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Stability Improvement of Oil Contaminated Soil Using Cement and Rice Husk Ash

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Abstract

Oil spills severely degrade soil engineering properties, reducing shear strength and making it unsuitable for construction. This study investigates stabilizing oil-contaminated clayey soils using a Portland Limestone Cement (PLC) and Rice Husk Ash (RHA) blend. Results showed optimal strength at 8% PLC with 4% RHA, improving undrained shear strength from 32.24 to 140.77 kN/m^2 and bearing capacity from 67.40 to 244.86 kN/m^2, while 8% PLC with 2% RHA optimally reduced settlement from 117 mm to 11 mm. For cost-effectiveness, 6% PLC with 8% RHA is recommended as the most economical and environmentally sustainable solution for foundation applications.

Keywords: Geotechnical properties, Oil-contaminated soil, Portland Limestone Cement, Rice Husk Ash, Soil stabilization

1. Introduction

Oil spills severely degrade the engineering properties of soils, reducing their shear strength and making them unsuitable for use in foundations and earthworks. Rivers State, Nigeria, plays a crucial role in the oil and gas sector, possessing significant oil reserves that bolster the national economy [1]. The region's complex geological profile, characterized by a high-water table, soft clay-rich soils, and organic matter, significantly impacts the engineering qualities of the soil [2]. Oil contamination negatively impacts soil characteristics and groundwater, consequently making foundations of buildings, roadways, and other earth-retaining structures vulnerable to changes in geotechnical properties [3]. Hydrocarbon pollution modifies the physical characteristics of soils and gives rise to geotechnical challenges associated with constructing structures on oil-affected soils [4]. These oil spills on land lead to soil contamination, thereby modifying vital geotechnical properties like soil-bearing capacity, foundation settling, shear strength, permeability, plasticity, and compressibility [5,6].

Portland Limestone Cement (PLC) has been demonstrated to enhance the engineering characteristics of oil-contaminated soils; however, its rising market cost and significant CO_2 emissions are detrimental to both the economy and the environment [7]. In an effort to make soil stabilization more affordable and mitigate environmental pollution, research initiatives have focused on employing less expensive and abundantly available agricultural waste materials like Rice Husk Ash (RHA) as an alternative or supplementary binder. RHA, a by-product of rice milling, contains approximately 67-70% silica in an amorphous state, which can react with CaOH released during cement hardening to form additional cementitious compounds [8]. This research focuses on enhancing the stability of oil-contaminated soils using blended ratios of PLC and RHA, with the aim of determining the most effective and economically advantageous mix proportion.

1.1 Literature Survey/Review

Extensive research has been conducted on the geotechnical properties of soils in the Niger Delta region and the implications of oil contamination on soil behavior. The area is mainly characterized by soft and clay-rich soils with high water content and low shear strength, which introduce significant difficulties into foundation design efforts [9]. Studies have shown that soils in the region typically consist of 18-35% fines and 55-82% sand, with inorganic silty clay exhibiting medium plasticity [10]. Oil content in soil increases inter-particle slippage, reducing shear strength, with undrained cohesion and friction angle decreasing by averages of 22.92% and 27.78%, respectively [11]. The pollution index related to undrained cohesion and friction angle signifies a significant impact of hydrocarbon pollution on shear strength parameters. Previous research has demonstrated that stabilization with Portland cement effectively improves the properties of oil-contaminated soils, with cement-stabilized contaminated soil showing significant increases in unconfined compressive strength (UCS) and bearing capacity [12]. Studies using cement kiln dust and lime have similarly shown improved compaction, UCS, and strength properties, while the incorporation of oil-contaminated soil in cement-based materials has proven to be a lucrative and environmental solution [13,14].

Research on RHA as a soil stabilization agent has revealed that treating oil-contaminated soil with RHA improves index properties and strength, with maximum UCS values obtained at 2-8% RHA content [15,16]. The addition of RHA has been shown to decrease liquid limit and plasticity index while increasing internal friction angle, and consolidation studies indicate that RHA treatment reduces compression and swelling indices [17,18].

Studies combining cement and RHA have demonstrated significant improvements in the geotechnical properties of contaminated soils, with the blend effectively enhancing strength and reducing permeability [19]. Research on cement-RHA stabilization of oil-polluted laterite soil showed that the addition of 10% RHA or 8% OPC effectively restored and enhanced geotechnical characteristics [20]. Investigations into consolidation properties have shown that cement-RHA blends reduce the compression index and coefficient of volume change while improving settlement characteristics [21]. However, a significant knowledge gap exists in the literature regarding the strength and settlement characteristics of oil depot soils stabilized with PLC and RHA blends, as previous studies have primarily focused on road pavements or manually contaminated soils rather than field-contaminated oil depot soils. This study therefore aims to bridge this gap by investigating the use of PLC-RHA mixtures for stabilizing oil-contaminated soils from actual oil depot sites in the Niger Delta, focusing on strength enhancement and settlement reduction, while identifying the most effective proportions for practical application.

