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The Effects of Cement Kiln Dust on the Soil Electrical Resistivity

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Abstract: Electrical resistivity is a non-destructive, cost-effective and sensitive method to evaluate soil's physical and chemical properties. Electrical resistivity has been used widely in surface and subsurface exploration. The electrical resistivity is directly related to the subsurface geotechnical and geothermal properties like porosity, temperature, salinity and water content. Recently uses of waste material as an additive to improve the soil engineering properties are growing because of their cost-effectiveness. Cement Kiln Dust (CKD) is a waste material of the cement manufacturing process. CKD is widely used as an additive material in ground improvement to improve soil's geotechnical properties. This study is mainly focused on the effect of CKD on the electrical resistivity properties of the soil. In this study, the electrical resistivity of a natural soil slope treated with CKD and a test model in the laboratory was investigated. Besides, the effects of CKD on soil pH and electrical resistivity were studied by performing a series of tests to predict the soil's corrosivity potential. The soil was treated with 0, 5, 10 and 15% of CKD and the electrical resistivity of the soil was measured at different water contents, porosities and curing times. The results indicate that the soil's electrical resistivity increases by increasing the CKD content and curing time. Additionally, an increase in water content or porosity decreases the electrical resistivity of CKD treated soil. Furthermore, the electrical resistivity measurement is a practical method to determine the stabilized soil's geotechnical and geomechanical properties.

Keywords: Cement Kiln Dust (CKD), Electrical Resistivity, Soil pH, Soil Corrosion, Soil Stabilization

Introduction

Soil electrical resistivity measurements determine how much the soil's resistance is in the flow of electricity. The soil resistivity patterns in different depths provide the subsurface heterogeneities and geotechnical properties (Samouëlian *et al*., 2005). Many factors affect the soil resistivity, including particle shape and size, moisture content, temperature, degree of saturation, porosity and chemical content. Due to these parameters' effect, the soil electrical resistivity has an extensive range and changes widely throughout the world and seasonally (Abu-Hassanein *et al*., 1996). The purpose of soil electrical resistivity measurement is to obtain geophysical and geotechnical data such as depth to bedrock, ore location, soil hydraulic conductivity, soil corrosiveness and its effects on the design of a grounding system (Kalinski and Kelly, 1993).

Recently waste materials are widely used for soil improvement (Rouhanifar *et al*., 2020). Cement kiln dust is a waste material generated from the cement manufacturing process. This by-product of cement production is fine, powdery and alkaline and has wide application for many fields, especially in civil engineering works (Baghdadi *et al*., 1995). Soil stabilization with CKD increases the soil strength, soil pH and optimum water content and decreases the permeability and plasticity index (Ghazvinian and Razavi, 2010; Faramarzi *et al*., 2016; Ranjkesh Adarmanabadi *et al*., 2020). Electrical resistivity is an effective method to assess the physicochemical properties of natural and engineered soils (Cai *et al*., 2015). Some investigations indicate that the soil's electrical resistivity can determine the soil characterization and mechanical properties (Damasceno *et al*., 2009; Rinaldi and Cuestas, 2002).

Komine (1997) conducted an experimental study on the chemical grouted sand to evaluate the soil geotechnical properties using the electrical resistivity method. The results indicate that grouted sand's electrical resistivity correlates with water content, void ratio and particle size distribution (Komine, 1997). Liu *et al.* (2008) investigated the soil-cement admixture's electrical resistivity by considering the curing time and water content ratio. The results showed by increasing the quantity of cement and curing time, the electrical resistivity of soil risen. As the water content and soil degree of saturation increased, the electrical resistivity was reduced (Liu *et al*., 2008).

Chen *et al.* (2011) conducted a study to determine cement-stabilized lead-contaminated soils' geotechnical properties using electrical resistivity measurements. In this study, the soil was contaminated with various lead concentrations and treated in three Portland cement content levels. The results showed that soil's electrical resistivity was enhanced by increasing the amount of cement and time and it declined by increasing the lead concentration (Chen *et al*., 2011). Zhang *et al*. (2012) examined the electrical resistivity and unconfined compression strength of cement-treated soil. For this purpose, the effect of cement content, porosity and time on the electrical resistivity of cement-treated soil were evaluated. This investigation proved that the cement content and curing time are meaningful parameters to increase soil's electrical resistivity (Zhang *et al.*, 2012). An experimental study reviewed the effect of heavy metal concentration on stabilized soil's electrical resistivity behavior with cement and fly ash. For this investigation, Pb, Zn and Cr were selected to prepare contaminated soil because of their high solubility. The two-electrode probe method was applied to measure the electrical resistivity of samples in curing time. The results demonstrated that electrical resistivity was raised by increasing curing time. On the other hand, by increasing heavy metal concentration, the soil electrical resistivity was reduced (Liu *et al.*, 2019).

Electrical resistivity is one of the most significant geophysical methods to investigate stabilized soil properties (Tabbagh *et al.*, 2000). The electrical resistivity method was used in an experimental study to determine the fly ash's hydration process. Different amounts of fly ash were added to the Portland cement paste to monitor the electrical resistivity behavior. The results showed that the electrical resistivity increased as fly ash contents increased (Liao *et al*., 2019).

