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Improvement of Crude Oil–Contaminated Lateritic Soil Using Steam Injection and Periwinkle Shell Ash for Road Subbase Applications

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Abstract

Contamination from petroleum hydrocarbons poses a significant threat to soil and groundwater systems, thereby endangering ecosystems, human health, and socio-economic sustainability. This study evaluates the combined effectiveness of steam injection remediation and periwinkle shell ash (PSA) stabilization in improving the geotechnical properties of crude oil–contaminated lateritic soil for road subbase applications. Steam injection was applied at durations of 1 hour, 1 hour 30 minutes, 2 hours, and 2 hours 30 minutes. The remediated soil was subsequently stabilized with PSA at incremental additions of 4% up to 16%. Geotechnical tests were conducted in accordance with BS 1377. Results showed that steam injection achieved a maximum total petroleum hydrocarbon (TPH) removal efficiency of 75.89% at 1 hour 30 minutes, beyond which efficiency declined. Compaction results indicated that the untreated soil had Maximum Dry Density (MDD) values of 1.60 Mg/m³ for British Standard Light (BSL) and 1.75 Mg/m³ for British Standard Heavy (BSH), which increased to peak values of 1.69 Mg/m³ and 1.88 Mg/m³, respectively, after treatment. Optimum moisture content (OMC) increased with PSA content, reaching 16.56% for BSL and 14.65% for BSH at 12% PSA. The untreated soil recorded an unsoaked CBR of 19.3%, while peak values of 65.78% for BSL and 83.48% for BSH were obtained at 8% PSA with 1 hour 30 minutes of steam injection. Soaked CBR improved from 6.81% to 31.82% for BSL and 49.64% for BSH, satisfying Nigerian General Specifications for subbase materials. The study demonstrates that the combined use of steam injection and PSA provides a sustainable and effective method for improving crude oil contaminated lateritic soils for road subbase material.

KEYWORDS: Steam Injection, Periwinkle shell Ash (PSA), Compaction (OMC and MDD), CBR



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1. INTRODUCTION

Environmental pollution has emerged as one of the most critical global challenges, with its intensity and spatial extent increasing rapidly due to industrialization, urbanization, and energy exploitation activities. Among the various forms of pollution, contamination arising from petroleum hydrocarbons poses a severe threat to soil and groundwater systems, thereby endangering ecosystems, human health, and socio-economic sustainability. Hydrocarbon contaminants migrate through soil profiles and aquifers, leading to persistent groundwater pollution and long-term environmental degradation [1], [2].

Soil contamination results in the accumulation of hazardous substances such as total petroleum hydrocarbons (TPH), polycyclic aromatic hydrocarbons (PAHs), heavy metals, and other toxic compounds, which impair soil fertility, reduce agricultural productivity, and compromise engineering performance [3], [4].

Steam injection technology, originally developed in petroleum engineering as an Enhanced Oil Recovery (EOR) technique, has demonstrated considerable potential for application in environmental remediation. Enhanced Oil Recovery methods are broadly classified into thermal and non-thermal processes. Thermal methods include steam injection, hot water flooding, and in-situ combustion, whereas non-thermal methods include chemical flooding using surfactants and polymers, as well as gas injection such as CO₂ [5], [6]. Steam injection enhances contaminant removal by increasing temperature, reducing hydrocarbon viscosity, and weakening the bond between hydrocarbons and soil particles.

The use of agricultural waste materials such as periwinkle shell ash (PSA) has gained increasing attention in geotechnical engineering due to its pozzolanic properties. PSA contains calcium oxide, silica, and alumina, which react with soil minerals in the presence of moisture to form cementitious compounds such as calcium silicate hydrate and calcium aluminate hydrate. These reactions improve soil strength, reduce plasticity, and enhance durability [7]–[9].

Despite the effectiveness of steam injection in hydrocarbon removal and the proven potential of PSA in soil stabilization, these methods have largely been investigated independently. There is limited information on the combined application of steam injection remediation and PSA stabilization for crude oil-contaminated lateritic soils. Furthermore, the influence of steam injection duration on the efficiency of subsequent stabilization, as well as its impact on key engineering properties such as compaction characteristics and California Bearing Ratio (CBR), has not been adequately established. This gap limits the development of an integrated and sustainable approach for improving contaminated soils for road construction applications.

In view of this, the present study evaluates the effectiveness of steam injection remediation combined with periwinkle shell ash stabilization in improving the engineering properties of crude oil-contaminated lateritic soil. Specifically, the study assesses the efficiency of steam injection in removing total petroleum hydrocarbons (TPH), determines the optimum percentage of PSA required for effective stabilization, and evaluates the resulting engineering properties of the treated soil, including compaction characteristics (Optimum Moisture Content and Maximum Dry Density) and California Bearing Ratio (CBR).

