

An Experimental Investigation of Galvanic Anode Specifications for Suitable Cathodic Corrosion Protection of Low Carbon Steel in Kaduna Metropolitan Soil

T.N. Guma, S.U. Mohammed and A.J. Tanimu

Department of Mechanical Engineering,
Nigerian Defence Academy, Kaduna,
Kaduna State, Nigeria

Abstract: The paper stresses corrosion risks from huge underground engineering steel structures within the metropolitan area of Kaduna-a top city in Nigeria. Cathodic protection (CP) is examined as an effective, economical and durable method of preventing corrosion of such structures if suitably designed-installed. Variables that can cause wide differences and difficulties in CP designs such as material make, surface area and nature of structure, corrosivity level of environment, etc, are recognized. Some supplementary information that accounts for complexity of such variables which can be used to optimize CP design of the structures was sought experimentally. Relative performances by zinc, pure magnesium and magnesium alloy as common and cheap galvanic anodes were investigated in a laboratory CP of polished bare low carbon steel specimens in soil of surveyed resistivity spectrum 31.9-152.9 ohm-m from the area. Specimens were exposed with and without CP by the anodes at ambient temperature up to 40 days in various samples of the soil. Levels of specimen protections were determined by analysis of obtained information on their corrosion rates and polarized potentials relative to the un-protected ones at 8-day intervals. The analysis indicated that; corrosion of the structures can be optimally reduced to negligible rates by polarizing them to -0.85V versus Cu/CuSO₄ electrode with the anodes, pure magnesium is comparatively the best of the anodes for CP of the structures in terms of economy and effectiveness followed by magnesium alloy, and a unit surface area of the anodes can protect up to nearly 1200 units of the structure with the -0.85V protective potential depending on the anode type.

Key words: Underground engineering assets, variation in soil corrosivity level and risks, Kaduna metropolitan area, steel structures, cathodic protection, some supplementary design information

I. INTRODUCTION

One of the biggest challenges facing our aging infrastructures is material loss and deterioration by electrochemical reactions that cause corrosion [1]. High liability and costs can arise due to corrosive actions of soils that underground engineering structures are in associated contact with. Study by the Federal Highway Administration of United States showed that the total direct cost of corrosion in the United States alone was \$279 billion per year, which is about 3.2 percent of the nation's present gross domestic product (GDP). The study also showed that the major contribution to this value was from corrosion occurring in the ground. These included drinking water and sewer systems, highway bridges, oil and gas and other fluid transmission pipelines [2 and 3]. Corrosion attacks are frequently responsible for most material failures or limitations by causing them to lose their cherished strength, ductility and other mechanical properties. The problem is especially to steel structures and the extent depends on the corrosivity level of the environment. The frequent collapse of critical underground engineering structures such as pipelines due to corrosion is a serious concern to engineers, governments and the general populace. The adverse effects are colossal loss of lives and properties. Unprotected pipelines, buildings, and other engineering structures erected on corrosive soils usually have shorter life span [4, 5, and 6]. Therefore, when construction of a new buried or submerged system is being planned, the corrosivity of the environment should be considered as one of the factors in the design of the system. If corrosion is not considered, the service life of the system may be severely overestimated and public safety may be at risk [2]. The critical material of construction with regard to corrosion in soil environment is carbon steel. Low carbon steel is the most widely used engineering material but has the least corrosion resistance and accounts to about 90% of all steels used for structural works because of its good fabrication and formability properties as well as

availability in various structural sizes and shapes at relatively cheaper prices compared to other structural materials [7 and 8].

Kaduna is one of the top cities in the ranking of population, industrialization, military garrison and administrative importance in Nigeria. The city is located on the southern end of the high plains of Northern Nigeria, gridded by Latitude 10° 40'N and 10° 60'N and Longitude 7° 10'E and 7° 35'E [9]. It is a noted centre for refining crude oil, automobile manufacturing, producing weapons, brewing and bottling, textile manufacturing, sand-casting, metal forging, civil engineering construction works, agricultural processing, metalworking, electric power distributing, warehousing, machinery manufacturing, steel working, treating water, etc [10]. One of the three refineries in Nigeria is located in the metropolitan area of the city. The refinery has a production capacity of about 110,000 barrels per stream day. A number of pipelines transport large quantities of crude oil, natural gas, petroleum products in the process of feeding the refinery with raw stock and distributing its products to some away locations. To keep pace with the growing levels of industrialization, military garrison, population and social needs; underground engineering structures such as drinking water and sewer municipal conduits, foundations of highway bridges and buildings, hydraulic tunnels, reservoirs for drinking water, storage facilities for oil and gas, pedestrian underpasses, military installations, containers for burying harmful industrial wastes, electric power transmission and communication facilities, etc have inevitably continued to be constructed in the city metropolis as more beneficial technological means of developments. Site surveys by Tanimu [10] showed that most of the structures were made of steel or consisted of steel components and designed with corrosion consideration. Some of them were subjected to various levels of corrosion attributable to lapses, accessibility difficulties, and costs in maintenance. Changing some of the structures can be very time consuming and expensive procedure while their corrosion problems can be technically corrected or not corrected, and incur losses with or without awareness. Given the implications of failures from such important structures and the role that external corrosion can play in their failures, it is apparent that proper corrosion control can have a major impact on safety, environmental preservation and economics of their operation or services [6 and 10].

