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Enhancing the Geotechnical Properties of Oil-Contaminated Soils Using a Hybrid Blend of Rice Husk Ash and Charcoal Powder

Uguru, H.[1]*, ***Akwenuke, M.O***[2], ***Ikoko, O***[3]
[1]Department of Agricultural Engineering, Delta State University of Science and Technology, Ozoro, Nigeria
[2]Department of Civil and Water Resources Engineering, Delta State University of Science and Technology, Ozoro, Nigeria
[3]Department of Agricultural and Bio-Environmental Engineering Technology, Delta State Polytechnic, Ogwashi-Uku, Nigeria
*corresponding author: erobo2011@gmail.com

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Abstract

Petroleum pollution has become a significant concern for public health and infrastructural development. This research was embarked upon to assess the remediation potential of sustainable materials on oil-contaminated lateritic soil. Soil samples contaminated with spent vehicle oil (SVO) were treated with combined rice husk ash (RHA) and charcoal powder (CP) at various quantities. The geotechnical properties (California Bearing Ratio (CBR), permeability, maximum dry density (MDD), optimal moisture content (OMC), and consistency limits) of the natural, contaminated, and remediated soil samples were determined in accordance with ASTM International guidelines. The results gotten from the remediated soil specimens revealed that, the two agricultural products substantially reduced the impact of the SVO on the lateritic soil geotechnical properties. The soil's CBR increased from 6.91 to 17.85% (158% improvement), the permeability declined from 9.19 x10^{-8} *to 3.11 x10*$^{-8}$ *m/s (195% improvement), while the plasticity index (PI) decreased from 14 to 8% (75% improvement) as the content of the remediating agents increased from 4% to 20%. Interestingly, the results depicted that the stabilized soil can be utilized as sub-grade material in road construction. Remarkably, this research outcome highlights that, in addition to mitigating the SVO effects on the soil, the rice husk ash and charcoal powder were able to enhance the soil's geotechnical properties, rendering it suitable for road sub-grade construction.*

1.0. Introduction

Soil is one of the fundamental materials used in both infrastructural and agricultural development, playing essential roles in the stability of structures and food security. The design and construction of civil engineering structures are influenced by the soil's geotechnical properties, while its physicochemical properties impact crop yield patterns [1, 2]. Soil organic matter and water content influences its mechanical properties, fertility, and microbial activity, which in turn determine the soil's suitability for various engineering applications [3, 4]. Soil's load-bearing capacity (LBC) is a crucial factor in pavement design, as soils with higher load-bearing capacities allow for thinner pavement layers. This reduces the amount of soil needed for road construction, conserves natural resources, and helps minimize the environmental impacts associated with climate change [5-7].

Despite the importance of soil in engineering applications, it presents challenges due to its significant variability in physical and geotechnical characteristics. This inherent variability in soil properties, which already poses serious challenges in construction and crop production, is further exacerbated by soil contamination, making it a complex and intricate issue to manage effectively and accurately [8]. These pollutants alter the soil's physicochemical properties, resulting in a reduction in its LBC and fertility levels. Petroleum and its derivatives are major contaminants that severely impact soil's engineering properties, leading to multiple issues in construction and land use [9,10]. Petroleum and its derivatives have the ability of altering the physical, mechanical and chemical properties of soil [11]. This will affect the soil compaction, infiltration and load bearing levels by reducing its cohesiveness and altering the frictional properties of soil particles [12-14].

Singh [15] reported that crude oil pollution can disrupt the soil's microscopic structure, resulting in a decrease in the velocity of shear waves as they pass through the contaminated soil. According to Ref [16], as the volume of oil increases, the permeability of silty loam soil decreases, suggesting that the soil's ability to absorb water is impaired as it becomes more heavily contaminated with petroleum. Hydrocarbons seriously affect the consolidation characteristics of fine-grained soils, causing them to behave unpredictably under load and leading to differential settlement in structures [17]. According to Odoh [18] research, oil pollution has a considerable effect on the properties of contaminated soil, leading to a notable decrease in soil’s liquid and plastic limits. The presence of petroleum contaminants in soil can considerably reduce its shear strength. This situation can cause foundations, embankments, and other structures built on or with this contaminated soil to become unstable and susceptible to failure [19].

