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Use of an Eletrokinetic Remediated Soil as a Road Subgrade Material

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A B S T R A C T

The soil investigated for suitability checks, as a subgrade material in this study, was a crude oil contaminated (COC) soil treated using an electrokinetic technique. The index properties and compaction characteristics of the electrokinetic remediated (EKR) soil are natural moisture content was 10.97%; The Atterberg limit test showed liquid limit, plastic limit, plasticity index and linear shrinkage of 36.50%, 22.05%,14.45 %, and 4.30%, respectively. The percentage of 62.80% passes 0.075mm sieve with a maximum dry density (MDD) of 1.77 Mg/m^3, and the moisture content decreased from 13.2% to 11.81%. The soil is classified as A-6 according to AASHTO classification system and belong to clay of low plasticity CL or OL group according to the Unified Soil Classification System. The unconfined compression strength, (UCS), durability, and California bearing ratio (CBR) of the electrokinetic remediated soil improved marginally from 46.63kN/m^2 to 92.64kN/m^2; from 18% to 23%; and from 2.55% to 4.05% respectively. However, these results obtained, do not meet the minimum requirement of the Nigerian General Specification. As a result, it is advised for further research, that an EKR soil be stabilized using cement stabilization to achieve the desired subgrade strength.

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INTRODUCTION

In past decades, there have been a progressive increase in the use of an electrokinetic technology for the recovery of a polluted or contaminated soil. Though little or not much work have been carried out on the geotechnical engineering properties of an electrokinetic remediated soil to know their suitability or the needs for improvement that might be required on the material.

Electrokinetic (EK) remediation still a new technology used in soil remediation in polluted soils that has low permeability [1–6].

Recently, many works have been done by researchers with a positive breakthrough by the application or combination of enhancement method to improve the degree or quality of remediation. It involves the application of low electric voltage to an electrokinetic cell containing two or a couple of electrodes inserted in an electrolyte at both ends of the cell to remove, organic, inorganic, and heavy metal compounds from a contaminated soil [2, 5, 7, 8].

EKR achieves the purpose of remediation by applying an electric field to the contaminated soil/sediment, enriching the pollutants to the cathode or anode zone through electroosmosis, electromigration, and electrophoresis (Figure 1). Electric migration is the movement of charged dissolved ions through an aqueous medium toward the electrode with a polarity opposite the ion charge [9]. Electro-osmosis is the movement of pore fluid and dissolved constituents within a porous medium that typically occurs between the anode and cathode, because of the negative charge characteristic of the soil particle surface [10]. However, the change of surface charge of soil may change the direction of electroosmosis.

Electrophoresis refers to the transport of charged particles or colloids in soil under the action of an electric field. Soil organic matter, microbial cells, and small soil

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particles are colloids, and when heavy metals and other pollutants are adsorbed on the surface of colloid or charged particles, they will be discharged together. However, the effect of electrophoresis can be ignored, because of the low mobility of charged soil particles in the process of electric remediation. Therefore, the actual migration speed of heavy metal ions in soil pore water is determined by the action of electric migration and electroosmosis under the action of an external direct current electric field. In the electro-kinetic remediation process, the liquid phase mass transfer of pollutants is mainly realized through four processes: electromigration, electroosmotic flow, convection, and diffusion [11]. For EKR, electroosmosis and electromigration contribute most to the pollutant removal, while electrophoresis and electrochemical oxidation occurs only for some types of pollutants.

In this study, an electrokinetic remediated soil is investigated for use as a subgrade material. Being that the remediated soil was an in-situ-crude oil contaminated soil, they have been major concern in Nigeria on the level of oil spillage contamination both arable and natural soil properties.

