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Degradation Rates of Various Earthing Conductors in Different Soil Environments

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ABSTRACT

The study evaluates the degradation of electrical earthing conductors that are commonly used in electrical earthing. Electrical earthing equipment is exposed to various environments that causes it to corrode and obstruct the proper function of the electrical protection system of any structure. There have been numerous reports of integrity loss of the electrical protection system encased in soil. The aim of this study is to explore the most durable metal when encased in native and aggressive soil conditions and corrosion protection techniques through sealing. Earthing electrodes samples are encased in the soil for 3 months to evaluate their corrosion rates. Aluminium was seen to have the best performance of withstanding corrosion at 0.1792 mpy (mpy stands for mils per year) and 0.0758 mpy when partially immersed in soil vertically without seal in bentonite and native soil respectively. Copper bonded steel when fully immersed horizontally, was shown to have the least effective performance at values of 0.9960 mpy and 1.6101 mpy in bentonite and native soil individually. Copper showed high corrosion rates of 0.3917 mpy when immersed in bentonite when it is partially air sealed. Partial sealing of metals samples shows significant corrosion rate reduction up to 91.41 %. Visual observations show various corrosion product formations to the metals. These findings highlight the importance of selecting the best materials for earthing to

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secure the most efficient metals against corrosion and the mitigation methods to sustain electrical earthing systems in the long term.

Keywords: Corrosion rate, earth enhancing compounds, electrical earthing, corrosive environment, metal sustainability, aluminium, copper, copper bonded steel

INTRODUCTION

Corrosion is a concern for the integrity of earthing systems as metals will tend to oxidise to their ore state when exposed to the underground soil environment (Balangao, 2024). The cost of corrosion was found to be in the trillions of dollars globally (Aljibori et al., 2023). Failure of earthing systems have heavy implications such as causing halt in industrial operations that can cause economic loss (Zhang et al., 2021). The ability of an earthing system to clear electrical discharges can be impacted by corrosion. Heavily corroded earthing conductors will not be able to clear faults in time, that can cause significant damage and operational failures (Song et al., 2022). Over time, severe corrosion can compromise the overall performance of an earthing system, especially in highly corrosive soil and atmospheric environments such as coastal, marine, petroleum, swampy region and high salinity areas (Fu et al., 2024; Godbole & Mondal, 2022; Sharmila & Vasanthi, 2024). The corrosion rate of a metal can be measured in millimetres per year (mm/y) or mils per year (mpy) units.

Soil resistivity is a measure of soil corrosivity. Wasim et al. (2018) reports that the higher the soil resistivity the less corrosive the soil is towards a metal. This is as depicted in Table 1 where lower soil resistivity causes more corrosion to underground metals. Consequently, the orientation in which the earthing electrodes are placed can also cause more corrosion to different parts of the earthing electrodes. This is due to the irregular and complex soil profile that exists in soils. Different areas of soil in the world will have different natures of soil profiles. For example, middle eastern soils are generally sandy

Table 1
Soil resistivity in relation to their corrosivity classifications (Adopted from Arriba-Rodriguez et al., 2018)

Soil Resistivity (Ω-cm)	Soil Resistivity (Ω-m)	NACE	ASTM
>10, 000	>100	Negligible	Very Mildly Corrosive
5001-10,000	50.01-100	Mildly Corrosive	Mildly Corrosive
2001-5000	20.01-50	Mildly Corrosive	Moderately Corrosive
1001-2000	10.01-20	Moderately Corrosive	Severely Corrosive
501-1000	5.01-10	Corrosive	Extremely Corrosive
0-500	0-5	Very Corrosive	Extremely Corrosive

Note. NACE stands for the National Association Corrosion Engineers; ASTM stands for the American Society for Testing and Materials having increasing resistivity with depth while having ununiform resistivity due to its irregular moisture and saline contents across the soils (Malik & Al-Arainy, 2008). Malaysia generally has lateritic soils with soil resistivity decreasing with depth but has a moderate lateral variability (Nasha et al., 2020).

To reduce the earthing resistance of the earthing system to earth to the desired level, earth resistance reduction agents or materials are employed with the earthing systems in the ground (Hamzah et al., 2023; Wooi et al., 2024). Some of the materials that have been used in the past include bentonite, concrete encasement, and chemical treatments (Androvitsaneas & Hatziargyriou, 2017). Sodium bentonite and calcium bentonite were reported to have soil resistivities of 0.1 – 20 Ωm and 2.8 – 72.5 Ωm respectively which falls in the category of very corrosive or extremely corrosive (Azmi et al., 2021). This raises concerns of when the earthing conductors are encased with such materials that have the potential to create aggressive corrosive environments, causing a detrimental long term safety hazard. Consequently, the metal selection of the earthing must be chosen that resists corrosion in the long term. The typical metals used for electrical earthing include copper bonded steel, copper, and aluminium. Therefore, this study attempts to explore the degradation rates of these metals in both the native and aggressive soil environments while attempting to reduce these rates using sealing measures. Consequently, this information will be vital in selecting the type of metal when installing earthing systems to withstand the degradation effects of corrosion.

Generally, the degree of the corrosiveness of the environment will determine the corrosion rates of the metals exposed to the environment, which can be measured using millimetres per year (mm/y) or mils per year (mpy) units. Although the mechanism of corrosion is often complex, the degree of corrosion rates can be found in the standards, as depicted in Table 2. The corrosion rate can vary from less than 0.025 mm/year (0.985 mpy) to more than 0.25 mm/year (9.846 mpy) which translates to low to severe degrees of corrosiveness according to the National Association of Corrosion Engineers (NACE, 2018), in the oilfield environment. However, there is no available literature that specifies the degree of corrosiveness that specifically caters for the soil environment.