This investigation aims to determine the effect of cement kiln dust content, water content, porosity and curing time on stabilized soil's electrical resistivity. Besides, the relation between the unconfined compression strength and soil electrical resistivity was examined. For this purpose, a natural slope treated with different amounts of CKD was chosen to perform the field test. The test was simulated to evaluate the soil electrical resistivity with the same structure by considering the different water content and curing time in the laboratory.

Methodology

Field Electrical Resistivity Measurement

For this investigation, a natural slope stabilized with 0, 5, 10 and 15% CKD in 2008 was selected to determine the field's electrical resistivity. The slope is located west of the New Mexico Institute of Mining and Technology (34.080056, 106.917583) in Socorro, NM, United States. Figure 1 presents the slope location.

The slope with about 64 m^2 area and angle of 23 degrees divided into four sections and stabilized with 0, 5, 10 and 15% of Cement Kiln Dust to a depth of 30 cm respectively from left to right Fig. 2 to determine the soil's geotechnical properties. A series of pH tests were performed to prove CKD's existence on the slope after more than eleven years. pH tests were done according to (ASTM, 2019b); samples were taken from the slope surface and depths of 15 and 30 cm in each section with a spacing of 2 m in the X and Y directions.

For measuring the electrical resistivity of the slope, the 4-point Wenner method was followed per ASTM G57. Electrical resistivity sounding measurements involve placing four electrodes (stainless steel probes) in a straight line. A current is injected into the outer two probes and the potential difference is measured across the inner two probes. The resistance is calculated from the known current and the measured voltage. Seven resistivities sounding was measured for each section with a spacing of 1 m between the resistivity lines and 0.3 m between the electrodes from the slope's toe to the portion top Fig. 3. An analog resistivity meter called Humboldt H4385 with a resistant measurement range from 0.01 Ω to 1.1 MΩ. A potential of 12 V (Root Mean Square or RMS) crystal-controlled 97 Hz square wave oscillator was used to measure the slope's electrical resistivity. Figure 4 presents the schematic electrical resistivity measurements of the slope on the field. The electrical resistivity of slope computed by using the following equation:

$$\rho = 2\pi SR \quad (1)$$

Where:
ρ = The resistivity of the materials (Ω-m)
R = The resistance obtained from the tester (Ω)
π = The constant (≈ 3.1416)
S = Electrodes spacing (m)

Laboratory Electrical Resistivity Measurement

A series of laboratory tests were conducted to evaluate CKD's effect, water content, porosity and curing time on soil's electrical resistivity. The soil sample was taken from the untreated part of the slope at a depth of 30 cm. The grain size distribution per ASTM D-422-63, moisture content per (ASTM, 2019a), unit weight per (ASTM, 2018), atterberg limits per (ASTM, 2017) and specific gravity per (ASTM, 2014) were conducted on the soil samples to estimate the soil physical properties. The pure soil and soil CKD mixed electrical resistivity was measured using the four-electrode probe method and a test apparatus called Humboldt analog resistivity meter using a Miler soil box Fig. 5. For this test, four electrodes have been used, an integral part of the electrolyte box. The electric frequency of the test apparatus was the same as the field measurements. To measure the electrical resistivity of samples, the (ASTM, 2020) was followed. The samples were dried to constant mass in an oven to follow the ASTM standard and then cooled at room temperature. The samples were passed through sieve number 10 to obtain 1300 g of passing. The samples were treated with 0, 5, 10 and 15% of CKD by dry weight of the soil and the electrical resistivity of samples was determined through different water content and curing time. Each test was identified for the specific CKD content, water content and curing period. Figure 5 illustrates the schematic electrical resistivity measurement in the laboratory. The soil resistivity of samples in the laboratory is computed using the following relation:

$$\rho = RA / L \tag{2}$$

Where:
ρ = The resistivity of the materials (Ω-m)
R = The resistance obtained from the tester (Ω)
A = The cross-sectional area of the current electrodes (cm^2)
S = Electrodes spacing (m)
L = The separation between the potential electrodes (cm)

During the laboratory test, the sample's porosity was determined based on the void ratio to evaluate the efficiency of Archie's law for this application. In this study, a simple regression analysis was adopted to analyze and correlate results using the least-squares regression method. Also, the slope soil corrosivity potential is discussed.

Fig. 1: Slope location (source: google earth)