MATERIALS AND METHODS

Elecrokinetic remediated soil

In this study, the electrokinetic remediated soil was collected from the Kaduna Refining and Petrochemical Company (KRPC) along Kachia road in Kajuru LGA, Kaduna State. The average crude oil contaminant removals for Total petroleum content (TPC); Benzene, toluene, ethylene, xylene (BTEX); and the total petroleum hydrocarbon (TPH)were 92%, 75%, 93%, respectively. Table 1 summarized the concentration of crude oil contaminants before and after an electrokinetic remediation.

Physiochemical analysis

From the work of the oxide concentration the electrokinetic remediated soil is given in Table 2. The oxide composition of both the COC soil and the EKR Soil was determined using the X-ray florescence analyzer. From the oxide concentration for crude oil contaminated soil had, Fe_2O_3 (9.27%); SiO_2 (42.22%); Al_2O_3(19.80%) with the electrokinetic remediated soil having its own oxide concentration as Fe_2O_3 (24.00%); SiO_2 (42.10%); Al_2O_3 (29.20%).

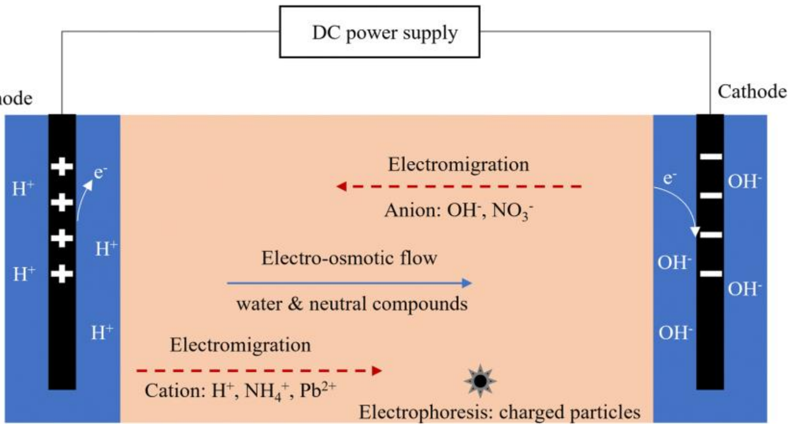


Figure 1. Schematic diagram of the electro-kinetic remediation principle (DC, direct current); and comparison of electroosmotic flow in a single capillary [12]

Table 1. Crude oil concentration of crude contaminated soil (COCS) and the electrokinetic remediated soil (EKRS)

Parameter	COC Soil	EKR Soil	Unit
Total Hydrocarbon Content (THC)	33.764	2.56213	(mg/kg)
Benzene, Toluene ethylene Xylene (BTEX)	6.9234	1.726	(mg/kg)
Total Petroleum Hydrocarbon (TPH)	36.573	2.60688	(mg/kg)
Hydraulic Conductivity	7.2×10^{-8}	7.2×10^{-8}	cm/s

Index properties of the soil

The index properties which include, the natural moisture content, particle size distribution, Atterberg limit, specific gravity and compaction characteristics of electrokinetic remediated soil were determined, respectively.

Strength characteristics of crude oil and Electrokinetic remediated soil

Unconfined compressive strength

British Standard light (BSL) energy level was used to conduct the unconfined compressive strength (UCS) [13] on the crude contaminated and remediated soil samples.

Table 2. Oxide concentration of crude oil contaminated soil (COCS) and the electrokinetic remediated soil (EKRS)

S/N	OXIDEs	COCS (%)	EKR Soil %
1	Fe_2O_3	9.27	24.00
2	SiO_2	42.22	42.10
3	Al_2O_3	19.80	29.20
4	MgO	2.08	0.12
5	P_2O_5	0.11	0.07
6	SO_3	0.34	0.30
7	TiO_2	0.99	2.17
8	MnO	0.29	0.10
9	CaO	0.13	0.12
10	K_2O	0.37	0.73
11	Cl	0.13	0.50
12	ZrO_2	0.19	0.21
13	SnO_2	0.00	0.24

