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Use of Crude Oil- Electrokinetic Remediated Soil as Liners and Covers.

[1*] Ige A.O, [2]Oyelami A.K, [3]Olaniyi O.A, [4]Adeyokunnu A. T [5]Hassan D.E

[12345]Department of Civil Engineering, Ajayi Crowther Univeristy, Oyo

[*] Corresponding Author E-mail: ao.ige@acu.edu.ng

Abstract

A successful construction project has many important components, one of which is labour. Many The soil investigated in this study for suitability checks as liners and covers material was a crude oil contaminated (COC) soil treated using Electrokinetic technique. The contaminated soil was remediated with 0.05M of sodium dodecyl sulphate (SDS) at the anode chamber and sodium sulphate (Na_2SO_4) varied at 0.05, 0.10, 0.15 and 0.20M respectively at the cathode chambers and at a constant voltage of 30 Volts. Graphite electrodes were employed for the electrokinetic remediation. The index properties, specific gravity, and the compaction characteristics of the contaminated and remediated soil were investigated. The soil is classified as A-7-6 according to AASHTO classification system and belongs to clay of low plasticity CL or OL group according to the Unified Soil Classification System. The unconfined compressive strength (UCS) of the remediated soil samples were compared with the regulatory standards by most agencies and found to be above 200KN/m^2. The TPH removal efficiency for the remediated soil was 42.55% for EKR-A, 48.94% for EKR- B, 58.51% for EKR- C and 67.02% for EKR- D respectively. Hydraulic conductivity and the volumetric shrinkage strain have been a key engineering parameter used in evaluating the performance of potential material for use as waste containment facility; and these were also investigated for the remediated soil samples. It is recommended that the remediated soil at WAS and BSH compactive efforts can be employed as waste containment facility only when the material is compacted and placed as instructed.

Keywords: Electrokinetic remediation, Crude oil contaminated (COC) soil, Unified Soil Classification System, Unconfined compressive strength (UCS).

Introduction

The use of Electrokinetic technology has been helpful in the recovery of polluted or contaminated soil in the past decades. Recent studies show clear improvement in remediation efficiency when researchers combine enhancement methods such as electrokinetics, phytoremediation, and chemical additives (Yuan et al., 2020). Electrokinetic remediation involves the application of low electric voltage to an electrokinetic cell containing two or more electrodes inserted in an electrolyte at both ends of the cell to remove organic, inorganic and heavy metal compounds from a contaminated soil. The Electrokinetic cell used in this study was based on a model adopted by Yu et al., (2019), and in line with Claudio Cameselle recommendation of a simple Electrokinetic set up. The laboratory test was repeated for Sodium sulphate (Na_2SO_4) varied at 0.05M, 0.1M, 0.15M AND 0.20M concentrations, while Sodium dodecyl sulphate ($C_{12}H_{25}NaSO_4$) was kept constant at 0.05M concentration. The significance of this study is about varying the concentration of the reagents and at a constant voltage to ascertain the best removal efficiency. Recent research shows that electrokinetic remediation has effectively treated crude oil contaminated soils and reduce petroleum hydrocarbon concentrations under controlled conditions (Sani et al., 2021). However, the suitability of the resulting remediated soils for use as waste containment facility has not been well reported. This work investigates the useability of remediated soil as Liners and covers in waste containment facility.

Materials and Methods

In this study, crude-oil-contaminated soil was collected from Elelenwo (Postal Code 500102), Obio- Akpor Local Government area, Port Harcourt, Rivers State, Nigeria. Soil samples were obtained at a depth of 300 mm from the top soil, sealed in polyethylene bags, and tied securely to minimise moisture loss during transportation to the geotechnical Engineering laboratory, Nigerian Defence Academy, Afaka-Kaduna. The site is located at approximately longitude 4°50′19″ N and latitude 7°04′18″ E. Electrokinetic remediation was conducted using Sodium Dodecyl Sulphate ($C_{12}H_{25}NaSO_4$) at a concentration of 0.05 M in the anode chamber, while sodium sulphate (Na_2SO_4) was applied in the cathode chamber at concentrations of 0.05, 0.10, 0.15, and 0.20 M. A constant voltage gradient of 30 V was maintained throughout the experiment, consistent with recent electrokinetic remediation studies on hydrocarbon-contaminated soils (Boulakradeche et al., 2021). The total petroleum hydrocarbon (TPH) for the contaminated and the remediated soils were analysed by gravimetric method at the Nigerian Defence Academy laboratory, Afaka-Kaduna. This is done to establish the hydrocarbon content before and after the remediation and the electrokinetic efficiency.

The electrokinetic cell was constructed using a rectangular Plexiglas chamber measuring 400 mm × 250 mm × 300 mm. Each electrode compartment measured 50 mm × 250 mm × 300 mm and housed graphite electrodes of 300 mm length and 10 mm diameter. The system was powered by a 30 V DC power supply, and electrical parameters were monitored using a digital Multimeter. The soil section had a length of 300 mm. The soil compartment was separated from the electrode chambers using perforated Plexiglas plates with 6 mm diameter holes spaced at 30 mm centre-to-centre. Whatman filter paper No. 41 was placed between the soil and electrode chambers to prevent soil particle migration and to eliminate hydraulic gradients during treatment. This cell configuration follows the simplified electrokinetic cell design recommended in recent electrokinetic remediation literature (Cameselle, 2021). The overall remediation work plan is summarised in Table 1, while the electrokinetic cell setup is presented in Figure 1.

Table 1: Remediation Work Plan for EKR- A, B, C, and D.

S/no	Test Code	Volt (V)	Voltage Gradient	Purging Solution at Anode	Purging Solution at Cathode	Mode of Electric Field
1.	EKR-A	30V	1.0V/cm	0.05M Na_2SO_4	0.05M SDS	Continuous
2.	EKR-B	30V	1.0V/cm	0.10M Na_2SO_4	0.05M SDS	Continuous
3.	EKR-C	30V	1.0V/cm	0.15M Na_2SO_4	0.05M SDS	Continuous
4.	EKR-D	30V	1.0V/cm	0.20M Na_2SO_4	0.05M SDS	Continuous

Figure 1: Electrokinetic cell set up for the crude oil contaminated soil.