There are limited studies on the corrosion rate of metals buried underground especially in the context of electrical earthing. Table 3 depicts various metals with different exposure

Table 2
Corrosion rate and their degrees of corrosiveness. NACE, 2018

Corrosion Rate (mm/year)	Corrosion Rate (mpy)	Degree of Corrosiveness
< 0.025	< 0.985	Low
0.025 – 0.12	0.985 – 4.726	Moderate
0.13 – 0.25	5.120 – 9.846	High
> 0.25	> 9.846	Severe

to soil, depth in soil, durations, and applications of full immersion of the metal samples in the soil. All experiments were done based on burying the metals in a certain depth for a duration of 1 to 6 years and measuring their corrosion rates according to the standard. Aluminium is seen to have the least amount of corrosion rate compared to copper and steel at the value of 0.00153 mpy when exposed in the arid vadose zone environment for a duration of 1 year. SS304 Stainless Steel and SS316 Stainless Steel have 0.071 mpy and 0.057 mpy rates when exposed to the native soil of the study while copper was found to have 0.427 mpy when encased in the soil of the study. X70 Carbon Steel is then found to have the highest corrosion rate of 3.150 mpy when exposed to the soil environment of its study. Soil resistivity values were not found in any of the studies.

In the case of Aluminium 6061 of the 6-year exposure, it is indicative that the soil resistivity at the lower depth of 3.05 m has higher resistivity based on the classification of Table 1. This is due to it having a lower corrosion rate of 0.00063 mpy at this depth when compared to Aluminium 6061 buried at 1.22 m that has a corrosion rate of 0.00151 mpy,

Table 3
Corrosion rate of various metals in soil

Metal	Corrosion Rate mpy	Underground Soil Environment	Depth	Duration	Context of Metal Use	Reference
Aluminium	0.185	Sulphate and chloride present in soil samples.	70 cm	15 Months	Applications in the Industrial and Coastal Environment.	Ul-Hamid et al., 2017a
Aluminium 6061	0.00153 0.00393 0.00151 0.00178 0.00063	Arid vadose zone moderate chloride concentrations.	1.22 m 3.05 m	1 Years 3 Years 6 Years 3 Year 6 Year	Nuclear Waste Management Systems.	Adler Flitton & Yoder, 2006
Copper	0.427	Sulphate and chloride present in soil samples.	70 cm	15 Months	Applications in the Industrial and Coastal Environment.	Saricimen et al., 2009
X70 Carbon Steel	Approximately 3.150	Varied moisture and clay content.	0.5 m – 1 m	12 Months	Buried Metallic Structures	Yahaya et al., 2011
SS304 Stainless Steel SS316 Stainless Steel	0.071 0.057	Sulphate and chloride present in soil samples.	70 cm	15 months	Applications in the Industrial and Coastal Environment.	Ul-Hamid et al., 2017b

which is about 2.4 times higher. There is no linear relationship between the corrosion rates and time of when Aluminium 6061 is exposed to the native soil environment at 1, 3 and 6 years of exposure. However, the data sets are insufficient to make any direct correlation. Hence, more information is needed to have a meaningful connection between corrosion rates and time of duration in these studies.

Due to the irregular nature of soils, different representations of soil profiles may exist (Arriba-Rodriguez et al., 2018). The behaviour of soils has been studied in the past for its resistivity at different points in the soil. This can be advantageous or disadvantageous for the electrical engineer studying or installing earthing systems by locating the features of interest of the soil. Generally, soil may behave in a certain pattern displayed by the measure of its resistivity and is indicative of the soil conditions. In certain areas, soil resistivity may behave in a way that its soil resistivity becomes lower as its depth increases or vice versa (Lech et al., 2020). This is important to emphasise since corrosion can become more intense in soils with lower resistivity. This is evident as seen in Table 3, the corrosion rate of Aluminium 6061 buried at 1.22 m depth was observed to be double the corrosion rate of Aluminium 6061 buried at 3.05 m depth in a 3-year exposure to the same soil (Adler Flitton & Yoder, 2006).

Corrosion can be mitigated by using protective coating or sealing methods to significantly reduce the amount of corrosion that occurs (Bastidas, 2020). 89% of the anti-corrosion protection cost is associated with the coatings sector (Gąsiorek et al., 2022). In the study of (Gąsiorek et al., 2022), methanol-based coatings were found to significantly improve the efficiency of corrosion reduction by approximately 98% on steel. Sharmila and Vasanthi (2024), reports that rebar in the context of marine concrete piles is significantly protected against corrosion by using polyurethane coatings. Hence, it is vital that any corrosion coating or sealing be implemented when needed. This study will test different ways of sealing to protect earthing conductors from corroding.

METHODOLOGY

A total of 24 samples of earthing electrodes is exposed to native and aggressive (bentonite) soil environments for 3 months in rows and columns at the premises of Universiti Putra Malaysia (UPM). Aluminium, copper, and copper bonded steel earthing electrodes samples were exposed in different configurations and cases. Copper bonded steel is a metal with steel core that its copper exterior is bonded through the electroplating process. These three materials are commonly used metal conductors for electrical earthing.

Table 4 shows the metal sample description of all the configurations and cases tested in this work. The four configurations serve different purposes for the study. Figure 1 depicts configuration 1 (case 1-6), where the metal is fully immersed in soil horizontally at a 15 cm depth. This is to simulate the corrosion of horizontal earthing system configurations

Table 4
Metal description of each configuration and case of metal encased in soils

