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The Effects of Soil Resistivity on The Corrosion Resistance of Carbon Steel

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Abstract: Indonesia, as a tropical country with high humidity, faces corrosion challenges in the underground infrastructure of the oil and gas industry, causing significant economic losses. This study analyzed the effect of soil characteristics on the corrosion rate of carbon steel using the weight loss and linear polarization methods. The weight loss method was used to determine the corrosion rate based on the mass reduction of the sample, while the linear polarization method evaluated the corrosion kinetics through icorr and polarization resistance values. The results showed that soil characteristics, especially moisture and resistivity, had a significant effect on the corrosion rate. Pakis Karawang beach sand soil with pH 5.2, humidity 87%, and resistivity 59.03 Ω-cm had the highest corrosion rate of 42.57 mpy and the lowest polarization resistance of 11.16 Ω. In contrast, the UI Native Forest Ravine soil showed the lowest corrosion rate of 16.89 mpy with the highest polarization resistance of 2,820.11 Ω. These findings confirm that environmental factors, particularly soil type, should be considered in corrosion mitigation strategies to improve the resilience of underground infrastructure.

Keywords: Corrosion; Soil Moisture; Soil Resistivity; EIS Method; Soil Corrosion

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1. Introduction

Indonesia as a tropical country has high levels of humidity and rainfall that affect soil conditions. This affects the systematics of industries that operate underground and depend on the environment, one of which is the oil and gas industry. The main challenge in this industry is failure or unexpected costs stemming from corrosion issues. The production process of this industry utilizes underground piping systems. Behind the ease of access, there are challenges that are difficult to avoid, one of which is contact with the underground environment [1,2]. The contact between the pipe material and its environment will trigger a process of degradation of the material's ability to operate according to its function, namely corrosion.

Corrosion is the process of deterioration of a metal material [3]. Corrosion in soil is a type of corrosion that is often the cause of failure of underground piping installation systems. Electrochemical corrosion of metals buried in soil with high humidity causes corrosion cells to form from paired anodes and cathodes [4].

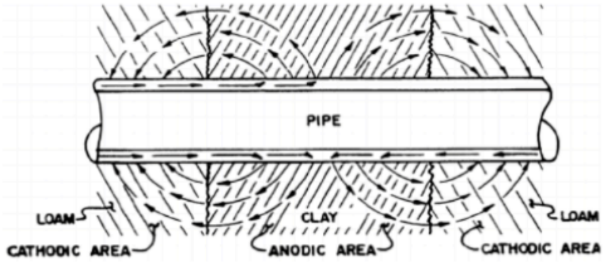

Figure 1. Ilustrasi mekanisme korosi pada pipa bawah tanah

Corrosion is influenced by soil aeration levels, acidity (soil pH), soil moisture, soil content, oxygen content and resistivity values. Soil moisture content represents the amount of water in the soil. High soil moisture can increase the corrosion rate of underground piping systems. Different soil types can affect the corrosiveness of the soil to the material being tested (5]. Acidity (soil pH) will affect the tendency for corrosion to occur or not (6]. The chemical composition contained in the soil has a significant effect on the soil resistivity value. And soil resistivity will affect the corrosion rate of materials exposed to the soil environment.

Failure or unexpected costs allocated to corrosion aspects can be reduced by 15-35% [7] by performing preventive methods so that corrosion does not occur, such as coating, inhibition, cathodic protection and other types of methods that are deemed appropriate. However, to determine the appropriate method, predictive analysis is needed related to corrosion that may occur, in this study a predictive analysis will be carried out related to the effect of soil on the corrosion resistance of carbon steel. Carbon steel is quite often used as the main material for making pipes. The choice of carbon steel as a pipe material is based on the suitability of the mechanical properties that can be produced, namely carbon steel has good plastic properties and will facilitate the manufacturing and machining process of pipe products [8]. Carbon steel also has a fairly good level of strength and is balanced with good toughness in absorbing energy.

Based on the background, this study aims to evaluate the relationship of soil moisture content to soil resistivity values, analyze how variations in soil resistivity affect the corrosion resistance of carbon steel and explore the relationship between variations in soil type to the composition and corrosion resistance of carbon steel under different environmental conditions. It is hoped that the findings of this research will contribute to the development of effective corrosion mitigation strategies for underground piping infrastructure in tropical countries such as Indonesia.

2. Materials and Experiment Methods

2.1 Sample Preparation

Carbon steel was divided into two sizes: 1 × 2.5 cm² for the weight loss method and 5 × 5 cm² for Electrochemical Impedance Spectroscopy (EIS) and linear polarization testing. The steel surfaces were cleaned using sandpaper to SP2 [9], cleanliness level, washed with Alconox, dried, and then soaked in acetone before being buried in soil.