Scientists are actively working to minimize the adverse effects of oil pollution on soil's engineering characteristics. Soil stabilization and remediation are vital methods for enhancing the physicochemical and geotechnical properties of oil-contaminated soils. These techniques effectively degrade the pollutant(s) concentrations and mitigate the associated risks [20-22]. The efficiency of bioremediation in contaminated soils is influenced by the nature of the microbes and their ability to degrade petroleum pollutants [23]. Petroleum-degrading microorganisms have been found to enhance (increase) the shear strength of soils impacted with oil, in an investigation conducted by Ref [9]. Mekkiyah [16] reported that cement helps to increase the permeability rate and specific gravity of soil polluted with crude oil. Adebayo [24] observed in their research that utilization of charcoal powder, as filter medium during electrokinetic remediation of petroleum polluted soil, substantially increases the compaction level and California bearing ratio (CBR) values of the various soil samples used for the experiment.

Although numerous scientific investigations have been conducted on the remediation of hydrocarbons polluted soils, a review of related literature reveals limited information on the use of a hybrid approach combining agricultural sustainable materials as remediation agents for petroleum hydrocarbons contaminated soils. Therefore the major goal of this present study is to evaluate the remediation potential of eggshell powder and charcoal powder in enhancing the geotechnical properties of spent vehicle oil-contaminated lateritic soil. The information obtained from this research will help to design and develop a sustainable remediation solution for contaminated soil bodies.

2.0 Materials and methods

2.1 Materials

2.1.1 Soil specimen

The lateritic soil was dug (sampled) from the flood plains of Niger Delta and air-dried for two weeks.

2.1.2 Spent vehicle oil (SVO), charcoal powder and rice hush ash (RHA)

The Spent vehicle oil (SVO) was obtained from automobile workshop in Ughelli, Delta State, while the charcoal powder (CP) and rice hush ash (RHA) were obtained from the bio-materials laboratory of the Delta State University of Science and Technology, Ozoro, Nigeria.

2.2 Methods

2.2.1 Soil contamination and remediation plans

One hundred kilogram of the dried lateritic soil was contaminated with 10 L of SVO and left to acclimatize for two weeks. The contaminated soil (CS) was thoroughly mixed and filled into stainless steel containers at the rate specified in Table 1. This blending ratio of rice husk ash (RHA) and charcoal powder (CP) was adopted based on the ratios used in previous research studies for similar agricultural byproducts [33]. The experimental setups were left to stand for eight weeks in a shaded environment, where they were exposed to the same environmental conditions throughout the duration of the bioremediation program. This study was conducted between March 2024 and May 2024, with temperatures averaging 29±6°C.

Table 1: Remediation set-ups

Sample code	Constituents
Control	100% contaminated soil (CS)
Treatment 1 (SAM 1)	2% RHA + 2% CP + 96% CS
Treatment 2 (SAM 2)	4% RHA + 4% CP + 92% CS
Treatment 3 (SAM 3)	6% RHA + 6% CP + 88% CS
Treatment 4 (SAM 4)	8% RHA + 8% CP + 84% CS
Treatment 5 (SAM 5)	10% RHA + 10% CP + 80% CS

2.2.2 Geotechnical properties determination

Geotechnical characteristics of the lateritic soil were investigated prior to contamination, after contamination, and at the end of the remediation program. This was done to ascertain the impact of the spent vegetable oil (SVO) and remediating agents on the soil samples. The tests were conducted in triplicate and the mean value recorded.

Sieve analysis and Consistency limits test

The soil's sieve analysis was conducted in harmony with ASTM standards, using 0.5 kg of the dried soil sample (Figure 1). Also, the soil sample consistency limits (liquid limit "LL", plastic limit "PL", and plasticity index "PI") test was determined in agreement with ASTM D4318 procedures [25].

