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FILTER MEDIA ENHANCED ELECTROKINETIC REMEDIATED CRUDE OIL CONTAMINATED SOIL: INVESTIGATION OF ITS ENGINEERING PROPERTIES AND ITS SUITABILITY FOR ROAD CONSTRUCTION

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Abstract
Research have shown how electrokinetic remediation (EKR) technology attempts to tackle the challenge of soil contamination by crude oil. However, the suitability of the resulting remediated soils for use in road construction have not been well reported. This work investigates the engineering properties of filter media enhanced electrokinetic remediated crude oil contaminated soil (COCS) with a view to ascertain its suitability for use in road construction by comparing the performance of charcoal and active carbon as filter materials. COCS collected at a depth of 1m from the Nigerian Pipeline and Storage Company, Kaduna was remediated by using graphite electrodes to pass 1V DC/cm across EKR setups enhanced by incorporating a 1cm thick charcoal and active carbon separately as filter materials across the setups. Average removal efficiencies of 81.4% and 84.6% were obtained against the 78,600 mg/kg oil content of the COCS from charcoal and active carbon filter media enhancements respectively. This showed that active carbon, with higher removal efficiency, is a better filter medium for COCS than charcoal. The compaction and California bearing ratio (CBR) properties of the COCS also improved with the filter media enhanced EKR. However, the CBR values for the filter media enhanced EKR soils only meet the 20% minimum requirements for Type 2 sub-base course materials specified for light trafficked Nigeria roads. As such, charcoal or active carbon filter media enhanced EKR technology can be adopted for remediating COCS for light trafficked Nigeria road construction in areas not subjected to flooding.

Keywords: Crude oil contaminated soils, Electrokinetic remediation, Engineering properties, Filter media, Base course.

1.0 INTRODUCTION

Engineering properties of soils like compaction parameters, strength properties, permeability properties, shrinkage property and compressibility properties are particularly important for specifying the engineering uses of soils [1]. Failure of road structures has been attributed to so many causative factors like poor quality construction materials [2, 3], poor design and construction procedures [4], overstressing from overloading [5], poor drainage design and construction [4], poor supervision and workmanship, and poor maintenance practice [6] among others.

[1] specifies the CBR values of materials to be used as sub-base and base courses for Nigeria roads as: Normally the minimum strength of such base course material shall not be less than 80% CBR value being determined at maximum dry density and optimum moisture content un-soaked with either West African or Modified AASHTO. However, where the Engineer's Representative considers it necessary on account of perched water-table or any other reasons, he may specify that a CBR value of 80% be obtained after at least 24 hours soaking.

Such sub-base material classified as, Type 1 is made from pit-run laterite, sand, or screening, and soil of other similar binding or filler material. A minimum CBR of 30% after at least 24 hours soaking is also required as determined by British Standard. Type 2 requires that the CBR assessed by West African Standard Compaction test shall not be less than 20% after at least 24 hours of soaking, for light traffic. Type 3 consists of materials designated as sub-standard but may be used for sub-base or base when suitable materials are not available [1].

Engineering properties of soils are very important in deciding the suitability of soils for structural uses. These properties of soil do not always remain the same throughout the design life of roads. They can vary as a result of capillarity action, flooding, seismic loads, frost action, and exposure to various contaminants [7]. Soils that experience variations due to one or some of these reasons are considered not durable for road use [8, 9]. One of the contaminants which have led to the abandonment of projects, change in projects scope or great increase in projects cost is oil in the form of hydrocarbon, which can be crude oil or any of its fractions [10].

The variations in the engineering properties of soils due to the presence of oil have been reported in many research. [11] maintained that the lubricating effect of crude oil led to the decrease in the optimum moisture content (OMC) and an increase in the maximum dry density (MDD) of crude oil contaminated alluvial soil. An increase in the compressibility and a decrease in permeability of Faw soil was reported by [12] when contaminated with black oil. The unconfined compressive strength increases with up to 10% oil content before decreasing at higher percentages. The in-situ condition of the contaminated Faw soil was recommended for use under the foundation as long as it is isolated from living creatures. Remediation or stabilization was recommended due to a reported decrease in compaction parameters (OMC and MDD), California Bearing Ratio (CBR) and permeability of crude oil contaminated lateritic soil with increasing oil content [7]. [13] have reported a sinusoidal trend in the permeability of an A-6 (CL) soil with crude oil, an initial decrease in permeability from 0% to 2% crude oil content is followed by subsequent non-proportional increase. This trend can affect the natural groundwater recharge of the soil and soil aeration through bioremediation can be used to remedy the defect [13].