The soil samples were compacted in 1000 cm^3 moulds at their respective OMC. The samples were extruded from the moulds and trimmed into sizes of 38.1mm diameter and 76.2mm length. A total of six samples was used, two were cured for 7 days, second batch (of four specimen) have two continued curing for 14 days and the other two soaked in water for 7 days. At the elapsed day of curing and soaking, the specimens were then placed centrally on the lower platen of a compression testing machine and a compressive force is applied to the specimen with a strain control at 0.10% mm. Record was taken simultaneously of the axial deformation and the axial force at regular interval until failure of the sample occurs. The UCS of the sample was determined at the point on the stress–strain curve at which failure occurred. The UCS was calculated from the following equation:

$$UCS = \frac{Failure\ load}{Surface\ Area\ of\ Specimen} \times 100\ \% \qquad (1)$$

Durability assessment

The durability assessment of the crude contaminated, and remediated soil samples was determined by subjecting the sample to a similar adverse field condition which is a measure of resistance to loss in strength when immersed in water. It was expressed as the ratio of UCS of the specimen cured for 7 days and soaked for another 7 days to the UCS of the specimen cured for 14 days with all samples having the same start date:

$$Durability = \frac{UCS\ (7days\ cured + 7\ days\ soaked)}{UCS\ (14\ days\ cured)} \times 100 \qquad (2)$$

California bearing ratio

In accordance with British Standards 1377 [13], California bearing ratio (CBR) test were conducted for the crude contaminated and remediated soils. The CBR is measure in terms of the force exerted by the plunger and the depth of its pen et ration into the specimen; it is aimed at determining the relationship b et ween force and penetration to evaluate the mechanical strength of the remediated soils as a subgrade material. Soil samples weighed 6kg were thoroughly mixed at their respective optimum moisture contents in 2360 cm^3 mould using BSL energy level. The compaction was in three layers each receiving 62 blows from the 2.5kg rammer.

The base plates were removed (after compaction) and the compacted specimens placed in sealed plastic bag for curing (for 6 days) and after the 6^{th} day the specimen was immersed in water for 24 hours before testing according to Nigerian General Specifications [14]. The base plates were later replaced, and the specimen transferred to the CBR testing machine and positioned on the lower plate of the machine. The plunger was then made to pen et rate the specimen at a rate 1.3mm/min until the specimen failed. The mould was then inverted, base plate removed, and the procedure repeated for the base of the specimen.

From the values of the pen et ration and force recorded, a curve of force against penetration was obtained. The CBR value was calculated at pen et ration 2.5mm or 5.0mm; the greater of the two or mean values were recorded as the CBR of the specimen. The value was then compared with the recommended value for subgrade by Nigerian General Specifications [14] if it meets the specification.

The CBR was calculated as:

$$CBR = \frac{Measured\ load}{Standard\ load} \times 100\% \qquad (3)$$

where standard load = 13.24kN of 2.5mm penetration
= 19.96kN of 5.0mm penetration

RESULTS AND DISCUSSION

Index properties

The index properties and compaction characteristics of the electrokinetic remediated soil are shown in Table 3. The natural moisture content of EKR soil was 10.97%. The particle size distribution curves are shown in Figure 2. The soil is classified as A-6 according to AASHTO classification system [15] and belong to clay of low plasticity CL or OL group according to the Unified Soil Classification System [16]. The Atterberg limit test shows liquid limit, plastic limit, plasticity index and linear shrinkage of 36.50%, 22.05%, 14.45 %, and 4.30%, respectively. It was also obtained that 62.80% passes 0.075mm sieve. This means that the EKR soil properties slightly improved. The decrease in the moisture content induced by the modification of soil geochemistry favors increased soil strength due to precipitation of amorphous cementing agents as evident in the oxide concentrations [17].