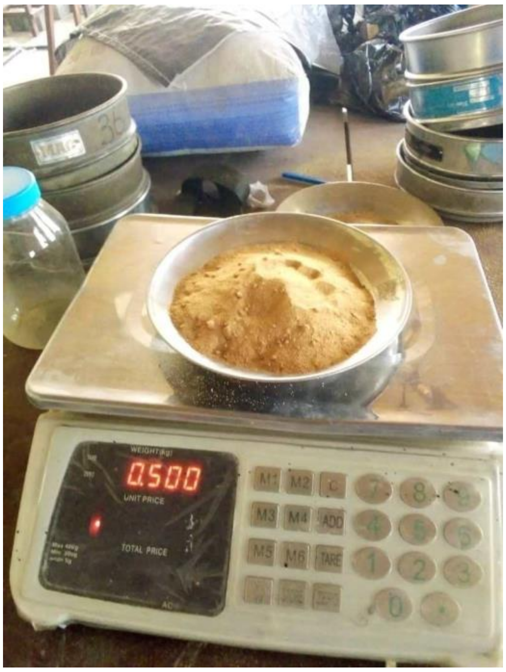

Figure 1: The dried uncontaminated soil sample

Proctor compaction test

The compaction characteristics (maximum dry density (MDD) and optimal moisture content (OMC)) of the soil specimens were determined by, employing the proctor compaction technique, in harmony with the approved ASTM D698-12 guidelines [26].

Soaked California Bearing Ratio (CBR) and Permeability tests

The soaked CBR values of the laboratory compacted soil were measured in accordance with ASTM D1883 standards [27]. The permeability of the soil specimens was evaluated using the standard procedures outlined in ASTM D2434-22 [28].

3.0 Results and discussion

3.1 Results

3.1.1 Sieve analysis

The sieve analysis results presented in Figure 2, depicted that the soil had fine content of 20.14%, Coefficient of Uniformity (C_u) of 1.59 and Coefficient of Curvature (Cc) of 0.69. Using the American Association of State Highway and Transportation Officials (AASHTO) guidelines, this soil can be classified as A-2-6 soil [29].