Negative effects of using crude oil contaminated soil for roads and building construction is further stressed when [14] observed a decrease in the MDD, CBR and cohesion of clay soil. These effects are further strengthened by the decrease in shear strength and an increase in compressibility of oil contaminated clay soil obtained by [15]. The loose packing of clay particles and their separation from grain surface in cohesion with increasing oil content is maintained as the cause of the decline in the unconfined compressive strength (UCS) of a clay soil contaminated with diesel oil [16]. [17] with lean clay, noticed an increase in the angle of internal friction, MDD, and compression index, with a decrease in OMC and cohesion of the soil as the oil content increases. [18] noticed that the presence of crude oil on highly plastic clayey soil manifests itself by decreasing the compaction parameters, swelling pressure, coefficient of consolidation, UCS and shear strength parameters of the soil together with an increase in the compression and swelling indices and compressibility of the soil. It was also stated that oil content of the highly plastic clayey soil has no effect on the chemical and mineralogical composition of the soil.

[19] had earlier demonstrated how oil contamination can result in lower compaction parameters, coefficient of permeability, undrained shear strength cohesion (CU) of a basaltic residual soil of grades V and VI. [20] noticed an increase in MDD and UCS of unexposed soil with increase in oil content up to 4%, but a decrease as oil content increased above 4%. Unlike MDD, UCS was seen to decrease with increase in curing time. The hydraulic conductivity decreases with increase in oil and curing time. For the exposed soils, MDD showed same variation trend to that shown by the unexposed soils. Hydraulic conductivity was observed to increase with increase in oil and curing time. [21] supported his view on the negative effect of crude oil on clay soil by reporting a decrease in MDD and an increase in OMC of crude oil contaminated clay soil.

Similar to [22] where oil contaminated was reported to affect the geotechnical behaviour of bridge pile foundation, [23] also acknowledged the negative effects of oil in soils but still maintained that oil contaminated soils can be re-used in construction involving hot-mix asphalt production, concrete production and sandcrete block production as long as the oil leaching rate from the structure is minimal. However, Soils containing oil may generally be contemplated for road constructions as evident from [24] where the shear strength, allowable bearing pressure and hydraulic conductivity on granular soil were reported to decrease significantly upon contamination with used motor oil, it was further concluded that a structure that is already constructed on such soil will experience distress, such as cracks, upon subsequent contamination of the supporting soil. In the case of fire, the crude oil incinerated (COI) soil may be incorporated into roads as evident from [25] where an initial increase and gradual decrease in the MDD with decrease in OMC were observed as the percentage incineration increased. Peak CBR of 70% at 20% COI for British standard high (BSH) compaction energy and 32% peak at 16% COI for British standard low (BSL) compaction energy were also reported. Incorporation of 12% COI lateritic soil into sub-base road constructions was recommended as it met the 30% CBR value requirement for lightly trafficked roads by the Nigerian General Specification. The presence of oil in soils have been shown by these researchers to not only affect the index properties of soils but the engineering properties have also been shown to be of low qualities as their oil contents increase.

Contaminants-free soils do not only translate directly to good human health and environment, they may also imply soils with good properties for structural uses. Due to anthropogenic activities of man, soils get contaminated, the levels of these contaminants may sometimes get to limits that pose threat to man [26]. Several technologies like immobilization [27], soil washing [28], phytoremediation [29], bioremediation [30], thermal desorption [31], soil vapour extraction [30] and soil flushing [30] have demonstrated limited remediation measures to decontaminating these soils [32]. The quest for a technology that can decontaminate the soils and also restore their engineering properties to its before contamination level or to a better one has led to the investigation of electrokinetic remediation (EKR) technology for treating contaminated soils [33].

The most outstanding technical benefits of EKR technology are its safeness, simplicity, can operate in-situ or ex-situ, can be combined with other technologies, economical and can be adopted for many contaminants and materials. The use of EKR in large scale has been demonstrated to be a viable and economic remediation technology. This is emphasised when [34] integrated EKR into bioremediation of low permeable hydrocarbon contaminated soil and was able to achieve 46.4% removal efficiency in 7 days' operation. [35] showed that with 300% increase in the quantity of petroleum contaminated soils using electrochemical technique, about 44% (2.94 kWh/kg to 1.64 kWh/kg) decrease in remediation energy requirement was achieved. [36] also used an unenhanced EKR setup to remove 80% and 45% of contaminants at cathode and anode respectively from an oil contaminated clayey soil after 18 days by using 0.6 V/cm specific voltage. The overall efficiency of the treatment and restoration of properties was in the range of 65-75%.