Table 3. The index properties and compaction characteristic of COC and EKR Soil

Properties	COC Soil	EKR Soil
Liquid Limit, %	38.50	36.50
Plastic Limit, %	22.17	22.05
Plasticity Index, %	16.33	14.45
Linear Shrinkage, %	7.14	4.30
Percentage Passing BS No. No. 200 Sieve.	67.43	62.80
AASHTO Classification	A-6	A-6
USCS Classification	CL	CL
Specific Gravity	2.16	2.23
MDD mg/m^3		
British Standard Light	1.73	1.77
OMC%		
British Standard Light	13.2	11.81

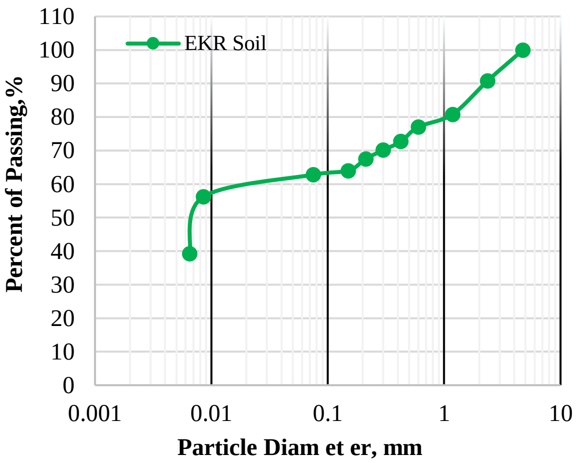


Figure 2. Particle size distribution curve EKR soil

Liquid limit

The liquid limit slightly decreased in value from 38.50% to 36.50% (see Table 3). This decrease can be attributed to an increase in water absorption or changes in the particle packing of the mixture due to the electrical charges induced. Reduction in LL could be due to the new chemical properties exhibited by the EKR soil due to the double layer water presents in the clay mineral structure [17, 18]. However, this improvement increased the soil interparticle force that binds them together and the formation of aggregates, clods, and lumps or otherwise called crumbs, which agrees with literature [17, 18].

Plastic limit, plasticity index and linear shrinkage

The plastic limit for the COC and EKR soil used in this study is 38.50% and 36.50%, respectively. The plasticity of EKR of the soil slightly changes 16.33% to 14.45% while the linear shrinkage decreased from 7.14% to 4.30%, respectively. This marginal improvement was due to the dominance of clay particles which agrees with the work of Jayasekera [17], Fatemeh et al. [18] and Sani et al. [19].

Specific gravity

The specific gravity of the COC soil improved from 2.16 to 2.23 for the EKR soil. That confirms the clogging and closure of pores preoccupied by the crude oil, thereby making the soil denser compared to its status before remediation. This result, however, is similar to the reported data by Jayasekera [17] and Fatemeh et al. [18].

Compaction characteristics

The compacion characteristics of both the crude oil contaminated and electrokinetic remediated soil are expressed in terms of their maximum dry density and optimum moisture content respectively.

Maximum dry density (MDD)

The MDD for BSL compactive effort is 1.73 Mg/m^3 for COC soil while 1.77 Mg/m^3 for EKR soil as presented in Figure 3. This shows an increase in maximum dry density resulting from the physico-chemical changes and its consequent influence on the diffused double layer leading to the arrangement, grouping, orientation of clay particles and pore spaces within the soil mass and soil fabrics [17, 18].

Optimum moisture content

From Figure 3, there is a decrease in the optimum moisture content (OMC) from 13.2% (COC soil) to 11.81% (EKR soil). This was due to an increase in fines