Strength characteristics of crude oil contaminated and electrokinetic remediated soil
Unconfined compressive strength:

West African Standard (WAS) and the British Standard Heavy (BSH) energy levels were used to conduct the unconfined compressive strength (UCS) test on the COC soil and EKR- A, B, C, and D soil samples. The British Standard heavy (BSH) compactive effort consists of the energy derived from a 4.5 kg rammer falling freely through a height of 450mm onto 5 (five) equal layers of the soil in a 1000 cm^3 mould. Each layer was subjected to 27 blows of the rammer. For West Africa Standards compaction energy, the sample was compacted into 1000cm^3 cylindrical mould, of mass M_1, in (5) five layers of approximately equal mass, with each layer receiving 10 blows from a 4.5kg rammer falling through a height of 450mm,. The respective soil samples were compacted in 38.1mm diameter and 76.2mm length cylindrical mould at their OMC. They were later extruded and kept in a cellophane bag to avoid moisture loss for 24 hours prior to compression test. The unconfined strength test results for the contaminated and the remediated soils are shown in Table 2A to E

Table 2A: Unconfined compressive strength test for COC soil.

DEFORMATION DIAL READING (DIV)	SAMPLE DEFORMATION ΔL (MM)	LOAD DIAL READINGS (DIV)					
		BSH			WAS		
		1	2	3	1	2	3
0	0	0	0	0	0	0	0
20	0.2	4	5	14	13	9	13
40	0.4	10	12	19	19	15	18
60	0.6	16	21	21	24	19	22
80	0.8	21	28	22	28	25	24
100	1.0	26	32	22	30	30	26
120	1.2	30	36	21	32	33	27.5
140	1.4	33.5	39	19	32	34.5	28
160	1.6	35	40	18	32	35	29
180	1.8	35	40	18	32	35	29
200	2.0	35	41	18	31	35	29

250	2.5	35	39	17	30	34	29
300	3.0	34	37			33	27.5
350	3.5		34				
400	4.0						
450	4.5						
500	5.0						
550	5.5						
600	6.0						

Table 2B: Unconfined compressive strength test for EKR- A soil.

DEFORMATION DIAL READING (DIV)	SAMPLE DEFORMATION ΔL (MM)	LOAD DIAL READINGS (DIV)					
		BSH			WAS		
		1	2	3	1	2	3
0	0	0	0	0	0	0	0
20	0.2	10	19	8	1	8	4
40	0.4	17	30	19	3	15	7
60	0.6	22	38	25	7	20	10
80	0.8	28	40	31	10	27	14
100	1.0	31	41	35	12	32	18
120	1.2	36	40	37	20	35	22
140	1.4	36		39	26	37	25
160	1.6	34		40	30	38	30
180	1.8			40	32	39	34
200	2.0			40	34	30	37
250	2.5			38	35		45
300	3.0				34		44
350	3.5						
400	4.0						
450	4.5						
500	5.0						
550	5.5						
600	6.0						

Table 2C: Unconfined compressive strength test for EKR- B soil.

DEFORMATION DIAL READING (DIV)	SAMPLE DEFORMATION ΔL (MM)	LOAD DIAL READINGS (DIV)					
		BSH			**WAS**		
		1	2	3	1	2	3
0	**0**	0	0	0	0	0	0
20	**0.2**	9	10	9	9	8	10
40	**0.4**	12	18	14	12	12	11
60	**0.6**	22	28	19	17	16	14
80	**0.8**	26	37	23	19	25	17
100	**1.0**	33	**43**	27	21	34	19

120	**1.2**	**39**	40	32	27	35	22
140	**1.4**	36	38	39	30	**39**	26
160	**1.6**	34	32	**42**	32	36	29
180	**1.8**		29	39	34	31	34
200	**2.0**			36	**35**	27	**39**
250	**2.5**				33		36
300	**3.0**				30		33
350	**3.5**						26
400	**4.0**						
450	**4.5**						
500	**5.0**						
550	**5.5**						
600	**6.0**						

Table 2D: Unconfined compressive strength test for EKR- C soil.

DEFORMATION DIAL READING (DIV)	SAMPLE DEFORMATION ΔL (MM)	LOAD DIAL READINGS (DIV)					
		BSH			WAS		
		1	2	3	1	2	3
0	0	0	0	0	0	0	0
20	0.2	10	18	9	1	9	4
40	0.4	16	28	13	2	14	8
60	0.6	23	37	24	5	19	10
80	0.8	29	40	30	10	25	13
100	1.0	32	42	36	13	31	17
120	1.2	37	41	37	19	36	21
140	1.4	37	36	39	25	38	26
160	1.6	35		41	29	38	31
180	1.8	32		40	33	37	35
200	2.0				34	36	37
250	2.5				32		35
300	3.0						30
350	3.5						
400	4.0						
450	4.5						
500	5.0						
550	5.5						
600	6.0						

Table 2E: Unconfined compressive strength test for EKR- D soil.

DEFORMATION DIAL READING (DIV)	SAMPLE DEFORMATION ΔL (MM)	LOAD DIAL READINGS (DIV)					
		BSH			WAS		
		1	2	3	1	2	3
0	0	0	0	0	0	0	0
20	0.2	12	10	8	10	11	7
40	0.4	16	25	12	12	14	13
60	0.6	23	36	20	14	21	17
80	0.8	29	42	25	16	28	19
100	1.0	35	44	28	21	32	22
120	1.2	40	32	31	25	37	24
140	1.4	36	27	38	27	40	27
160	1.6	31	23	43	32	40	32
180	1.8			38	35	40	36
200	2.0			35	36	37	40
250	2.5				36	35	37
300	3.0				32	30	33
350	3.5				28		30
400	4.0						
450	4.5						
500	5.0						
550	5.5						
600	6.0						

Hydraulic Conductivity

Hydraulic conductivity is a key engineering parameter used to assess the performance of potential materials for liner and cover systems in engineered waste containment facilities. Recent studies show that low hydraulic conductivity is essential to minimise contaminant migration through compacted soil and geosynthetic barriers in landfill designs and waste repositories (Silva et al., 2024; Dong et al., 2024; Adebayo et al., 2023; Lawal et al., 2023; Sani et al., 2024). In this study, the hydraulic conductivity test was carried out using the falling head permeameter following standard laboratory procedures. Test specimens were compacted using two compactive efforts, then soaked in a water tank for 24 hours to ensure full saturation. The saturated samples were installed in the falling head permeameter, and permeation was carried out with tap water as the permeating fluid. During permeation, the specimens were allowed to undergo free vertical swelling, as shown in Figure 2. The test lasted 6 hours, with changes in hydraulic head measured at 0, 3, and 6 hours to determine the coefficient of permeability.