There has been need for combining EKR with other technologies to achieve the effect of contaminant migration and removal [37] since EKR can only make the pollutants in the soil move to the designated region, but cannot easily eliminate the pollutants. This is necessary as the mobilized contaminants, when not removed after their transport, can lead to reversal of electroosmotic (EO) flow, thereby prolonging the duration of the remediation [38]. The technology combining EKR and permeable reactive barrier (PRB) can improve the removal efficiency of pollutants and the performance of EKR by accelerating the transport and removal of pollutants, thus reducing manpower and material inputs [39].

The use of carbonaceous materials like charcoal and activated carbon have been contemplated as filter materials in EKR setups for contaminants removal [40]. A large number of hydroxyl, phenol and carboxyl groups are distributed on the surface of charcoal and activated carbon and the internal pores are well developed [40]. Therefore, charcoal like activated carbon has excellent adsorption and chemical stability, which is a commonly used material in the early stage of permeable reactive barrier (PRB). Use of carbon active materials as membranes in between contaminated soils and electrodes in EKR setups have demonstrated up to six times improvement in the removal of organic contaminants and 72% removal efficiency have also been reported for inorganic contaminants [41]. This is possible as contaminated materials can be adsorbed or precipitated by physical, chemical or biological means as they pass through the reactive membranes with high surface area and porous structures [39, 41-44].

Cost analysis of the use of active carbon which requires chemical or very high temperature for its activation as filter material against other readily available materials like charcoal and other fibers in the EKR of contaminated soils may not be economically feasible. This gap in literature necessitates the research into reactive materials that are natural or synthetic, easy to obtain, economical and environmentally friendly as possible substitutes for the active carbon to be used as filters in the removal of contaminants. However, new alternatives such as charcoal, natural fibers, zeolites, among others, have gained interest among the scientific community as cheap and easy to obtain filtering material. In technical literature, there is a large number of materials with high removal rates for different types of compounds. For example, charcoal which is similar to active carbon but has not been activated to improve its surface area and reactivity can be used. This is because of its cheap availability and the possibility to increase its surface area by simply grinding it to finer sizes [45].

The foregoing has shown that crude oil content in soils can exceed permissible limits thereby posing dangers to human, environments and structures. These contaminated soils can be remediated by EKR technology. However, previous research work [7, 13-15, 22, 23, 25, 34, 41] have indicated a gap that no thorough investigation of the impacts of filter media enhanced EKR on the engineering properties of crude oil contaminated soils for subgrades, sub-bases and road bases has been reported. This research would look into investigating the effect of charcoal and active carbon as filter media on electrokinetic remediated crude oil contaminated soil to ascertain its suitability for use in road construction.

2.0 MATERIALS AND METHODS

2.1 Materials

The materials for this research work include:

Contaminated soil: The crude oil contaminated soil (COCS) used for this work was obtained at a depth of 1 m from the Nigerian Pipeline and Storage Company, Kaduna State, Nigeria located around latitude $10^0$24’6” and longitude $7^0$29’32”.

Distilled water: The distilled water obtained from the Department of Fashion Design and Clothing Technology; Kaduna Polytechnic, Kaduna State, Nigeria was used.

Water: Tap water from the borehole provided near the Civil Engineering laboratory of the Nigerian Defence Academy, Kaduna State, Nigeria was used.

Electrodes: 8 mm diameter by 300 mm long graphite electrode rods, obtained from a Parsity laboratory store at Lagos Street in Kaduna State, Nigeria was used.

EKR cell: With little modifications to the set-up adopted by [44], EKR cell made from clear plexiglass plate of overall dimension, 400 mm by 200 mm by 300 mm, with middle internal partition, 300 mm by 200 mm by 300 mm and two outer partitions, 50 mm by 200 mm by 300 mm adjoining the middle was used.

Connecting wires and clips: Flexible connecting wires and battery clips obtained from Parsity laboratory store at Lagos Street in Kaduna State, Nigeria were used.

Direct current (DC) supply: DC supply of 30 Volt, 5 Ampere capacity was used.

