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ELECTRICAL AND GEOTECHNICAL PROPERTIES OF SOILS AROUND ELECTRICAL POWER TRANSFORMERS

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ABSTRACT

Geophysical investigation of the soil was embarked upon in this research, to evaluate the effects of power transformer oil spill on the immediate environment. The impact of electrical transformer oil on the soil's heavy metals content (lead "Pb", Cadmium "Cd" and zinc "Cd), geotechnical properties (Atterberg limits) and electrical resistivity, were determined using standard procedures. Findings obtained from the laboratory tests signified that the oil significantly increased the soil's Pb, Zn, Cd content, and the soil's electrical resistivity. Remarkably, the soil liquid limit "LL", plasticity index "PI" and plastic limit "PL", declined in an uneven pattern with an increase in oil pollution rate. In the soil specimens sampled from the vicinities of the transformers, the Cd content ranged from 0.23 - 1.42 mg/kg, Pb content ranged from 21 - 35 mg/kg, and Zn concentration ranged from 17 - 36 mg/kg. It was also observed from the contaminated soil samples that LL values varied from 40.51 - 53.63%, PL values ranged from 19.88 - 23.88%, and the PI values varied between 19.7 and 32.32%; while the control site's soil had LL, PL and PI values of 59.23%, 25.27% and 28.96% respectively. Regarding soil electrical resistivity, the transformer oil impacted soil samples developed resistivity that varied from 374 Ωm to 877 Ωm; which were higher than the resistivity value of 284 Ωm recorded for the reference point's soil. The increase in the soil resistivity of the contaminated soil, poses a momentous threat to the transformer's grounding structure. Results obtained from this research revealed the necessity for regular monitoring of the electrical distribution installations to enhance their working conditions.

Keywords: Electrical installation, health hazards, heavy metals, oil pollution, soil properties.

INTRODUCTION

Power transformer integrity is dependent on, the quality of the materials used for the electrical installation, the grounding system, the environmental condition, and the adherence of the installation procedures to the international approved electrical standards (Kumar and Hans, 2010; Obukoeroro and Uguru, 2021a). Electrical earthing, a major component of electrical installations which protects electrical/electronic appliances from voltage surge hazard, is greatly affected by the prevailing soil conditions (Obukoeroro and Uguru, 2021b). Electrical resistivity is one of the intrinsic electrical properties of the soil, that measures how intensely the soil resists the flow of counters electrical current; it is dependent on the soil's geotechnical properties (Dahlin, 2001). Soil geotechnical properties are essential parameters to be considered during building constructions and installations of electrical earthing system. Therefore, serious alterations in the geotechnical properties of soil pose serious threats to the structural and electrical integrities of buildings. According to Akpokodje *et al*. (2021), soil with poor particle size grading tend to produce sandcrete blocks with low mechanical properties, which can result in high cost of post construction maintenance or even structural failures.

Transformer oil is one of the numerous derivatives of crude oil, which is used in lubricating and cooling of oil-immersed power transformers during power transmission and distribution. It has high dielectric, thermal and chemical properties; hence, it can withstand harsh working conditions (Abdi *et al*., 2022). The engineering properties of transformer oils are functions of the production process, additives added, oxidation rate, contamination level and the working environment. Contamination and high oxidation can result to degradation of the oil's thermal and mechanical properties. These are usually associated with decline in the operational capacity of the transformer, power blackout and leakage of the oil from the oil sink into the environment (Salama *et al*., 2020; Awad *et al*., 2022). According to Saeid *et al.* (2022), the quality of oil inside a working transformer can be used to diagnose its electrical health status. High dissolve gases (mainly carbon (ii) oxide and carbon (iv) oxide) in a transformer's oil is an indication of decomposition and dilapidation of the paper lagging of the oil; while the presence of ethyne in the soil is an indication that the transformer is experiencing arcing problems.