Configuration	**Case**	**Configuration 1: Horizontally Fixed Electrode**
		Metal Description
1: Horizontally Fixed Electrode	**1**	Horizontally Fixed Copper Bonded Steel (8 cm) Encased in Bentonite
	2	Horizontally Fixed Copper (8cm) Encased in Bentonite
	3	Horizontally Fixed Aluminium (8cm) Encased in Bentonite
	4	Horizontally Fixed Copper Bonded Steel (8 cm) Encased in Native Soil
	5	Horizontally Fixed Copper (8cm) Encased in Native Soil
	6	Horizontally Fixed Aluminium (8cm) Encased in Native Soil
2: Vertically Fixed Electrode – Without Sealant	**7**	Vertically Fixed Copper Bonded Steel (16 cm) (Without Sealant) Encased in Bentonite
	8	Vertically Fixed Copper (16 cm) (Without Sealant) Encased in Bentonite
	9	Vertically Fixed Aluminium (16 cm) (Without Sealant) Encased in Bentonite
	10	Vertically Fixed Copper Bonded Steel (16 cm) (Without Sealant) Encased in Native Soil
	11	Vertically Fixed Copper (16 cm) (Without Sealant) Encased in Native Soil
	12	Vertically Fixed Aluminium (16 cm) (Without Sealant) Encased in Native Soil
3: Vertically Fixed Electrode – Soil Sealed	**13**	Vertically Fixed Copper Bonded Steel (16 cm) (Soil Sealed) Encased in Bentonite
	14	Vertically Fixed Copper (16 cm) (Soil Sealed) Encased in Bentonite
	15	Vertically Fixed Aluminium (16 cm) (Soil Sealed) Encased in Bentonite
	16	Vertically Fixed Copper Bonded Steel (16 cm) (Soil Sealed) Encased in Native Soil
	17	Vertically Fixed Copper (16 cm) (Soil Sealed) Encased in Native Soil
	18	Vertically Fixed Aluminium (16 cm) (Soil Sealed) Encased in Native Soil
4: Vertically Fixed Electrode – Air Sealed	**19**	Vertically Fixed Copper Bonded Steel (16 cm) (Air Sealed) Encased in Bentonite
	20	Vertically Fixed Copper (16 cm) (Air Sealed) Encased in Bentonite
	21	Vertically Fixed Aluminium (16 cm) (Air Sealed) Encased in Bentonite
	22	Vertically Fixed Copper Bonded Steel (16 cm) (Air Sealed) Encased in Native Soil
	23	Vertically Fixed Copper (16 cm) (Air Sealed) Encased in Native Soil
	24	Vertically Fixed Aluminium (16 cm) (Air Sealed) Encased in Native Soil

fully encased in the soil. Figure 2 depicts configuration 2 (cases 7-12), where the metal is partially immersed in soil vertically at a depth of 4 cm. This is to simulate the corrosion of vertical earthing system configurations encased in soil and partly exposed to air. Figure 3 depicts configuration 3 (case 13-18), where the metal is partially immersed in soil vertically at a depth of 4 cm while the section of the metal that is buried is sealed with silicon sealant. This is to simulate the corrosion of the metal without the effects of corrosion from the soil

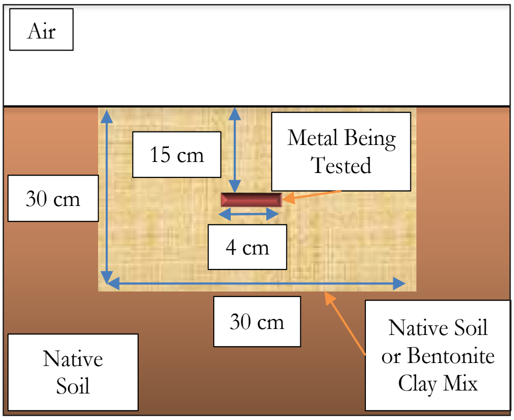


Figure 1. Horizontally fixed earthing metal sample fully encased in soil (Configuration 1)

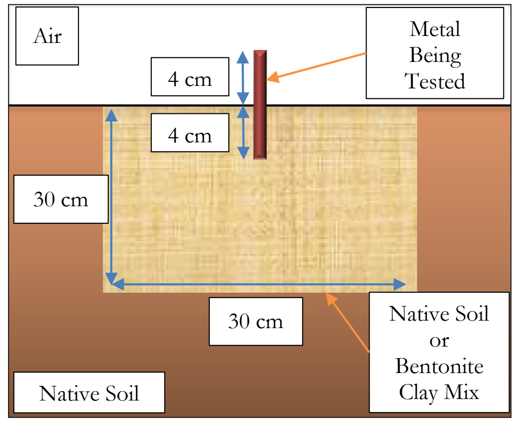


Figure 2. Vertically fixed earthing metal sample partially encased in soil (Configuration 2)

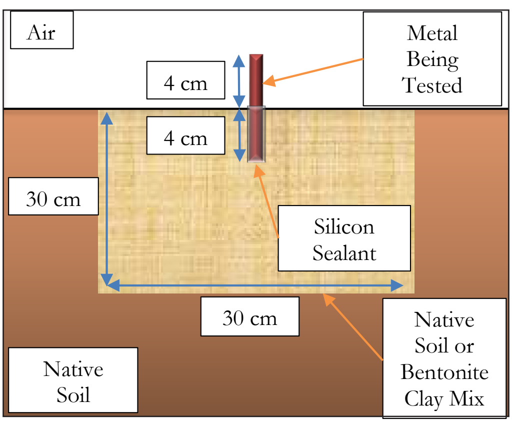


Figure 3. Vertically fixed earthing metal sample (air sealed) partially encased in soil (Configuration 3)

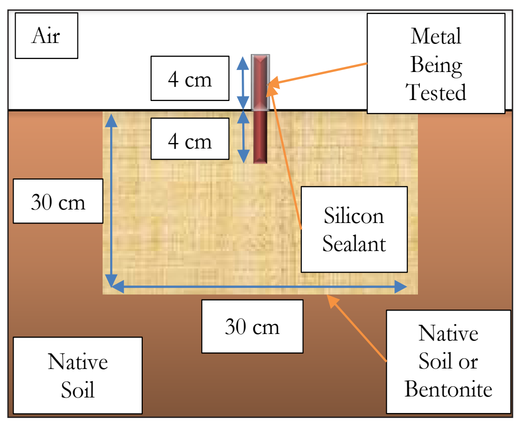


Figure 4. Vertically fixed earthing metal sample (soil sealed) partially encased in soil (Configuration 4)

as a protective measure. Figure 4 depicts case 4 (cases 19-24), where the metal is partially immersed in soil vertically at a depth of 4 cm while the section of the metal that is exposed to the air is sealed with silicon sealant. This is to simulate the corrosion of the metal without the effects of corrosion from the atmosphere as a protective measure. Figure 5 shows one of the experimented earthing conductor samples. The process of preparing, measuring, cleaning, and evaluating the exposed metals was done based on the ASTM G1-03(2017) e1 standard (ASTM International, 2017). This study will adopt the mils per year (mpy) unit as a standard of measurement. The corrosion rate is given by:

$$Corosion\ Rate\ (CR) = \frac{(K \times W)}{(A \times T \times D)} \quad [1]$$

Where K is the constant for mils per year (mpy) given by 3.45 × 106, T is the time of exposure in hours, A is the area in cm2, W is the mass loss in grammes and D is the density in g/cm3. Table S1 in the appendix shows the raw data related to the corrosion rate calculation of each case of metal. The environment that a metal is exposed to determines the corrosion rates of metals. Hence, the atmospheric and soil environment should be taken into consideration as factors that influence the corrosion rate. For atmospheric environment, the temperature and humidity measurements were taken once a week for a total of three months using the Hygrometer testo 608-H1. The rainfall data were acquired from the Malaysian Meteorological Department for the period of when the experiment was done. For soil environment, the acidity, volumetric water content (VWC), soil temperature, soil salinity, and soil resistivity were taken three times every week for each parameter during the three-month period of the experiment. The measurements for VWC, soil temperature and soil salinity were taken using the Procheck handheld multifunctional meter device. The acidity of the soils was taken using the Takemura soil pH meter. Finally, the soil resistivity readings were taken using the Megger soil resistivity tester. Table S2, S3 and S4 show the raw data of the atmospheric and soil environment measured during the experiment.

Figure 5. One of the samples of metals during experimentation: aluminum partially encased in native soil (Case 12)

In understanding the relationship of the results between different configurations, the ratios of each configuration against another configuration are calculated. The general formula for the ratio of configurations is given by:

$$Ratio\ (S) = \frac{CR_I}{CR_B} \quad [2]$$

Where S is the soil type of native soil or bentonite, CRI is the corrosion rate of configuration of interest and CRB is the base corrosion rate configuration. The configuration ratios of interest include configuration 2 to configuration 1, configuration 3 to configuration 2 and configuration 4 to configuration 2 for all metals and soils. The ratio values are calculated based on the corrosion rate values of each metal case. The percentage of the corrosion reduction due to the sealants are then calculated using the following formula:

$$Percentage\ Reduction\ (\%) = 1\text{-}Ratio\ (S) \quad [3]$$

Where Ratio (S) is the ratio of the configurations of interest. The percentage reduction values are calculated based on the corrosion rate values of each metal case.

RESULTS AND DISCUSSIONS

Environmental Parameters

The temperature, humidity and rainfall data obtained from meteorological department recorded average values of 30.28 °C, 88.08 % and 10.54 mm respectively. Table 5 shows the soil environment of the exposed metals during the experiment. The average soil acidity and temperature is seen to have low differences. In terms of volumetric water content, bentonite is seen to have about 3 times higher the VWC of native soil. Moisture in this study is depicted in VWC where moisture is directly correlated to corrosion (Arriba-Rodriguez et al., 2018). Bentonite is seen to have about 37 times higher salinity than native soil. Salinity levels in soil show the presence of ionic salts which are directly correlated to the processes of corrosion (Arriba-Rodriguez et al., 2018). For soil resistivity, bentonite is seen to have 25 times lower resistivity than native soil. These parameters suggest that bentonite is more aggressive than native soil in terms of corrosion.

Table 5
Native and bentonite soil environment

Property	Native Soil	Bentonite
Acidity (pH)	5.47	6.41
Volumetric Water Content (VWC) (%)	28.49	92.39
Soil Temperature (°C)	32.20	31.93
Soil Salinity (dS/m)	0.16	6.06
Soil Resistivity (Ωm)	238.49	9.43

Corrosion Rates of Earthing Conductors in Various Configurations

Figure 6 depicts the corrosion rates of encased electrodes of cases 1 to 6 which encompasses the horizontally fixed metals. It is evident that copper bonded steel (Case 1 and 4) displays the highest corrosion rate among the other metals with values of 0.9960 mpy and 1.6101 mpy in bentonite and native soil respectively. This is followed by copper (Case 2 and 5) at 0.2825 mpy and 0.4284 mpy bentonite and native soil respectively. Aluminium (Case 3 and 6) corrodes at a rate of 0.3567 mpy and 0.1122 mpy in bentonite and native soil respectively. Aluminium is seen to have the most resistance towards bentonite and native soil. However, Aluminium is seen to corrode more in bentonite compared to native soil, unlike copper bonded steel and copper. Unexpectedly, copper bonded steel and copper corrode more in native soil when bentonite has more aggressive corrosion attributes. It is highly likely that there is an accumulation of moisture due to rainfall in these two areas of

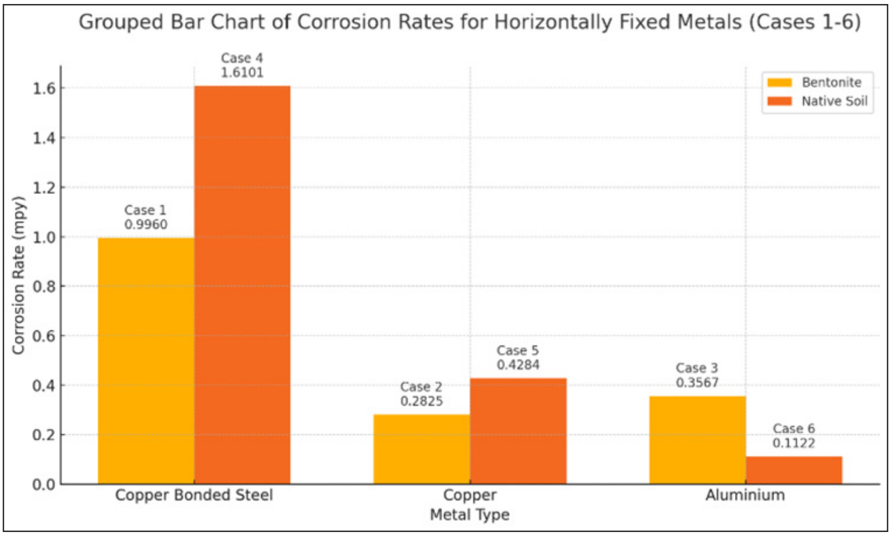


Figure 6. Corrosion rates of horizontally fixed metals (Case 1-6)

soil that contributed to the higher corrosion rates. Copper bonded steel encased in bentonite and native soil lies (Case 1 and 4) in the moderate degree of corrosiveness. For the other cases (Case 2, 3, 5 and 6), the degree of corrosiveness lies in the low category.