2.2 Soil Preparation

The soil will serve as the electrolyte medium in direct contact with the carbon steel material. The soils used are sourced from three different locations: the Department of Metallurgy and Materials Engineering, the UI Original Forest Ravine, and Pakis Karawang Beach Sand.

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(a) Plan of Soil Retrieval Area in the Department of Metallurgy and Materials Engineering

(b) Plan of Ravine Soil Retrieval Area in the UI Original Forest

(c) Plan of the Karawang Pakis Beach Sand Retrieval Area

Figure 2. Plan of Soil Retrieval Area

The soil was tested before collection using a resistivity meter with the four-wenner pin method, then stored in a soil storing box in the laboratory. The parameters measured were moisture, pH, and temperature.

2.3 Testing Methods

• Weight Loss Method: Carbon steel samples (1×2.5 cm²) with a contact area of 1×1 cm² were immersed in soil (≥200 mL) for 7, 14, and 21 days. After immersion, the samples were weighed before and after sanding to determine the weight lost and calculate the corrosion rate using the ASTM G31-12a equation.

• Linear Polarization Method: Carbon steel samples (5×5 cm²) were placed in a flat cell containing soil as the electrolyte medium. The electrodes used included carbon steel (working electrode), carbon (counter electrode), and $Cu/CuSO_4$ and Ag/AgCl (reference electrodes). After configuring the Nova Autolab device, the test began by measuring the Open Circuit Potential (OCP) for 900 seconds, followed by Linear Polarization within a potential range of -1V to 1V at a scan rate of 1 mV/s. The results were analyzed using the Tafel Slope method to determine the corrosion kinetics.

• EIS Method: Carbon steel samples (5×5 cm^2) were placed in a flat cell containing soil as the electrolyte medium. The electrodes used included carbon steel (working electrode), carbon (counter electrode), and Cu/$CuSO_4$ and Ag/AgCl (reference electrodes). After configuring the Nova Autolab device, the tests were conducted with a frequency range of 10^{-2} to 10^5 Hz, where parameters such as scan rate and the number of reading points could be adjusted. The data obtained were analyzed to evaluate the impedance properties and corrosion mechanisms of carbon steel.

2.4 Characterization Methods

- XRF (X-Ray Fluorescence): to analyze the elemental composition of soil samples. The sample is homogenized, divided into three containers, and then loaded into the XRF apparatus. X-rays are fired to excite atoms, producing fluorescent X-rays that are detected and analyzed based on their wavelength and intensity to determine the constituent elements and their concentration.
- OES (Optical Emission Spectroscopy): analyzes elements in steel samples that have been cleaned and sanded grit 80, 120, 240. The sample is placed on an OES electrode and given a spark shot, causing the atoms to be excited and emit light. The wavelength of the light is analyzed to identify the element, while its intensity determines the concentration.

3. Results and Discussion

3.1 Material Characterization Results

3.1.1 Carbon Steel OES Characterization Results

Table 1. Composition Results using OES Method

Fe	Mn	C	Cu	Si
99,590%	0,179%	0,046%	0,036%	0,025%
Al	**Cr**	**Ni**	**As**	**P**
0,025%	0,019%	0,018%	0,017%	0,012%
Trace Elements				
Fe.				

Table 2. Composition of Q235 Carbon Steel

C	Si	Mn	P	S
0,190%	**0,105%**	**0,145%**	**0,020%**	**0,020%**

Based on the results in Table 1, the Optical Emission Spectroscopy (OES) analysis shows that the carbon steel used has a carbon content (C) of 0.046%, classifying it as low-carbon steel. This carbon steel composition is similar to that of Q235 steel, as presented in Table 4.2, which is known for its good mechanical properties, particularly in terms of ductility and weldability [10].

3.1.2 Results of Soil Characterization Analysis

Table 3. Characterization data of soil variation

Soil Name	ϱ(Ω/cm)	Soil Characteristics		
		Temperature (℃)	Humidity (%)	pH
Department of Metallurgical and Materials Engineering soil	4.577,17	29	65	6,6
Natural forest Universitas Indonesia's soil	21.772,70	26	51	5,9
Pakis Beach Karawang Sand	59,03	33	87	5,2

The soil of the Department of Metallurgical and Materials Engineering exhibits the second highest resistivity (4,577.17 Ω-cm) and moisture content (65%). The soil in the UI Original Forest Ravine has the highest resistivity (21,772.70 Ω-cm) and a more acidic pH (5.9), which contributes to better corrosion resistance. In contrast, Pakis Beach Karawang Sand has the lowest resistivity (59.03 Ω-cm) and the highest moisture content (87%), making it the most corrosive environment for carbon steel.