The novelty of this study lies in the integration of steam injection remediation and PSA stabilization as a unified treatment approach, thereby establishing a link between contaminant removal and geotechnical improvement. In addition, the study identifies the optimum steam injection duration and PSA content required to achieve both environmental remediation and engineering suitability. This provides a sustainable, cost-effective, and environmentally friendly solution for converting contaminated lateritic soils into suitable materials for road subbase construction.

II. MATERIALS AND METHODS

2.1 Materials

2.1.1 Lateritic Soil

The lateritic soil used in this study was obtained through disturbed sampling from a laterite formation in Shika, Zaria, Kaduna State, Nigeria (Latitude 11°15'N, Longitude 7°45'E). Soil samples were collected at depths ranging from 1.5 m to 2.0 m. Lateritic soils at this depth are considered suitable for geotechnical evaluation due to their relative homogeneity and reduced organic content [10].



2.1.2 Water

Tap water used in the study was collected from the Soil Laboratory of the Department of Civil Engineering, Nigerian Defence Academy, Kaduna, Nigeria.

2.1.3 Crude Oil

A representative crude oil sample was sourced to simulate soil contamination. The crude oil used for this study was obtained from the Pipelines and Products Marketing Company (PPMC), Kaduna (Latitude 10°24'06"N, Longitude 7°29'32"E). The use of crude oil to artificially contaminate soil samples is consistent with established laboratory practices for petroleum-contaminated soil studies [11].

2.1.4 Steam Injection (SI) Cell

The steam injection remediation cell was constructed using transparent plexiglass plates, with overall external dimensions of 400 mm × 200 mm × 300 mm. Inside the cell, a central partition measuring 300 mm × 200 mm × 300 mm was incorporated to hold the contaminated soil during treatment. A top cover of 400 mm was provided to contain and distribute the steam evenly over the soil, while an adjoining heater chamber (50 mm × 200 mm × 300 mm) was connected to a steam boiler to supply the necessary thermal energy. The SI cell allows controlled steam flow through the contaminated soil, facilitating the volatilization and removal of petroleum hydrocarbons. This design ensures uniform heating, prevents steam escape, and simulates laboratory-scale thermal remediation conditions. The configuration and operation of the SI cell follow principles established in previous studies on laboratory-scale thermal remediation systems [1]–[3].

2.1.5 Periwinkle Shell Ash (PSA)

Periwinkle shells were obtained from Central Market, Kaduna State. The shells were thoroughly washed and sun-dried to remove moisture before being calcined in an electric muffle furnace at 1000°C. The calcined material was ground and sieved through a 75 µm British Standard (BS) sieve to obtain fine ash. As reported by [12] who established the pozzolanic potential of periwinkle shell ash for soil stabilization.

2.2.1 Steam Injection Procedure

The steam injection procedure was carried out using the steam injection (SI) cell described in Section 2.1.4. Cold water was first supplied to the steam generation unit (boiler), where it was heated to produce saturated steam. To ensure efficient steam delivery, the injection line was preheated to minimize thermal losses and prevent premature condensation. A steam trap was installed along the line to remove condensate and maintain continuous and stable steam flow [12].

Steam was subsequently introduced into the heater chamber and distributed into the soil chamber through the perforated partition. As steam permeated the contaminated soil, heat transfer processes increased the soil temperature, leading to a reduction in hydrocarbon viscosity and a weakening of the physicochemical bonds between hydrocarbons and soil particles. This enhanced both the mobility and volatilization of the contaminants, thereby facilitating their removal [13], [14].

The injected steam propagated horizontally through the soil matrix, forming a distinct steam front as observed through the transparent walls of the SI cell. The mobilized oil–water mixture migrated toward the outlet zone, where it was collected and condensed. Phase separation was then achieved by gravity settling, allowing for the recovery of hydrocarbons from the aqueous phase [15].

Upon completion of the remediation process, the treated soil was removed from the SI cell and air-dried under ambient laboratory conditions prior to further testing. The residual total petroleum hydrocarbon (TPH) content was subsequently determined to quantify the efficiency of the remediation process, as expressed in (1) [16].

2.2.2 Total Petroleum Hydrocarbon (TPH) Determination

The gravimetric method (toluene cold extraction) was adopted due to its simplicity, reliability, and suitability for routine laboratory assessment of petroleum-contaminated soils, as recommended by USEPA Method 9071B and reported in previous studies [4], [6].