2. Materials and Methods

The research utilized oil-contaminated soil collected from Abuloma in Rivers State, Nigeria, at depths of 1 meter, 2 meters, and 3 meters below the surface. Portland Limestone Cement (PLC) was sourced from local vendors at the Mile 3 market in Diobu, Port Harcourt, while Rice Husk Ash (RHA) was obtained from rice vendors in Abakaliki, Ebonyi State. The RHA was dried in an oven at 100°C for 24 hours and subsequently sieved through a 425-micron mesh to eliminate impurities. The physical and chemical properties of the PLC and RHA materials are presented in Table 1.

Table 1: Physical and Chemical Properties of PLC and RHA

PROPERTY	PLC	RHA
pH	13	-
CaO (%)	68.22	1.38
SiO_2 (%)	22.80	65.8
Al_2O_3 (%)	5.14	5.2
Fe_2O_3 (%)	3.72	0.88
MgO (%)	1.44	1.94
SO_3 (%)	2.63	-
LOI (%)	1.46	16.56
Specific gravity	3.11	2.08

2.1 Sample Preparation and Testing

All laboratory tests and data analyses were conducted following the American Society for Testing and Materials (ASTM D2487-17, 2017) and British Standard (BS 1377: 1990) guidelines for soil testing [22,23]. Uncontaminated soil adjacent to the oil-contaminated soil was collected, and samples of the contaminated soil were sent to a chemical laboratory to determine the level of oil contamination. The oil-contaminated soil underwent tests for specific gravity, moisture content, Atterberg limits, particle size distribution, unconfined compressive strength (UCS), and consolidation. The specific gravity of both the PLC and RHA was also measured. Previous research indicates that the optimal contents for stability are 10% for PLC and 6% for RHA [20, 21]. Consequently, the following mix proportions were investigated: 1% PLC - 9% RHA, 2% PLC - 8% RHA, 3% PLC - 7% RHA, 4% PLC - 6% RHA, and 5% PLC - 5% RHA based on the weight of the contaminated soil. The tests conducted, standards used, and parameters measured are outlined in Table 2.

Table 2: Test, Standard used and Parameters Measured.

Test on Soil, PLC and RHA	Test	Standard Used	Parameters Measured
Soil	Specific gravity	ASTM D792 [24]	Specific gravity
	Bulk density	ASTM D7263-21 [25]	Bulk density
	Moisture content	ASTM D4959-16 [26]	Moisture content
	Atterberg limit	ASTM D4318-17e1 [27]	Consistency limits
	Particle size distribution	ASTM D6913/D6913M-17 [28]	Grain size distribution
	Unconfined compressive strength	ASTM D2166 [29]	Shear strength
	Consolidation test	ASTM D2435/D2435M-11 [30]	Coefficient of compressibility a_v, Coefficient of volume change m_v, Coefficient of

			Consolidation C_v, Compression Index C_c , Pre-consolidation Pressure ρ_c and Coefficient of Permeability k
PLC	Specific gravity	IS 2720- part 3 [31]	Specific gravity
RHA	Specific gravity	ASTM C311M-18 [32]	Specific gravity

The UCS test was conducted on both natural and modified soil samples following ASTM D2166 procedures [29]. Soil samples were mixed with varying percentages of PLC and RHA (1% PLC - 9% RHA, 2% PLC - 8% RHA, 3% PLC - 7% RHA, 4% PLC - 6% RHA, and 5% PLC - 5% RHA). The split mold was lightly oiled on the inside, and samples were placed in the mold with a height of 76 mm and diameter of 38 mm. Specimens were compressed until failure, with load readings recorded approximately every 20 mm of deformation. The unconfined compressive strength (q_u) was determined from the peak stress-strain curve. The undrained shear strength (cohesion, C_u) was calculated as

$$C_u = {}^{q_u}/_{2} \quad (1)$$

The ultimate bearing capacity was calculated using Terzaghi's bearing capacity equation [33]

$$Q_u = CN_c + qN_q + ½B\gamma N_\gamma. \quad (2)$$

For oil-contaminated soils where $\phi = 0$, $N_\gamma = 0$, $N_c = 5.7$, and $N_q = 1$, thus

$$Q_u = CN_c + q. \quad (3)$$

A total of 48 samples (3 per percentage and depth) of PLC and RHA varying mixed proportions were prepared for UCS testing.