These resistivity values align with existing literature regarding the relationship between moisture content and resistivity. Specifically, as moisture content increases, the resistivity value decreases, as higher water content in the soil facilitates the movement of ions, thus lowering the resistivity.

Table 4. Results of Soil Composition Using XRF Method

Compotition	Department of Metallurgical and Materials Engineering soil (ppm)	Natural forest Universitas Indonesia's soil (ppm)	Pakis Beach Karawang Sand (ppm)
C	94.700,00	95.060,00	96.630,00
Si	**19.059,57**	**18.260,07**	**15.136,64**
Al	**17.544,81**	**17.438,75**	**6.054,69**
Fe	14.290,09	12.626,09	7.423,06
Ti	**1.233,92**	**1.081,11**	**488,76**
Ca	**445,48**	**77,34**	**2.232,23**
Mg	**0**	**0**	**1.436,49**
Mn	493,65	357,63	146,36
Ba	78,94	80,49	35,64
K	**27,85**	**0**	**617,30**
Ag	71,17	2,12	80,71
Na	**0**	**0**	**123,70**
V	45,19	41,85	18,65
Cu	40,20	9,60	23,25
Sn	30.53	17.20	23.31
Zn	38,17	14,28	8,02
Cr	14,06	9,59	17,51
P	0	0	40,30
Pb	13,90	1,43	8,76
Ni	14,05	4,44	4,37
Mo	4,63	3,06	2,61
S	0	0	47,35
Sb	0	0	20,92
Cd	0	0,75	6,15

In Table 4, the red-colored column will serve as a reference for considering several elemental compositions that show significant differences and influence soil variables as electrolyte media. The highest moisture content is observed in Pakis Beach Karawang Sand, while the lowest moisture content is found in the Natural Forest

Universitas Indonesia's soil. The calcium (Ca) content in the soil can form a barrier layer on the surface of carbon steel, inhibiting the diffusion of dissolved oxygen to the metal surface and thereby reducing the corrosion rate [11].

Pakis Beach Karawang Sand has a high content of sodium (Na, 123.70 ppm) and potassium (K, 617.30 ppm). Sodium can form NaCl, which increases soil conductivity and accelerates metal corrosion [12, 13]. Soil conductivity and acidity (pH) are influenced by the salt content, as well as aluminum (Al) and silicon (Si) levels. The lower Al and Si concentrations in Pakis Beach Karawang Sand contribute to a lower pH [14]. Iron (Fe) and carbon (C) elements in the soil play a role in maintaining pH stability, where Fe promotes corrosion by forming an acidic environment, while C helps neutralize acidity and reduce soil corrosivity [15, 16, 17].

3.2 Corrosion Resistance Test Results

3.2.1 Weight Loss Method

Table 5. Corrosion Rate Value using Weight Loss Method Based on Burial Duration

Soil Name	Corrotion Rate (mpy)		
	7 Days	14 Days	21 Days
Department of Metallurgical and Materials Engineering soil	15,81 mpy	17,66 mpy	20,52 mpy
Natural forest Universitas Indonesia's soil	14,57 mpy	15,36 mpy	16,89 mpy
Pakis Beach Karawang Sand	33,12 mpy	36,56 mpy	42,57 mpy

The weight loss method measures the corrosion rate by calculating the mass of material lost during the burial period. The test results indicate that the longer the burial time, the greater the mass loss, leading to an increase in the corrosion rate (measured in mils per year, mpy). The daily corrosion rate trend displayed linear values across all soil types tested, with the Natural Forest Universitas Indonesia's soil exhibiting the lowest corrosion rate and Pakis Beach Karawang Sand showing the highest. Soil characteristics, such as moisture content and resistivity, significantly affect the corrosion rate. Soils with higher moisture content and lower resistivity, such as Pakis Beach Karawang Sand, tend to be more corrosive.