Just like other petroleum products, transformer oil has serious negative consequences on the soil's geotechnical properties and the vegetation (Akpokodje *et al*., 2018; Akhigbe *et al*., 2020; Uguru and Udubra, 2021). Petroleum derivatives (including transformer's oil) contain significant amounts of sulfur, aromatic hydrocarbons, and toxic elements – cadmium "Cd", copper "Cu" and lead "Pb". Effects of petroleum toxicity includes cancer, respiratory disorder and liver problems in human beings, and stunted growth and poor productivity in plants (Igboama and Ugwu, 2016; Akpomrere and Uguru, 2020). Oils tend to alter the biochemical composition of the soil; hence, reducing the rate of nutrients, water and air availability to the plants and thereby inhibiting the metabolic processes of several crops (Leighton, 2000; Akpokodje *et al*., 2022). Oil reduces the soil's shear strength, permeability coefficient and angle of internal friction; but causes complex non-linearly increases in the soil's unconfined compressive strength and compression modulus, which can be attributed to an increment in the viscosity of the soil particles (Akpokodje and Uguru, 2019; Zhang et al., 2021). Kermani and Ebadi (2012) stated that oil pollution caused remarkable increase in a soil's plastic limit (PL) and liquid limit (LL), but a decrease was noticed in the soil's plasticity index (PI). Akpokodje *et al.* (2022) reported that oils cause significant adjustment in a soil's load bearing capacity.

Electrical conductively and resistivity are essential electrical properties of the soil, which are usually considered during electrical installations and earthing. These electrical parameters, like others soil engineering properties are greatly affected by the soil pollution level, moisture content, temperature, organic matter content and vegetative cover (Yan *et al*., 2012; Afa and Ngobia, 2013; Idisi and Uguru, 2020). Although recent studies have revealed the impact of transformer oil on the environment (Stojic *et al*., 2014; Ogunlana *et al*. 2020) not much research have been carried out on the influence of transformer oil on the geotechnical and electrical properties of soil within the neighborhood of the transformer. Therefore, it has become necessary to investigate the impact of oils leaking from transformers on the soil's geotechnical and electrical properties, and consequently evaluate it hazards on human beings.

MATERIALS AND METHODS

Study area

This study was conducted in Isoko region of Delta State, Southern Nigeria. The region's soil experiences high moisture content for most parts of the year, due to high rainfall and prolonged rainfall duration. Delta has an average rainfall of 1800 mm per annual, which last for about 8 months, while the temperature ranges between 20 to 350C, depending on the climatic season. High water tables and thick vegetative cover are predominant in the study region, mostly during the rainy season (Eboibi and Uguru, 2018).

Farming in a major preoccupation of the people, and the inhabitants of the region depend mainly on untreated borehole water for drinking and other domestic activities (Uguru et al., 2021; Uguru et al., 2022a). The area experiences serious electrical power problems and power outages, which are mainly attributed, to power (load) sharing and faulty power distribution equipment. Defective transformer, faulty feeder pillar, broken crossbars and sagging cables are common occurrence in the region (Figure 1).

Figure 1: A damaged feeder pillar of a transformer

Samples collection

Four 'topsoil' soil samples were collected randomly within a radius of 10.5 m from each spatial location of each transformer. The spatial location of the transformer station was recorded with the aid of a handheld GPS device. In each spatial station, the 4 soil samples taken were mixed carefully and poured into a black polythene bag. Spatial locations of the transformers and their adjoining spill related environmental conditions are given in Table 1.

Table 1: Transformers location and condition

Transformer	**Co-ordinates**	**Remark**
1	Lat. 5.461 N;Long. 6.204 E	Large oilspill
2	Lat. 5.471 N;Long. 6.202 E	Medium oil spill
3	Lat. 5.443 N;Long. 6.196 E	Medium oil spill
4	Lat. 5.456 N;Long. 6.206 E	Very little oil spill
5	Lat. 5.458 N;Long. 6.208 E	Medium oil spill
6	Lat. 5.462 N;Long. 6.207 E	Medium oil spill
7	Lat. 5.467 N;Long. 6.209 E	Little oil spill
8	Lat. 5.467 N;Long. 6.211 E	Large oil spill
9	Lat. 5.471 N;Long. 6.205 E	Medium oil spill
10	Lat. 5.482 N;Long. 6.199 E	Very little oil spill
11	Lat. 5.542 N; Long. 6.215 E	Large oil spill
12	Lat. 5.547 N; Long. 6.221 E	Medium oil spill

Heavy metals determination

All the soil samples were dried, crushed and sieved with a 0.850 mm gauge sieve, as explained by Ogbaran and Uguru (2021).The sieved soil samples were digested with a combination of concentrated HNO3 and (HNO3, HCl, and H2SO4) added in the ratio of 5:1:1, and diluted with double distill water as described by Agbi *et al*. (2021). Thereafter, the Cd, Zn, and Pb concentration in the digested soil samples were measured by using the atomic absorption spectrophotometer, in accordance with ASTM international procedures.