The consolidation test was conducted to assess the one-dimensional consolidation characteristics of both natural and modified soils using an oedometer apparatus following ASTM D2435/D2435M-11 procedures [30]. Soil samples were mixed with varying proportions of PLC and RHA and placed in the consolidation ring. The oedometer was set up, and loads of 2.27 kg, 4.54 kg, 9.07 kg, and 18.14 kg were applied sequentially, with dial gauge readings recorded at intervals of 10, 15, and 30 seconds, as well as at 10, 15, and 30 minutes, and 1, 2, 4, 8, 20, and 24 hours. The height of solids (H_s) was calculated from

$$H_s = M_d/(G_s A \rho_w) \quad (4)$$

Where M_d = dry mass of soil specimen, A = cross sectional area of the specimen, G_s = specific gravity of soil solids and ρ_w = density of water.

The voids ratio (e_0) from [34]

$$e_0 = \frac{H - H_s}{H_s} \quad (5)$$

The compression index (C_c) was determined from the slope of the e versus log σ' curve, calculated as

$$C_c = \frac{e_0 - e_1}{\log(\frac{p_1}{p_0})} \quad (6)$$

The coefficient of compressibility (a_v) was calculated as

$$a_v = \frac{0.435 C_c}{\sigma'} \quad (7)$$

while the coefficient of volume change (m_v) was determined as

$$m_v = -\frac{a_v}{1+e_0} \quad (8)$$

Consolidation settlement was calculated as [35]

$$\rho_f = m_v H \Delta\sigma' = \frac{e_0 - e_1}{1+e_0}\, x.H \quad (9)$$

A total of 48 samples (3 per percentage and depth) were prepared for consolidation testing at depths of 1 m, 2 m, and 3 m. In total, 96 samples were tested for both UCS and consolidation for the modified soil samples, while 18 samples were tested for both UCS and consolidation for the unmodified soil samples, resulting in a grand total of 114 samples. The Unified Soil Classification System (USCS) was used to classify the soil based on the laboratory results obtained [22].

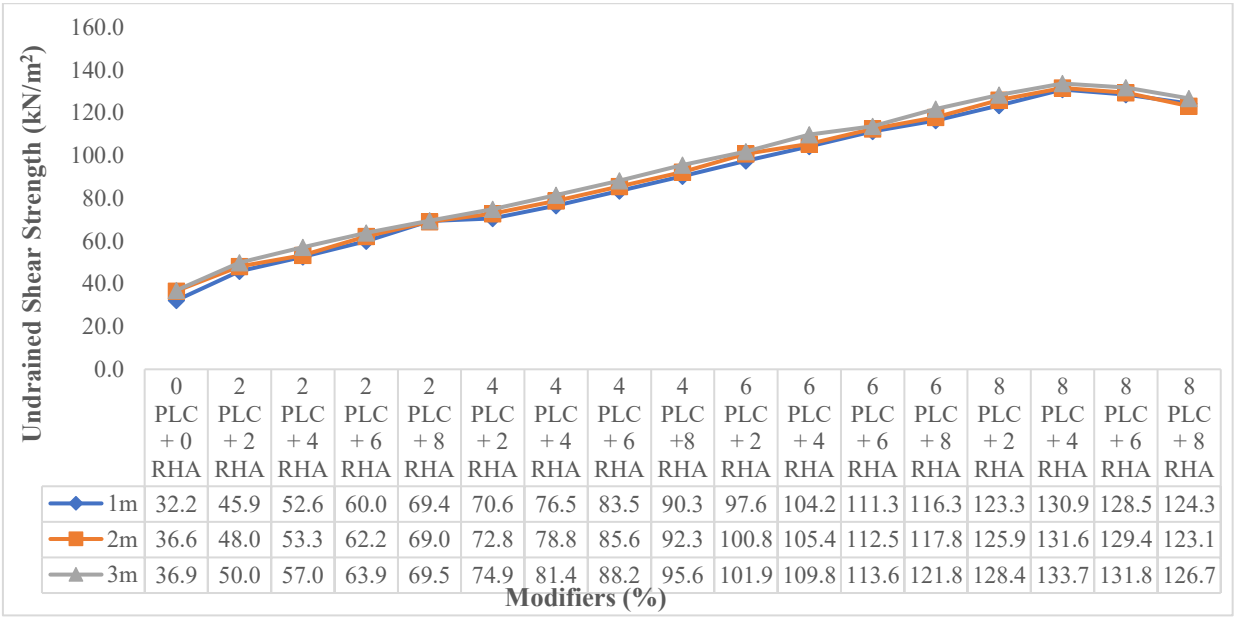
3. Results & Discussion

The laboratory test results obtained from geotechnical characterization, unconfined compressive strength (UCS), and consolidation tests were analysed to evaluate the performance of PLC-RHA stabilized oil-contaminated soils. The engineering properties, undrained shear strength, bearing capacity, consolidation characteristics, and settlement behavior of both natural and modified soils at depths of 1 m, 2 m, and 3 m are presented and discussed in this section. Figures 1–5 illustrate the behavior of the oil-contaminated soil modified with varying proportions of PLC and RHA.