Aluminium, copper, and copper bonded steel from this study are compared to aluminium, copper and X70 Carbon Steel from another research as depicted in Table 6. In general, the results from this study come to an agreement of the findings of the literature when X70 Carbon Steel corrodes most followed by copper and aluminium at the values of 3.150 mpy, 0.427 mpy and 0.185 mpy respectively. However, at longer durations of exposure of 15 months, aluminium in the findings of Ul-Hamid et al. (2017a), recorded comparable corrosion rate when compared to case 3 and case 6 of this study at 3 months of exposure. According to Adler Flitton and Yoder (2006), longer exposure to soil does not necessitate higher corrosion rates, when they found Aluminium 6061 that was exposed to the soil at 1, 3, and 6 years recorded values of 0.00153 mpy, 0.00393 mpy and 0.00151 mpy respectively.

Copper corrosion rate values from Saricimen et al. (2009) and this study is also seen to have comparable values although their periods of exposure differ. X70 Carbon Steel when exposed for 12 months is shown to have a significantly higher corrosion rate compared to the copper bonded steel of case 1 and case 4 that was exposed for 3 months. This suggests that in the case of steel, the period of exposure may play a significant role in increasing its corrosion rate. Since soil resistivity values are not available to understand the corrosivity of the soil especially in the areas of concern at different depths, it is challenging to make a direct comparison of the results that are occurring in the literature. To summarise in general,

Table 6
Comparison of corrosion rates of this study to previous findings

Metal	**Corrosion Rate (mpy)**	**Underground Soil Environment**	**Depth**	**Duration**	**Context of Metal Use**	**Reference**
Aluminium	0.1850	Sulphate and chloride present in soil samples.	70 cm	15 Months	Applications in the Industrial and Coastal Environment.	Ul-Hamid et al. (2017a)
Aluminium (Case 3)	0.3567	Bentonite with high soil salinity and water content. Low resistivity	15 cm	3 Months	Electrical Earthing	This Study
Aluminium (Case 6)	0.1122	Native soil with low soil salinity and water content. High resistivity.				
Copper	0.4270	Sulphate and chloride present in soil samples.	70 cm	15 Months	Applications in the Industrial and Coastal Environment.	Saricimen et al. (2009)
Copper (Case 2)	0.2825	Bentonite with high soil salinity and water content. Low resistivity	15 cm	3 Months	Electrical Earthing	This Study
Copper (Case 5)	0.4284	Native soil with low soil salinity and water content. High resistivity.				
X70 Carbon Steel	Approximately 3.150	Varied moisture and clay content.	0.5 m – 1 m	12 Months	Buried Metallic Structures	Yahaya et al. (2011)
Copper Bonded Steel (Case 1)	0.9960	Bentonite with high soil salinity and water content. Low resistivity	15 cm	3 Months	Electrical Earthing	This Study
Copper Bonded Steel (Case 4)	1.6101	Native soil with low soil salinity and water content. High resistivity.				

aluminium and copper are seen to have better corrosion resistance over time while the corrosion rate of steel can worsen over time in the context of fully immersed metals in soil.

Figure 7 depicts the corrosion rates of encased electrodes of the vertically fixed metals (without sealant). Interestingly, in the case of copper bonded steel (Case 7 and 10), there is a massive difference of corrosion rate observed between its corrosion in bentonite and native soil at the values of 4.2464 mpy and 0.6744 mpy respectively with a difference of 3.572 mpy. Copper (Case 8 and 11) showed lower corrosive rates in bentonite and native soil at 0.3319 mpy and 0.1823 mpy respectively. Aluminium (Case 9 and 12) resulted in the least corrosion rate in comparison of 0.1792 mpy and 0.0758 mpy in both types of soil. It can be deduced from these results in this case that Aluminium is most resistant to corrosion, followed by copper and copper bonded steel. According to NACE (2018), copper bonded steel encased in bentonite (Case 7) lies in the moderate degree of corrosiveness. Overall, cases 8-12 lie in the low degree of corrosiveness.

Figure 8 depicts the corrosion rate values of the vertically fixed metals (soil sealed). Corrosion is seen to be highest for copper bonded steel (Case 13 and 16) when exposed to bentonite and native soil at the values of 1.4956 mpy and 0.0579 mpy individually. However, in comparison to the vertically fixed metals (without sealant) case, copper bonded steel corrodes at a much higher rate. This is followed by copper (Case 14 and 17) with 0.1078 mpy and 0.0467 mpy in bentonite and native soil respectively. Aluminium (Case 15 and 18) showed the lowest corrosion rate of the metals at 0.0744 mpy and 0.0146 mpy in bentonite and native soil respectively. According to NACE (2018), copper bonded steel encased in bentonite (Case 13) lies in the moderate degree of corrosiveness. Overall, cases 14-18 lies in the low degree of corrosiveness.