Figure 2: Falling Head Permeameter Set up.

Volumetric Shrinkage Strain (VSS)

The tests involving moisture-density relationships and volumetric shrinkage were carried out using the air-dried soil mixtures (crude oil contaminated and the remediated soils) compacted at -4%, -2%, 0%, +2% and +4% of the optimum moisture content. The moisture contents were varied to bracket the expected compaction range in the field. This allows for how sensitive the soil is to drying and predict whether it will crack or settle regardless of whether it was placed slightly dry or slightly wet of the OMC. Also, the -4% to +4% range ensures that enough data points are obtained to accurately draw the curve and identify the point where the soil stops shrinking (transition from plastic to solid state). The extruded cylindrical specimens were placed on a laboratory bench at a uniform temperature of 25 ± 2 ^{0}C for 30 days to dry naturally, as shown in Figure 3. Measurements of diameters and heights of each specimen were taken with the aid of a vernier caliper accurate to 0.05 mm. The average diameter and height were used to compute the volumetric shrinkage strain.

Figure 3: Arranged cylindrical specimen for the Volumetric Shrinkage Strain test.

Results and Discussion

Physiochemical analysis:

The oxide composition of the COC soil and the EKR-A, B, C&D Soils were determined using the X-ray florescence analyzer. The oxide concentration of crude oil contaminated (COC) soil and the remediated soils EKR-A, B, C and D are shown in Table 2 below.

Table 2: Oxide Concentration of COC soil and the EKR soil.

S/No	OXIDES	COCS (%)	EKR- A (%)	EKR- B (%)	EKR- C (%)	EKR- D (%)
1.	Fe_2O_3	20.337	10.368	10.331	12.745	12.689
2.	SiO_2	47.022	61.803	61.880	61.746	60,634
3.	Al_2O_3	25.679	21.942	21.071	18.372	17.073
4.	MgO	0.000	0.000	0.000	0.000	0.000
5.	P_2O_5	0.489	0.280	0.226	0.146	0.253
6.	SO_3	0.415	1.342	2.187	1.832	4.535
7.	TiO_2	3.173	2.016	2.036	2.354	2.293
8.	MnO	0.109	0.044	0.047	0.086	0.090
9.	CaO	0.632	0.505	0.712	0.791	0.363
10.	K_2O	0.475	0.378	0.347	0.378	0.451
12.	Cl	0.525	0.723	0.654	0.863	0.912
13.	ZrO_2	0.368	0.169	0.161	0.179	0.230
14.	SnO_2	0.000	0.000	0.000	0.000	0.000

The silicon dioxide–to–aluminium oxide (SiO_2/Al_2O_3) ratio for EKR-A exceeds 2.0, indicating that the soil is non-lateritic. The same condition applies to EKR-B, EKR-C, and EKR-D. This result shows that the application of sodium sulphate and sodium dodecyl sulphate ($C_{12}H_{25}NaSO_4$) as electrolytes during electrokinetic remediation altered the degree of laterization of the crude-oil-contaminated soil, transforming it from lateritic to non-lateritic.

The major oxide constituents responsible for pozzolanic behaviour were not depleted during remediation. Instead, the preserved sesquioxide composition promoted the formation of cementitious compounds, which contributed to the improved strength characteristics of the remediated soil. This behaviour aligns with recent findings that electrochemical treatment can enhance mineral reactivity and bonding potential in contaminated soils without degrading their pozzolanic constituents (Zhang et al., 2022; Adewuyi et al., 2023).
Furthermore, the dominant oxides present in the treated soil SiO_2, Fe_2O_3, Al_2O_3, and CaO fall within the compositional ranges reported for effective pozzolanic materials in recent studies on soil stabilization and waste-derived binders (Siddique and Cachim, 2021; Kumar et al., 2024).

Total Petroleum Hydrocarbon (TPH):

The Total Petroleum Hydrocarbon (TPH) removal efficiency for the remediated soils was 42.55% for EKR- A, 48.94% for EKR- B, 58.51% for EKR- C and 67.02% for EKR- D respectively. Table 3 below summarized the concentration of crude oil before and after electrokinetic remediation.

Table 3: Total Petroleum Hydrocarbon of the soil Samples

S/no	Soil Sample	Weight Before Extraction (mg)	Weight After Extraction (mg)	TPH (mg/kg)	TPH Removal Efficiency (%)
1.	COCS	5,000.00	4,906.00	18,800.00	-
2.	EKR- A	5,000.00	4,946.00	10,800.00	42.55%
3.	EKR- B	5,000.00	4,952.00	9,600.00	48.94%
4.	EKR- C	5,000.00	4,961.00	7,800.00	58.51%
5.	EKR- D	5,000.00	4,969.00	6,200.00	67.02%

Index Properties

The index properties and compaction characteristics of COC and EKR-A, B, C, and D soils are summarised in Table 4, with particle size distribution curves presented in Figure 2. The soils are classified as A-7-6 under the AASHTO system and as low-plasticity clays (CL/OL) according to the Unified Soil Classification System. Atterberg limit tests showed that liquid limit, plastic limit, plasticity index, and linear shrinkage values decreased in the remediated soils. Liquid limits reduced from 46.00% in COC to 40.80%, 43.00%, 40.00%, and 37.50% for EKR-A, B, C, and D, respectively, likely due to increased water absorption or internal particle rearrangement caused by electric charge inducement. Specific gravity increased for EKR-A, C, and D from 2.36 to 2.37, 2.39, and 2.39, reflecting pore closure from crude oil removal, while EKR-B showed a slight reduction, possibly due to physico-chemical changes. Overall, the remediated soils exhibited lower plasticity and higher density, making them suitable for geotechnical applications such as embankments and construction works.