Charcoal: Charcoal (Figure 1), passing sieve size 300 µm and retained on sieve size 150 µm, obtained by incinerating hardwood to a temperature of 300^0C was used.

Active carbon: Active carbon (Figure 1), passing sieve size 300 µm and retained on sieve size 150 µm, obtained from Bijo laboratory and surgical store at Kano Road in Kaduna State, Nigeria was used.

Sodium hydroxide (NaOH): NaOH obtained from United surgical store at Constitution Road in Kaduna State, Nigeria was used.

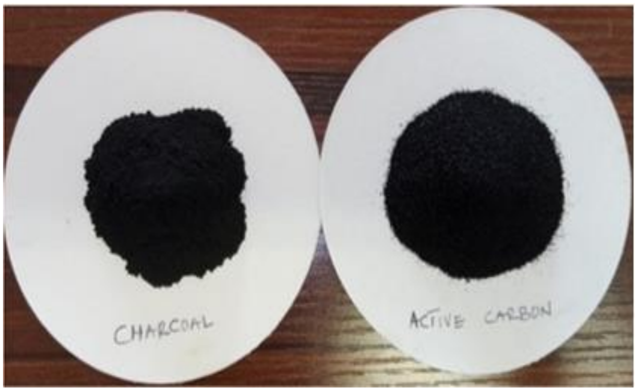

Figure 1: Charcoal and Active Carbon Filter Materilals

2.2 Methods

The crude oil contaminated soil was subjected to the following:

2.2.1 Total petroleum hydrocarbon (TPH) test

The TPH contents of the crude oil contaminated soils and those of the filter media enhanced electrokinetic remediated soils in this research were conducted by gravimetric method (the Toluene cold extraction method) as described in [46]. The removal efficiencies of the filter media were evaluated from [47];

$$\text{Re}\ (\%) = \left(\frac{C_0 - C}{C0}\right) * 100 \tag{1}$$

Where; C_0 is the initial contaminant concentration in soil (mg/kg) and C is the residual concentration of contaminant in soil after the treatment (mg/kg).

2.2.2 Electrokinetic remediation (EKR)

With little modification to the electrokinetic remediation setup by [44]. The solar powered charcoal and active carbon filter media enhanced EKR setup used in this study is shown in Figure 2 and described in Table 1 below. The DC supply is used to supply constant 30 V and maximum of 5 A through graphite electrodes (two at both ends) to the contaminated soil in the setup to achieve 1 V DC/cm across the setup. The setup was maintained under such condition until no effluent was observed from the cathode valve.

Figure 2: Filter Media Enhanced EKR Setup for Crude-oil Contaminated Soil

Table 1: Summary of Electrokinetic Remediation Setup

Details	Experiment 1	Experiment 2
Contaminant	Crude Oil	Crude Oil
Length of Soil (cm)	30.0	30.0
Width of Soil (cm)	20.0	20.0
Depth of Soil (cm)	30.0	30.0
Electrical potential (V)	30.0	30.0
Filter Medium	Charcoal	Active Carbon
Filter Thickness (cm)	1.00	1.00
Width of Filter (cm)	20.0	20.0
Depth of Filter (cm)	30.0	30.0
Anode Purging Solution	0.01 M NaOH	0.01 M NaOH
Cathode Purging Solution	0.01 M NaOH	0.01 M NaOH

For the purpose of classification, checking compliance and determining the degree of improvement obtained in the engineering properties of the enhanced EKR crude oil contaminated soil, the following laboratory tests were carried out on both the COCS and the EKR soils in accordance with [48] "Methods of Tests for Soil for Civil Engineering Purposes" as recommended in [1] "Tests to be Carried Out":

i. Compaction test
ii. California Bearing Ratio (CBR) test
iii. Durability test (Unconfined Compressive Strength, UCS).

3.0 RESULTS AND DISCUSSION

The results of all the laboratory experiments carried out on the COCS and the filter media enhanced EKR soils were reported and discussed accordingly under the different subsections.

3.1 Contaminant Level

Table 2: Summary of Filter Media Enhanced EKR of COCS

Details	Charcoal	Active Carbon
Initial TPH (mg/kg)	78,600	78,600
Duration (days)	18	14
Average Remediation Efficiency (%)	81.4	84.6

Table 2 shows the TPH of the crude oil contaminated soil (COCS) obtained at a depth of 1 m from the Nigerian Pipeline and Storage Company, Kaduna determined to be 78,600 mg/kg, this value far exceeds the permissible limits for soils and thus needed to be remediated before its engineering usage [49]. Crude oil removal efficiencies of 81.4% and 84.6% from the incorporation of charcoal and active carbon seperately as filter media respectively into EKR technology adopted in remediating this soil gave remarkable results.