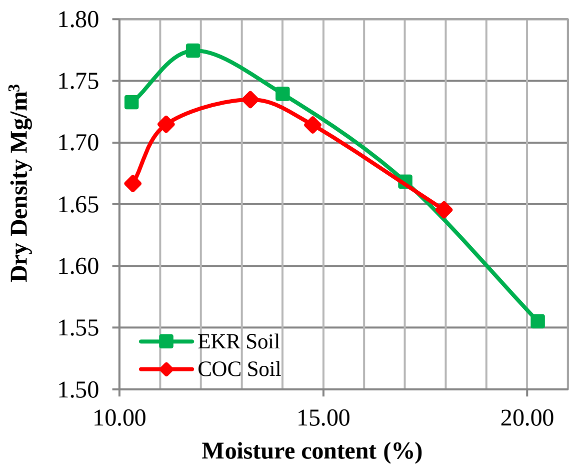


Figure 3. Compaction curve of COC and EKR soil

content resulting from the inclusion of electrical charges reacting with the contaminated crude oil. It also could be due to the larger amounts of charges required for the hydration of contaminated soil particle.

Strength characteristics

Strength characteristic is a major criterion in the selection of soil materials for the construction of roadways and other.

Unconfined compressive strength (UCS)

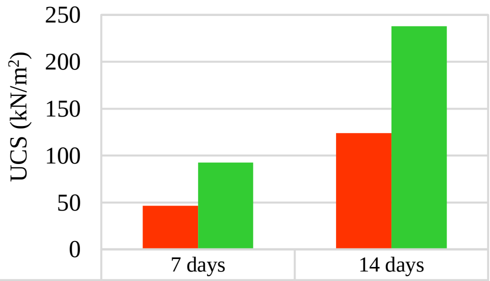
The unconfined compressive strength (UCS) test is a general test that is recommended for determining the additive to be used in soil stabilization [20]. It is a critical consideration while evaluating the design criteria for using soil as a pavement material [21].

From Figure 4, the UCS value of BSL compaction energy increased from 46.63kN/m^2 (COC soil) to 92.64kN/m^2 for the EKR soil. An increase in the UCS value was primarily due to the formation of various compounds such hydrated aluminum silicate (HAS) which are responsible for strength development [18]. The observed trend can also be attributed to the complexity and interrelated geochemical alteration as well as charged ions interaction with clay minerals due to variations in the diffused double layer ionic concentration and subsequent modifications in the soil structure [17].

This value obtained does not meet the minimum UCS requirements of 600 kN/m^2 to 1,720 kN/m^2 as specified by Road Note 31 [22] for a subgrade or subbase materials.

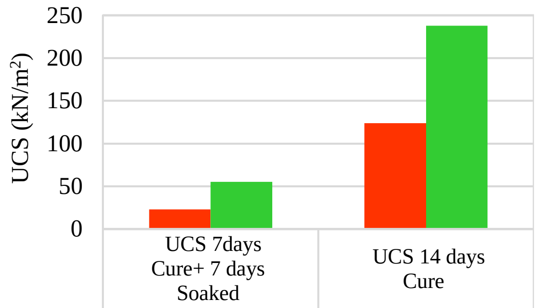
Durability

The modelling of some of the worst conditions that could occur in the field is used to evaluate the durability of soil samples. It was tested by immersing the specimen in water to see how resistant it was to losing strength, which is more suitable for tropical areas like Nigeria [21]. The ratio of the UCS of specimens wax-cured for 7 days, de-waxed top and bottom to allow water absorption, and then immersed in water for 7 days to those cured for 14 days determines the resistance to loss in strength.



	7 days	14 days
COC Soil	46.63	123.77
EKR Soil	92.64	237.85

Figure 4. UCS for COC and EKR soil



	UCS 7days Cure+ 7 days Soaked	UCS 14 days Cure
COC Soil	22.87	123.77
EKR Soil	55.24	237.87