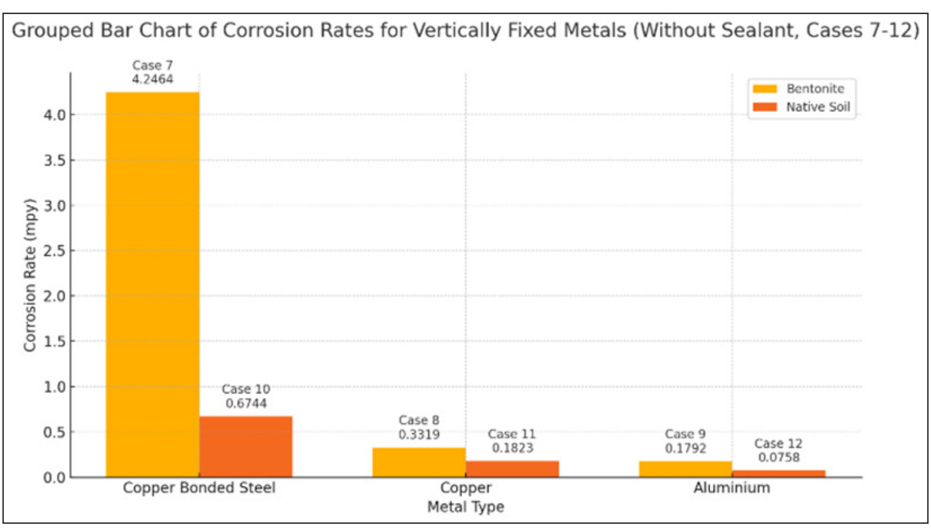


Figure 7. Corrosion rates of vertically fixed metals (Case 7-12)

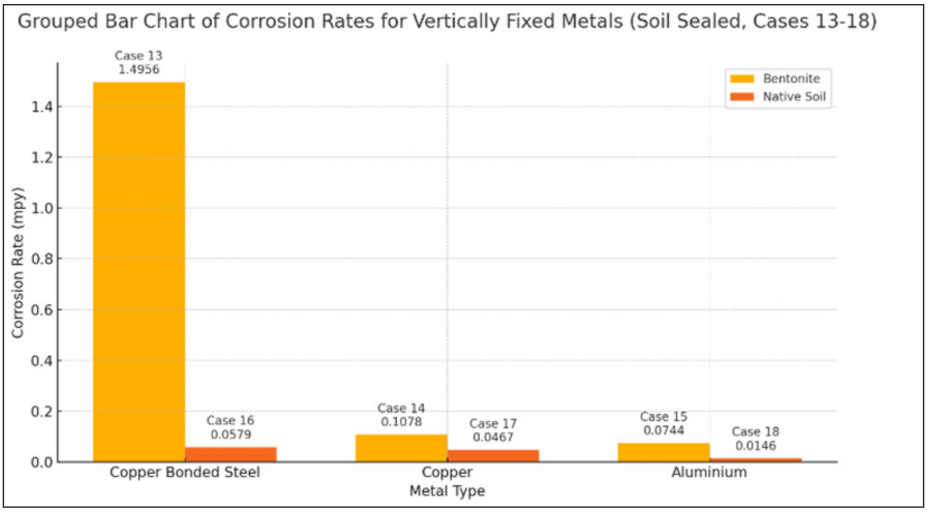


Figure 8. Corrosion rates of vertically fixed metals (Soil Sealed) (Case 13-18)

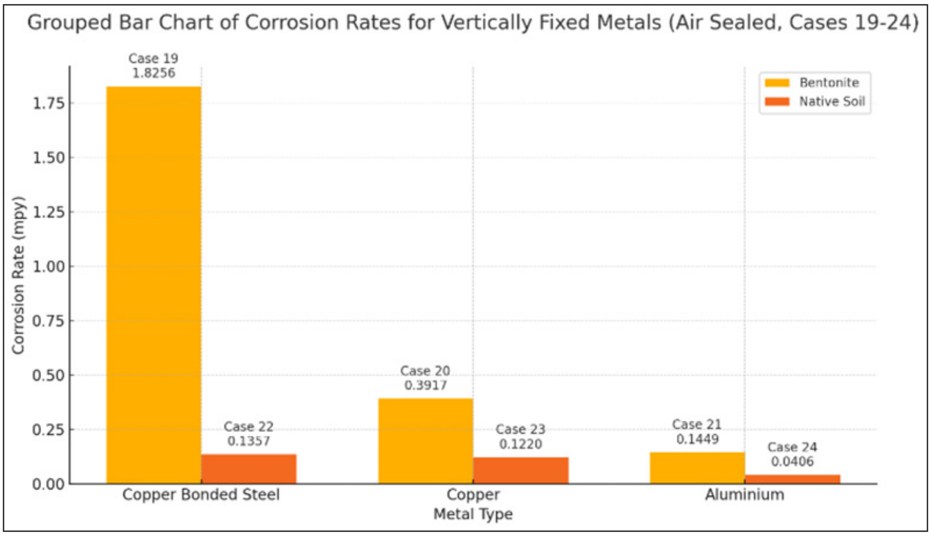


Figure 9. Corrosion rates of vertically fixed metals (Air Sealed) (Case 19-24)

Figure 9 depicts the corrosion rate values of the vertically fixed metals (air sealed). Copper bonded steel (Case 19) showed to have the highest corrosion rate when encased in bentonite at 1.8256 mpy and 0.1357 mpy when exposed to native soil (Case 22). Copper (Case 20) is shown to have a corrosion rate of 0.3917 mpy. Copper has less corrosion rates when exposed to native soil at 0.1220 mpy. Aluminium (Case 21 and 24) showed the best performance when exposed in bentonite and native soil at values of 0.1449 mpy and 0.0406 mpy respectively. According to NACE (2018), copper bonded steel encased in bentonite (Case 19) lies in the moderate degree of corrosiveness. Overall, cases 20-24 lie in the low degree of corrosiveness.

In general, copper bonded steel encased in bentonite exhibits significant corrosion rates except for Case 4. Copper and aluminium show high resistance performance against their respective soil. Horizontal placement of the earthing electrodes shows generally higher corrosion rates when compared to the vertically fixed electrodes.

Behaviour of Horizontal and Vertical Earthing Conductors

Table 7 shows the behaviour of vertically fixed earthing conductors (without sealant) to horizontally fixed earthing conductors exposed to soils. As the results are using ratios to depict their behaviour, ratios of the value of more than 1 indicate vertically fixed configuration corrosion dominance and vice versa. Ratios in the value of 1 indicate that there is no difference in terms of corrosion when the sample metal is placed vertically or horizontally.