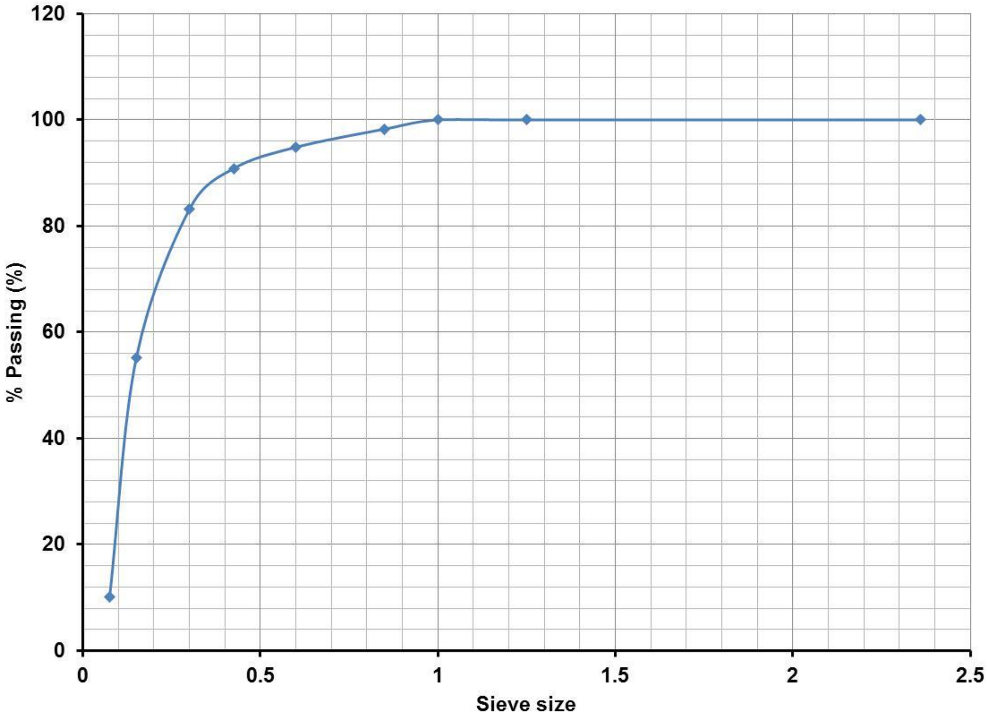

Figure 2: The particle size grading chart

3.1.2 Uncontaminated and contaminated soil samples geotechnical parameters

The results of the geotechnical properties of the uncontaminated and contaminated lateritic soil samples are presented in Table 2. It was noted that the LL, PI, CBR, permeability, MDD and OMC of the natural laterite were 35%, 16%, 4.71%, 2.24 x10^{-7} m/s, 1.45 g/cm^3 and 15.49%, respectively; while the soil impacted with SVO had LL, PI, CBR, permeability, MDD and OMC values were 43%, 21%, 2.04%, 2.53 x10^{-7} m/s, 1.21 g/cm^3 and 19.37%, respectively. The results indicated that SVO has a substantial impact on the engineering properties of the soil. Oil contamination disrupts the soil's intricate microstructure, subsequently affecting its mechanical properties [15]. The results showed that SVO increased the soil's LL, PI, and OMC, while decreasing the California Bearing Ratio, permeability, and MDD of the soil. Similar to the findings of Iloeje [30], which examined the impact of SVO contamination on soil permeability, our study observes that as the volume of oil increases, the soil permeability rate decreases in a non-uniform manner.

Table 2: The geotechnical properties of the lateritic soils samples

S/No	Parameter	Uncontaminated	Contaminated
1	Liquid limit	35%	43%
2	Plasticity index	16%	21%
3	CBR	4.71%	2.04%
4	Permeability	2.24 x10^{-7} m/s	2.53 x10^{-7} m/s
5	Maximum dry density	1.45 g/cm^3	1.21 g/cm^3
6	Optimal moisture content	15.49 %	19.37%

3.1.3 Remediated contaminated soil (CS) geotechnical properties

The results of the geotechnical properties of the soil after the remediation are presented in Table 3 and Figure 2. It was observed that the MDD values of the Control, Treatments 1 - 5 remediated soil specimens were 12.14, 14.03, 15.67, 14.93, 13.45 and 12.66 g/cm^3, respectively; while the OMC values were 17.27, 15.93, 15.04, 16.72, 17.54 and 18.38%, respectively. Similarly, the LL and PI values of the various treated specimens of SAMs 1 - 5, were 40, 43, 44, 46 and 49%, respectively, and 14, 12, 11, 9 and 8%, respectively. The soaked CBR values of the various remediated soil samples inclined from 6.91 to 17.85% as the quantity of the hybrid RHA and CP increased from 4 to 20% (Figure 2). Additionally, the permeability values of the remediated soil samples - SAM 1, SAM 2, SAM 3, SAM 4 and SAM 5 – were 9.19 x10^{-8}, 7.06 x10^{-8}, 6.22 x10^{-8}, 4.49 x10^{-8} and 3.11 x10^{-8} m/s, respectively. These results underscore the ability of sustainable materials to remediate petroleum, mitigating the harmful effects of hydrocarbons. This finding is consistent with the observations of Ref [9] regarding crude oil-polluted soils.

