition was modeled using a log-linear model to capture both the chemical activation and time-dependent curing effect:

$$q_u = \gamma_0 + \gamma_1 \cdot C + \gamma_2 \cdot \log(t) \quad (3)$$

Where q_u is the Unconfined Compressive Strength (kN/m^2), C is the percentage of RoadCem content, t is curing time in days and $\gamma_0, \gamma_1, \gamma_2$ are regression coefficients.

An interaction model was also tested to determine the combined influence of RoadCem and RS content on strength:

$$q_u = \delta_0 + \delta_1F + \delta_2C + \delta_1RC \quad (4)$$

This model captures synergistic effects, allowing assessment of how RS helps optimize RC's performance, particularly in reducing OMC and enhancing strength.

2.4 Data Calibration and Model Fitting

The models were calibrated using Microsoft Excel and MATLAB's Curve Fitting Toolbox. Coefficients were optimized using nonlinear regression, with performance metrics including R^2 , Adjusted R^2 , and RMSE to assess model validity. Acceptable fits were defined by $R^2 > 0.90$. The strength prediction model was validated against experimental UCS values at 7 and 28 days.

2.5 Supporting Indices and Classification

Plasticity Index (PI) and Linear Shrinkage (LS) were measured and interpreted as qualitative support parameters. PI was calculated from the difference between Liquid Limit (LL) and Plastic Limit (PL), while LS was fitted against RC content using a linear decay model. AASHTO soil classification was determined based on particle size and PI, providing a compatibility check for subgrade application suitability.

3. Results and Discussion

3.1 Compaction Characteristics

The compaction behavior of the soil mixtures, as presented in Table 1 and Figure 1, shows a positive trend with increasing River Sand (RS) content. The Maximum Dry Density (MDD) increased from 1.70 g/cm^3 (100% DS) to 1.80 g/cm^3 (50% RS), indicating denser packing due to the well-graded nature of RS. The Optimum Moisture Content (OMC) increased to a peak of 9.50% at 30–40% RS before slightly decreasing at 50%. This suggests that the addition of RS improves compaction up to an optimum threshold, beyond which excess sand reduces moisture absorption capacity. These results are consistent with findings by Almadwi and Assaf (2018), who reported improved compaction characteristics of desert sands blended with cement and river sand. Similarly, AlKarni and ElKholly (2012) observed enhanced MDD and reduced



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voids when cement was used to improve dune sands, highlighting the importance of gradation and blending in subgrade treatment.

Table 1: Regression Model for MDD and OMC

RS (%)	MDD (g/cm ³)	OMC (%)
0	1.7	7
10	1.72	7.5
20	1.73	8.5
30	1.77	9.5
40	1.79	9.5
50	1.8	9.1