Fig. 2: Natural slope used for investigation after 11 years of treatment

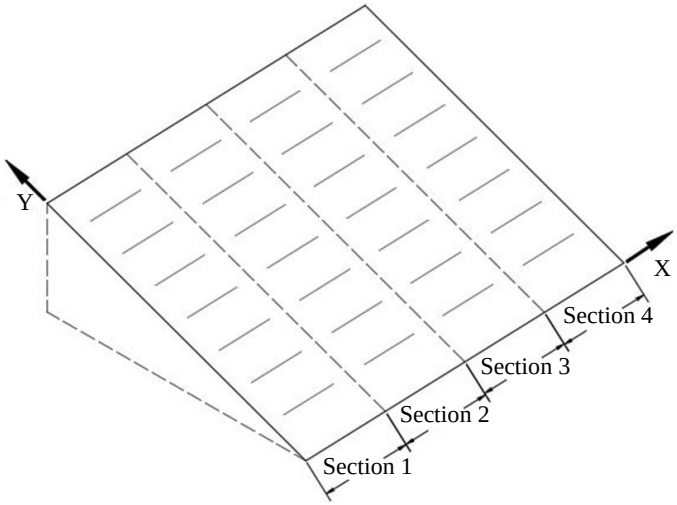

Fig. 3: Schematic of resistivity sounding lines on the slope

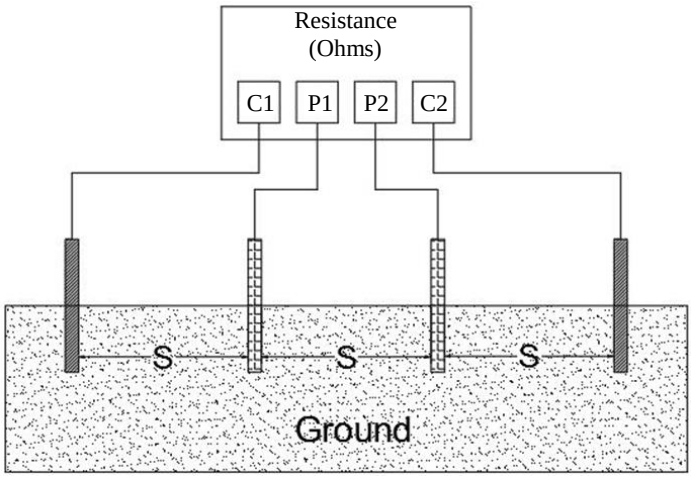

Fig. 4: Schematic of the four-electrode probe method for field measurements

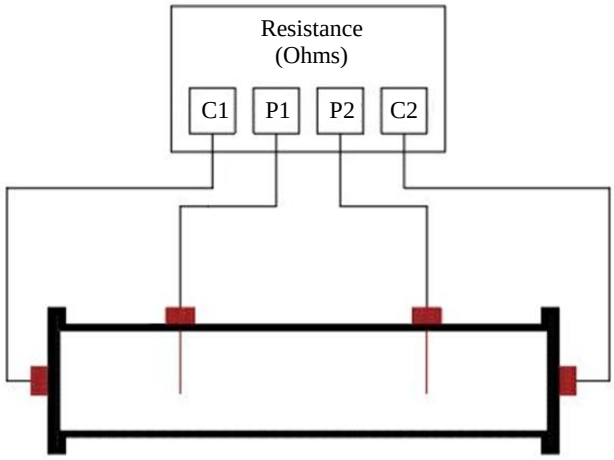

Fig. 5: A schematic drawing of the laboratory resistivity measurement instrument

Results and Discussion

Materials Properties

Engineering properties of the soil sample are summarized in Table 1. Figure 6 represents the particle size analysis of the soil sample according to (ASTM, 2007). The soil is classified as SM-SC according to the USCS classification. The natural water content of slope soil is measured as 2.5%.

The present CKD content of the soil was traced using the correlation between the soil pH and CKD content. Figure 7 presents the soil pH at different CKD content. The soil pH was measured by sampling through all sections from the surface to the depth of 30 cm. Figure 8 shows the CKD distribution based on pH measurements from the slope surface to 30 cm depth. It can be observed from the graph; there is a sign of CKD percent at the toe of the slope in section 1, which stabilized with no CKD. The pH results indicate the CKD existence on the slope from section 2 to section 4, almost with the same treatment pattern in 2008. The pH is changing for different locations, but it shows the CKD presence until 30 cm depth from section 2 to 4 with more concentration at 15 cm depth. The pH at the toe is more than the top of the slope. Besides, pH is increasing from section 2 to 4 by increasing the CKD content. The 30 cm depth is the boundary of treated soil with native soil and due to the settlement and error in measuring and sampling, the soil pH at 15 cm depth is more than 30 cm depth.

Field Electrical Resistivity

Twenty-eight sounding lines of electrical resistivity measurement were conducted at different sections to evaluate the slope electrical resistivity. Each unit includes seven sounding lines to determine the effect of different CKD amounts on soil electrical resistivity. The CKD was examined to a depth of 30 cm with different content of 0, 5, 10 and 15%, respectively, from left to right. The field electrical resistivity results conducted at different sections are presented in Table 2.

From the results, it is clear that electrical resistivity is increased as CKD content increases and section 4, which stabilized with 15% of CKD, shows the higher resistivity from the other sections. The electrical resistivity results for each section indicate that electrical resistivity for the same material is close. The mean of all line's electrical resistivity in each section is calculated as the final electrical resistivity for that section to compare with laboratory results. The first two lines' electrical resistivity in section 1 is not close to other lines due to CKD's presence at the toe of the slope in this section, proven by pH results. Consequently, to make an average and find the mean value for section 1, the first two lines' resistivity results are not considered further. Standard deviation is calculated for each section to measure how the resistivity results spread out in each section. A low standard deviation for each section's electrical resistivity indicates that the data points tend to be very close to the mean.

Laboratory Electrical Resistivity

Effect of CKD Content on the Electrical Resistivity

The relationship between the CKD content (0, 5, 10 and 15%) and electrical resistivity for the CKD treated soil for different moisture contents of 2.5, 5.0, 7.5, 10.0, 12.5, 15.0, 17.5, 20, 22.5 and 25% is determined and presented in Figs. 9 and 10. The results show that the electrical resistivity increases as CKD content increases, keeping moisture content constant. Mixing CKD with the soil causes a more incredible hydration reaction showing a higher electrical resistivity, so it is expected to record more electrical resistivity for higher CKD contents. Due to the hydration reaction between soil and CKD, the water content and void ratio of soil-CKD admixture will be decreased. In this model, the electrical resistivity depends on three factors: Soil type, CKD and pore water. Among all these factors, the effect of water on electrical resistivity is more than the other parameters.