The commonly used parameters for evaluating corrosion potential of soil are resistivity, pH, sulfate content, chloride content, Redox potential and sulfide content. Soils usually have a pH range of 5-8. In this range, pH is generally not considered to be a dominant variable affecting corrosion rates. More acidic soils represent serious corrosion risk to common structural materials such as steel, cast iron and zinc coatings. Soil resistivity is historically a broad indicator of soil corrosivity. Soil corrosivity resistivity generally decreases with increasing moisture content and the concentration of chemical species. Soil corrosivity is inversely related to soil resistivity so that low soil resistivity indicates high probability of corrosion potential. Soil resistivity is typically indicative of soil corrosivity in alkaline soils and is useful as a guide in acid soils. Although a high soil resistivity alone will not guarantee absence of serious corrosion, electrical resistivity is effective, suitable and most important parameter for assessment of soil corrosivity/aggressiveness level [6 and 11]. Soil corrosivity level can vary widely from one geographical area or location to another so engineering principle demands that specific corrosivity levels at the locations should be used in optimal protective design of underground structures. Guma *et al* [6] reported that the soil resistivity of Kaduna metropolitan area varies within the extremes of about 31.9 Ohm-m at the depth of 0.5m to 152.9 Ohm-m at the depth of 4.5m with overall mean value of 72.13481 Ohm-m, standard deviation of 33.78109 Ohm-m and coefficient of variation 46.83%. Translated into corrosivity, the report represented a stochastically variable soil corrosivity spectrum that is mildly corrosive on average and generally varies downwards underground from aggressive at depths of less than about 0.5m to slightly corrosive around 4.5m [6].

In order for corrosion to occur, four components must be active. These components are the anode, cathode, electrolyte and metallic path [12]. Cathodic protection is an electrical method of preventing corrosion of metallic structures which are in electrolytes such as soil or water. The technique was first used in 1824 by Sir Humphrey Davy and described in a series of papers presented to the Royal society in London [1 and 12]. It is second only to the use of protective coatings as a mean of corrosion control. Cathodic protection is usually technically feasible and a standard procedure for many external surfaces of underground or underwater structures such as pipelines, ship hulls and interiors, lock gates and dams, water treatment facilities, well casings, trash racks and screens, bridge decks, steel pilings, the interiors of underground storage tanks that contain electrolytes such as water or acid; offshore steel structures such as platforms and oil rigs, waterfront structures such as sheet pilings or bearing piles, and concrete structures exposed to seawater. In practical applications, structures commonly provided with cathodic protection are constructed of iron or steel including stainless steel and the electrolytes are often soil and water. Other metals commonly provided with cathodic protection include lead sheathed cables, copper and aluminum piping, galvanized steel, and cast iron. The problems presented in attempting to provide cathodic protection for existing bare structures are much more difficult than those on coated structures. The major difficulty arises because of the much greater magnitude of anode size or current required [13].

Cathodic protection is achieved by applying counter-corrosion current through the use of sacrificial (galvanic) anodes or impressed current with inert anodes to the structure to be protected. When enough current is applied, the whole structure will be at one potential; thus anode and cathode sites will not exist and the entire structure will be well protected. Little current will lead to ineffective protection. High current will lead to disbondment of any applied coatings, hydrogen embrittlement, more power consumption and higher cost. Installation also demands that the potential of the structure to be protected should be kept less than the protection potential. Sacrificial anode materials used in CP are required to be capable of providing sufficient current to adequately protect a structure, to be self-regulating in terms of potential, to have high driving voltage difference between the operating voltage of the anode and the polarized structure they are protecting over their lifetimes, to consistently have a high capacity to deliver electric current per unit mass of material consumed, not to passivate, and to be easy of manufacturing in bulk available quantities and adequate mechanical properties. CP designs can differ widely for different locations or environments due to variations in corrosivity levels, material make of the structure to be protected, surface area and nature of the structure, type and size of anode used or amount of protective current applied, and degree of interference by stray currents in the environment [14 and 15]. Proper CP can therefore require pertinent preliminary studies in specific environments to reveal abnormal conditions not suspected that can be used to improve design [16 and 17]. The aims of the paper are:

- i. To create public awareness of much underground steel structural assets or component parts within the metropolitan area of Kaduna and highlight potential corrosion risks, hazards and liabilities from them.
- ii. To examine some basic supplementary criteria that can be used to augment cathodic protection adequacy of such assets with zinc, pure magnesium, and magnesium alloy as relatively common, cheap and available galvanic anodes world over.
- iii. To contribute to the total research efforts towards control of structural steel work corrosion in the area to the barest level.