3.2.2 Linear Polarization Method

Table 6. Error Value vs Iccor (Linear Polarization Test Results by Soil Type)

(a) Tafel Slope Data of Carbon Steel in Department of Metallurgical and Materials Engineering soil

Tafel Slope Data of Carbon Steel in Department of Metallurgical and Materials Engineering soil				
Components	Day 0	Day 7	Day 14	Day 21
Ecorr, Calc (mV)	-736.000	-673.350	-725.850	-635.620
icorr ($\mu A/m^2$)	0.00617	0.40611	0.47674	0.45319

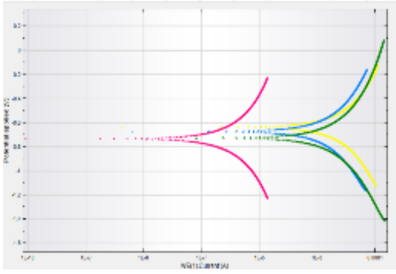
(b) Tafel Slope Data of Carbon Steel in Natural forest Universitas Indonesia's soil

Tafel Slope Data of Carbon Steel in Natural forest Universitas Indonesia's soil				
Components	Day 0	Day 7	Day 14	Day 21
Ecorr, Calc (mV)	-739.410	-734.500	-671.840	-720.220
icorr ($\mu A/m^2$)	0.28683	0.37888	0.17981	0.11903

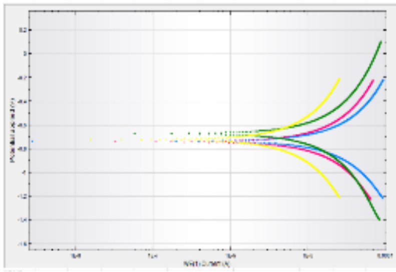
(c) Tafel Slope Data of Carbon Steel in Pakis Beach Karawang Sand

Tafel Slope Data of Carbon Steel in Pakis Beach Karawang Sand				
Components	Day 0	Day 7	Day 14	Day 21
Ecorr, Calc (mV)	-718.960	-747.790	-581.600	-728.260
icorr ($\mu A/m^2$)	2.2478	2.2362	3.2244	4.1246

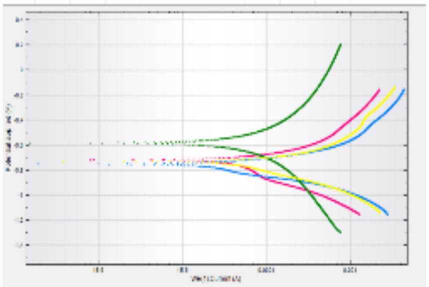
The highest corrosion current density (icorr) was observed for carbon steel buried in Pakis Beach Karawang Sand, reaching 4.1246 $\mu A/cm^2$, indicating high corrosion activity. In contrast, the Natural Forest Universitas Indonesia's soil exhibited the lowest icorr value of 0.11903 $\mu A/cm^2$, suggesting a less aggressive corrosion environment. Meanwhile, the Department Metallurgical and Materials Engineering soil had an icorr value of 0.45319 $\mu A/cm^2$.



(a) Linear Polarization Test Results of Department Metallurgical and Materials Engineering soil (●) Day 0 (●) Day 7 (●) Day 14 (●) Day 21



(b) Linear Polarization Test Results of Natural forest Universitas Indonesia's soil (●) Day 0 (●) Day 7 (●) Day 14 (●) Day 21



(c) Linear Polarization Test Results of Pakis Beach Karawang Sand

(●) **Day** 0 (●) **Day** 7 (●) **Day** 14 (●) **Day** 21

Figure 3. Linear Polarization Test Results by Soil Type

Table 7. Error Value vs Iccor (Linear Polarization Time Range Test Results)

(a) Day 0 Tafel Slope Data

Tafel Slope Data of			
Components	Pakis Beach Karawang Sand	Natural forest Universitas Indonesia's soil	Department Metallurgical and Materials Engineering soil
Ecorr, Calc (mV)	-718.960	-739.410	-736.000
icorr $(\mu A/m^2)$	2.2478	0.28683	0.0061759
Corrate (mm/yr)	0.02611	0.00333	0.00007

(b) Day 7 Tafel Slope Data

Tafel Slope Data of			
Components	Pakis Beach Karawang Sand	Natural forest Universitas Indonesia's soil	Department Metallurgical and Materials Engineering soil
Ecorr, Calc (mV)	-747.790	-734.500	-673.350
icorr $(\mu A/m^2)$	2.2362	0.3788	0.4061
Corrate (mm/yr)	0.02598	0.00440	0.00471

(c) Day 14 Tafel Slope Data

Tafel Slope Data of			
Components	Pakis Beach Karawang Sand	Natural forest Universitas Indonesia's soil	Department Metallurgical and Materials Engineering soil
Ecorr, Calc (mV)	-581.600 mV	-671.840 mV	-724.310 mV
icorr $(\mu A/m^2)$	3.2244 μA/m2	0.1798 μA/m2	0.4767 μA/m2
Corrate (mm/yr)	0.00374	0.00208	0.00553