Electrical properties determination

The soil's electrical resistivity and electrical conductivity were determined in the laboratory, according to procedures explained by Igboama and Ugwu (2016), as shown in the experimental arrangement in Figure 2. To have experimental consistency, the soil specimens were air dried to a moisture content of 18% (wet basis). The freshly prepared soil samples were filled into 6'' diameter pipes and compacted 25 times by using an iron ramming rod. Both ends of the pipe were leveled with a hand trowel, before the metallic conductors were inserted into the soil column (one at each end). PVC pipe was chosen for the experiment due to its high insulating property. After the connections were secured, the apparatus was switched on, and the current (A) and voltage (V) in the soil were read from the digital ammeter and voltmeter.

The experiment was conducted at uniform laboratory temperature of 28±20C, since temperature greatly affects soil resistance (Obukoeroro and Uguru, 2021b). At the end of the experiment, the resistance (R) and resistivity (ρ) of each soil sample was calculated through Equations 1 and 2 respectively.

$$R = \frac{V}{I} \qquad 1$$

$$\rho = \frac{RA}{L} \qquad 2$$

Where: A ~area of the soil column and L ~soil's column length

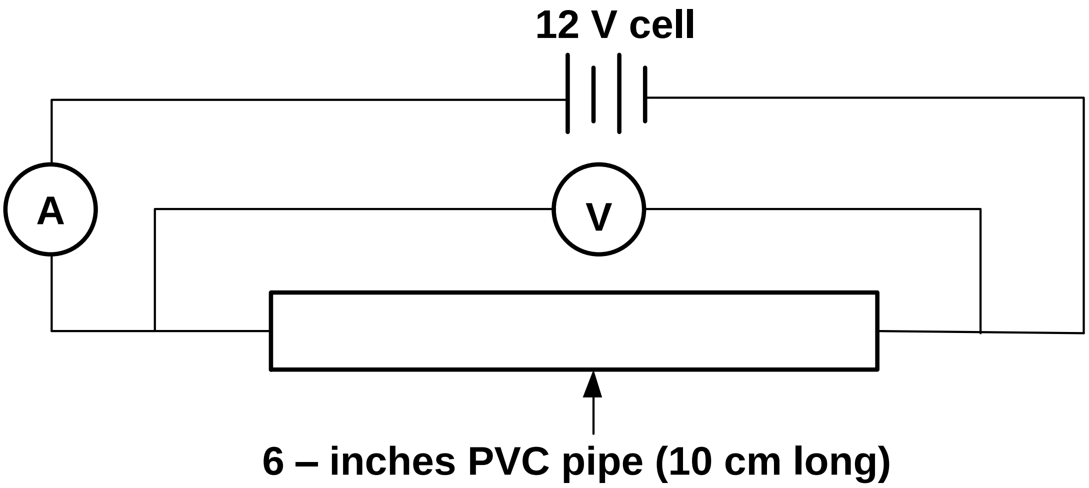

Figure 2: Experimental arrangement for the soil resistance

Geotechnical properties determination

The consistency limits (liquid limits “LL”, plastic limits “PL” and plasticity index “PI”) of the soil samples were determined in accordance with ASTM D4318 (2017) procedures, as explained by Onyebuchi and Mathias (2016).

Data analysis

Readings obtained in this research were subjected to statistical analysis – employing charts and graphs, by using the Microsoft Excel for Windows.