For the analysis, 5000 g of each contaminated and steam-injection-treated soil sample was air-dried at room temperature for 72 hours. Thereafter, 2500 g of each dried sample was placed into a 50 ml beaker, and 10 ml of toluene was added as the extracting solvent. The mixture was manually stirred continuously for 30 minutes, allowed to stand in a fume cupboard for 2 hours, and subsequently filtered using Whatman No. 42 filter paper. The soil residue was then dried in an oven at 50°C prior to further analysis. This procedure is consistent with gravimetric TPH extraction techniques described by USEPA [7]. TPH was computed as:

$$\text{TPH (mg/kg)} = (W_0 - W_1) / W_0 \times 100 \quad (1)$$

Where;

W_0 = initial weight of sample

W_1 = weight of sample after solvent extraction.

2.2.3 Experimental Determination of Optimum Moisture Content and Maximum Dry Density Using the British Standard Light (BSL) and British Standard Heavy (BSH) Test

The determination of the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) was carried out using the British Standard Light (BSL) and British Standard Heavy (BSH) compaction methods in accordance with BS 1377: Part 4 [18].

About 3 kg of air-dried and pulverized soil samples passing the 4.75 mm sieve were prepared separately for crude oil-contaminated soil and steam-injection-treated soil. Each sample was thoroughly mixed with water to achieve varying moisture contents.

The compaction mould, having an internal diameter of 105 mm, height of 116 mm, and volume of 1000 cm³, was fitted with a collar and placed on a rigid base plate. The empty mould weight was recorded. The soil was compacted in layers using BSL (3 layers, 27 blows, 2.5 kg rammer) and BSH (5 layers, 27 blows, 4.5 kg rammer), with a drop height of 300 mm, as specified in BS 1377 [18].

After compaction, the collar was removed and the excess soil trimmed flush with the mould. The mould with compacted soil was weighed and recorded. Moisture content samples were taken in accordance with BS 1377: Part.

The procedure was repeated with increasing moisture content until the maximum dry density was achieved. The bulk density and dry density were computed where:

$$\text{Bulk density } \rho = \frac{W_2 - W_1}{V} \text{ (g/cm}^3\text{)} \quad (2)$$

$$\text{Dry density } \rho_d = \frac{\text{bulk density}}{1+w} \text{ (g/cm}^3\text{)} \quad (3)$$

$W_2 - W_1$ = mass of wet compacted soil

w = moisture content

v = volume of mould.

2.2.4 Experimental Determination of California Bearing Ratio (CBR)

The California Bearing Ratio (CBR) test was conducted in accordance with ASTM D1883 and BS 1377: Part 4 standards [18].

Approximately 5 kg of air-dried and pulverized soil samples passing the 4.75 mm sieve were prepared for both contaminated and treated soils. Each sample was mixed with water and allowed to equilibrate for at least 12 hours to ensure uniform moisture distribution.

The soil was compacted into a CBR mould (150 mm diameter, 125 mm height, 2210 cm³ volume). The soil was compacted in layers using BSL (3layers, 62blows, 2.5 kg rammer) and BSH (5 layers, 62blows, 4.5 kg rammer), [15]. The specimen was soaked in water for 24 hours prior to testing.

After soaking, surcharge weights were applied, and the specimen was subjected to penetration using a 50 mm diameter plunger at a rate of 1.25 mm/min. Load-penetration data were recorded, and the corresponding loads at 2.5 mm and 5.0 mm penetrations were obtained.



The CBR value was calculated as the ratio of the measured load to the standard load required to achieve the same penetration in crushed stone, expressed as a percentage.

P = load carried by the soil sample at a given penetration (kN)

P_s = standard load for crushed stone (kN), taken as 13.44 kN for 2.5 mm penetration and 20.15 kN for 5.0 mm penetration.

III. RESULTS AND DISCUSSION

3.1 Engineering Properties of the Natural Soil

The natural lateritic soil exhibited Maximum Dry Density (MDD) values of 1.60 Mg/m³ (BSL) and 1.75 Mg/m³ (BSH), with corresponding Optimum Moisture Content (OMC) values of 16.6% and 14.6%, respectively. The California Bearing Ratio (CBR) values were 19.3% and 34.23% (unsoaked) and 6.81% and 9.42% (soaked) for BSL and BSH compaction. These results indicate that the soil does not satisfy the Nigerian General Specifications for subbase materials, particularly under soaked conditions. The low soaked CBR reflects the soil's susceptibility to moisture weakening, typical of lateritic soils dominated by kaolinite clay minerals. Similar observations have been reported in previous studies [2], [16], [7]. The engineering properties of the natural soil are presented in table 1.