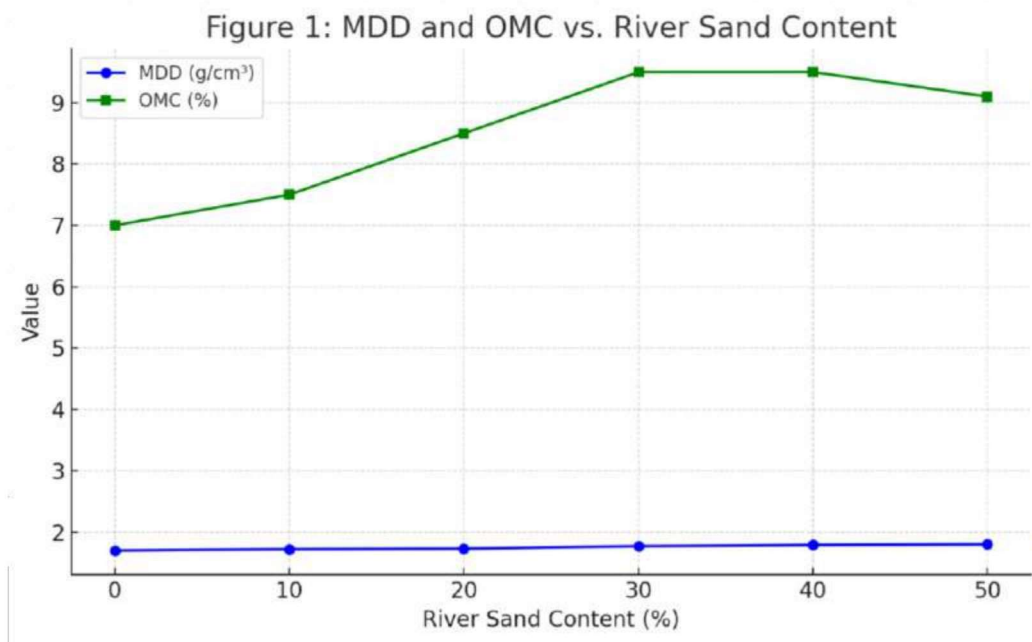


Figure 1: Maximum Dry Density and Optimum Moisture Content vs. RS Content

3.2 Strength Performance with RoadCem

Table 2 and Figure 2 clearly demonstrate the influence of RoadCem (RC) on the Unconfined Compressive Strength (UCS) of the 70DS/30RS mix. While the untreated mix recorded a static UCS of 74.32 kN/m² at both 7 and 28 days, the addition of 1%, 3%, and 5% RC resulted in strength increases to 134.00, 261.75, and 384.45 kN/m² respectively after 28 days. This exponential increase in UCS with RC addition validate the effectiveness of RoadCem as a soil stabilizer. Holmes (2015) reported similar UCS improvements with RoadCem due to its pozzolanic properties and ability to enhance calcium silicate-hydrate (C-S-H) bonding.

Additionally, Amhadi and Assaf (2019) demonstrated strength development in cemented desert soils, confirming the compatibility of siliceous additives with sandy soils for road construction.

Table 2: UCS Values for 70DS/30RS Mix at Varying RoadCem Content

RC (%)	UCS at 7 Days (kN/m ²)	UCS at 28 Days (kN/m ²)
0	74.32	74.32
1	89.33	134
3	174.5	261.75
5	256.3	384.45

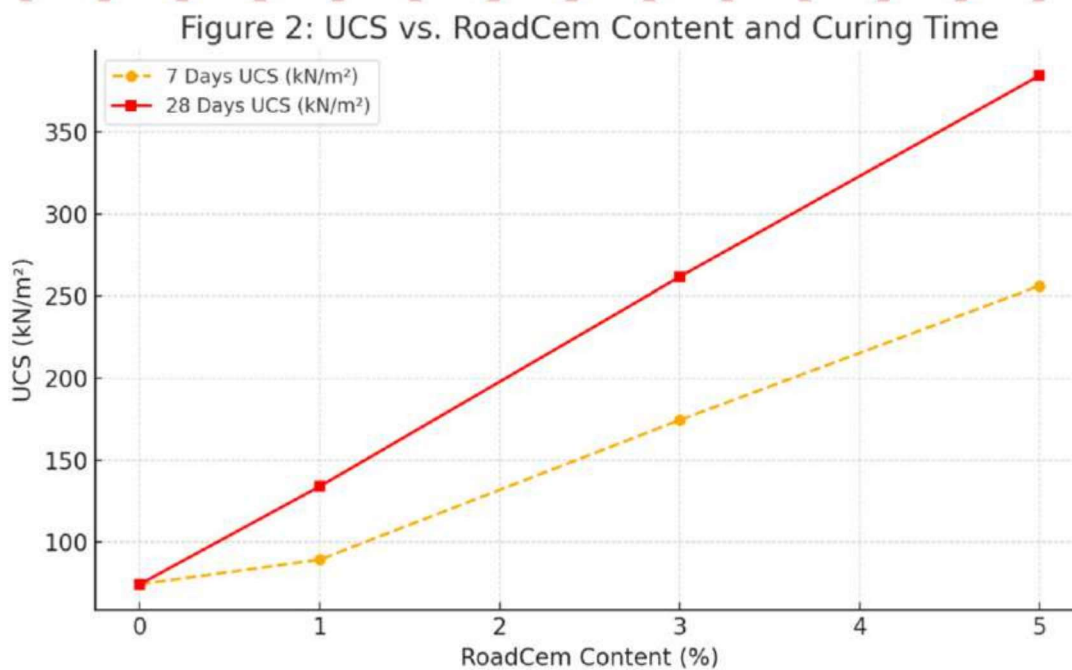


Figure 2: UCS vs. RoadCem Content and Curing Time

3.3 Interaction of River Sand and RoadCem Strength

The 3D interaction surface shown in Figure 3 and data from Table 3 reveal that both River Sand and RoadCem synergistically contribute to UCS improvements. While RC was the primary source of chemical stabilization, RS provided a granular skeleton on that enhanced load distribution and reduced compressibility. The combination of 70DS/30RS with 5% RC gave the peak UCS of 384.45 kN/m². These results are consistent with findings by Ghrieb, Mitiche -Kettab, and Bali (2014), who demonstrated that stabilization of dune sand using both mechanical blending and cement -based additives significantly improves strength performance. Similarly, Fattah et al. (2016) reported that lime -silica fume-stabilized sands achieved higher load resistance when supplemented with a well-graded filler material.