1.1 Galvanic anodes in cathodic protection

Advantages of cathodic protection using galvanic or sacrificial anodes are; no external power source is required, ease of installation and relatively low installation costs, unlikely cathodic interference in other structures so popular for protection in congested and complex locations, Low maintenance systems, self-regulation, relatively low risk of overprotection and relatively uniform potential distributions. Disadvantages include: limited current and power output, high-corrosivity environments or large structures may require excessive number of anodes, anodes may have to be replaced frequently under high current demand and anodes can increase structural weight if directly attached to a structure. Numerous materials may be used as galvanic anodes, but only few can economically satisfy all the parameters required for practical applications in view of limitations imposed by electrochemical dissolution rate and/or mechanical durability [18]. A side effect of improperly performed cathodic protection may be production of molecular hydrogen, leading to its absorption in the protected metal and subsequent hydrogen embrittlement; which can cause some metals such as high strength steel to become brittle and crack following exposure to hydrogen [1]. There are three main metals used as galvanic anodes for buried structures such as pipes and tanks. These are pure magnesium, magnesium alloy, and pure zinc. Galvanic anodes are designed and selected to have a more active voltage (technically a more negative electrochemical potential) than the metal to be protected. Magnesium and zinc anodes are commercially available in all sizes and shapes such as blocks, rods, plates or extruded ribbon. Each anode type has relative performance advantages in specific aqueous environments [19].

The design of galvanic anode CP system requires consideration many factors such as the type of structure, resistivity of the electrolyte typically soil or water it will operate in, the type of coating and the desired service life. The primary calculation is how much anode material will be just enough to completely mitigate corrosion of the structure in a specific environment. Too little material will provide protection for a while, but need to be replaced regularly. Too much material would provide protection at an unnecessary cost. The mass in kg for design life in years in which one year is equal to 8760 hour is given by equation 1 [19]:

$$\text{Mass} = \frac{\text{Current Required} \times \text{Design Life} \times 8760}{\text{Utilization Factor} \times \text{Anode Capacity}} \quad (1)$$

The utilization factor (UF) of the anode is a constant value, depending on the shape of the anode and how it is attached, which signifies how much of the anode can be consumed, before it ceases to be effective. A value of 0.8 indicates that 80% of the anode can be consumed before it should be replaced. A long slender stand-off anode installed on legs to keep the anode away from the structure has a UF value of 0.9, whereas the UF of a short, flush mounted anode is 0.8. Anode capacity is an indication of how much material is consumed as current flows over time [19].

II. MATERIALS AND METHODOLOGY

2.1 Materials

The materials used for the tests were available and easily obtained from reputable commercial sources in Kaduna, Nigeria. They were.

- i. A flat low carbon steel sheet of about 3000mm by 5000mm and 3mm-thickness.
- ii. 40 litres of distilled water.
- iii. 12 litres of 0.8M Analar grade sulphuric acid (H_2SO_4).
- iv. Five soil samples of respective average resistivity 31.9, 43.69, 68.3, 90.75 and 152.9 ohm-metre harvested from previously surveyed different underground locations within the metropolitan area of Kaduna by Guma *et al* [6], and
- v. Enough number of zinc, pure magnesium and magnesium alloy galvanic anodes of cylindrical shapes, 300 cm^2 surface areas and 0.5Kg masses.

2.2 Test Procedure

The percentage elemental weight composition of the procured low carbon steel sheet was analyzed at 10 locations using suitable mechanically sawn off pieces at the locations and the Japanese-made Shimadzu-PDA-7000 optical emission spectrometer metal analyzer. The analysis confirmed that the sheet was indeed low carbon steel with average percentage elemental weight composition shown in Table 1:

Table 1: Average elemental weight composition of the procured steel

Element	C	Mn	Si	S	Cr	Cu	Fe
Composition [%]	0.02	0.26	0.014	0.009	0.017	0.013	99.6

The three procured anode materials were also each analyzed using the analyzer. The analyses showed on average; 99.95% purity level of the zinc, 99.99% purity level of the pure magnesium anodes and 6.01% Al, 2.98% Zn, 0.15% Mn and 90.84% Mg composition for the magnesium alloy anodes. Steel specimens in form of pieces each 100 by 100mm and 3mm thick were sawn off from the procured and confirmed low carbon steel sheet and used for corrosion rate and potentiostatic polarization studies in parallel experiments. The sheet were used because they were light-weight and flat and considered more suitable for proper cleaning and detection of small changes in their masses for the test.