3.2 Compaction Parameters

West African Standard (WAS) Compaction

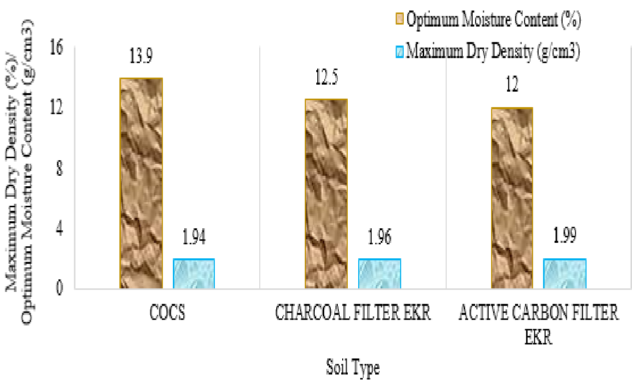

Figure 3: WAS Compaction Parameters of COCS and Filter Media Enhanced EKR Soils

The compaction parameters (MDD and OMC) of the COCS at WAS compaction energy are obtained as 1.94 g/cm^3 and 13.9% respectively as shown in Figure 3. This MDD is seen to increase to 1.96 g/cm^3 and OMC decrease to 12.5% when the contaminated soil was remediated using charcoal filter medium enhanced EKR technology. These parameters with charcoal filter medium enhanced EKR represent an increase of 4.3% in the MDD and a decrease of 11.2% in the OMC to those for COCS. When further compared to 1.99 g/cm^3 MDD and 12.0% OMC obtained with active carbon filter medium enhanced EKR, the MDD for the COCS is increased by 2.6% and the OMC decreases by 15.8%. When the parameters for active carbon filter medium enhanced EKR are compared to those for charcoal filter medium enhanced EKR, the MDD and OMC for active carbon filter medium enhanced EKR are better by 1.5% and 4.0% respectively. The behavior of the compaction parameters at WAS energy agrees with those reported by [7, 14, 17-19, 21].

The OMC for the COCS is seen to be highest. This could be due to thick adsorbed water on the contaminated soil particles which is covered by the crude oil, this makes the particle-to-particle contact required in compaction difficult. The addition of water, at first, breaks the separation layer between the adsorbed water and the free water before the lubrication of the particles for compaction starts. The lower OMC for the filter media enhanced EKR can be seen to be due to the reduced crude oil content of the soils which reduces the thickness of the adsorbed water and relatively increases the particle-to-particle contact of the soil grains. The addition of water ensures the lubrication of the particles and closer packing of the soil grains. The MDD which increases as the particle-to-particle contact increases is observed to be highest with active carbon filter medium enhanced EKR soil, followed by the charcoal filter medium enhanced EKR soil before the COCS. This could be due to the higher desorption ability of active carbon relative to charcoal which allows the oil contents in the contaminated soil to be remove more faster and with more efficiency than with the charcoal filter [39]. This shows that active carbon filter medium enhanced EKR soils with lower crude oil content produces soils with better compaction parameters than the charcoal filter medium enhanced EKR soils.

3.3 California Bearing Ratio (C.B.R.)

From Figure 4, the CBR values obtained by West African Standard Compaction after 24 hours of soaking shows variations between the COCS and the filter media enhanced EKR soils. The CBR value of the COCS is 6.70%. The value increases to 35.88% for charcoal filter medium enhanced EKR soil. This 35.88% represents 435.5% improvement to the value for COCS. This shows that the use of charcoal as filter medium in enhancing EKR of COCS can significantly improve its CBR value. The CBR value with active carbon filter medium enhanced EKR soil is 46.05%. This represents 587.3% improvement to the value for COCS and 28.3% improvement to the value for the charcoal filter medium enhanced EKR soil. This generally concludes that for a road structure subjected to inundation by water, COCS should not be used where high CBR value is a requirement of the road structure and COCS remediated by the use of either charcoal or active carbon as filter media can be recommended for possible usage [1].