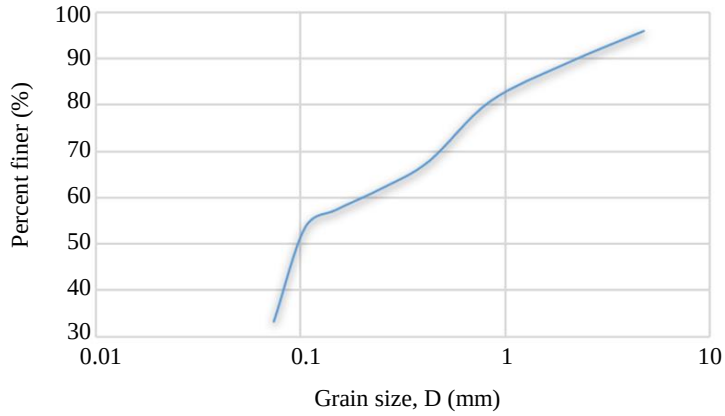

Fig. 6: Particle size distribution curve

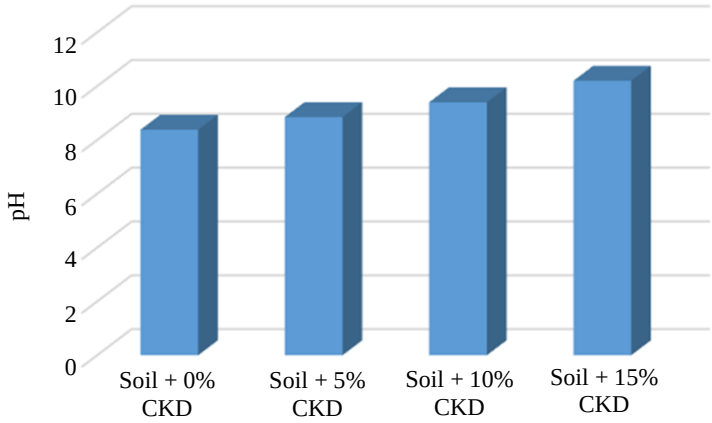

Fig. 7: Soil's pH at different CKD content

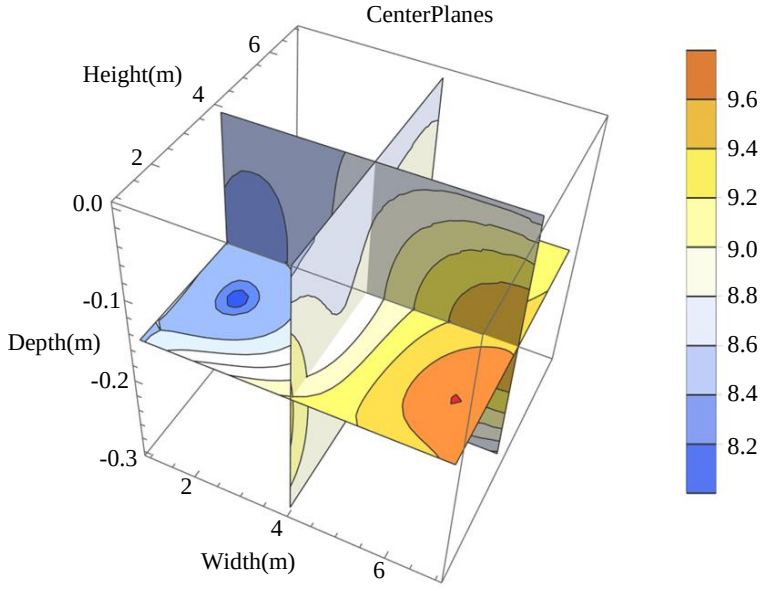

Fig. 8: 3D plot of CKD distribution based on pH measurements

Correlation Between Field and Laboratory Electrical Resistivity

The electrical resistivity results from field and laboratory are analyzed to determine the similarities. The field electrical resistivity of the slope was measured at a water content of 2.5% and then compared with the laboratory results for the same water content. Figure 11 presents the field and laboratory's electrical resistivity for the same water content and a linear correlation is evaluated. The results indicate that the field and laboratory outcomes are similar and by increasing the CKD content, the soil electrical resistivity will be increased. The calculated correlation coefficient is 0.99, indicating that the laboratory and field results are in good agreement. It signifies that the results obtained from the lab and field have a perfect positive relationship. Electrical resistivity results in the lab and electrical resistivity in the field are positively correlated besides. This conclusion is verified in Fig. 11. There is a difference between laboratory and field results, which may happen because of long-term curing of CKD or depth and a small change in water content.