Table 7
Behaviour of vertically fixed earthing conductors (without sealant) partially exposed to soils to horizontally fixed earthing conductors exposed to soils (configuration 2 to configuration 1)

Metal Type	Ratio (C_2/C_1, Bentonite)	Ratio (C_2/C_1, Native Soil)
Copper Bonded Steel	4.263	0.419
Copper	1.175	0.426
Aluminium	0.502	0.676

Note. C_1 stands for horizontally fixed earthing conductors exposed to soils; C_2 stands for vertically fixed earthing conductors (without sealant) partially exposed to soils

Copper bonded steel shows extreme values of corroding significantly higher at 4.263 in bentonite when placed vertically as opposed to when it is exposed in native soil. The high salinity and moisture count as displayed in Table 5 have likely contributed to this value. However, it is interesting to note that the corrosion of this metal leans more towards the metal partially exposed than the fully encased. It is expected that the full immersion of the metal in bentonite would lead towards higher corrosion rates, since the metal is wholly covered with bentonite which is a more aggressive environment. This is highly likely due to the differential oxygen available at the air-soil boundary, that causes it to corrode more in the case of partial horizontal immersion.

This behaviour is also seen in copper but at a lower value of 1.175 which is closer to the value of 1. This means copper is more adaptive to both configurations compared to the other metals in bentonite. Aluminium is seen to corrode more in horizontally fixed configurations in bentonite and native soil. This is the opposite to the case of copper bonded steel where the aluminium placed horizontally with full immersion showed higher corrosion rates than partial immersion. Hence, copper bonded steel does not adjust well when placed vertically when there is an air-soil boundary compared to copper and aluminium in bentonite. All metals show tendencies of corroding more in native soil for horizontal configurations.

Table 8 shows the percentage reduction of vertically fixed earthing conductors sealed partially exposed to soils for the different configurations. The results compare the reduction percentage of sealed metals partially encased in soil vertically to the ones that are not sealed. Positive percentages mean there is an increase in corrosion protection while negative percentages mean there is a decrease in corrosion protection. 0 percentage would indicate that there is no improvement or corrosion reduction.

Table 8
Corrosion percentage reduction of vertically fixed earthing conductors sealed partially encased in soils (configuration 3 to configuration 2 and configuration 4 to configuration 2)

Metal Type	Corrosion Percentage Reduction			
	C_3/C_2	C_4/C_2	C_3/C_2	C_4/C_2
	Bentonite		Native Soil	
Copper Bonded Steel	64.78	57.01	91.41	79.88
Copper	67.52	-18.02	74.38	33.08
Aluminium	58.48	19.14	80.74	46.44

Note. C_2 stands for vertically fixed earthing conductors (without sealant) partially exposed to soils; C_3 stands for vertically fixed earthing conductors (soil sealed) partially exposed to soils; C_4 stands for vertically fixed earthing conductors (air sealed) partially exposed to soils

All metal samples show significant corrosion percentage reduction, especially in the case of copper bonded steel at 91.41 %. This means copper bonded steel has the highest reduction in corrosion rate when it is encased in soil while partially sealed in soil. Generally, higher corrosion protection is seen in the cases of native soil. However, copper showed an increase in corrosion when it is partially air sealed in bentonite at -18.02 %. This is likely due to the galvanic effects of the metal especially when interacting with bentonite. Partial soil and air sealing is shown to be effective at reducing the corrosion of copper bonded steel in both soil environments.

Sealing is not very effective when aluminium is partially air sealed in bentonite. However, aluminium has better corrosion reduction in native soil. Thus, since copper bonded steel was seen as the most corrosive material in the result in Figure 7, it is highly recommended that it is implemented with sealing to protect it from corroding even further. Generally, soil sealing is seen to be more effective in reducing the corrosion in metals in both environments.

Visual Inspection of Selected Cases

Figure 10 shows the copper bonded steel surface after exposure to bentonite metal of case 7. The corrosion observed in the metal shows that there is a major surface discoloration of copper, which severely affects the quality of the copper bonded steel metal. As expected, a higher rate of corrosion is observed on the parts of copper bonded steel exposed to the bentonite section. However, corrosion is seen to be uniform on the entire metal surface, given the exposure to air and bentonite. The cases are alike for front and back sections of the metal.

The darker spots on the metal indicate that the steel section of the metal is also starting to corrode. The copper bond is supposed to protect the steel from corroding due to its resistance to corrosion from being a more noble metal in the galvanic series. This shows that the copper bond has failed to protect the steel inside from corroding. The potential cause of this may be due to galvanic corrosion of the copper and steel interaction, where steel acts as the anode that corrodes faster in comparison to copper (Yan et al., 2018). Mechanical defects that occur during manufacturing may also have initiated the corrosion of the metal. For instance, intrinsic manufacturing defects affect the corrosion resistance of steel as in the study of (Zhu et al., 2023).

There are three major areas that are distinct in colour that are green areas, darkened areas and rust-coloured areas. The green areas suggest that it is likely that copper carbonates or Copper Chlorides may have been present (Peng et al., 2022). The chemical reaction associated with copper carbonates is $2Cu(OH)_2+CO_2 \rightarrow Cu_2(OH)2CO_3+H_2O$ The darkened areas are highly or iron oxides (Adhav et al., 2024). The chemical reaction associated with iron oxides is $2Fe+O_2 \rightarrow 2FeO$. The rust-coloured areas suggest the presence of iron oxides from the exposed steel core.

Figure 11 shows the metal after exposure to bentonite of case 20. It is observed that the metal does not result in uniform corrosion when the metal is exposed partially to air (sealed) and partially to bentonite. The corrosion product is seen more in the bentonite exposed section with areas of green. The green area suggests that Copper Carbonates have formed in these areas (Peng et al., 2022). The corrosion of the air-sealed copper partially buried in bentonite has no severe degradation compared to Case 7. There is also no indication of pitting corrosion when only surface level corrosion can be observed. The cases are alike for front and back sections of the metal.