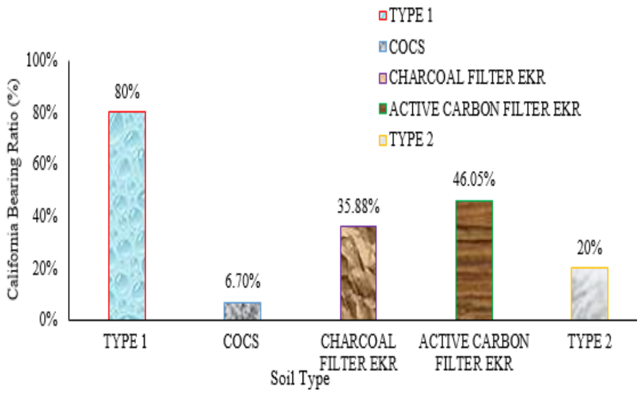

Figure 4: CBR Values of COCS and Filter Media Enhanced EKR Soils

The CBR value generally decreases with increase in crude oil content, this trend is similar to those reported by [7] and [14]. From Figure 4 above, the CBR values are obtained at West African Standard compaction energy compaction, the 6.7% value obtained from the COCS does not meet the 80% minimum requirements for Type 1 base or sub-base materials for Nigerian roads nor does it meet the 20% minimum requirements for Type 2 sub-base materials for light trafficked roads but may be classified as sub-standard material for sub-base by [1]. The higher CBR values with the active carbon filter medium enhanced EKR compared to the charcoal filter medium enhanced EKR shows that active carbon is a better material compared to charcoal for enhancing EKR of COCS [41, 44]. However, the CBR values for the charcoal and active carbon filter media enhanced EKR soils, obtained at WAS compaction energies as 35.88% and 46.05% respectively, only meet the 20% minimum requirements for Type 2 sub-base course materials for light trafficked roads specified by [1].

3.4 Durability Analysis

The durability of the COCS and EKR soil enhanced by the use of charcoal and active carbon as filters are presented in Figure 5. The active carbon filter media enhanced EKR soil has the highest durability with resistance of 15.24% to loss in strength when subjected to alternate drying and wetting conditions. This, when compared to the resistance to strength loss of 8.57% in the COCS, has 77.83% durability advantages. With 10.10% resistance to strength loss with the charcoal filter medium enhanced EKR soil, the active carbon filter medium enhanced EKR soil has 50.89% durability advantages when used over it as a road material in an area subjected to alternate drying and wetting conditions. Although, the COCS and filter media enhanced EKR soils are not stabilized soils. The very low resistance to loss in strength could be due to the residual oil content of the COCS and the filter media enhanced EKR soils. None of the samples meet the 80% resistance to strength loss required for a durable road soil material recommended by [8].

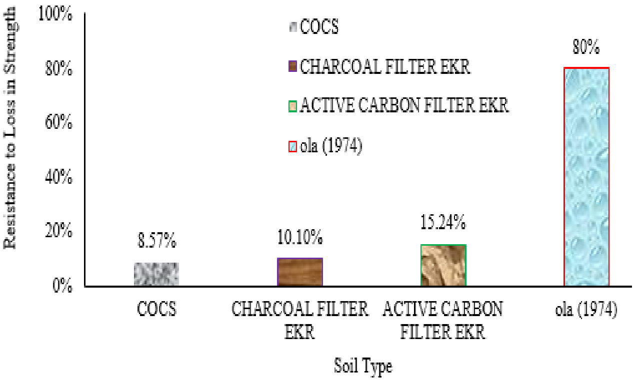

Figure 5: Durability of Filter Media Enhanced EKR Soils

4.0 CONCLUSION

Engineering properties and suitability of filter media enhanced electrokinetic remediated COCS for use in road construction have been investigated and the results have been presented, analysed and discussed. From the study, the following conclusions are drawn:

i. The incorporation of charcoal and active carbon as filter media into electrokinetic remediation technology for crude oil contaminated soil can enhance the removal efficiency of crude oil from soils

ii. The CBR values of charcoal and active carbon filter media enhanced electrokinetic remediated crude oil contaminated soils assessed by West African Standard Compaction after 24 hours soaking are adequate for their use as sub-base materials in the construction of light trafficked roads in Nigeria.

iii. Decontaminated soils obtained from filter media enhanced electrokinetic remediation of crude oil contaminated soil which incorporates charcoal or active carbon as filter material have very low resistance to loss in shear strength. As such, filter media enhanced electrokinetic remediated crude oil contaminated soils are not suitable for use in road construction in areas of periodic wet and dry season.

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