Table 1: Engineering properties of the natural lateritic soil

Property	Quantity
Maximum Dry Density, Mg/m ³	
British Standard light	1.60
British Standard heavy	1.75
Optimum Moisture Content, %	
British Standard light	16.6
British Standard heavy	14.6
California Bearing Ratio, %	
Unsoaked	
British Standard light	19.3
British Standard heavy	34.23
Soaked	
British Standard light	6.81
British Standard heavy	9.42
Colour	Light Brown
Dominant clay mineral	kaolinite

3.2 Effect of Steam Injection on Total Petroleum Hydrocarbon (TPH) Removal

The contaminated soil recorded an initial TPH concentration of 10,865 mg/kg, indicating severe hydrocarbon pollution. Steam injection significantly improved contaminant removal, with efficiency increasing from 71.74% at 1 hour to a peak of 75.89% at 1 hour 30 minutes, followed by a decline at longer durations.

This trend can be explained by the thermal desorption mechanism. At optimal duration (1.5 hours), steam increased soil temperature, reduced hydrocarbon viscosity, and enhanced volatilization and mobilization of contaminants. Prolonged steam exposure (beyond 1.5 hours) resulted in: (i) re-condensation of hydrocarbons within soil pores, (ii) redistribution of contaminants to less accessible zones, and (iii) reduction in temperature gradients driving mass



transfer, explaining the decline to 54.29% at 2 hours 30 minutes. These observations are consistent with previous studies [2]– [8]. The variation of remediation efficiency with steam injection duration is presented in Figure 1.

Table 2: Effect of steam injection duration on TPH removal efficiency

Treatment Time	1hour	1hour 30min	2hours	2hour 30min
Remediation Efficiency (%)	71.74	75.89	71.47	54.29

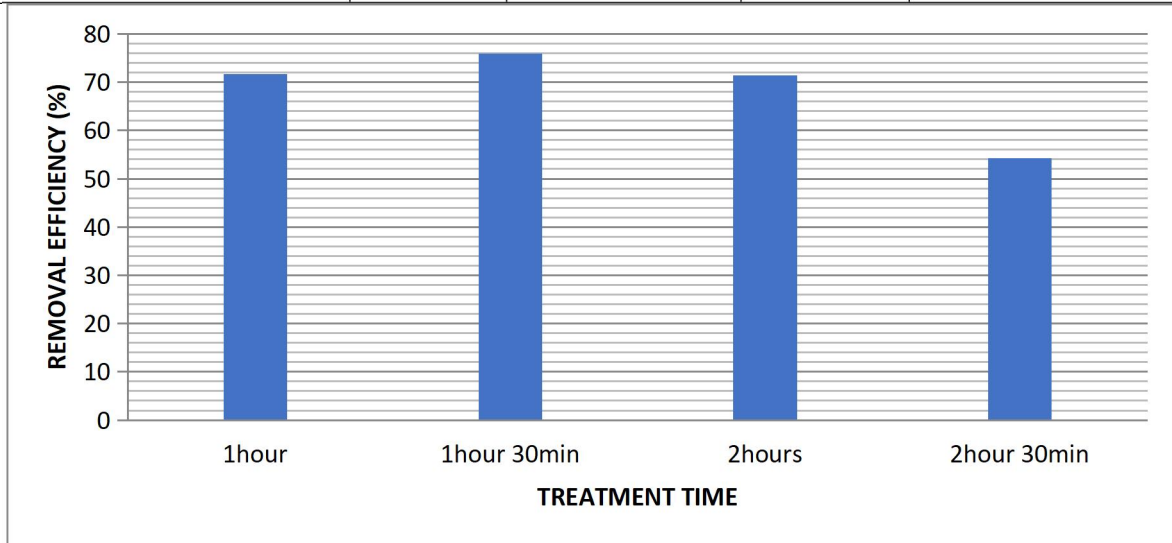


Figure 1: Variation of total petroleum hydrocarbon (TPH) removal efficiency with steam injection time

3.3 Effect of Periwinkle Shell Ash (PSA) Content and Steam Injection on Maximum Dry Density (MDD)

The results show that MDD initially increases with PSA content up to 4–8%, after which it decreases at higher percentages (12–16%). Under BSL, MDD increased from 1.60 Mg/m³ to 1.69 Mg/m³, while under BSH it increased from 1.75 Mg/m³ to 1.88 Mg/m³ at 1 hour 30 minutes of steam injection.