Effect of Water Content on the Electrical Resistivity

Some soil properties such as water content (water quality and quantity) affect the soil's electrical resistivity. Figure 12 shows the effect of water content on the electrical resistivity of the native soil and soil CKD mixtures with different CKD contents. The data show a reduction in electrical resistivity by increasing water content. The results for natural soil and soil treated with different amounts of CKD follow the same pattern of decline in electrical resistivity with an increase in moisture content. The electrical resistivity decreased rapidly for water content less than 15% and electrical resistivity reduction is getting less for water content more than 15%. (Komine, 1997) evaluated the electrical resistivity of soil, soil cement admixture and pore water, suggesting a model that indicates pore water's effect on the electrical resistivity was most significant compared to the other factors.

Effect of Porosity on the Electrical Resistivity

Soil void ratio and porosity are determined using Eqs. 3 and 4 to evaluate the effect of porosity on the electrical resistivity of the native soil and the soil treated with CKD. Besides, the accuracy of Archie's law is evaluated:

$$e = \left(\left((1+\omega)Gs\gamma w\right)/\gamma\right) - 1 \quad (3)$$

$$n = e/(1+e) \quad (4)$$

Where:
n = Porosity
e = A void ratio
ω = Water content
γ = The unit weight (kN/m^3)
Gs = The specific gravity
γ_w = The unit weight of water (kN/m^3)

CKD in the soil causes an increase in the soil's specific gravity and soil bulk density. CKD particles are very fine, so CKD acts like a filler, which reduces the void spacings or a decrease in soil porosity. The CKD treated soil specimens' initial porosities were determined at different water contents of 2.5, 7.5 and 12.5% at the mixing time. The soil porosity decreased as curing time due to hydration process development and bonding the soil particles with chemical materials. Figure 13 shows the electrical resistivity results as a function of the initial porosity. It can be concluded that the porosity has a significant effect on the electrical resistivity of soil treated with CKD, which shows the same pattern of Archie's law. However, Archie's law was for untreated saturated soil. The behavior of soil electrical resistivity as a function of porosity was reported by other researchers (Archie, 1942). These chemical products which cause by mixing CKD to the soil, filled in the pore space and bonded with solid particles to make a denser structure and thus reduced the porosity and increase the electric current, which is consistent with the results of literature (Liu *et al*., 2009; Chen *et al*., 2011).

Effect of Curing Time on the Electrical Resistivity

Figures 14 to 16 present the relationship between curing time and soil CKD mixture's electrical resistivity for different soil-CKD ratios. The soil electrical resistivity is measured at different water-CKD rates of 0.5, 1.5 and 2.5% for 1, 7, 14, 21 and 28 days curing for various CKD content soil admixtures under controlled conditions. The following graphs present the electrical resistivity versus curing time for soil mixed with 5, 10 and 15% of CKD by the soil's dry weight. The results prove an increase in electrical resistivity by increasing curing periods and CKD content. The pozzolanic reactions cause a decrease in water content and an increase in electrical resistivity by increasing the curing time (Horpibulsuk *et al*., 2003). Furthermore, the researchers indicate by increasing the curing time; contents of chemical reaction productions such as Calcium Silicate Hydrate (CSH) and Calcium Aluminate Hydrate (CAH) formed and lead more tortuous pathways for the flow of electrical current in the soil-CKD mixture and cause to increase the electrical resistivity (Liu *et al*., 2008; Bergado *et al*., 1996).

Relation of Soil Unconfined Compression Strength and Electrical Resistivity

The unconfined compression strength (UCS) test per (ASTM, 2006) was conducted for pure soil and stabilized soil with 5, 10 and 15% CKD (by the soil's dry weight) at curing times of 1, 7, 14, 21 and 28 days to evaluate the relation of electrical resistivity and unconfined compression strength. It was observed that soil particles, stabilizer agents, water content and curing time affect the soil resistivity and unconfined compression strength. Therefore, it should relate the soil electrical resistivity and unconfined compression strength (Horpibulsuk *et al*., 2003). The unconfined compression strength increased with rising CKD content and curing time. Figure 17 displays the results of the unconfined compression strength of laboratory tests versus the electrical resistivity measured. It can be seen that there is a linear relation between unconfined compression strength and electrical resistivity. As strength increases, the electrical resistivity will rise.

Soil Corrosivity

Soil corrosivity is soil potential to buried metals and concrete that is in direct contact with soil. Acidic or alkaline soils and organic soils can be corrosive. Moisture and oxygen are two essential factors for the corrosion process and above the groundwater level, the corrosion rate is greater. Some soil properties, including soil resistivity, soil pH, soluble salt content, moisture content and drainage conditions, affect soil corrosivity (Sadiq *et al*., 2004). Several classification systems are available to rate the soil corrosion potential. Table 3 presents a corrosivity score based on the soil resistivity, soil pH and moisture content and Table 4 shows the soil corrosion potential based on the corrosivity score.