Table 4: The index properties and compaction characteristic of COC and EKR- A, B, C and D Soil.

Properties	COCS	EKR- A	EKR-B	EKR- C	EKR- D
Liquid limit, %	46.00	40.80	43.00	40.00	37.50
Plastic limit, %	26.77	21.4	22.56	27.08	12.92
Plasticity index, %	19.23	19.4	20.44	12.92	4.50
Linear shrinkage, %	10.71	9.64	6.43	8.43	5.00
% Passing BS sieve 20	37.74	37.96	38.14	37.78	38.22
AASHTO classification	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6
USCS classification	CL or OL	CL or OL	CL or OL	CL or OL	CL or OL
Specific gravity	2.36	2.37	2.35	2.39	2.39
MDD mg/m^3 (WAS)	1.91	1.85	1.86	1.87	1.85
OMC% (WAS)	11.80	13.40	13.10	13.14	13.30
MDD mg/m^3 (BSH)	1.98	1.98	1.94	1.93	1.94
OMC% (BSH)	11.56	10.50	10.80	11.48	10.90

Plastic limit, Plasticity index and linear shrinkage:

The plastic limit for the COC and the EKR- A, B, C and D soils used in this research are 26.77%, 21.40%, 22.56%, 27.08% and 33.00% respectively. The plasticity index of EKR- A, B, C and D changes from 19.23% to 19.40%, 20.44%, 12.92% and 4.50% respectively. The Shrinkage limit for the EKR- A, B, C and D decreased from 10.71% to 9.64%, 8.43%, 6.43% and 5.00% respectively. The improvement experienced in the plastic limit was due to the dominance of clay particles which agrees with the research work done by Sani et al, 2020). The particle size distribution (Hydrometer analysis, as shown in Figure 5.) curves for the contaminated and remediated soil samples are shown in Figure 4 below.

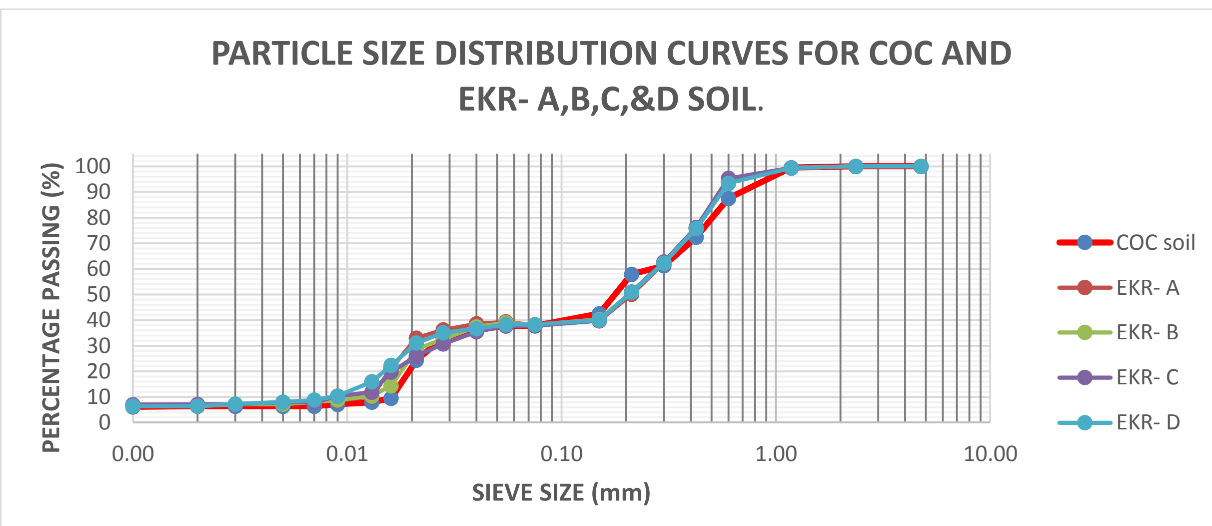

Figure 4: Particle size distribution (Hydrometer analysis) curves for COC and EKR-A, B, C and D.

Figure 5: Hydrometer Test of Soil Samples.

Specific Gravity:

Figure 6 shows the specific gravity of the COC soil improved from 2.36 to 2.37, 2.39 and 2.39 respectively for EKR- A, C and D. However, the reverse was the scenario for EKR- B, as this could be because of physio-chemical changes in the soil after remediation. The incremental change in specific gravity confirms the closure of pores preoccupied by the crude oil, thereby causing the soil to be denser as compared to when remediation was to be done.