The initial increase in MDD is attributed to the void-filling effect of fine PSA particles, improved particle packing and gradation, and enhanced interparticle bonding. The reduction at higher PSA content is due to flocculated soil structure formation, increased water demand, and reduced specific gravity of ash relative to soil [4]– [8], [6]. Steam injection further enhances MDD up to the optimum duration (1.5 hours) due to better moisture distribution, breakdown of hydrocarbon coatings, and enhanced soil–ash interaction. Beyond this, MDD slightly decreases due to excess moisture absorption and structural loosening [5], [17]. The relationship between MDD, PSA content, and steam injection time under BSL and BSH compaction is shown in Figure 2

Table 3: Variation of MDD with PSA content and steam injection time

Remediation Time	0% PSA BSL (mg/m ³)	4%PSA BSL (mg/m ³)	8%PSA BSL (mg/m ³)	12%PSA BSL (mg/m ³)	16%PSA BSL (mg/m ³)	0% PSA BSH (mg/m ³)	4%PSA BSH (mg/m ³)	8%PSA BSH (mg/m ³)	12%PSA BSH (mg/m ³)	16%PSA BSH (mg/m ³)
0hr	1.60	1.67	1.66	1.65	1.63	1.75	1.79	1.79	1.73	1.73
1hr	1.63	1.67	1.68	1.66	1.65	1.77	1.83	1.84	1.81	1.80
1hr 30min	1.66	1.68	1.69	1.67	1.66	1.80	1.86	1.88	1.83	1.81

2hr	1.65	1.67	1.67	1.64	1.64	1.78	1.80	1.81	1.78	1.78
2hr 30min	1.65	1.66	1.65	1.65	1.64	1.78	1.79	1.81	1.75	1.74

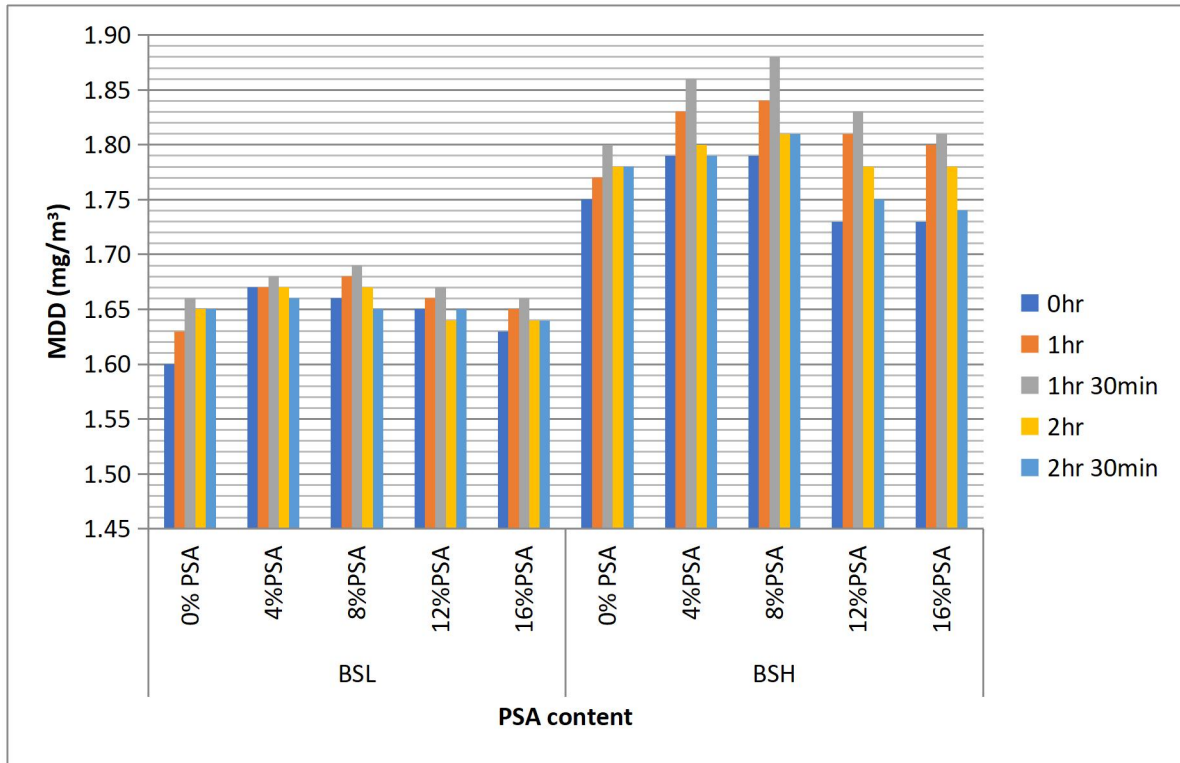


Figure 2: Relationship between MDD and PSA content under BSL and BSH compaction

3.4 Effect of PSA and Steam Injection on Optimum Moisture Content (OMC)

The variation of OMC with PSA content and steam treatment duration is presented in Figure 3. OMC increased with increasing PSA content for all treatment conditions. Under BSL, OMC increased from 16.6% to 19.29%, while under BSH it ranged from 13.53% to 16.01%. The increase is attributed to high surface area and porosity of PSA, enhanced water absorption, lubrication during compaction, and cation exchange/flocculation processes [14], [15], [19].