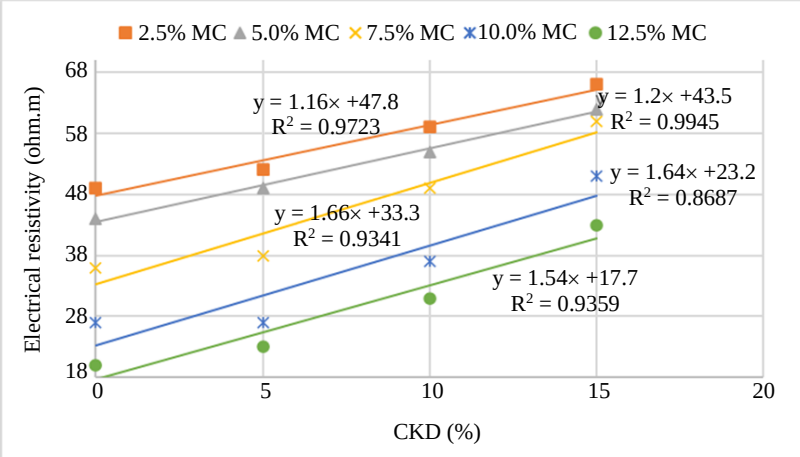

Fig. 9: Electrical resistivity versus CKD content for 2.5 to 12.5% MC

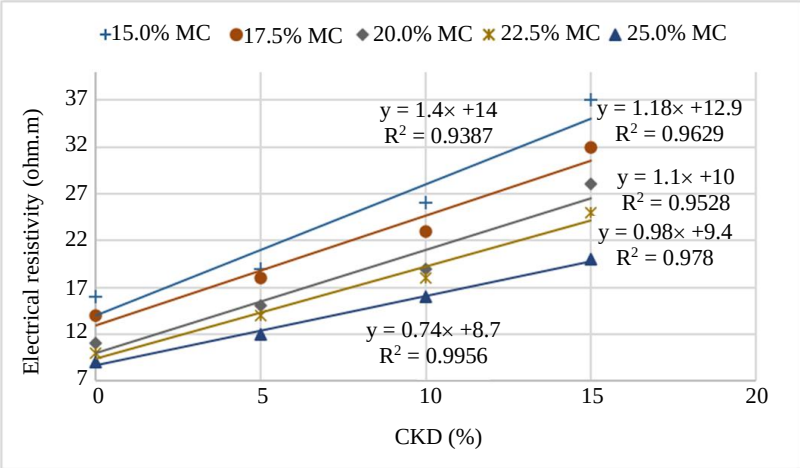

Fig. 10: Electrical resistivity versus CKD content for 15.0 to 25.0% MC

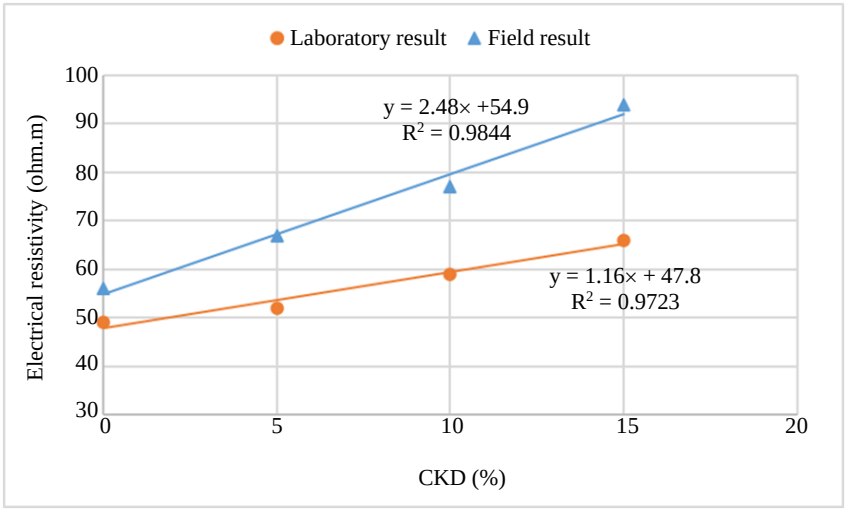

Fig. 11: Field and laboratory results for 2.5% MC

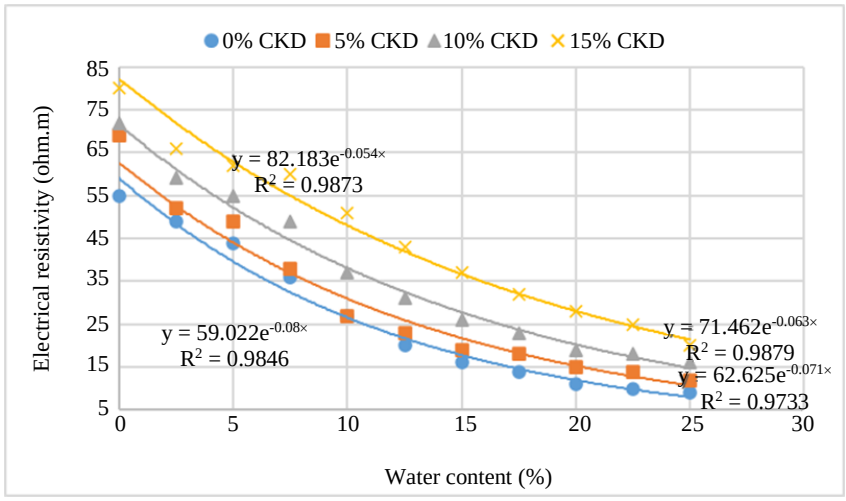

Fig. 12: Electrical resistivity versus water content

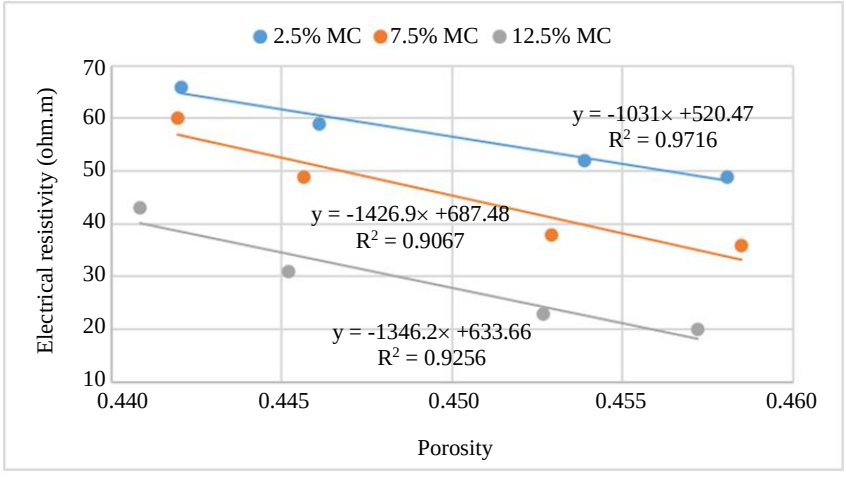

Fig. 13: Electrical resistivity versus porosity

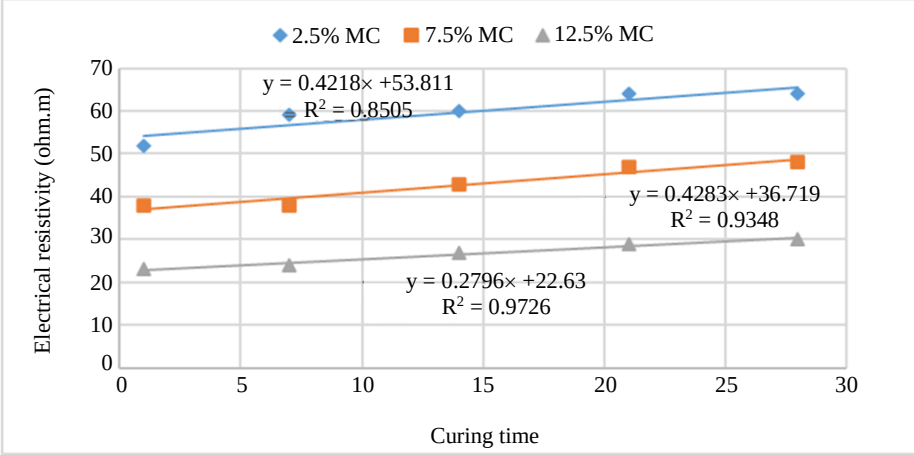

Fig. 14: Electrical resistivity versus curing time for soil +5% CKD

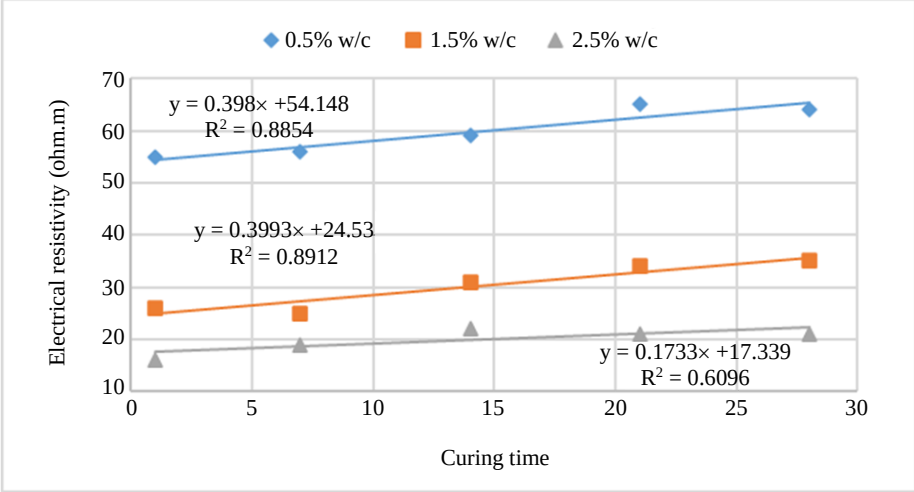

Fig. 15: Electrical resistivity versus curing time for soil +10% CKD

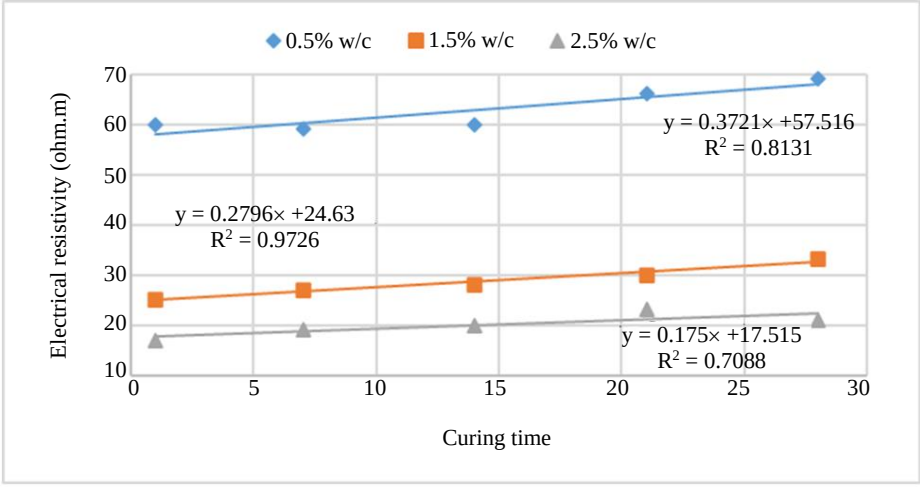

Fig. 16: Electrical resistivity versus curing time for soil +15% CKD

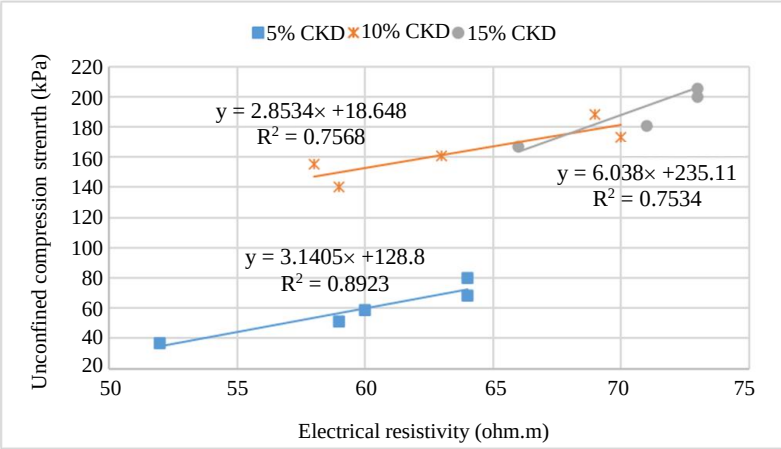

Fig. 17: Electrical resistivity versus UCS

Table 1: Physical properties of soil used for this study

Properties	Characteristics values
USCS Symbol	SM-SC
Specific Gravity G_s	2.68
Liquid Limit w_l (%)	-
Plastic Limit w_p (%)	-
Natural Water Content ω (%)	2.5
Unit Weight γ (kN/m^3)	14.6

Table 2: Field electrical resistivity results

Field Electrical Resistivity Results (Ω-m)				
Sounding Line	Section 1 (0%CKD)	Section 2 (5%CKD)	Section 3 (10%CKD)	Section 4 (15%CKD)
1	66.00	70.00	81.00	99.0
2	67.00	68.00	79.00	95.0
3	59.00	62.00	76.00	92.0