Table 3: Remediated lateritic soil geotechnical properties

	MDD (g/cm^3)	OMC (%)	LL(%)	PI (%)	Permeability (m/s)
Control	12.14±0.59	17.27±0.42	36±1.52	17±1.83	2.67 x10^{-7}±1.10 x10^{-8}
SAM 1	14.03±0.26	15.93±0.51	40±1.21	14±1.52	9.19 x10^{-8}±2.01 x10^{-9}
SAM 2	15.67±0.72	15.04±0.34	43±1.48	12±0.70	7.06 x10^{-8}±2.13 x10^{-9}
SAM 3	14.93±0.44	16.72±0.51	44±1.09	11±0.75	6.22 x10^{-8}±2.07 x10^{-9}
SAM 4	13.45±0.31	17.54±0.57	46±1.16	9±0.72	4.49 x10^{-8}±1.61 x10^{-9}
SAM 5	12.66±0.46	18.38±0.49	49±1.74	8±0.41	3.11 x10^{-8}±4.93 x10^{-10}

Mean ±standard deviation, n = 3

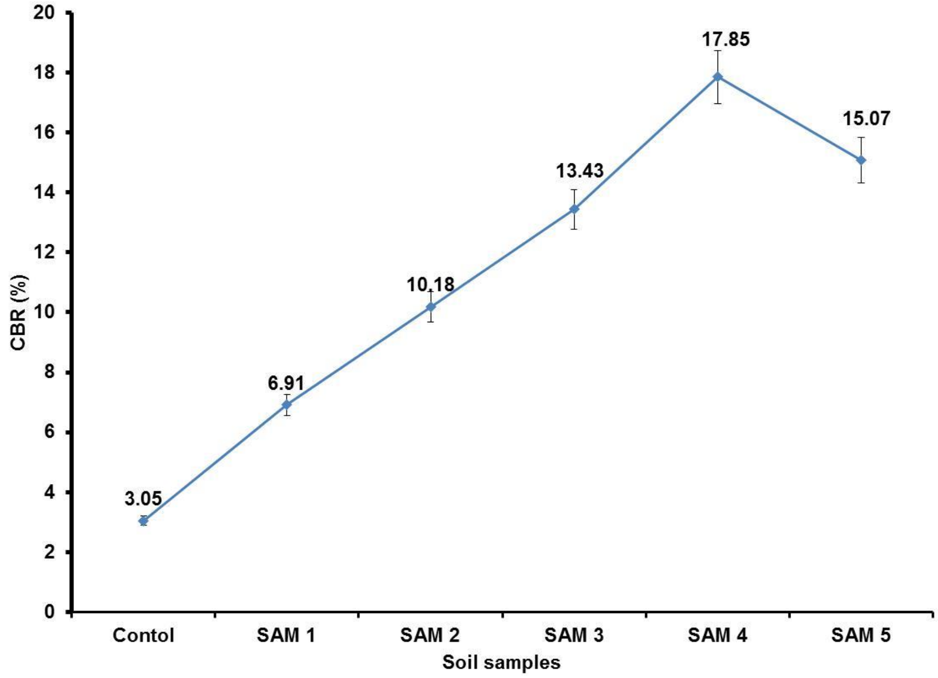

Figure 2: The soaked CBR values of the remediated SVO contaminated soil

3.2 Discussion

The results revealed that the combination of RHA and CP were able to improve the geotechnical properties of the soil impacted with hydrocarbons. This can be attributed to the dual functionality of rice husk ash (RHA) and charcoal powder (CP), which act both as stabilizing agents and as remediation agents. Being hygroscopic, charcoal and ash have the ability to absorb hydrocarbons from the soil and improve its fertility level, thereby reducing the harmful effects associated with diesel pollution [31]. During the experimental process (bioremediation), the RHA supplies nutrients that enhance the activity of indigenous hydrocarbons degrading microbes, thereby reduce the impact of the spent oil in the soil [32, 33]. This study's findings gave depicted that that a combination of rice husk ash and charcoal powder can be effectively used to remediate petroleum hydrocarbons contaminated ecosystems. This further supports the findings of Zahed [41], whose research concluded that biochar has the capability to remediate petroleum-contaminated soils.