(d) Day 21 Tafel Slope Data

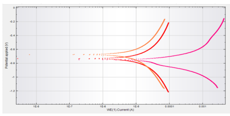
Tafel Slope Data of			
Components	Pakis Beach Karawang Sand	Natural forest Universitas Indonesia's soil	Department Metallurgical and Materials Engineering soil
Ecorr, Calc (mV)	-718.960	-739.410	-736.000
icorr $(\mu A/m^2)$	2.2478	0.28683	0.0061759
Corrate (mm/yr)	0.02611	0.00333	0.00007

On day 0, carbon steel buried in Pakis Beach Karawang Sand exhibited the highest corrosion current density (icorr) of 2.2478 μA/m² and the greatest corrosion rate of 0.0261 mm/year, indicating a highly corrosive environment. In contrast, the Department Metallurgical and Materials Engineering soil showed the lowest icorr value (0.0061759 μA/m²), suggesting minimal corrosion activity.

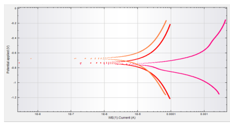
By day 7, the icorr value for the Pakis Beach Karawang Sand remained the highest at 2.2362 μA/m², while the Department Metallurgical and Materials Engineering soil experienced a notable increase in icorr to 0.4061 μA/m². Nevertheless, the highest corrosion rate was still observed in the Pakis Beach Karawang Sand (0.02598 mm/year).

On day 14, the icorr of the Pakis Beach Karawang Sand increased significantly to 3.2244 μA/m². Meanwhile, the icorr of the Natural Forest Universitas Indonesia's soil decreased, likely due to the formation of a protective rust layer. Interestingly, the highest corrosion rate at this stage shifted to the Department Metallurgical and Materials Engineering soil, reaching 0.00553 mm/year.

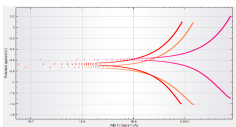
Finally, on day 21, the Pakis Beach Karawang Sand again recorded the highest icorr and corrosion rate, with values of 4.1246 μA/m² and 0.04792 mm/year, respectively, confirming that it remained the most corrosive environment compared to the Natural Forest Universitas Indonesia's soil and the Department Metallurgical and Materials Engineering soil.



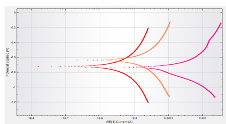
(a) Day 0 Linear Polarization Test Results, Pakis Beach Karawang Sand, Natural forest Universitas Indonesia's soil, and Department Metallurgical and Materials Engineering soil



(b) Day 7 Linear Polarization Test Results, Pakis Beach Karawang Sand, Natural forest Universitas Indonesia's soil, and Department Metallurgical and Materials Engineering soil



(c) Day 14 Linear Polarization Test Results, Pakis Beach Karawang Sand, Natural forest Universitas Indonesia's soil, and Department Metallurgical and Materials Engineering soil



(d) Day 21 Linear Polarization Test Results, Pakis Beach Karawang Sand, Natural forest Universitas Indonesia's soil, and Department Metallurgical and Materials Engineering soil

Figure 4. Linear Polarization Time Range Test Results

3.2.3 Electrochemical Impedance Spectroscopy Method (EIS)

Table 7. Day 0 EIS Testing Data and Results

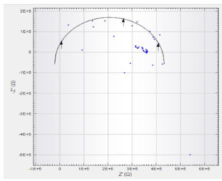
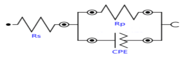
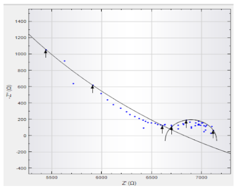
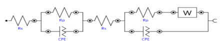
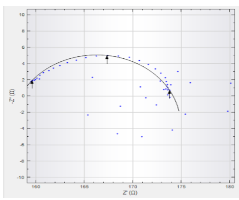
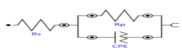
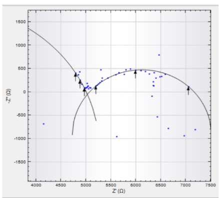
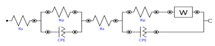
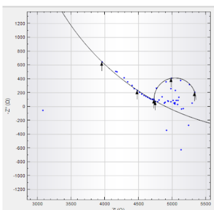
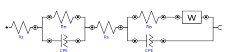
Soil Type	Electrochemical-fit Plot	Equivalent Circuit Model	EIS Data Values
Department Metallurgical and Materials Engineering soil			Chi-square (X^2) = 7.3716 FIT 1 Rs = -14.280 ohm Rp = 439.640,11 ohm CPE Y0 = 39.1910 mF CPE N = 0.99718
Natural forest Universitas Indonesia's soil			Chi-square (X^2) = 0.01265 FIT 1 Rs = 1.660 ohm Rp = 5.220,34 ohm CPE Y0 = 9.930 mF CPE N = 0.99675 FIT 2 Rs = 6.604 ohm Rp = 501,94 ohm CPE Y0 =31.7080 mF CPE N = 0.99733 Y0 W = 1.10 mho
Pakis Beach Karawang Sand			Chi-square (X^2) = 0.0143 FIT 1 Rs = 158,400 ohm Rp = 15.745,13 ohm CPE Y0 = 14.269 mF CPE N = 0.9952