A preliminary test was conducted on optimum amount of water and acid to be added to 3.1Kg of each harvested soil sample to account for losses due to evaporation from the sample during laboratory experimentation. Daily measurements taken with a pH meter and speedy moisture tester showed that 0.18 litres of water and 2ml of the Analar grade sulphuric acid when sprinkled daily on the samples in plastic containers did not cause average variation of more than $\pm 6.9\%$ moisture content and $\pm 2.3\%$ pH of the samples' predetermined average field conditions of 10% moisture content and Ph 5.8 respectively. This preliminary test method and information were applied to keep acidity and moisture content levels of each test soil sample of about 3.1Kg by mass fairly maintained. Soil samples were collected in impermeable covered plastic containers, conveyed on a motor bike within one hour to the laboratory and used immediately thereafter for the tests. Specimens were exposed at room temperatures in samples of the soil contained in plastic containers of about 0.35m-diameter and 0.3m-depth in the laboratory. The containers were wrapped with waterproofs that were perforated with similar holes so as to further reduce moisture evaporation from the soil samples during the experimentation time whilst ensuring natural aeration of the soil samples. One anode was used for one steel specimen in different containers.

Corrosion rate experiment

In order to establish the optimum CP potential for lowest corrosion rate, potentiostatic weight loss measurements were made and used to determine corrosion rate of each specimen under various exposure durations and soil resistivity. Before each experiment, surfaces of specimens were polished to average surface finishes of $1\mu m$ with 220, 500, 800 mesh grinding, washed by brushing with plastic brush and running tap water, cleaned with distilled water, wiped with tissue paper, oven-dried at $110^\circ C$ using an electrical oven and kept in desiccators. Just before exposure to the soil, specimens were removed from the desiccators, weighed to the nearest 0.1 milligram using a very accurate digital electronic scale with capability of weighing as low as 0.01 milligram and the weight of each noted as W_1 . To study the effect of variation of resistivity spectrum of the metropolitan soil on corrosion rates of the test steel, five specimens of the steel were each separately fully buried for 40 days in soil samples of resistivities 31.9, 43.69, 68.3, 90.7 and 152.9 ohm-m contained in five separate containers without protection and allowed to corrode freely at $25^\circ C$ ambient temperature. Each specimen was

removed at the same time after the 40th day; washed with running tap water and bristle brush to remove any corrosion products that formed on the surface of the specimen and then immersed in 10% hydrochloric acid containing chemical inhibitor (thiohanstoff) for 30 seconds, then washed by tap and then distilled water, dried with clean tissue, rinsed in ethanol and heat-dried in an electrical oven at a temperature of about 110°C for 10 minutes. Thereafter the specimens were kept in desiccators to cool and then weighted to obtain the weight each as (W_2). The weight loss of each specimen was obtained as $W = W_1 - W_2$ and converted into corrosion penetration rate (CPR), in terms of mm/yr. The experiment was carried out in accordance with the procedures used by Schwerdtfeger [20], Mahato *et al* [21] and Rashid [22]. The CPR of each specimen was evaluated as [7 and 22]:

$$\text{CPR} = \frac{8.76W}{DAT} \quad (2)$$

Where: W = weight loss in milligrams, D = density in g/cm^3 , A = area in cm^2 , and T = exposure time of the steel specimen in hours.