RESULTS AND DISCUSSION

Transformer oil effect on the soil heavy metals

The Cd, Pb and Zn accumulation levels in the soils around the transformers are presented in Figures 3, 4 and 5. The results depicted that the oil has remarkable influence on the soil’s heavy metals concentration, as the Cd, PN and Zn content in the soil specimens collected from around the transformers, were peculiarly higher than their colleague levels in the control site’s soil. Among the soil samples taken from the 12 transformer locations, the Cd concentration varied from 0.23 to 1.42 mg/kg of dry soil, the Pb content ranged from 21 to 35 mg/kg of dry soil, and the Zn concentration varied between 17 and 36 mg/kg of dry soil, while the Cd, Pb and Zn concentrations recorded at the control location were 0.36, 15 and 13 mg/kg of dry soil respectively. Interestingly, despite the high Zn and Pb concentrations in the contaminated soil samples, their values were within allowable limits (Pb ~ 85 mg/kg and Zn ~ mg/kg) approved by WHO (1996) for soils in municipal regions. However, it was observed that for four locations, the soil’s Cd concentration (Figure 3) exceeded the maximum permissible limit (0.8 mg/kg) recommended for soils in metropolitan areas (WHO, 1996).

This result – increment in the soil’s heavy metal concentration which is indicative of oil contamination – is similar to the findings of the following: Adesina and Adelasoye, 2014; Odiyi et al., 2020; Akpomrere and Uguru, 2020b. Radulescu et al. (2012) reported that the Cd and Zn content in soil samples collected from oil spill sites were approximately 70% higher, when compared to the results obtained for the control point. Apart from transformer oil, the metallic components of the burnt out fuses littered the grounds of the transformer environs, and could be linked to the high Zn, Cd and Pb concentrations in the soil samples collected from the neighborhood of the transformers. According to Chukwu*et al*. (2017) and Ogbaran and Uguru (2021), leachate from metallic materials pose a serious hazard to the landmass, as it tends to increase the soil/water toxic elements concentration. Toxic metals poisoning effects in human beings include, memory loss, various forms of cancer aliments, respiratory disorders and liver problems (Uguru *et al*., 2022b; Sani*et al*., 2022)