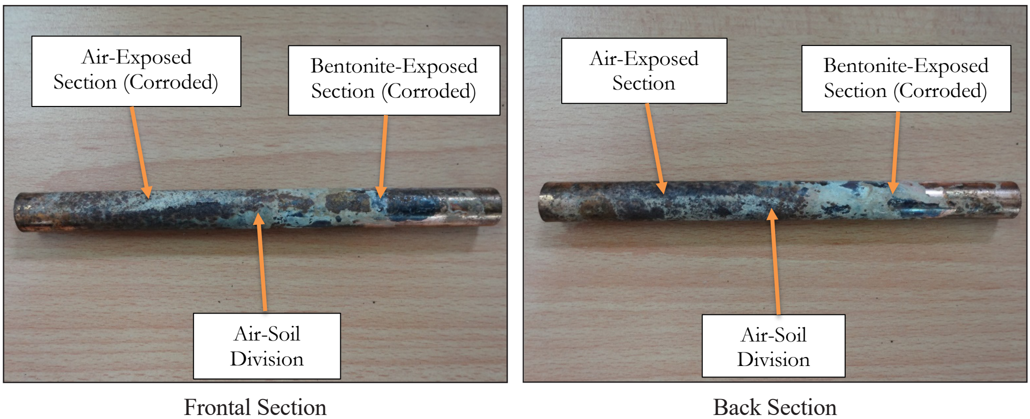
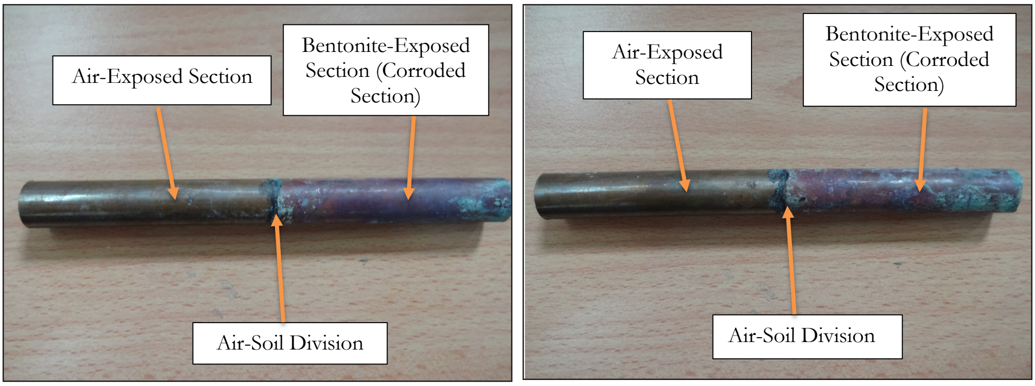
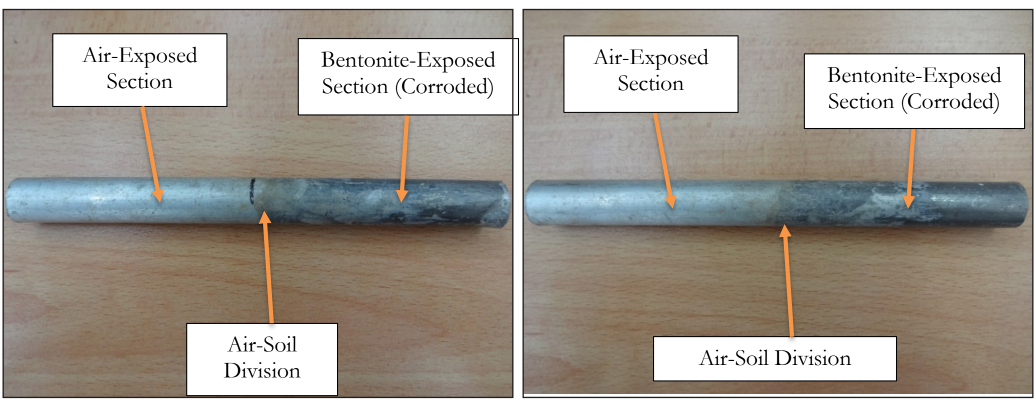


Figure 10. Copper bonded steel surface exposed to bentonite (Case 7)



Frontal Section Back Section

Figure 11. Copper exposed to bentonite (Case 20)



Frontal Section Back Section

Figure 12. Aluminium bonded steel exposed to bentonite (Case 9)

Figure 12 shows the metal after exposure to bentonite of case 9. There is an observable contrast between the air-exposed and bentonite-exposed sections of the aluminium given no sealing during the exposure to the environment. The darker areas of the aluminium may be the products of (Aluminium Oxide: $4Al+3O_2 \rightarrow 2Al2O_3$) or Aluminium Hydroxides ($2Al+6H_2O \rightarrow 2Al(OH)_3+3H_2$) of certain degrees of thickness. No pitting corrosion was observed on the metal. The cases are alike for front and back sections of the metal.

CONCLUSION

In conclusion, the corrosion rates of different conductors under different circumstances have been evaluated to see their performance when exposed to aggressive and native soil conditions with protective methods of sealing. Aluminium is seen to be effective under native and aggressive soil conditions in terms of resisting corrosion. This is followed by copper and copper bonded steel. Hence, based on this study, aluminium can be a metal of choice when designing earthing systems due to its low corrosion rates, abundance and low cost with the addition of design considerations for sustainability of metal use. On the other hand, copper shows stability in horizontal and vertical configurations while copper bonded steel can resist corrosion with the correct sealing methods. The corrosion products have also been categorised by visual inspection on the respective metals that provide more insights on the appearance of corrosion.

In terms of practical recommendations, copper is still the best material for long-term useability in both soil environments. Aluminium can be used if there is a need for cost-effective alternatives in native soil. However, it requires protection in Bentonite. Copper bonded steel should be avoided in aggressive conditions without proper protection. Sealing or coating should be prioritised in bentonite or highly corrosive environments to reduce the metal from corroding. In soils that are less aggressive, sealing does not provide significant protection. As for system design, earthing systems are better protected when they are configured horizontally with soil-side protection. Localised corrosion can be protected at the air-soil interface for vertically deployed system.

To conclude, this study has emphasised the significance of several issues of electrical earthing. It is important to understand the environmental conditions of the soil before installing earthing systems. This is also important in designing appropriate corrosion mitigation strategies. Soil sealing should be prioritised as it is the most reliable protection method especially when dealing with aggressive soil environments such as bentonite. Finally, the material and configuration of the earthing system placed in the soil should be based on the requirements of the application and challenges of the environment.

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