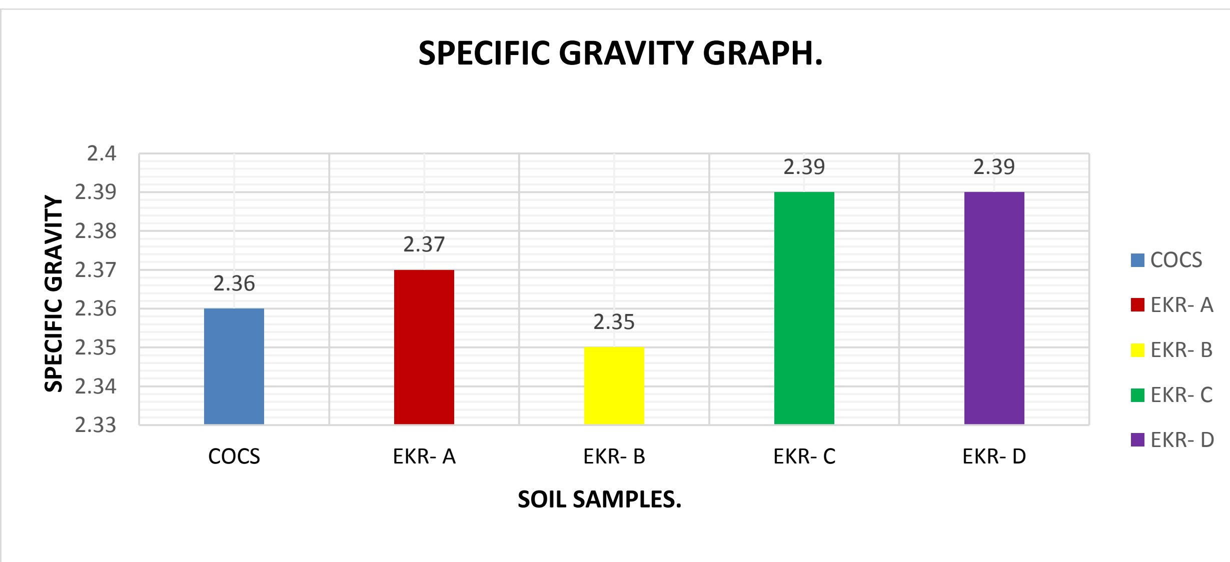

Figure 6: Specific gravity of soil samples

Maximum Dry Density (MDD) and Optimum Moisture Content (OMC):

The compaction parameters of the crude-oil-contaminated (COC) soil under WAS and BSH energies show notable variation after electrokinetic remediation. For the COC soil, the maximum dry density (MDD) and optimum moisture content (OMC) under WAS compaction were 1.91 g/cm³ and 11.80%, respectively, while under BSH they were 1.98 g/cm³ and 11.56%. After remediation, MDD at WAS decreased to 1.85 g/cm³ (EKR-A), 1.86 g/cm³ (EKR-B), 1.87 g/cm³ (EKR-C), and 1.85 g/cm³ (EKR-D). Under BSH, MDD reduced to 1.94 g/cm³ for EKR-B, 1.93 g/cm³ for EKR-C, and 1.94 g/cm³ for EKR-D. OMC values also showed slight reductions under BSH, with 10.50%, 10.80%, 11.48%, and 10.90% for EKR-A, B, C, and D, respectively. The higher compactive energy in BSH led to greater particle packing, requiring lower moisture for optimum compaction. This inverse relationship between compaction energy and OMC, and the corresponding trends in MDD, agree with recent studies showing that increased compactive effort improves particle rearrangement and reduces void ratios in treated soils (Ahmad and Uchimura, 2023; Qi et al., 2024).

Strength Characteristics

Unconfined Compressive Strength:

The strength characteristics is an important index in the selection of soil materials for construction and any other civil engineering works. The UCS shown in figure 7 increased from 173.42 KN/m^2 to 211.92 KN/m^2 for EKR-A at WAS compaction energy. For the BSH compaction energy, the UCS increased from 204.98 KN/m^2 to 212.65 KN/m^2. Generally, there is an improvement in the UCS for EKR- B, C and D as compared to the COC soil both at WAS and BSH compactive energy. The increase in the UCS experienced could be attributed to internal geochemical alteration, as well as charged ion interaction in the diffused double layer ionic concentration and subsequent modifications in the particle-to-particle rearrangement in the soil structure due to remediation. As reported by Qi et al., 2024, the minimum unconfined compression strength (UCS) of 200 kN/m^2 is adequate for compacted soil liner and cover.

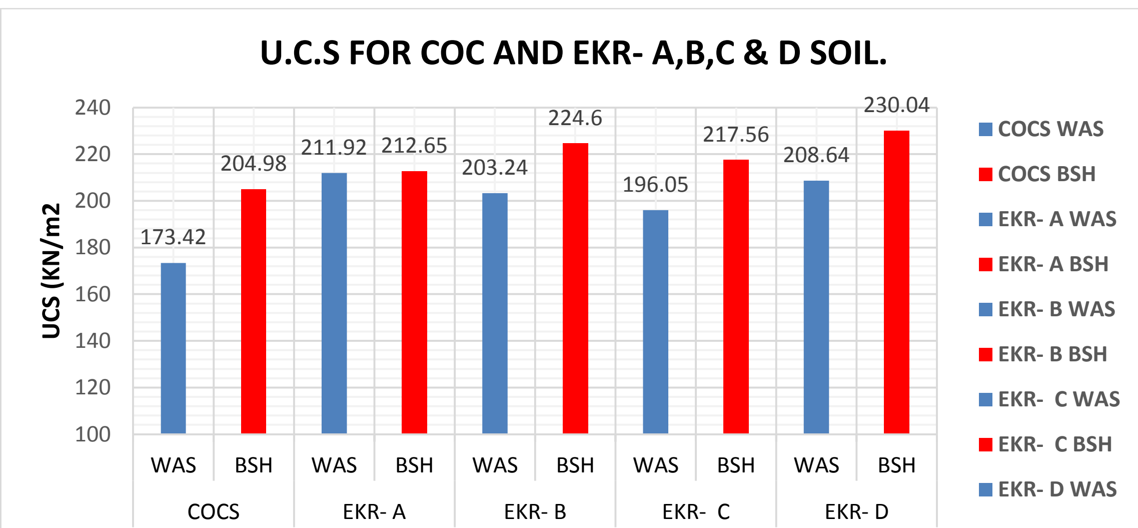

Figure 7: Unconfined Compressive Strength for COC and EKR- A, B, C and D

Hydraulic Conductivity

The results of the hydraulic conductivity test for the two compactive efforts for COC soil and EKR-A, B, C and D soil are shown in Figure 8 below.