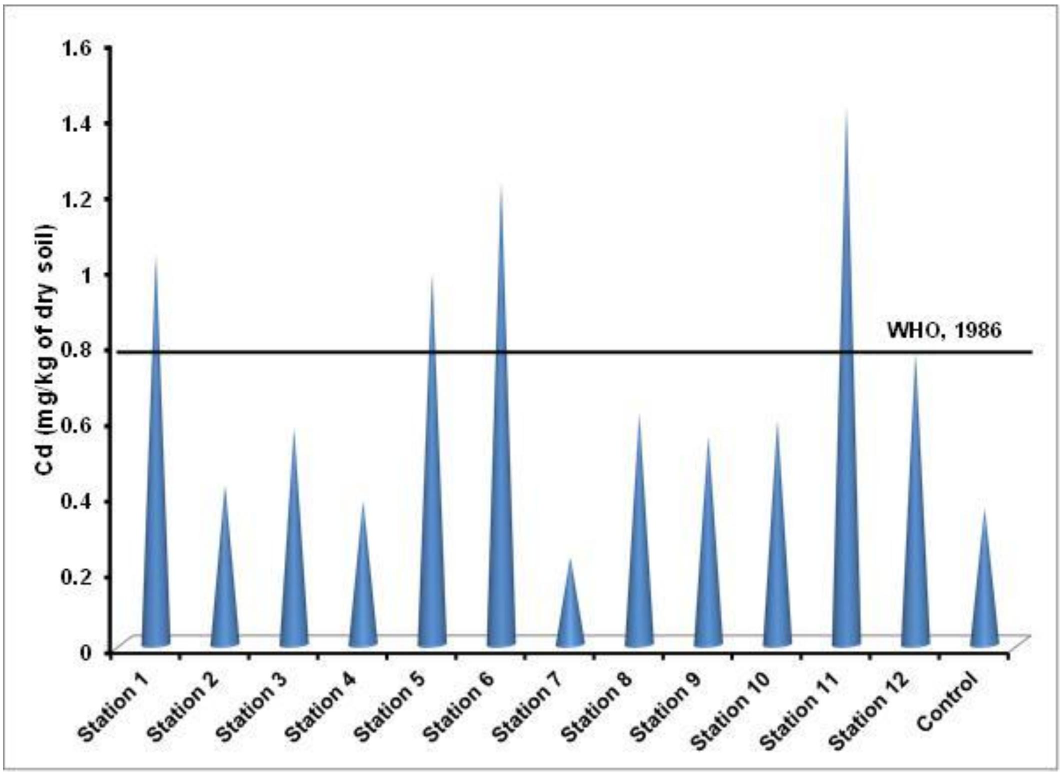

Figure 3: The soil's Cd concentration

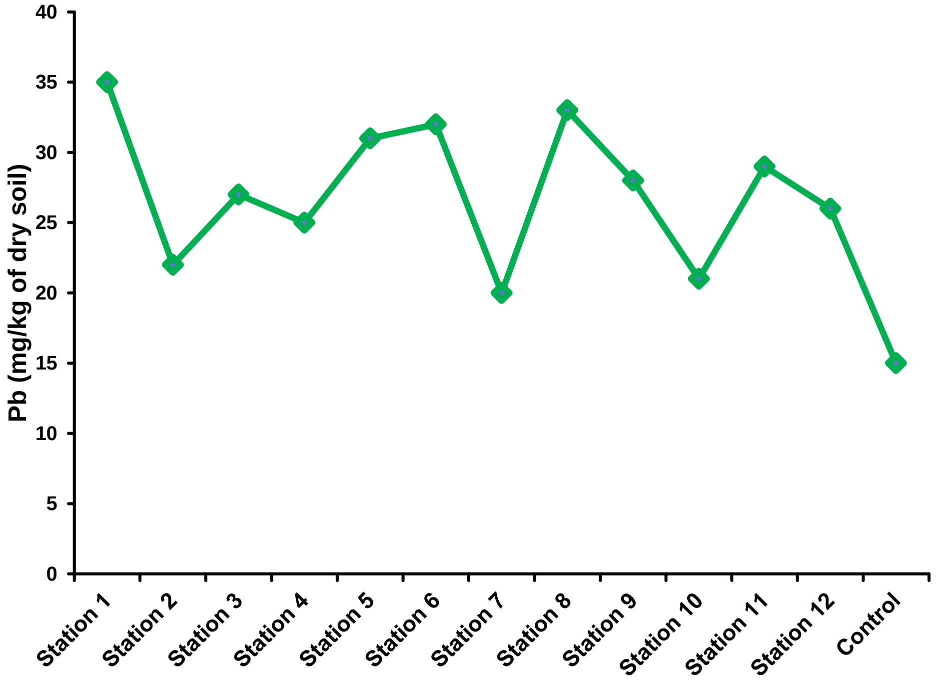

Figure 4: The concentration of Pb in the soil specimens

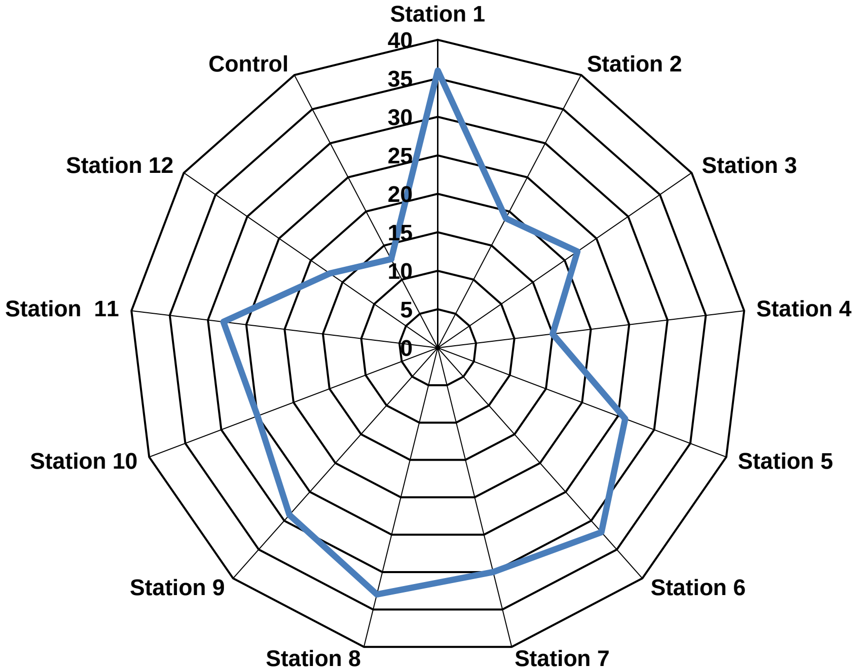

Figure 5: The soil's ZN accumulation level

Transformer oil effect on the soil's geotechnical properties

The results of effect of transformer oils on soil consistency limits are presented in Figure 6. The soil's LL, PL and PI fluctuated widely across the 12 transformers' surrounding soils investigated. Also, it was noted that the soil consistency limit values at the control point was considerably higher than the results recorded among the 12 transformers' soil samples. Among the soil samples collected from the 12 transformers' regions, the LL ranged from 40.51 to 53.63%, PL varied from 19.88 to 23.88%, and the PI ranged from 19.7 to 32.32%; while soil specimens taken from the control point had LL, PL and PI of 59.23%, 25.27% and 28.96% respectively. This revealed that the oil had substantial effect (by reducing their values) on soil LL, PL and PI; which is in conformity with Iqbal *et al*. (2020) reports on the effect of oil pollution on the mechanical properties of coarse grain particle size soils.

Consistency limits of soil's adjoining the earthing electrodes play a significant role in designing grounding systems for power transformer (Vasilios et al., 2020). The Liquid limit is an essential geotechnical parameter of the soil, which affects the hydraulic conductivity and shear strength of the soil. According to Okiotor *et al*. (2019), soils having high plasticity are not suitable for civil engineering construction tasks; unless they are stabilized with appropriate materials.