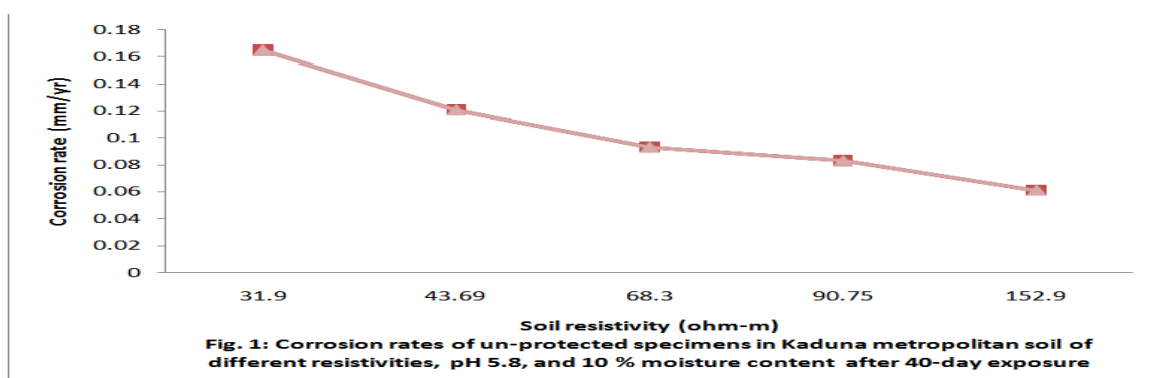
Soil of resistivities 31.9, 90.7 and 152.9 Ohm-m essentially fall in the ranges of aggressive, slight, and progressively less corrosivities respectively [6]. Soil samples of resistivities 31.9, 90.7, and 152.9 Ohm-m from the metropolitan area, were used to study the effect of variation in exposure duration on unprotected and protected specimens exposed to the soil. Five specimens were buried in soil samples of each resistivity for various durations up to 40 days without protection. One specimen was removed from each soil sample at 8-day intervals, and had its CPR determined by equation 2 according to the foregoing procedure. Thereafter, 45 specimens were used to study the effect 8-day interval variation on the corrosion rate of protected specimens. A rubber-covered stranded copper wire was soldered to one end of each of the specimens for electrical connection to the anodes. 15 of the 45 specimens were submerged in separate plastic containers each containing soil sample of resistivity 31.9 Ohm-m. Five of the 15 specimens were each connected to a zinc anode, five each to a magnesium alloy anode, and five each to a pure magnesium anode with each anode buried 10cm away from the specimen in the soil in the respective containers. This was similarly done with the 90.7 Ohm-m, and then 152.9 Ohm-m resistivity soil samples. One protected specimen by each anode was removed at 8-day intervals up to 40 days from the soil samples for each case of 31.9, 90.7, and 152.9 Ohm-m resistivity and had its CPR determined by equation 2 after similar cleaning and weight loss by the earlier used procedure.

Potential measurement

Various sizes of prepared specimens of the steel were used for the potential measurement. For the corrosion rate, the same mass and specimen exposure area (300cm^2) were used. Specimens were immersed in turn in test soil of given resistivity in a similar procedure to the foregoing section after being connected to a specified anode with the same size of copper wire. The tube saturated Cu/CuSO_4 was placed within 2mm from the specimen and electrically connected to it whilst the Cu/CuSO_4 electrode was connected to the negative terminal of the voltmeter type E7000 and the positive terminal of the voltmeter to the specimen. Specimen potentials were recorded at intervals of eight days using the voltmeter and Cu/CuSO_4 electrode as the reference electrode. After removing the specimens, the soldered wire connection of the specimens were carefully removed by applying heat from a soldering iron and the last bits of solder were removed by scrapping with a soft metal tool. Cleaning and weighing of specimen before the tests and after polarization were as explained in the foregoing section. After wards the specimen sizes were increased relative to that of one anode in the same procedure and the corresponding protective potentials noted.

III. RESULTS AND DISCUSSIONS

The test results of the study are presented in Figures 1-10.



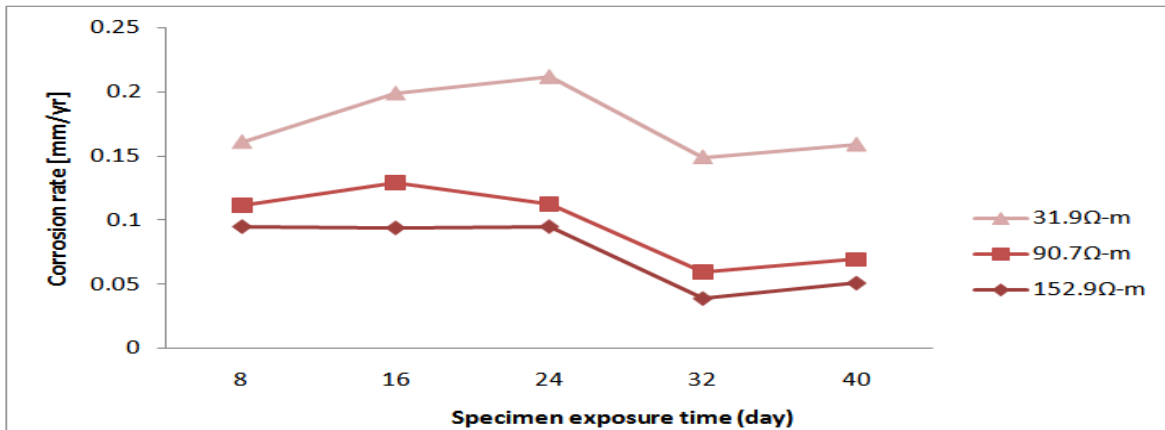


Fig.2: Effect of exposure time on CPR of unprotected low carbon steel specimens in soil samples of specified resistivities, Ph 5.8, and 10% moisture content