Table 3: Summary of Geotechnical Properties of Oil Contaminated Soil

Geotechnical Property	**Value**		
	1 m Depth	**2 m Depth**	**3 m Depth**
Moisture content (%)	17.44	19.70	22.37
Specific gravity – soil	2.02	2.25	2.58
Liquid Limit (%)	46.80	41.20	33.00
Plastic Limit (%)	17.70	20.32	22.23
Plasticity index (%)	29.10	20.88	10.77
Unconfined Compression Strength (kN/m^2)	64.47	73.28	73.86
Undrained Shear Strength (kN/m^2)	32.24	36.64	36.92
Bearing Capacity (kN/m^2)	67.40	82.22	89.61
Coefficient of Volume Change, m_v (m^2/kN)	0.00292	0.00280	0.00274
Compression Index, C_c	0.274	0.265	0.260
Settlement, ρ_f (mm)	117	112	110
Unified soil Classification System (USCS)	CL	CL	CL

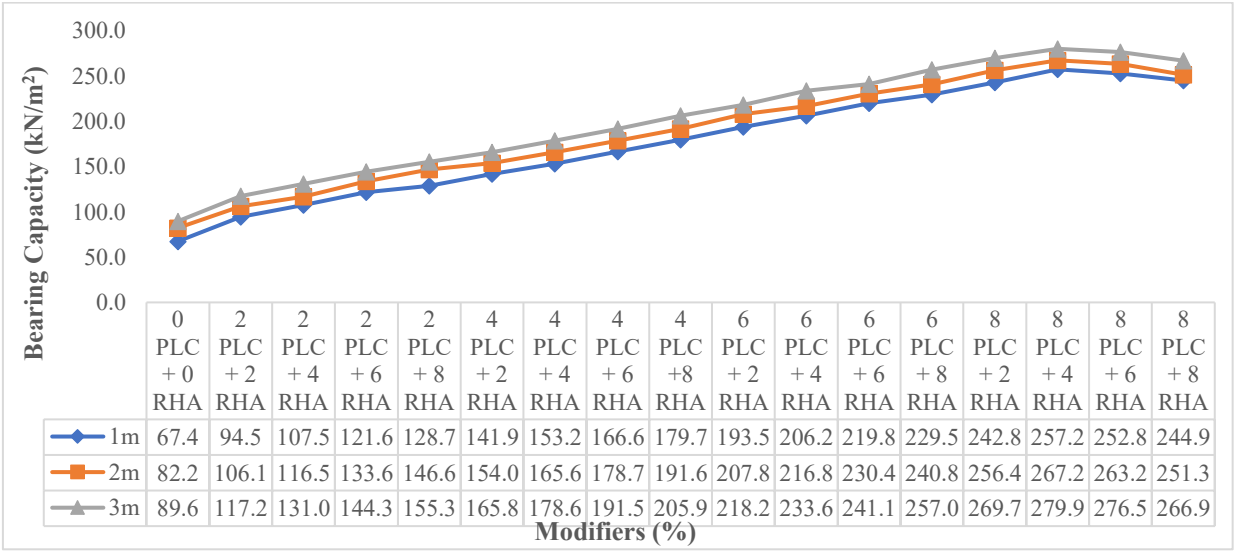
The natural oil-contaminated soil was classified as low plasticity clay (CL) using the Unified Soil Classification System, with plasticity index values ranging from 10.77% to 29.10%. Moisture content increased with depth from 17.44% to 22.37%, while specific gravity ranged from 2.02 to 2.58. The unconfined compressive strength (64.47–73.86 kN/m^2) and undrained shear strength (32.24–36.92 kN/m^2) indicate the soil is a soft clay in its natural state. The bearing capacity values (67.40–89.61 kN/m^2) suggest limited load-bearing capability, while the compression index (0.260–0.274) and settlement values (110–117 mm) confirm the soil is highly compressible and unsuitable for construction without stabilization.