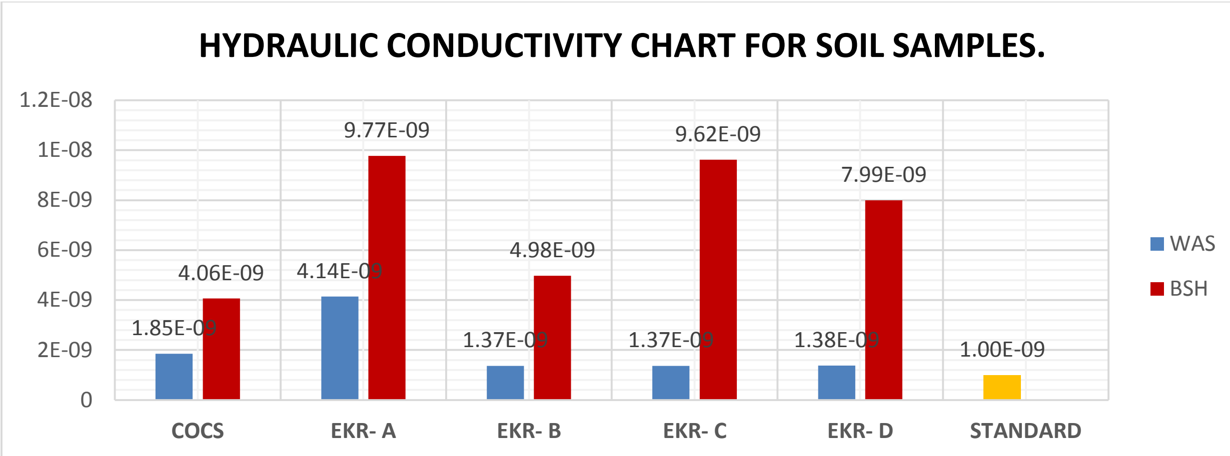

Figure 8: Hydraulic conductivity chart for soil samples.

These results are consistent with recent findings showing that low hydraulic conductivity is achievable in treated soils through appropriate remediation and compaction techniques (Ahmad and Uchimura, 2023; Qi et al., 2024; Akter et al., 2025). In general, a hydraulic conductivity value below 1×10^{-9} m/s is considered adequate for landfill liners and cover systems by most regulatory agencies. The electrokinetically remediated soils (EKR-A, B, C, and D) demonstrated hydraulic conductivity values within this recommended range, confirming their suitability as Liners and cover materials. The reduction in hydraulic conductivity can be attributed to the combined effects of particle rearrangement, pore closure, and enhanced cementitious bonding induced during the electrokinetic remediation process. Consequently, these soils not only meet regulatory requirements but also provide improved geotechnical performance for use in landfill liner and cover applications.

Volumetric Shrinkage Strain (VSS)

The shrinkage is mainly due to water loss by evaporation, as the drying proceeds from the surface; it goes deeper downwards making the dehydrated surface layer to shrink (Khire et al., 1997.).The graphical charts for the V.S.S results for EKR-A, B, C& D are shown in Figure 9 to 12.

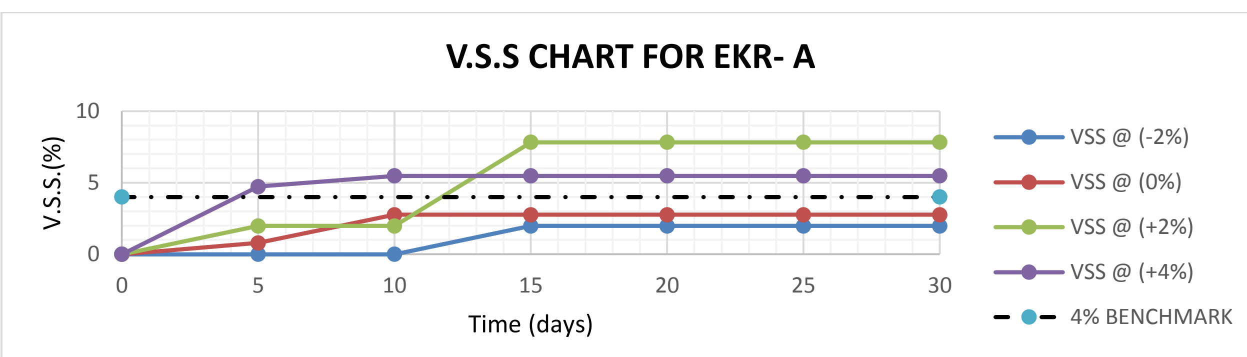

Figure 9: V.S.S for EKR- A soil @ -2, 0, +2 and +4% OMC (WAS compactive effort.)

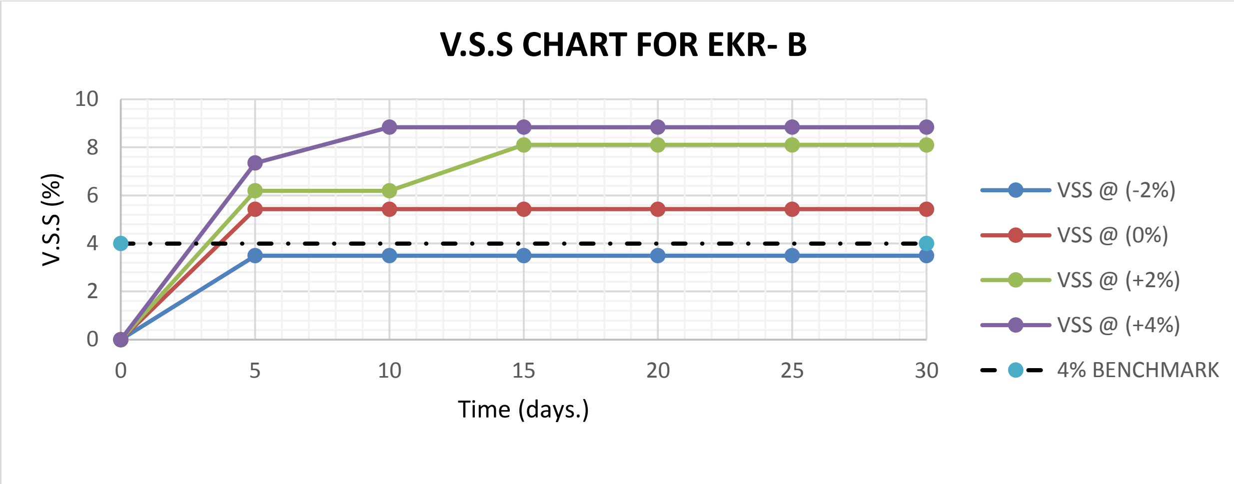

Figure 10: V.S.S for EKR- B soil @ -2, 0, +2 and +4% OMC (WAS compactive effort.)