Figure 5. Values of UCS for 14 days curing and 7 days curing + 7 days soaking

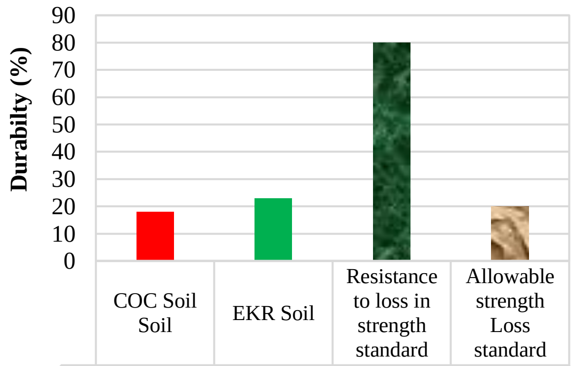
a. UCS 14 days curing

From Figure 5, the UCS value increased from 123.77 kN/m^2 (COC soil) to 237.87 kN/m^2 (EKR soil) after 14 days curing. This is because of the quick change in ion exchange, that leads to rapid increase in the UCS value and increased in treated concentration silcious, alluminuferite oxide [23, 24].

b. UCS 7 days curing and soaking

From Figure 5, a reduction in the UCS value occurred in both soil (COC soil and EKR soil). The UCS value reduced from 123.77 to 22.87 kN/m^2 (COC soil) and from 237.87 kN/m^2 to 55.24 kN/m^2 (EKR soil) under alternate dry and wet curing.

From the values obtained at 14 days curing and 7 days curing+ 7 days soaked, the resistance to loss in strength value (durability) increased slightly from 18% to 23% as shown in Figure 6. This could be attributed to the increased in cementitious properties of the EKR soil [17]. It is recommended that 80% resistance to loss in strength (with 20% allowable strength loss) for a sample specimen cured for 7 days and full immersion in water for 4 days [17, 21, 23, 25]. In Figure 5, the durability test values were compared to the recommended standard values.



	COC Soil Soil	EKR Soil	Resistance to loss in strength standard	Allowable strength Loss standard
%	18	23	80	20

Figure 6. Durability assessment for COC and EKR soil

California bearing ratio (CBR)

The soil's California bearing ratio value is a significant property in determining its suitability for engineering usage, as it indicates the soil's strength and bearing capacity. For cement stabilized materials to be constructed by the mix-in-place method, the Nigeria General Specification [14] specified a CBR value of 80%, which should be achieved in the laboratory.

From Figure 7, the CBR performance between the COC and EKR soils with BSL compactive effort. The CBR value increased from 2.55% (COC soil) to 4.05% (EKR soil). This reveals that EKR soil performs better than COC soil, this slight improvement is due to the electromigration of ions and the negative surface charge of clay particles and increased in the EKR cementitious properties [17, 18, 26].

However, the CBR value obtained from this study for both the COC and EKR soil falls short of the Nigerian General Specifications [10] for sub-base minimum strength requirement of CBR which ranges from not less than 80%; or not less than 30% CBR (type I) to not less than 20% CBR (type II light traffic) upon 24 hours of soaking as compacted base or subbase course respectively.

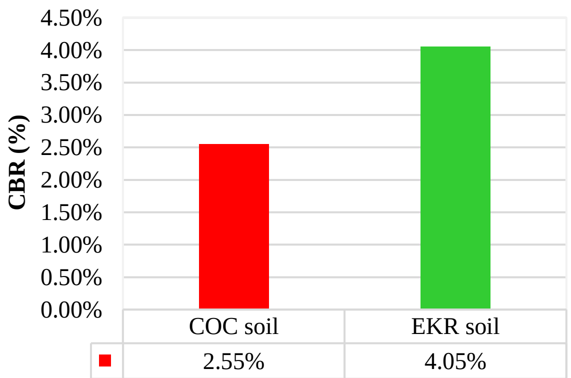


Figure 7. CBR for COC soil and EKR soil

CONCLUSION

- The EKR soil is classified as A-6 according to AASHTO classification system and belong to clay of low plasticity CL or OL group according to the Unified Soil Classification System for both the COC and the EKR soil.