Table 3: UCS Interaction Model Results

RS (%)	RC (%)	UCS at 7 Days (kN/m ²)	UCS at 28 Days (kN/m ²)
30	1	89.33	134
30	3	174.5	261.75
30	5	256.3	384.45
50	1	85	120
50	3	160	230
50	5	240	350

Figure 3: Interaction of RS and RC on UCS (28 Days)

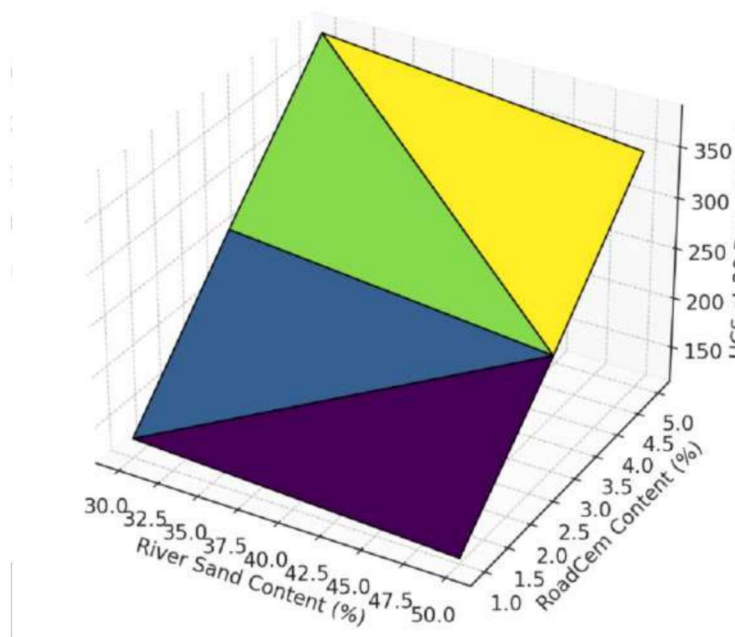


Figure 3: Interaction of UCS with RoadCem and River Sand

3.4 Plasticity and Shrinkage Behavior

As illustrated in Table 4 and Figure 4, the addition of RC led to a progressive reduction in both Plasticity Index (PI) and Linear Shrinkage (LS). The PI dropped from 35.63% to 23.90%, and LS from 13.24 % to 10.25%, indicating improved volumetric stability and reduced swelling potential. These outcomes align with the observations of Hossein, Najafi, and Haddad (2020), who found that slag -stabilized sandy soils exhibited reduced plasticity and shrinkage due to binder -soil matrix densification. Al -Aghbari, Mohamedzein, and Taha (2009) also noted similar reductions in plastic behavior when desert sands were treated with cement and cement dust.