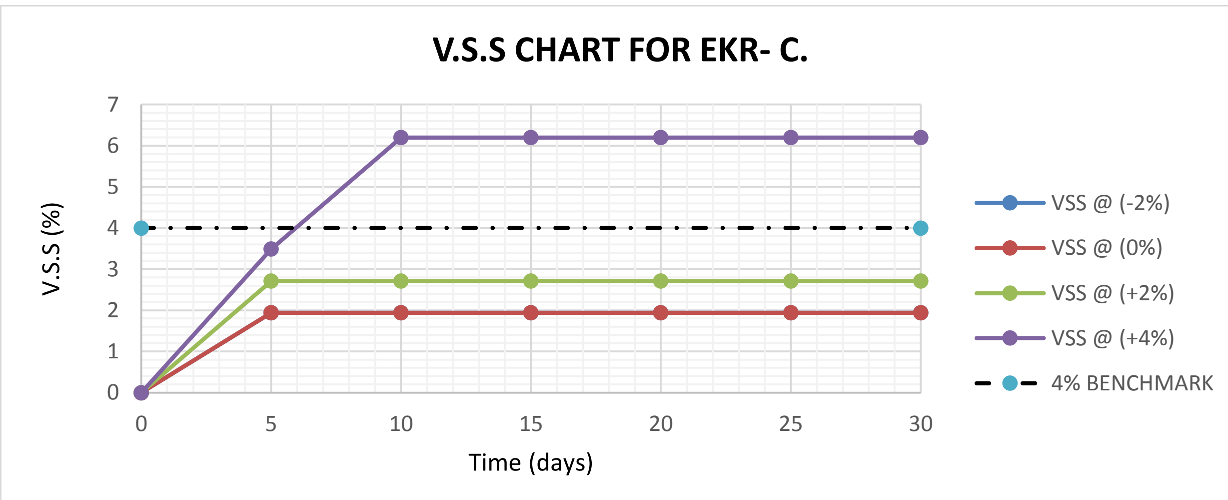

Figure 11: V.S.S for EKR- C soil @ -2, 0, +2 and +4% OMC (WAS compactive effort.)

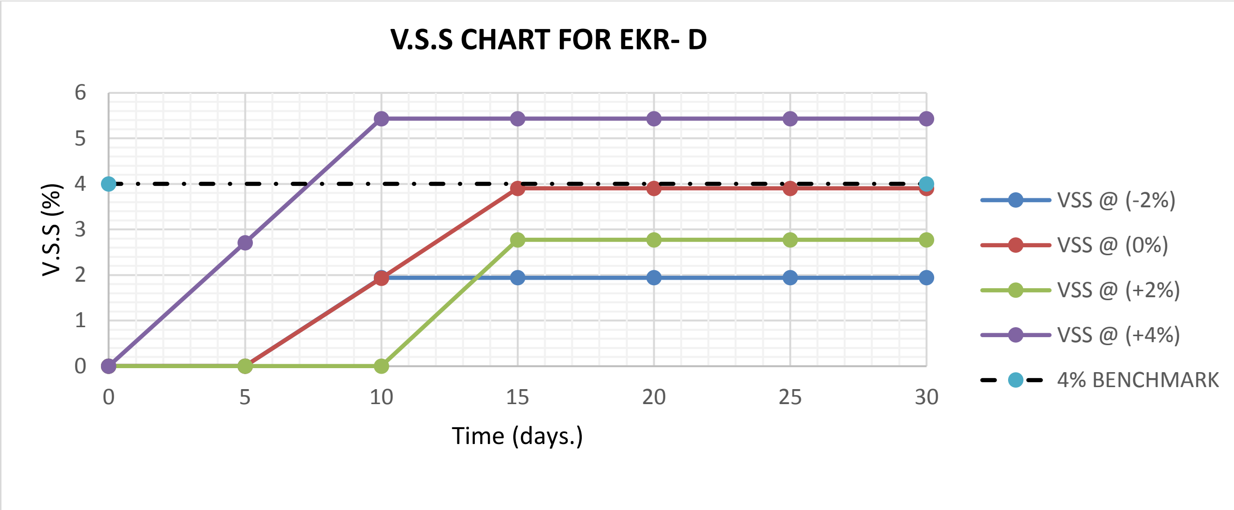

Figure 12: V.S.S for EKR-D soil @ -2, 0, +2, % +4% OMC (WAS compactive effort.)

For the remediated soils EKR-A, C, and D, specimens prepared at 2% dry of optimum and at optimum moisture content met regulatory limits, confirming their suitability for waste containment applications (Ahmad and Uchimura, 2023; Qi et al., 2024; Akter et al., 2025). EKR-B only met the requirements at 2% dry of optimum. To satisfy the recommended maximum volumetric shrinkage strain (VSS ≤ 4%) and in conjunction with the unconfined compressive strength and the Hydraulic conductivity tests, EKR-A, C, and D should be placed at 2% dry or optimum moisture content, while EKR-B should be placed at 2% dry of optimum.

Conclusion

1. The electrokinetic remediation efficiencies of the soils were 42.55% (EKR-A), 48.94% (EKR-B), 58.51% (EKR-C), and 67.02% (EKR-D), with the highest removal in EKR-D using 0.20 M sodium sulphate and 0.05 M SDS (Saini et al., 2021; Boulakradeche et al., 2021). The treatment increased SiO_2 content from 47.022% to 61.803–61.880% across EKR samples without depleting Al_2O_3 and Fe_2O_3, promoting cementitious properties. These chemical changes contributed to improved strength and durability, making the remediated soils suitable for geotechnical applications such as landfill liners and construction fill.