The Atterberg limit improved slightly from a LL of 38.50% down to a LL of 36.50% with LS record of 7.14% to 4.30%. The specific gravity improved from 2.16 to 2.23 making the EKR soil denser than the contaminated soil. The MDD for BSL compactive effort increased from is 1.73 mg/m^3 for COC soil to 1.77mg/m^3 for EKR soil while a reduction in OMC was achieved from 13.2% to 11.81%, respectively. From the properties exhibited by the EKR soil showed a slight improvement.

- From the results obtained in the RE wherein TPC, BTEX, TPH percentage removals were 92%,75% and 93%, respectively. This is due to the surfactants used as the electrolyte (SDS and tween 80) that enhances the crude contaminant desorption and ion migration.
- The UCS value of BSL compaction energy increased from 46.63kN/m^2 (COC soil) to 92.64kN/m^2 for the EKR soil. Though fell below standard specified by TRRL 1997 (1,720kNm^2). The resistance to loss in strength of EKR soil with 23% obtained as against the general recommendation of 80% resistance and 20% allowable strength loss.
- The CBR value increased from 2.55% (COC soil) to 4.05% (EKR soil). This reveals that EKR soil performs better than COC soil. This appreciable value in the EKR soil could be attributed to the increase in pozzolanic properties. The CBR value obtained from this study for both the COC and EKR soil fell short of the Nigerian General Specifications; which specified minimum strength requirement of CBR ranging from not less than 80%; or not less than 30% CBR (type I) to not less than 20% CBR (type II light traffic) upon 24 hours of soaking as compacted base or subbase course respectively.

Recommendations

- As a result of the inferred conclusion, an electrokinetically remediated soil cannot be recommended for use as a subgrade material unless it is additionally stabilized with a stabilizing agent such as cement to increasetheir strength properties.

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CONFLICT OF INTEREST

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Persian Abstract

چکیده

خاک مورد بررسی برای مناسب بودن، به عنوان ماده زیربنایی در این مطالعه، خاک آلوده به نفت خام (COC) بود که با استفاده از تکنیک الکتروکینتیک تیمار شد. خواص شاخص و ویژگی‌های تراکم خاک اصلاح شده الکتروسینتیک (EKR) رطوبت طبیعی ۱۰/۹۷ درصد بود. آزمون حد آتربرگ حد مایع، حد پلاستیک، شاخص پلاستیسیته و انقباض خطی را به ترتیب ۳۶/۵۰ درصد، ۲۲/۰۵ درصد، ۱۴/۴۵ درصد و ۴/۳۰ درصد نشان داد. ۶۲/۸۰ درصد از الک ۰/۰۷۵ میلی‌متری با حداکثر چگالی خشک (MDD) ۱/۷۷ میلی‌گرم بر متر مکعب عبور می‌کند و میزان رطوبت از ۱۳/۲ درصد به ۱۱/۸۱ درصد کاهش یافته است. خاک بر اساس سیستم طبقه‌بندی AASHTO به عنوان A-6 طبقه‌بندی می‌شود و طبق سیستم طبقه‌بندی یکپارچه خاک به خاک رس با پلاستیسیته کم گروه CL یا OL تعلق دارد. استحکام فشاری نامحدود، (UCS)، دوام، و نسبت بارگذاری کالیفرنیا (CBR) خاک اصلاح شده الکتروکینتیکی از ۴۶/۶۳ kN/m^2 به ۹۲/۶۴ kN/m^2، از ۱۸ تا ۲۳درصد و از ۲/۵۵ درصد تا ۴/۰۵ درصد؛ به ترتیب بهبود یافته است. با این حال، این نتایج به دست آمده، حداقل الزامات مشخصات عمومی نیجریه را برآورده نمی‌کند. در نتیجه، برای تحقیقات بیشتر توصیه می‌شود که یک خاک EKR با استفاده از تثبیت سیمان برای دستیابی به استحکام زیرسازی مورد نظر تثبیت شود.