	0 PLC + 0 RHA	2 PLC + 2 RHA	2 PLC + 4 RHA	2 PLC + 6 RHA	2 PLC + 8 RHA	4 PLC + 2 RHA	4 PLC + 4 RHA	4 PLC + 6 RHA	4 PLC +8 RHA	6 PLC + 2 RHA	6 PLC + 4 RHA	6 PLC + 6 RHA	6 PLC + 8 RHA	8 PLC + 2 RHA	8 PLC + 4 RHA	8 PLC + 6 RHA	8 PLC + 8 RHA
1m	32.2	45.9	52.6	60.0	69.4	70.6	76.5	83.5	90.3	97.6	104.2	111.3	116.3	123.3	130.9	128.5	124.3
2m	36.6	48.0	53.3	62.2	69.0	72.8	78.8	85.6	92.3	100.8	105.4	112.5	117.8	125.9	131.6	129.4	123.1
3m	36.9	50.0	57.0	63.9	69.5	74.9	81.4	88.2	95.6	101.9	109.8	113.6	121.8	128.4	133.7	131.8	126.7

Fig. 1: *Undrained Shear Strength of PLC and RHA Modified Oil contaminated Soil.*

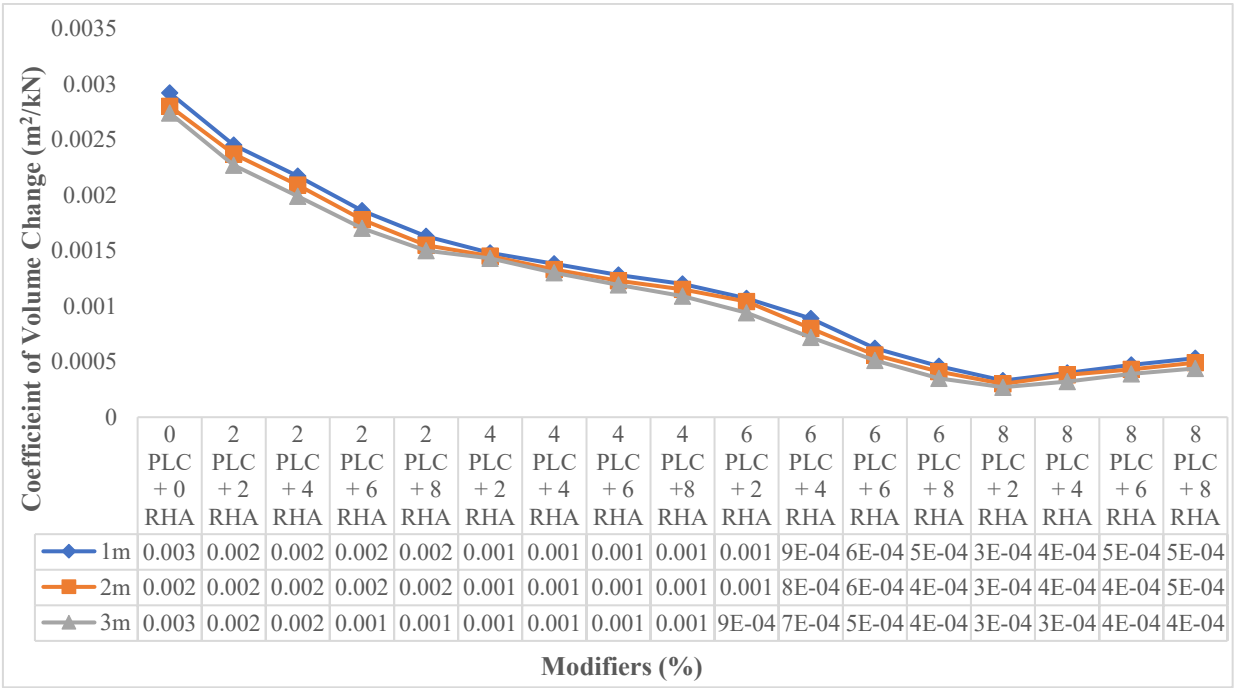
Figure 1 presents the undrained shear strength behavior of oil-contaminated soil stabilized with varying proportions of PLC (2–8%) and RHA (2–8%). The natural soil exhibited undrained shear strength values of 32.24 kN/m^2, 36.64 kN/m^2, and 36.92 kN/m^2 at depths of 1 m, 2 m, and 3 m, respectively, classifying it as soft clay. Upon stabilization, the undrained shear strength increased progressively with the addition of PLC and RHA, reaching peak values of 130.9 kN/m^2 (1 m), 131.6 kN/m^2 (2 m), and 133.7 kN/m^2 (3 m) at 8% PLC and 4% RHA, corresponding to a stiff clay classification. This improvement is attributed to the hydration of PLC and the pozzolanic reaction of RHA, which form cementitious compounds that bind soil particles and enhance inter-particle cohesion. However, further addition beyond 8% PLC and 4% RHA resulted in a decline in undrained shear strength, likely due to excessive binder content causing particle aggregation and reduced bonding efficiency within the soil matrix.