The significant improvement observed in the geotechnical properties of the control unit, after the experimental duration can be linked to the vaporization of the volatile hydrocarbons from the soil, as well as the degradation of petroleum by natural remediating agents [22]. The hydrophobic nature of oil reduces water absorption, which can potentially increase the soil’s PI value. The observed increment in PI values of soil samples as ash and charcoal quantities increase can be associated to the higher oil absorption rate by the soil particles. This enhances the soil's water absorption capacity and porosity, ultimately leading to a reduction in soil plasticity [22]. According to Li [34], ash particles function as fillers within the soil matrix, reducing the voids between fine soil particles. This, in turn, decreases the soil's capacity to exhibit plastic behavior, thereby lowering its plasticity index. RHA has high pozzolanic properties; therefore, apart from degrading the oil content in the soil, it will also react with the soil moisture to produce cementitious compounds, leading to increment in the soil’s resistance to deformation and CBR value. In addition to the charcoal's adsorptive properties for absorbing hydrocarbons from the CS, the fine charcoal powder also acts as a buffer material within the soil. This slows down the movement of water through the soil, effectively reducing its permeability [35].

The decrease in MDD observed in the soil samples as the volume of rice husk ash (RHA) and charcoal powder (CP) increases, despite the reduction in hydrocarbon content, can be attributed to the lower densities of these two remediating agents, and their ability to increase soil porosity. High-porosity materials with lower densities tend to influence soil compaction behavior, resulting in reduced MDD and increased OMC respectively, which can caused significant alteration in the compaction characteristics of soil mass [36]. Remarkably, this research finding demonstrates that in addition to remediating the harmful effects of the SVO on the environment, the RHA and CP also improved the soil's geotechnical properties, making it suitable subgrade materials during road design and construction. Based on Federal Ministry of Works and Housing recommendations, soil required for subgrade and sub-base materials should have minimum soaked CBR of 5 and 25%, respectively. Similarly, FMWH stated that soils suitable for sub-grade and base course materials should have maximum PI value of 16 and 13%, respectively [29].

Interestingly, beyond remediating the oil’s consequences on the soil, this study has demonstrated that agricultural waste can be effectively utilized to address environmental pollution problems. Rice husk is a significant byproduct of rice mills and can have detrimental environmental impacts if not managed properly. When rice husk is burned or left to decompose, it releases particulate matter, volatile organic compounds (VOCs), and other pollutants into the air, contributing to air pollution and respiratory problems [40]. This approach can significantly aid in addressing the waste management challenges faced by many developing and underdeveloped nations, effectively turning agricultural waste into valuable resources.

The variations observed in this study’s outcome, compared to other researchers' findings could be attributed to differences in fuel properties, as well as the concentration and quantity of petroleum products used by the various authors. Additionally, the mechanical and biochemical properties of the organic remediating agents play a decisive part in any remediation process [22,37]. Plant variety, maturity stage, processing methods, storage techniques, and environmental factors significantly influence the suitability of agricultural products for engineering applications [38, 39].

4.0 Conclusion

This study was undertaken to explore the prospects of utilizing agricultural waste materials as remediating agents for petroleum-contaminated soil. The geotechnical properties of lateritic soil contaminated with petroleum product (spent vehicle oil), and remediated using a combination of rice husk ash (RHA) and charcoal powder (CP), were determined in accordance with approved ASTM International approved guidelines. This study's results depicted that the hybridized RHA and CP effectively reduced the impact of hydrocarbons on the soil, by enhancing its geotechnical properties. It was observed that as the volume of remediating materials increased from 0% to 20%, the soil's plasticity index decreased, while the California Bearing Ratio increased, though not uniformly. Interestingly, this study outcome depicted that, in addition to alleviating the impacts of the spent vehicle oil on the soil engineering properties, the RHA and CP were able to improve the lateritic soil's geotechnical properties, making it suitable as a subgrade construction material. Remarkably, in addition to modifying the influence of the spent vehicle engine oil on the soil's engineering behaviors; this study has demonstrated that agricultural waste can be effectively utilized to tackle environmental pollution problems.

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