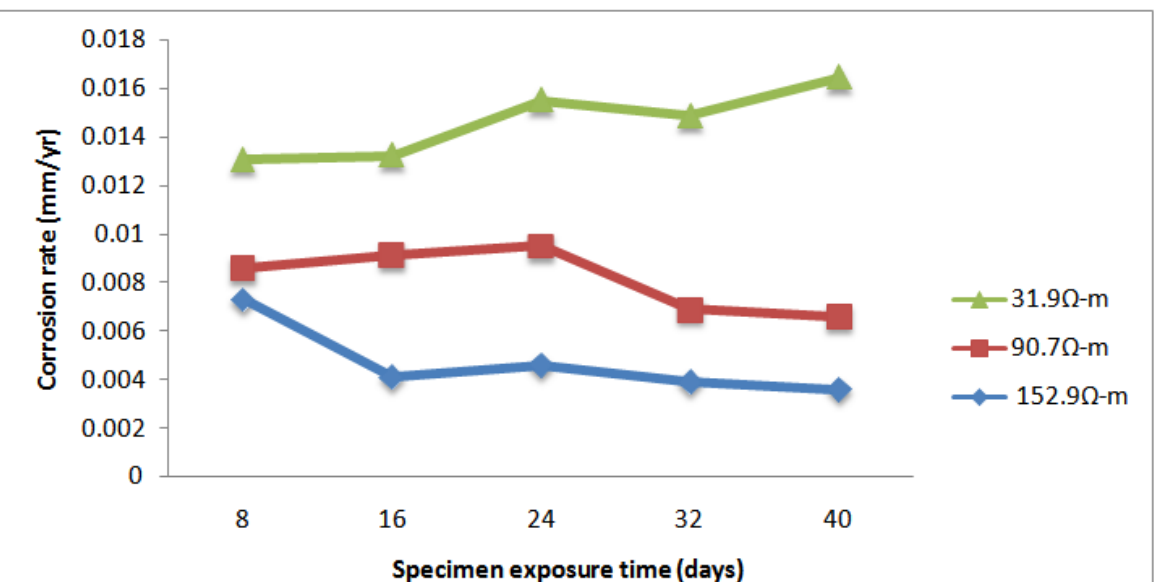


Fig. 3: Corrosion rates of the steel specimens protected by zinc anodes in soil samples of specified resistivity (ohm-m), Ph 5.8, and 10% moisture content