	0 PLC + 0 RHA	2 PLC + 2 RHA	2 PLC + 4 RHA	2 PLC + 6 RHA	2 PLC + 8 RHA	4 PLC + 2 RHA	4 PLC + 4 RHA	4 PLC + 6 RHA	4 PLC +8 RHA	6 PLC + 2 RHA	6 PLC + 4 RHA	6 PLC + 6 RHA	6 PLC + 8 RHA	8 PLC + 2 RHA	8 PLC + 4 RHA	8 PLC + 6 RHA	8 PLC + 8 RHA
1m	67.4	94.5	107.5	121.6	128.7	141.9	153.2	166.6	179.7	193.5	206.2	219.8	229.5	242.8	257.2	252.8	244.9
2m	82.2	106.1	116.5	133.6	146.6	154.0	165.6	178.7	191.6	207.8	216.8	230.4	240.8	256.4	267.2	263.2	251.3
3m	89.6	117.2	131.0	144.3	155.3	165.8	178.6	191.5	205.9	218.2	233.6	241.1	257.0	269.7	279.9	276.5	266.9

Fig. 2: *Bearing Capacity of PLC and RHA Modified Oil contaminated Soil*

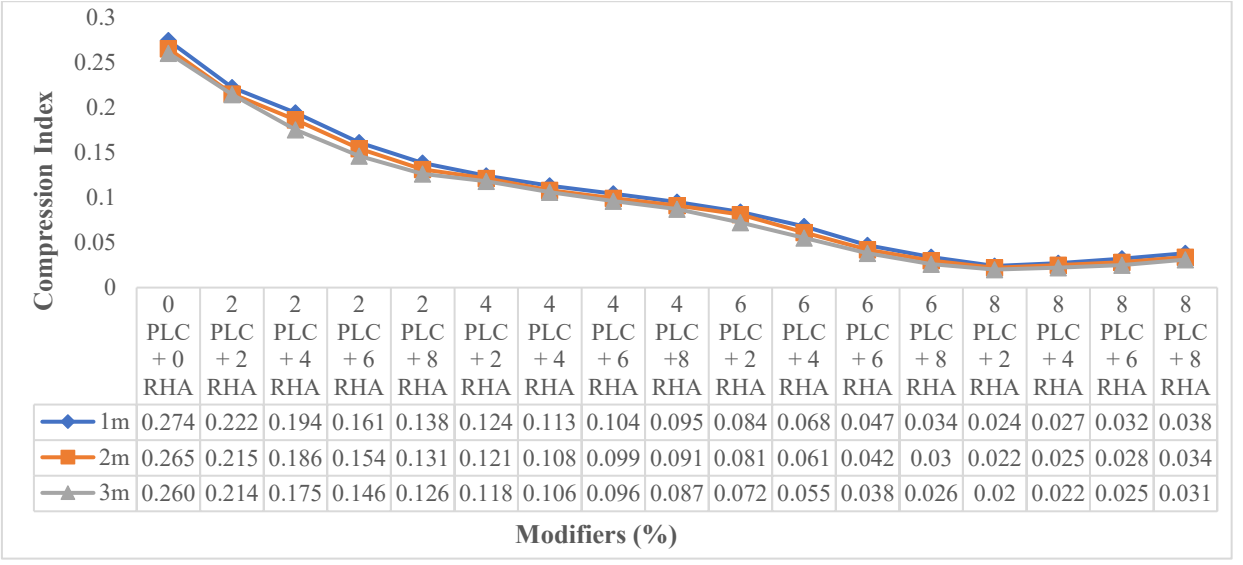
Figure 2 shows that the bearing capacity followed the same trend as undrained shear strength, increasing progressively with the addition of PLC and RHA. The natural soil exhibited bearing capacity values of 67.40 kN/m^2, 82.22 kN/m^2, and 89.61 kN/m^2 at depths of 1 m, 2 m, and 3 m, respectively, indicating poor load-bearing capability. The peak bearing capacity was achieved at 8% PLC and 4% RHA, reaching 244.86 kN/m^2, 251.34 kN/m^2, and 266.91 kN/m^2 at 1 m, 2 m, and 3 m depths, respectively. Beyond this optimum, further addition of stabilizers caused a decline in bearing capacity due to excessive binder content leading to particle aggregation and reduced bonding efficiency.