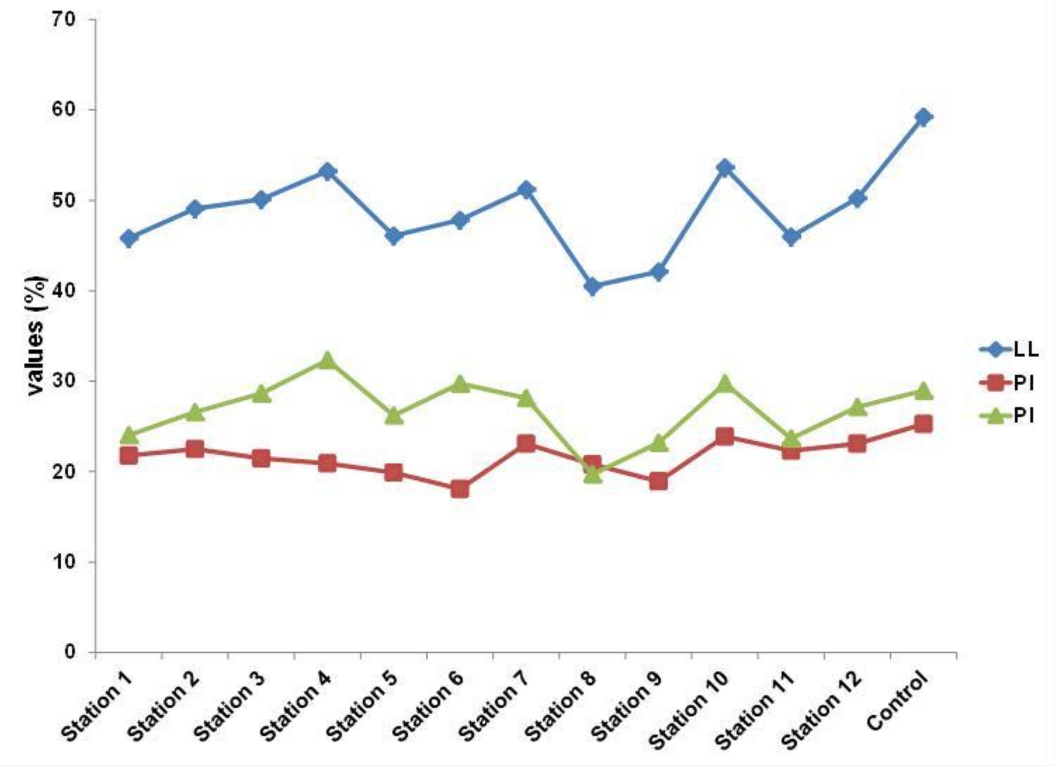

Figure 6: The LL, PL and PI of transformer oil impacted soil

Effect of the transformer oil on the soil Electrical properties

The impact of the transformer oil on the soil's resistivity is shown in Figure 7. Figure 7 shows that the oil had a significant effect on the soil's resistivity; as the resistivity values recorded across the 12 sampling stations, were remarkably higher, when compared to the results obtained at the reference site. Among the 12 Locations, the soil resistivity values ranged from 374 Ωm to 877 Ωm; while the soil at the control Location had electrical resistivity of 284 Ωm. The differences observed in the soil's resistance ability to current flow, can be linked to the quantity and concentration of transformer oil that the soils were impacted with. Similar observations were recorded by Igboama *et al*. (2016), where the soil's resistivity increased non-uniformly as the petroleum product content in the oil increased from 10% to 100%. Transformer oil is a poor current conductor, therefore it builds up insulating strata in the soil; thus increasing the soil's resistance and resistivity in the process (Fakunle *et al*., 2021).

Resistivity is one of the critical factors to be considered during electrical grounding design. According to Ahmed *et al*. (2013), the electrical resistivity of any soil type is inversely proportional to the volume of oil in the soil. The high soil resistivity noted in the soils around most of the transformers, is detrimental to the earthing system of the transformers. Although soils with lower resistivity are favored during electrical earthing; however, soils with very low resistivity ($\rho < 100$ Ωm) tends to induce corrosion of the grounding electrode (Afa and Ngobia, 2013). Soil with high resistivity provides hazardous pathway for excess current; hence, jeopardizing the safety of human lives and equipment within the immediate environment (Salam *et al*., 2017).

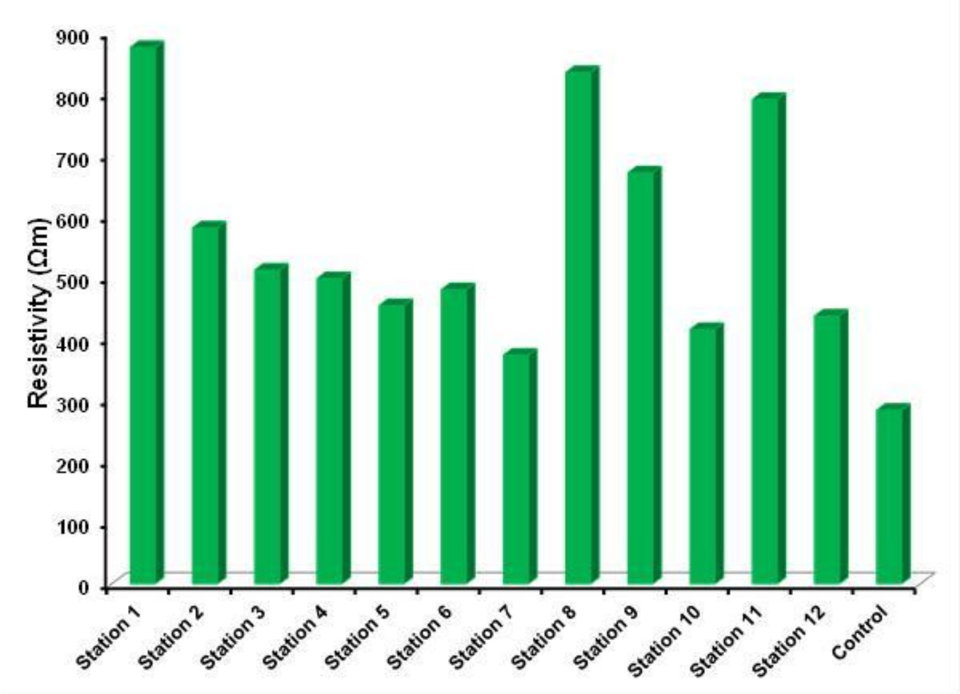

Figure 7: Soil's electrical resistivity

CONCLUSION

Environmental pollution is detrimental to both the biotic and abiotic components of the ecosystems. The findings of this research revealed that the oils that spilled from "faulty" transformers significantly altered the soil's heavy metals concentration, geotechnical and electrical properties. It was observed that the oil caused increments in the soil's lead, cadmium, zinc and electrical resistivity values; whereas, a declined was noted in soil liquid and plastic limits. Increase in the soil resistivity, probably caused by the transformer oil contamination of the soil pose a momentous danger to transformer's earthing systems, and the appliances connected to the power distribution system. Information provided by this study, necessitates regular monitoring of transformers within the country, to prevent electrical systems malfunction as a result of environmental pollution through transformer's oil spillage.

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