Table 7 shows that differences in resistance mechanisms among the three soil types are indicated by variations in curve shapes, with the Natural Forest Universitas Indonesia's soil displaying two reaction mechanisms characterized by a double semicircle and the presence of a Warburg element. The polarization resistance (Rp) values reflect the resistance of the electrolyte medium to corrosion, where the

Department Metallurgical and Materials Engineering soil exhibits the highest resistance, while the Natural Forest Universitas Indonesia's soil and Pakis Beach Karawang Sand are more susceptible to corrosion due to the presence of aggressive ions and their specific chemical compositions.

The constant phase element (CPE) Y_0 values indicate the charge storage capacity of the electrode, with the Department Metallurgical and Materials Engineering soil showing the greatest capacity. In contrast, the Natural Forest Universitas Indonesia's soil and Pakis Beach Karawang Sand demonstrate more limited charge storage capacities, influenced by environmental factors and ion diffusion characteristics. It is also observed that there is a difference in the trends between the polarization method and the EIS test results in evaluating the corrosion resistance of the different soil types.

Table 8. Day 7 EIS Testing Data and Results

Soil Type	Electrochemical-fit Plot	Equivalent Circuit Model	EIS Data Values
Department Metallurgical and Materials Engineering soil			Chi-square (X^2) = 0.4978 FIT 1 Rs = -634.57k ohm Rp = 5.640,00 ohm CPE Y0 = 1.035 mF CPE N = 0.99541 FIT 2 Rs = 5.070 ohm Rp = 2.090,00 ohm CPE Y0 = 11.176 mF CPE N = 0.99198 Y0 W = 0.9 mho
Natural forest Universitas Indonesia's soil			Chi-square (X^2) = 0.38014 FIT 1 Rs = 4.900 ohm Rp = 3.190,00 ohm CPE Y0 = 187.210 mF CPE N = 0.99234 FIT 2 Rs = 4.74 k ohm Rp = 586,20 ohm

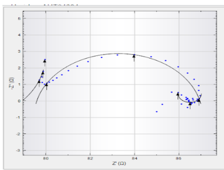
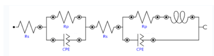
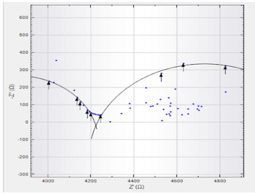
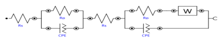
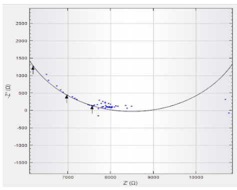
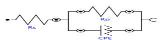
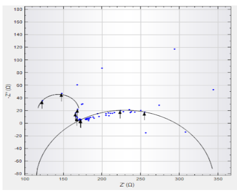
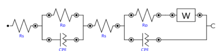
			CPE Y0 =365.120 mF CPE N = 0.99169 Y0 W = 90 mho
Pakis Beach Karawang Sand			Chi-square (X^2) = 0.00340 FIT 1 Rs = 73,054 ohm Rp =5,86 ohm CPE Y0 = -55.8080 mF CPE N = 0.99776 FIT 2 Rs = 79.580 ohm Rp =7,36 ohm CPE Y0 =30.482 mF CPE N = 0.99728 L = 39.5µH

Table 8 shows that on the 7th day of testing, the corrosion mechanisms in all three soil types involved a combination of charge transfer and mass transfer processes, as indicated by the presence of double semicircles in the impedance curves. The polarization resistance (Rp) values represent the resistance to electrochemical reactions, where the Natural Forest Universitas Indonesia's soil exhibits the lowest Rp value, suggesting that charge transfer and mass transfer processes occur more rapidly.