4	58.00	66.00	77.00	92.0
5	54.00	68.00	73.00	94.0
6	56.00	71.00	77.00	96.0
7	55.00	65.00	74.00	89.0
Mean	56.40	67.10	76.70	93.8
Standard deviation	2.07	3.08	2.75	3.2

Table 3: Typical numerical corrosivity scoring system (Clayton, 2013)

Soil parameter	Value	Score
Resistivity (Ω-m)	<5	10
	5 to 9.99	8
	10 to 19.9	5
	20 to 49.9	2
	50 to 100	1
	>100	0
pH	2 to 4.5	6
	5 to 6	0
	7 to 9	6
	10.5 to 12	2
Moisture	Tidal or Salt Water	5
	Poor Drainage-Always Wet	2
	Fair Drainage-Moist	1
	Good Drainage-Usually Dry	0

Table 4: Soil corrosion potential (Clayton, 2013)

Total Corrosivity Score	Soil Corrosion Potential
0 to 2	Unlikely
3 to 4	Slight
5 to 6	Mild
7 to 8	Moderate
9 to 13	Aggressive
14 to 20	Severe

Table 5: Slope soil corrosion potential

Section	CKD content	Score	Soil corrosion potential
1	0	8	Moderate
2	5	7	Moderate
3	10	7	Moderate
4	15	7	Moderate

Table 5 present the soil corrosion potential of slope for the different sections with different amounts of CKD. The results indicate that all sections' soil corrosion potential is almost the same and CKD can decrease the soil corrosion potential for a small amount.

Conclusion

The effects of different parameters on the CKD treated soil electrical resistivity were studied both in the lab and field. The relationship between the measured electrical resistivity with soil pH, CKD content, water content, porosity, curing time and soil corrosion potential were investigated. CKD increases soil pH and electrical resistivity. The electrical resistivity of the CKD treated soil increases by increasing the CKD content and the curing time. However, the soil's electrical resistivity and the CKD treated soil decrease with increasing the water content and porosity. Field and laboratory results indicate that the water content is a significant parameter affecting the electrical resistivity. Additionally, soil electrical resistivity, soil pH and soil moisture content are essential parameters to evaluate the soil corrosion potential and soil corrosion potential decreases by increasing the CKD content. It can be concluded that electrical resistivity is a significant parameter to evaluate the soil's geotechnical properties.

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Author's Contributions

Hamid Ranjkesh Adarmanabadi: Contributed to idea development and design the study, performing the experiments, data preparation and analysis and writing the manuscript.

Arezou Rasti: Contributed to design the study, performing the test, data analysis and writing the manuscript.

Mehrdad Razavi: Contributed to idea development analyzed the experiments results and review the manuscript.

Ethics

This article is original and contains unpublished materials. The authors have read and approved this manuscript and no ethical issues are involved.

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