	0 PLC + 0 RHA	2 PLC + 2 RHA	2 PLC + 4 RHA	2 PLC + 6 RHA	2 PLC + 8 RHA	4 PLC + 2 RHA	4 PLC + 4 RHA	4 PLC + 6 RHA	4 PLC +8 RHA	6 PLC + 2 RHA	6 PLC + 4 RHA	6 PLC + 6 RHA	6 PLC + 8 RHA	8 PLC + 2 RHA	8 PLC + 4 RHA	8 PLC + 6 RHA	8 PLC + 8 RHA
1m	0.003	0.002	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001	9E-04	6E-04	5E-04	3E-04	4E-04	5E-04	5E-04
2m	0.002	0.002	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001	8E-04	6E-04	4E-04	3E-04	4E-04	4E-04	5E-04
3m	0.003	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	9E-04	7E-04	5E-04	4E-04	3E-04	3E-04	4E-04	4E-04

Fig. 3: *Coefficient of Volume Change of PLC and RHA Modified Oil Contaminated Soil*

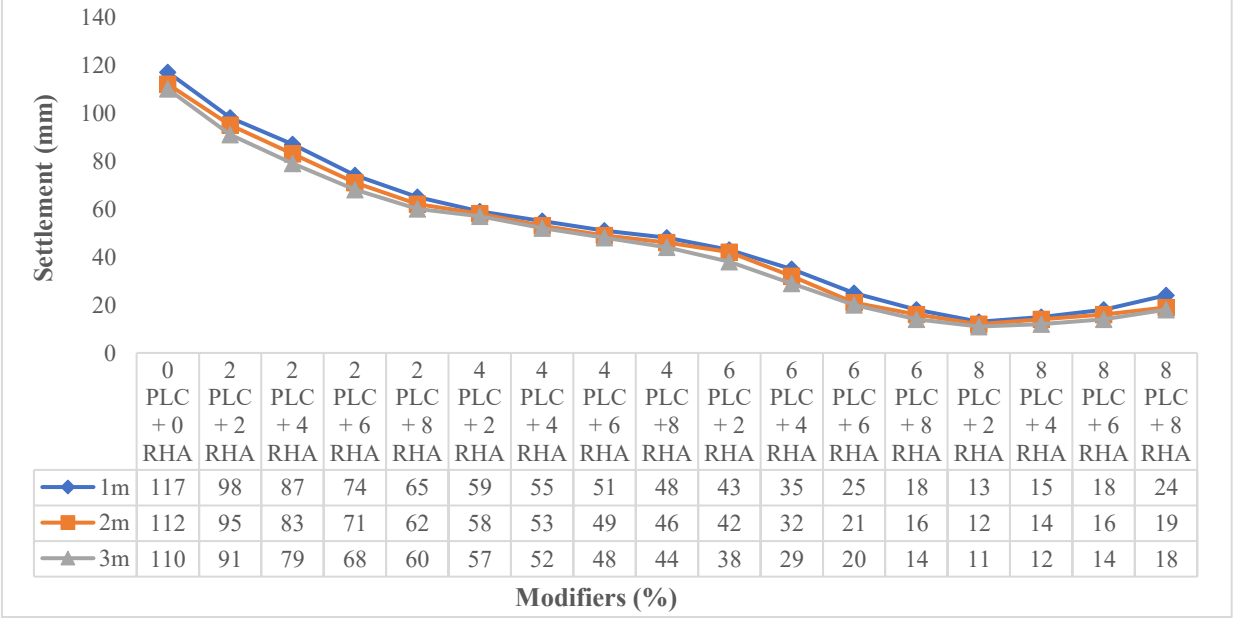
Figure 3 shows that the coefficient of volume change (m_v) decreased progressively with increasing PLC and RHA content from the natural state values of 0.00292 m^2/kN, 0.00280 m^2/kN, and 0.00274 m^2/kN at depths of 1 m, 2 m, and 3 m, respectively. The minimum m_v values of 0.00033 m^2/kN, 0.00030 m^2/kN, and 0.00027 m^2/kN were achieved at 8% PLC and 2% RHA. This reduction is attributed to the effective filling of soil pores by PLC and RHA particles, along with the binding properties that enhance soil strength and reduce volume susceptibility. Beyond this optimum, further addition of stabilizers caused an increase in m_v due to excessive binder content leading to particle aggregation and reduced bonding efficiency within the soil matrix.