OMC slightly decreased from 0 hr to 1.5 hr due to better moisture redistribution and breakdown of hydrocarbon coatings. Beyond 1.5 hr, OMC increased again as PSA continued to absorb water and form flocculated structures [17], [18], [19]. increased OMC with ash stabilization due to physicochemical interactions was also reported [18].

Table 4: Variation of OMC with PSA content and steam injection time

Remediation Time	0% PSA BSL (%)	4%PSA BSL (%)	8%PSA BSL (%)	12%PSA BSL (%)	16%PSA BSL (%)	0% PSA BSH (%)	4%PSA BSH (%)	8%PSA BSH (%)	12%PSA BSH (%)	16%PSA BSH (%)
0hr	16.6	17.8	18.3	18.73	19.29	14.64	15.3	15.6	15.9	16.01
1hr	16.2	16.8	16.92	17.25	17.17	13.82	14.81	14.89	15.25	15.20
1hr 30min	15.8	16.0	16.26	16.56	16.52	13.53	13.96	14.34	14.65	14.53
2hr	16.3	16.6	17.3	17.53	17.84	14.07	14.24	14.56	14.76	14.92
2hr 30min	16.5	17.4	17.8	18.25	18.38	14.46	14.83	15.26	15.41	15.57

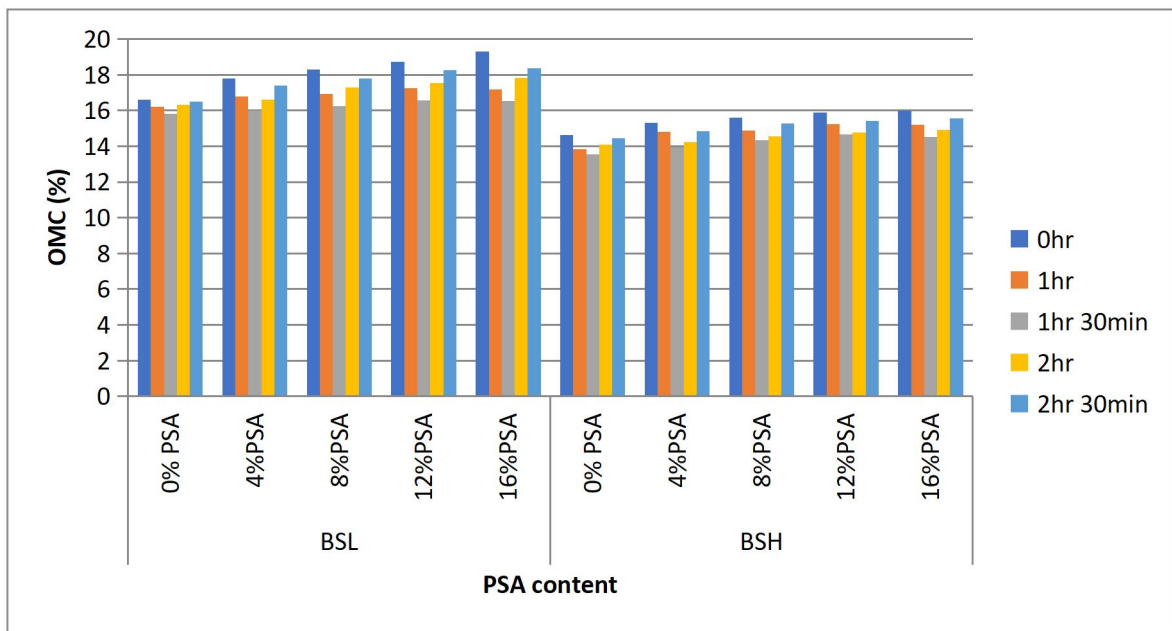


Figure 3: Relationship between OMC and PSA content under BSL and BSH compaction

3.5 California Bearing Ratio

3.5.1 Unsoaked CBR

Unsoaked CBR increased from 0% PSA to 8% PSA, then declined at higher percentages. BSL compaction increased from 19% (0% PSA) to 65.78% (8% PSA), and BSH increased from 34% (0% PSA) to 83.48% (8% PSA).

The increase is attributed to the formation of cementitious compounds (CSH and CAH), improved interparticle bonding, and reduced plasticity. The decrease at higher PSA is due to excess ash, weak bonding, and increased porosity [15], [7], [20], [9]. Steam injection enhances CBR by removing hydrocarbons from soil particles and improving interparticle bonding. The optimum performance at 1 hour 30 minutes indicates maximum synergy between remediation and stabilization. Optimum strength at moderate ash content with reduction at higher percentages was observed [9]. The effect of PSA content and steam injection time on unsoaked CBR is illustrated in Figure 4.