The Warburg and inductance values reflect differences in ion diffusion mechanisms among the soil types. The Department Metallurgical and Materials Engineering soil demonstrates easier ion diffusion, while the Natural Forest Universitas Indonesia's soil shows higher diffusion resistance. Meanwhile, the Pakis Beach Karawang Sand displays an ion inertia phenomenon that does not significantly impact the corrosion rate.

The highest constant phase element (CPE) Y_0 value is found in the Natural Forest Universitas Indonesia's soil, indicating a higher level of reactivity or charge storage capacity compared to the Department Metallurgical and Materials Engineering soil and the Pakis Beach Karawang Sand. The phase-shift values (CPE n) close to 1 suggest that the capacitive behavior is near ideal.Additionally, the corrosion resistance test results on the 7th day show differing trends between the EIS and linear polarization methods in evaluating the corrosion resistance of the different soil types

Table 9. Day 14 EIS Testing Data and Results

Soil Type	Electrochemical-fit Plot	Equivalent Circuit Model	EIS Data Values
Department Metallurgical and Materials Engineering soil			Chi-square (X^2) = 0.0572 FIT 1 Rs = 3.487,2 ohm Rp = 730,20 ohm CPE Y0 = -2.24200 mF CPE N = 0.9966 FIT 2 Rs = 4.230 ohm Rp = 996,49 ohm CPE Y0 =58.6240 mF CPE N = 0.9957 Y0 W = 1.15 x 10^{11} mho Y0 W = 0,00000842 Mho
Natural forest Universitas Indonesia's soil			Chi-square (X2) = 0.17635 FIT 1 Rs = 6.1250 ohm Rp = 2.108,00 ohm CPE Y0 = 109 mF CPE N = 0.99710
Pakis Beach Karawang Sand			Chi-square (X^2) = 1.5574 FIT 1 Rs = 131,550 ohm Rp = 23,71 ohm CPE Y0 = 525.630 mF CPE N = 0.98811 FIT 2 Rs = 162,090 ohm Rp = 171,85 ohm CPE Y0 =628.070 mF

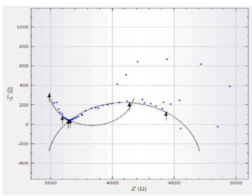
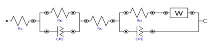
			CPE N = 0.98972 Y0 W = 0,00000842 Mho

Table 9 shows that on the 14th day of testing, differences in the shapes of the curves and equivalent circuits were observed, indicating changes in the charge transfer mechanisms in each type of soil used as the electrolyte medium. The polarization resistance (Rp) value reflects the resistance of the electrolyte medium to electrochemical reactions, with Pakis Beach Karawang Sand exhibiting the lowest Rp value, indicating its more corrosive nature compared to the Department Metallurgical and Materials Engineering soil and the Natural Forest Universitas Indonesia's soil.

The Warburg impedance (Y_0) value represents the ion diffusion resistance, where Pakis Beach Karawang Sand shows high diffusion resistance, thus inhibiting ion movement. In contrast, the Department Metallurgical and Materials Engineering soil displays lower diffusion resistance, allowing corrosive ions to move more easily and thereby accelerating the corrosion rate. The highest constant phase element (CPE) Y_0 values were also found in the Pakis Beach Karawang Sand, indicating greater charge storage capacity of the electrode and a higher degree of heterogeneity and irregularity in current distribution, which facilitates diffusion processes.

Overall, the results show that the capacitive behavior of the system approaches ideal conditions. The corrosion resistance of carbon steel is the lowest when buried in Pakis Beach Karawang Sand, followed by the Department Metallurgical and Materials Engineering soil, while the Natural Forest Universitas Indonesia's soil provides the best corrosion resistance, in accordance with the electrolyte characteristics of each soil type.

Table 10. Day 21 EIS Testing Data and Results

Soil Type	Electrochemical-fit Plot	Equivalent Circuit Model	EIS Data Values
Department Metallurgical and Materials Engineering soil			Chi-square (X^2) = 0.13673 FIT 1 Rs = 3.750 ohm Rp = 166,29 ohm CPE Y0 = -36.791 mF CPE N = 0.98111 FIT 2 Rs = 3.610 ohm Rp = 956,80 ohm CPE Y0 =12.689 mF CPE N = 0.99231 Y0 W = 1,3 Mho