	0 PLC + 0 RHA	2 PLC + 2 RHA	2 PLC + 4 RHA	2 PLC + 6 RHA	2 PLC + 8 RHA	4 PLC + 2 RHA	4 PLC + 4 RHA	4 PLC + 6 RHA	4 PLC +8 RHA	6 PLC + 2 RHA	6 PLC + 4 RHA	6 PLC + 6 RHA	6 PLC + 8 RHA	8 PLC + 2 RHA	8 PLC + 4 RHA	8 PLC + 6 RHA	8 PLC + 8 RHA
1m	0.274	0.222	0.194	0.161	0.138	0.124	0.113	0.104	0.095	0.084	0.068	0.047	0.034	0.024	0.027	0.032	0.038
2m	0.265	0.215	0.186	0.154	0.131	0.121	0.108	0.099	0.091	0.081	0.061	0.042	0.03	0.022	0.025	0.028	0.034
3m	0.260	0.214	0.175	0.146	0.126	0.118	0.106	0.096	0.087	0.072	0.055	0.038	0.026	0.02	0.022	0.025	0.031

Fig. 4: *Compression Index of PLC and RHA Modified Oil contaminated Soil*

Figure 4 shows that the compression index (C_c) decreased progressively with increasing PLC and RHA content from the natural state values of 0.274, 0.265, and 0.260 at depths of 1 m, 2 m, and 3 m, respectively. The minimum C_c values of 0.024, 0.022, and 0.020 were achieved at 8% PLC and 2% RHA. Beyond this optimum, further addition of stabilizers caused an increase in the compression index. The initial decrease is attributed to the effective filling of soil pores and enhanced binding properties of PLC and RHA, which reduce soil compressibility. The subsequent increase beyond the optimum is due to excessive binder content causing particle aggregation and reduced bonding efficiency within the soil matrix, consistent with the trend observed for the coefficient of volume change.



	0 PLC + 0 RHA	2 PLC + 2 RHA	2 PLC + 4 RHA	2 PLC + 6 RHA	2 PLC + 8 RHA	4 PLC + 2 RHA	4 PLC + 4 RHA	4 PLC + 6 RHA	4 PLC +8 RHA	6 PLC + 2 RHA	6 PLC + 4 RHA	6 PLC + 6 RHA	6 PLC + 8 RHA	8 PLC + 2 RHA	8 PLC + 4 RHA	8 PLC + 6 RHA	8 PLC + 8 RHA
1m	117	98	87	74	65	59	55	51	48	43	35	25	18	13	15	18	24
2m	112	95	83	71	62	58	53	49	46	42	32	21	16	12	14	16	19
3m	110	91	79	68	60	57	52	48	44	38	29	20	14	11	12	14	18

Fig. 5: *Settlement of PLC and RHA Modified Oil contaminated Soil*

Figure 5 illustrates the settlement behavior of oil-contaminated soil stabilized with varying proportions of PLC and RHA. The natural soil exhibited settlement values of 117 mm, 112 mm, and 110 mm at depths of 1 m, 2 m, and 3 m, respectively, which exceed the allowable settlement limits for shallow foundations. Upon stabilization, settlement decreased progressively with increasing PLC and RHA content, reaching minimum values of 13 mm, 12 mm, and 11 mm at 8% PLC and 2% RHA. This significant reduction is attributed to the effective pore filling and enhanced binding properties of the stabilizers, which reduce soil compressibility. Beyond this optimum, further addition of stabilizers caused an increase in settlement due to excessive binder content leading to particle aggregation and reduced bonding efficiency. The improved settlement values confirm that PLC-RHA stabilization effectively enhances the settlement characteristics of oil-contaminated soil to meet the minimum requirements for shallow foundation applications.

4. CONCLUSION

From the foregoing results, the following conclusions are drawn:

1. The index properties test reveals the oil contaminated soil at 1 m, 2 m and 3 m respectively as low plasticity inorganic clay in accordance with the unified soil classification system.
2. The modified oil contaminated soil in terms of undrained shear strength, performed better than the unmodified soil sample at 1 m, 2 m and 3 m respectively as the natural oil contaminated soil improved from soft clay to stiff clay upon addition of PLC and RHA.
3. The modified oil contaminated soil in terms of bearing capacity, performed better than the unmodified soil sample at 1 m (67.40), 2 m (82.22) and 3 m (89.61) respectively. Hence, the most suitable mixed proportion of PLC and RHA with oil contaminated soils for economic and environmental benefits is 2 % PLC and 8 % RHA.

The modified oil contaminated soil in terms of Coefficient of volume change 1m (0.00292) 2m (0.00280) and 3m (0.00274), Compression index and Settlement performed better than the unmodified soil sample. Hence, the most suitable mixed proportion of PLC and RHA with oil contaminated soils in relation to soil settlement is 6 % PLC and 8 % RHA for economic and environmental benefits.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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