2. The COC soil is classified as A-7-6 (AASHTO, 1986) and as low-plasticity clay (CL/OL) (ASTM, 1992), with EKR-A, B, C, and D maintaining the same classification. Electrokinetic remediation improved Atterberg limits, reducing LL from 46.00% to 40.80–37.50% and LS from 10.71% to 5.00–9.64%. Specific gravity increased from 2.36 to 2.37–2.39, reflecting denser, more stable soil properties.

3. The unconfined compressive strength (UCS) of COC soil increased from 173.42 kN/m² (WAS) and 204.98 kN/m² (BSH) to 196.05–211.92 kN/m² (WAS) and 212.65–230.04 kN/m² (BSH) for EKR-A, B, C, and D. Hydraulic conductivity varied with compactive energy, increasing by factors of 2.09–2.56 (WAS) and 0.92–5.71 (BSH) across remediated soils. These results indicate that EKR-A, B, C, and D, when compacted at higher energy, are suitable as landfill liners and covers. To satisfy the regulatory 4% maximum volumetric shrinkage strain, EKR-A, C, and D should be

placed at 2% dry of optimum or optimum moisture content, while EKR-B requires 2% dry of optimum water content.

4. The OMC under WAS compactive effort is higher than BSH due to void expulsion during compaction. MDD values are generally higher at BSH, reflecting closer particle packing and lower spacing under WAS. Consequently, BSH requires less moisture for optimum compaction, as higher energy densifies the soil, reducing voids and increasing the volume of soil per cubic metre in the compacted state.

5. The remediated soil samples EKR- D have the tendency to be adopted as Liners and covers in waste containment facility when compacted at West African Standards (WAS) compactive effort and placed at 2% dry of optimum and 0% optimum moisture content.

Recommendation

Electrokinetic remediated soil (EKR- D) can be adopted for use as Liners and covers if it is compacted and placed as recommended.

References

AASHTO (1986). Standard Specification for Transport Material and Methods of Sampling and Testing. 14th Edition, American Association of State Highway and Transport Officials (AASHTO), Washington, DC.

Adebayo K., Moses G., Sani J., Haruna Ibrahim B., Balarabe F. (2023). Filter Enhanced Electrokinetic Remediated Crude Oil Contaminated Soil: Investigation of Its Engineering Properties and Its Suitability For Road Construction. Vol. 42, No2, pp. 175 – 184. https://doi.org/10.4314/njt.v4212.3

Ahmad, W., and Uchimura, T. (2023). The effect of moisture content at compaction and grain size distribution on the shear strength of unsaturated soils. Sustainability, 15(6), 5123. https://doi.org/10.3390/su15065123

Akter, M. J., Aslam, M., Manan, A., Asif, M., Shah, S. Z. A., and Hassan, A. (2025). Soil compaction and classification analysis for enhanced load-bearing capacity in construction. European Journal of Theoretical and Applied Sciences, 3(1), 83–99

ASTM (1992). Annual Book of Standards Vol. 04.08, American Society for Testing and Material, Philadelphia.

BS 1377, (1990). Method of Testing Soils for Civil Engineering Purpose. British Standard Institute, BSI, London.

BS 1924, (1990). Method of Test for Stabilized Soils. British Standard Institute BSI London.

Dong Li, H., Zhao, H. R., and Tian, K. (2024). Hydraulic conductivity of bentonite-polymer geosynthetic clay liners to aggressive solid waste leachates. Geotextiles and Geomembranes, 52(5), 900–911.

Kumar, S., Gupta, R., and Mehta, A. (2024). Oxide composition and pozzolanic performance of alternative geomaterials. Materials Today: Proceedings, 86, 412–419.

Lawal A.A., Ijimdiya T.S., Moses G., Sani JE. (2023). Use of Electrokinetic Remediated Soil as A Subgrade Material. Iranian (Iranica) Journal of Energy and Environment. 14(4), 352 – 359.

Qi, S., Ma, W., Zhang, X., Wang, J., Hu, X., Wei, Z., and Liu, J. (2024). Effects of Remolding water content and compaction degree on the dynamic behaviour of compacted clay soils. Buildings, 14(8), 2258. https://doi.org/10.3390/buildings14082258

Saini, A., Bekele, D. N., Chadalavada, S., Fang, C., and Naidu, R. (2021). Electrokinetic remediation of petroleum hydrocarbon contaminated soil (I). Environmental Technology and Innovation, 23, 101585. https://doi.org/10.1016/j.eti.2021.101585

Sani, J.E., Moses, G., and Oriola, F.O.P., (2020). Evaluating the electrical resistivity of microbial-induced calcite precipitate-treated lateritic soil. SN Applied Sciences, 2(9), pp.1492. Doi: 10.1007/s42452-020-03285-x

Siddique, R., and Cachim, P. (2021). Waste and supplementary cementitious materials in concrete. Woodhead Publishing.

Silva, T. F. da, Lyra, M. V. M. de, Silva, I. F. da, Paiva, W. de, Melo, M. C. de, and Monteiro, V. E. D. (2024). Evaluation of water permeability in compacted sand-bentonite liners from landfill using planning and factorial analysis. Journal of Environmental Engineering and Landscape Management, 32(3), 182–190. https://doi.org/10.3846/jeelm.2024.21830

Yuan, L., Xu, X., Li, H., Wang, Y., and Wang, J. (2020). Synergistic remediation of heavy metal-contaminated soils by combined electrokinetic remediation and phytoremediation: A review. Chemosphere, 258, 127304. https://doi.org/10.1016/j.chemosphere.2020.127304

Zhang, Y., Li, J., Wang, Z., and Chen, Q. (2022). Pozzolanic reactivity and cementitious behaviour of treated soils for sustainable construction applications. Construction and Building Materials, 324, 126651. https://doi.org/10.1016/j.conbuildmat.2022.126651

Zulfahmi A. R., Umar H., Mohammad R. T., Norsheila S. I., and Noorulakma A. (2010) “Influence of oil contamination on geotechnical properties of basaltic residual soil”, American Journal of Applied Sciences, 7(7), 954-961.