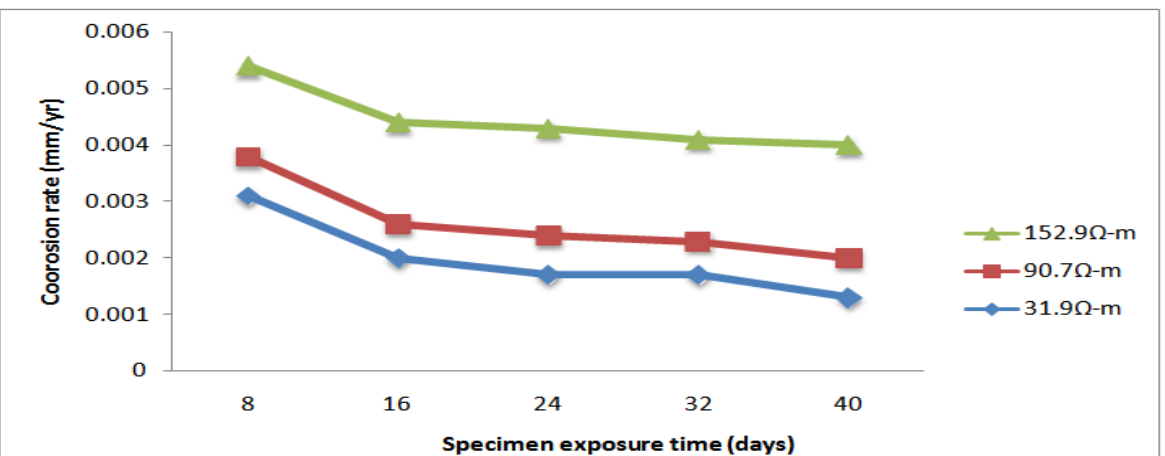
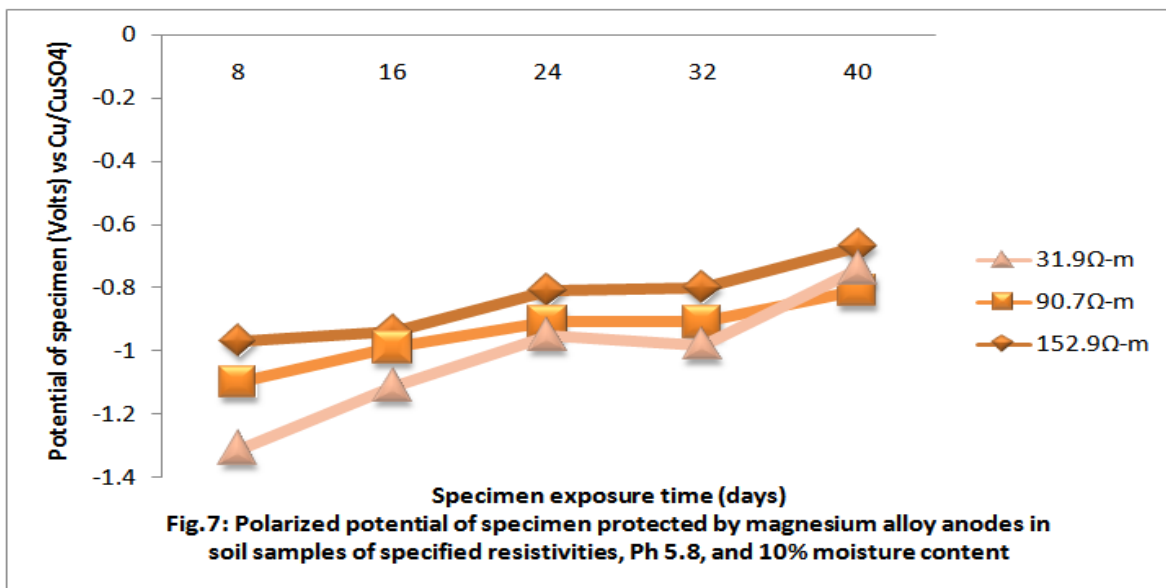
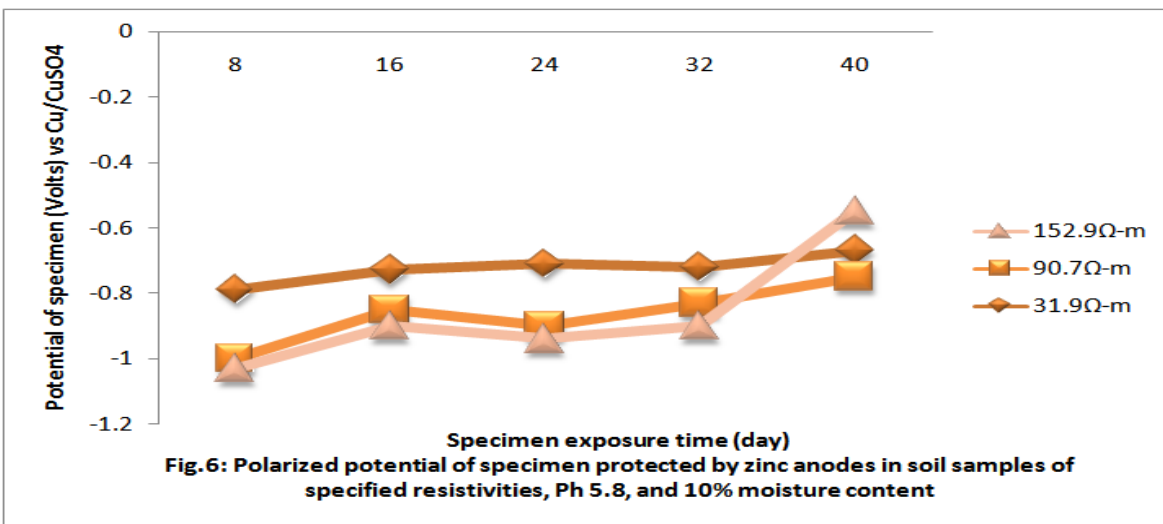
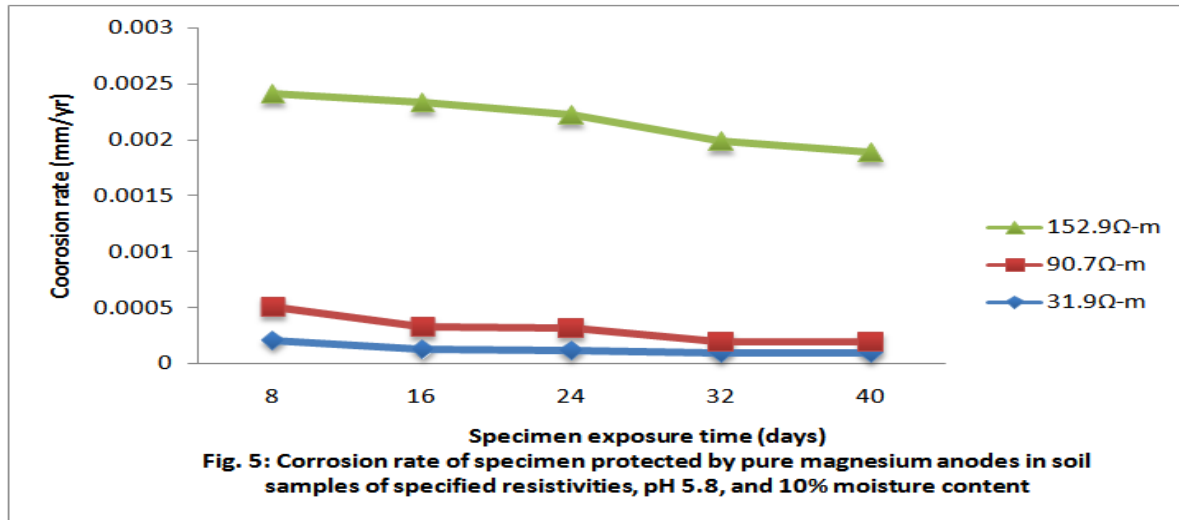