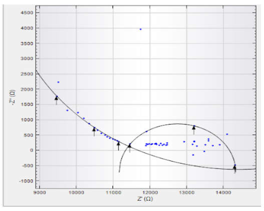
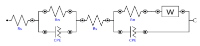
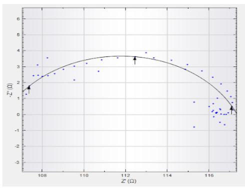
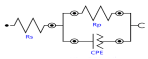
Natural forest Universitas Indonesia's soil			Chi-square (X^2) = 0.26339 FIT 1 Rs = 4.820 ohm Rp = 6.820,00 ohm CPE Y0 = 582.270 mF CPE N = 0.99420 FIT 2 Rs = 11.330 ohm Rp = 2.820,11 ohm CPE Y0 =104.570 mF CPE N = 0.99479 Y0 W = 7,8 Mho
Pakis Beach Karawang Sand			Chi-square (X^2) = 0.026067 FIT 1 Rs = 106,190 ohm Rp = 11,16 ohm CPE Y0 = 5.588 mF CPE N = 0.99547

Table 10 shows differences in the mechanisms of charge transfer and electrochemical reactions on the 21st day of testing, as indicated by changes in the curve shapes and the equivalent circuits for different types of soil used as the electrolyte medium. The polarization resistance (Rp) value indicates the resistance to electrochemical reactions, where Pakis Beach Karawang Sand exhibits the lowest Rp value, making it the most corrosive medium. Meanwhile, the Department Metallurgical and Materials Engineering soil shows a decrease in Rp on day 21, rendering it more corrosive than the Natural Forest Universitas Indonesia's soil.

The Warburg impedance Y_0 value indicates that the Natural Forest Universitas Indonesia's soil has higher diffusion resistance, meaning that ions experience greater resistance to movement. The constant phase element (CPE) Y_0 value reflects the electrode's charge storage capacity, with Pakis Beach Karawang Sand showing the highest CPE magnitude, indicating a greater charge storage capability compared to the Natural Forest Universitas Indonesia's soil. Meanwhile, the CPE n value suggests that the capacitive behavior of the system remains close to an ideal capacitor.

On the 21st day, the EIS and linear polarization method results show a similar trend: carbon steel embedded in Pakis Beach Karawang Sand has the lowest resistance, while carbon steel in the Natural Forest Universitas Indonesia's soil demonstrates the highest resistance. These findings are consistent with the resistivity and moisture content characteristics of each soil type.

3.3 Comparison of Carbon Steel Corrosion Resistance Research Data

Table 11. Comparison of Carbon Steel Corrosion Resistance Research Data

Soil Name	pH	Moisture Content (%)	Resistivity (Ω.cm)	Corrosion Rate (mpy)	icorr (µA/m^2)	Polarization Resistance (Ω)
Department Metallurgical and Materials Engineering soil	6,6	65	4.577,17	20,52	0,45	956,80
Natural forest Universitas Indonesia's soil	5,9	51	21.772,70	16,89	0,11	2.820,11
Pakis Beach Karawang Sand	5,2	87	59,03	42,57	4,12	11,16

Table 11 shows the comparison of the three evaluation methods used as parameters of corrosion resistance of steel in the soil, namely corrosion rate, current density, and polarization resistance. The relationship between the moisture content and the resistivity value of the three soil variations shows the same trend: as the moisture content increases, the soil resistivity value also increases.

The results of the three evaluation methods show the same overall trend, namely that Pakis Beach Karawang Sand acts as a more corrosive electrolyte medium compared to the Department Metallurgical and Materials Engineering soil or the Natural Forest Universitas Indonesia's soil. This is evidenced by Pakis Beach Karawang Sand having the highest corrosion rate of 42.57 mpy, the highest current density (icorr) of 4.12 µA/m², the lowest polarization resistance of 11.16 Ω, and the lowest resistivity of 59.03 Ω·cm with 87% moisture content.

Meanwhile, the Natural Forest Universitas Indonesia's soil provided better corrosion resistance results across all three evaluation methods. Carbon steel buried in the Natural Forest Universitas Indonesia's soil exhibited the lowest corrosion rate of 16.89 mpy, indicating less mass loss compared to the other two soil variations. The Department Metallurgical and Materials Engineering soil showed the lowest current density value at 0.11 µA/m², suggesting that the amount of current able to pass through the soil was much less than in the other two soil variations. This finding is further supported by its high polarization resistance value of 2,820.11 Ω. The polarization resistance value reflects the soil's ability to resist electrical conduction when in contact with the carbon steel surface area. The polarization resistance and resistivity values for the Natural Forest Universitas Indonesia's soil show a consistently higher trend compared to the other two soil variations, indicating a smaller likelihood of corrosion.

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