Table 5: Variation of unsoaked CBR with PSA content and steam injection time

Remediation Time	0% PSA BSL (%)	4%PS A BSL (%)	8%PS A BSL (%)	12%PS A BSL (%)	16%PS A BSL (%)	0% PSA BSH (%)	4%PS A BSH (%)	8%PS A BSH (%)	12%PS A BSH (%)	16%PS A BSH (%)
0hr	19.3	26.86	54.8	47.60	40.81	34.23	56.14	78.53	56.54	50.38
1hr	21.89	29.33	63.63	49.14	44.36	37.52	57.63	81.34	69.64	58.22
1hr 30min	23.18	30.15	65.78	50.35	46.74	37.76	60.11	83.48	70.98	64.34
2hr	21.67	29.65	62.14	49.63	43.79	35.66	58.14	80.78	68.25	60.84
2hr 30min	21.14	28	60.05	48.23	43.10	34.85	57.84	80.25	58.96	55.76

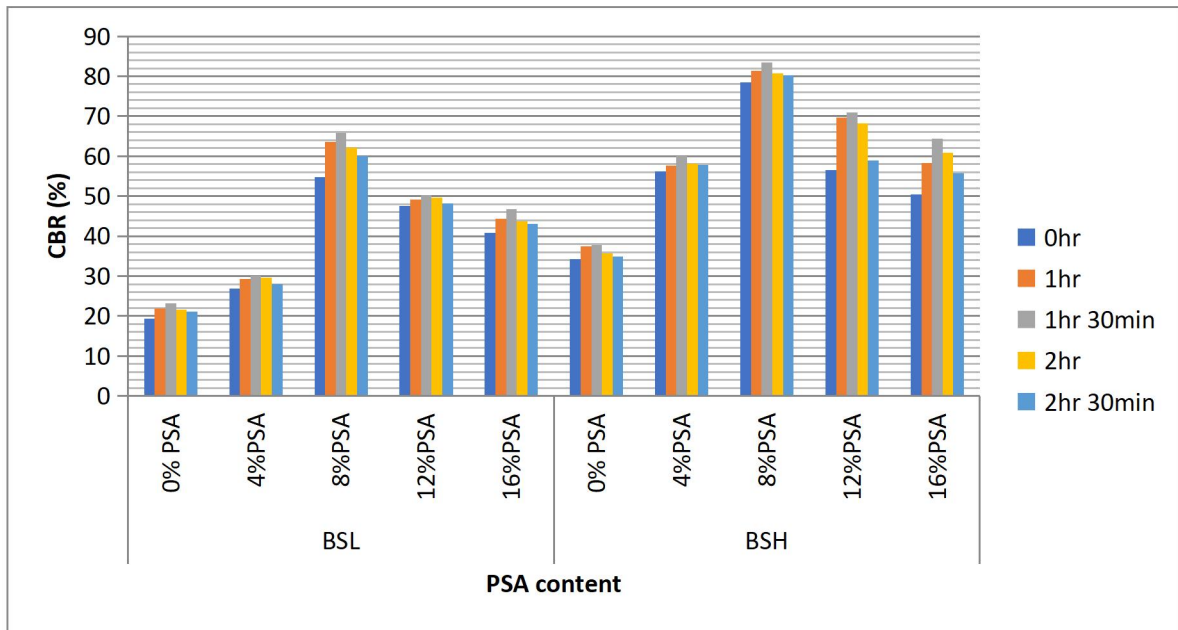


Figure 4: Effect of PSA content on unsoaked CBR under BSL and BSH compaction



3.5.2 Soaked CBR

Soaked CBR is critical for subgrade performance under wet conditions. 0% PSA soil under BSL had 6.81%, while 8% PSA with steam injection at 1 hr 30 min reached 31.82%, meeting Nigerian specifications ($\geq 30\%$). The improvement is due to reduced moisture susceptibility, stronger cementitious bonding, and enhanced soil structure [20], [1], [19]. Higher PSA contents (12–16%) reduced soaked CBR due to increased porosity and poor bonding under saturated conditions and Excess fines reducing strength. under BSL. This agrees with [16] who noted that over-stabilization reduces performance under soaked conditions. The variation of soaked CBR with PSA content and steam injection time is shown in Figure 5.