Table 4: Plasticity Index and Linear Shrinkage for Varying RC Content



RC (%)	PI (%)	LS (%)
0	35.63	13.24
1	32.1	12.5
3	28.15	11.5
5	23.9	10.25

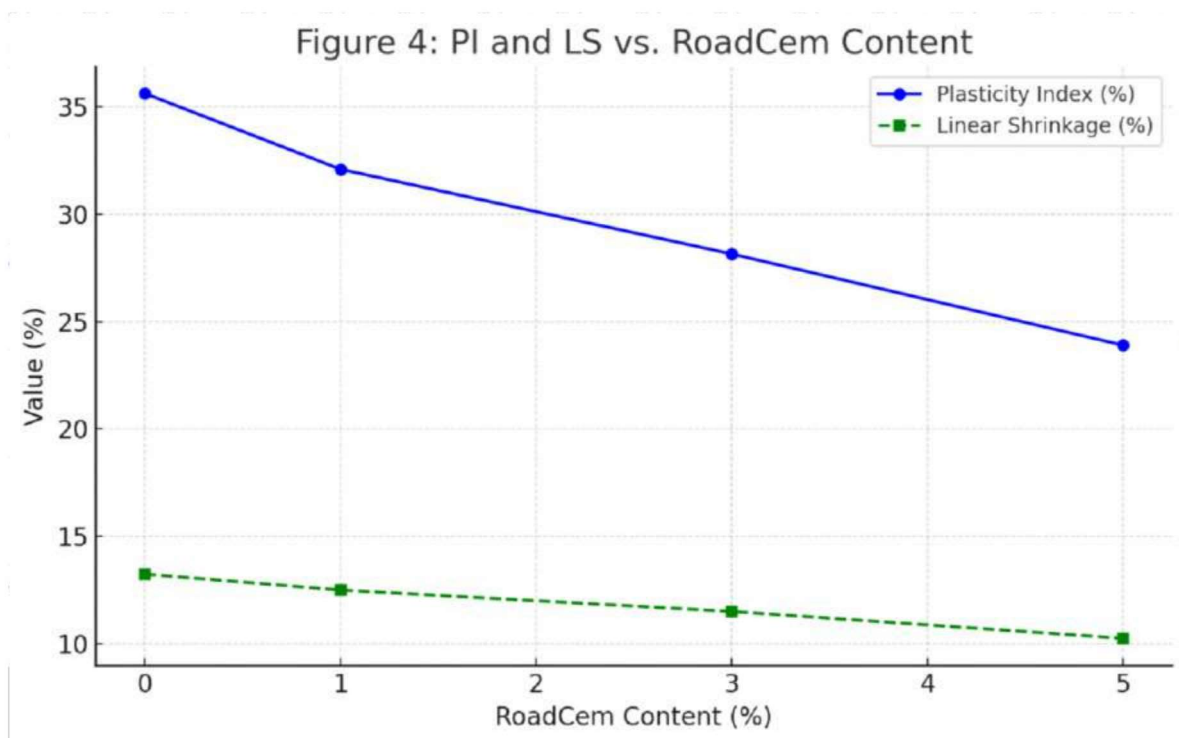


Figure 4: Plasticity Index and Linear Shrinkage vs. RoadCem Content

3.5 Soil Classification

Based on AASHTO classification (Table 5), all samples were consistently categorized as A -3, suitable for subgrade materials. This is attributed to the dominance of sandsized particles and low fines content after mixing DS and RS. These findings are consistent with earlier work by Abderrahmane and Ratiba (2013), who reported that stabilized dune sands retained their classification as sandy soils even after treatment, maintaining their suitability for use in pavement foundation layers. Similarly, Aaghbari and Dutta (2005) confirmed that desert sand-cement mixtures remained within acceptable gradation classes for base and sub-base courses.



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Table 5: Soil Classification Based on AASHTO Criteria

RS (%)	Soil Classification
0	A-3
10	A-3
20	A-3
30	A-3
40	A-3
50	A-3

4. Conclusion

This study evaluated the performance of Desert Sand (DS) blended with River Sand (RS) and stabilized with RoadCem (RC) for pavement subgrade applications, focusing on compaction characteristics, strength development, plasticity, and shrinkage behavior. The results clearly demonstrated that the addition of RC improved the gradation and compaction of the DS, with the Maximum Dry Density increasing from 1.70 g/cm³ to 1.80 g/cm³ and Optimum Moisture Content peaking at 9.5% for 30–40% RS blends. The mechanical strength, assessed through Unconfined Compressive Strength (UCS), significantly improved with RoadCem stabilization, reaching a maximum value of 384.45 kN/m² at 5% RC after 28 days. This indicates the effectiveness of RC in enhancing pozzolanic reactions and binding within the soil matrix.

Furthermore, the combined use of RS and RC showed synergistic benefits, with the 70DS/30RS + 5% RC blend emerging as the optimal mix for achieving both strength and compaction. Plasticity Index and Line Shrinkage were substantially reduced with increasing RC content, reflecting enhanced volumetric stability and reduced swell potential—key factors in the durability of pavement subgrades in expansive soil regions. Importantly, despite the modifications, all treated blends remained within the A-3 classification under AASHTO standards, confirming their continued suitability for use in road construction.

Comparisons with recent studies confirm the validity of these findings and support the assertion that combining mechanical and chemical stabilization methods yields superior results in soil improvement. The outcomes of this study provide a reliable basis for using locally available DS and RS materials, alongside RC, as cost-effective and performance-enhancing alternatives for pavement infrastructure, especially in semi-arid regions where expansive soils are prevalent.

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