Table 6: Variation of soaked CBR with PSA content and steam injection time

Remediation Time	0% PSA BSL (%)	4%PSA BSL (%)	8%PSA BSL (%)	12%PSA BSL (%)	16%PSA BSL (%)	0% PSA BSH (%)	4%PSA BSH (%)	8%PSA BSH (%)	12%PSA BSH (%)	16%PSA BSH (%)
0hr	6.81	11.96	27.15	19.8	17.30	9.42	14.87	48.52	28.5	20.63
1hr	8.48	13.63	30.66	25.72	20.73	11.95	17.53	47.63	32.10	28.77
1hr 30min	9.54	13.48	31.82	25.64	21.82	12.85	20.14	49.64	33.12	29.18
2hr	8.78	12.75	29.77	23.70	19.96	11.72	18.45	49.85	33.24	27.48
2hr 30min	7.64	12.23	27.63	20.58	19.27	10.28	16.63	48.76	32.16	28.59

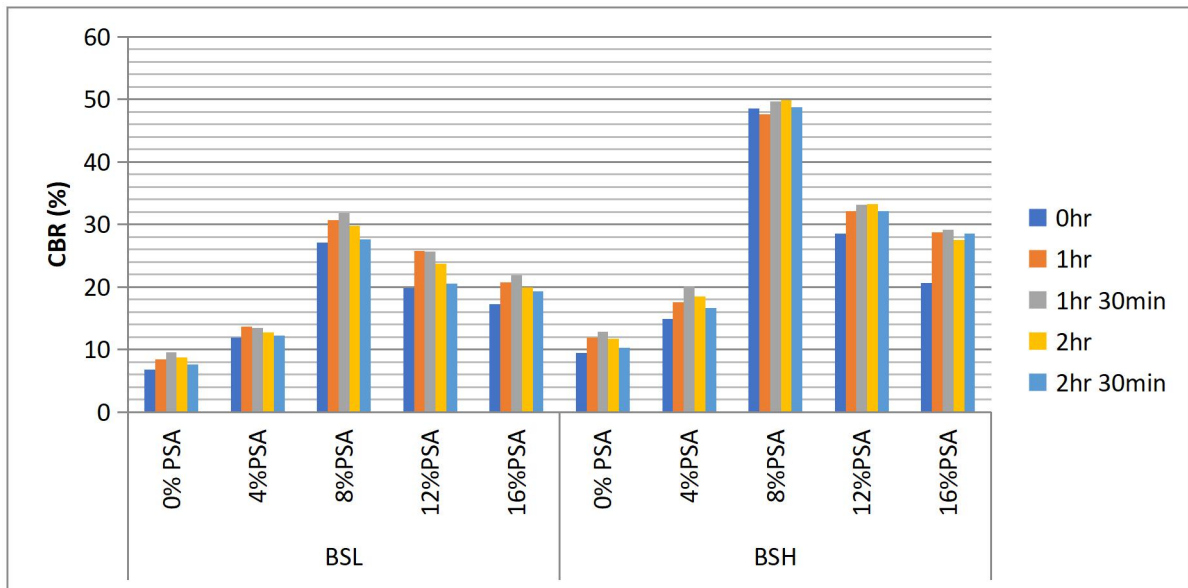


Figure 5: Effect of PSA content on soaked CBR under BSL and BSH compaction

IV. CONCLUSION

This study investigated the effectiveness of steam injection remediation combined with periwinkle shell ash (PSA) stabilization on crude oil-contaminated lateritic soil, focusing on contaminant removal efficiency and the subsequent improvement of engineering properties for use as subbase material. The highest TPH removal efficiency of 75.89% was achieved at 1 hour 30 minutes, while longer exposure times resulted in reduced efficiency. This indicates that excessive heating diminishes contaminant desorption due to stabilization of soil–hydrocarbon complexes and reduced surface activity.

The compaction characteristics of the soil improved with PSA treatment. The natural soil exhibited maximum dry density (MDD) values of 1.60 Mg/m³ (BSL) and 1.75 Mg/m³ (BSH), and optimum moisture content (OMC) values of 16.6% (BSL) and 14.6% (BSH). After treatment, MDD increased to 1.69 Mg/m³ (BSL) and 1.88 Mg/m³ (BSH) at 8–12% PSA with 1 hour 30 minutes of steam injection, while OMC rose to 19.29% (BSL) and 16.01% (BSH).

The natural soil's California Bearing Ratio (CBR) was 19.3% and 34.23% (unsoaked, BSL and BSH) and 6.81% and 9.42% (soaked, BSL and BSH), indicating that the soil does not meet subbase standards without stabilization. Following treatment, the unsoaked CBR peaked at 65.78% (BSL) and 83.48% (BSH) for 8% PSA at 1 hour 30 minutes of steam injection. The soaked CBR reached 31.82% (BSL) and 49.85% (BSH), meeting the Nigerian General Specifications for Roads subbase requirements at the optimum PSA content.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper. The research was conducted independently without any financial or commercial relationships that could be construed as a potential conflict of interest.

Data Availability Statement

The data used to support the findings of this study are available from the corresponding author upon reasonable request. The datasets generated and analyzed during the current study are not publicly available due to institutional and laboratory restrictions but can be provided for academic and research purposes.

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