Fig. 4: Corrosion rate of specimen protected by magnesium alloy anodes in soil samples of specified resistivities, pH 5.8, and 10% moisture content



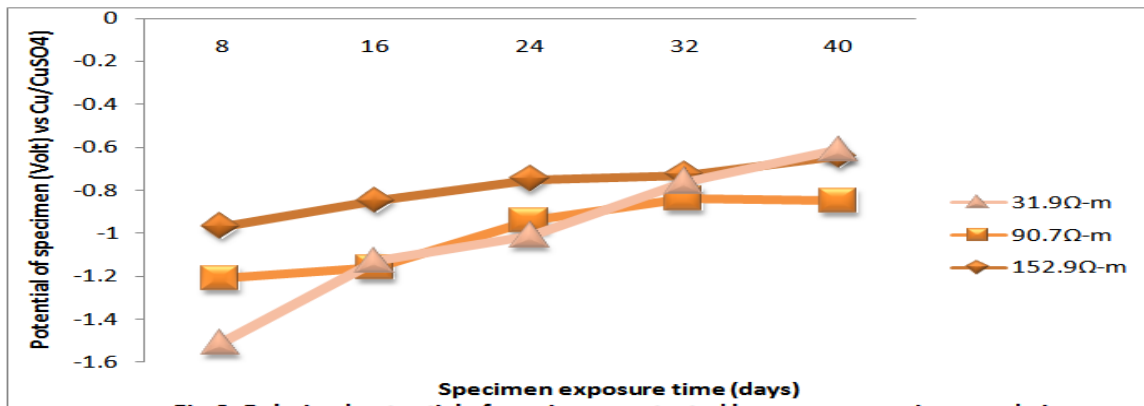


Fig.8: Polarized potential of specimen protected by pure magnesium anode in soil samples of specified resistivities, Ph 5.8, and 10% moisture content



Fig. 9: Effect of variation in polarized potential of specimen on specimen corrosion rate

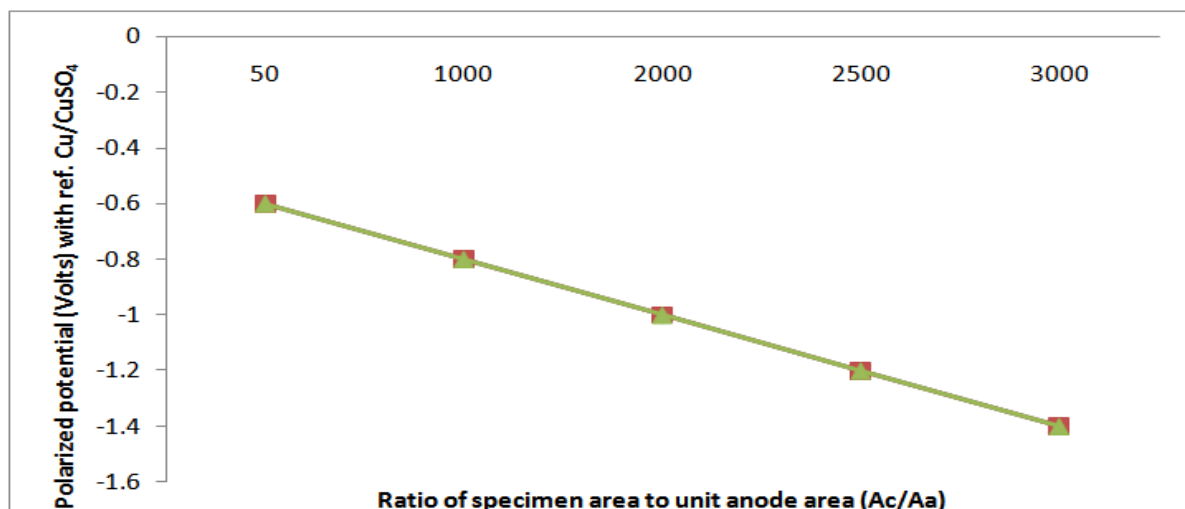


Fig. 10: Specimen exposure area that can be protected by a unit area of the anode at specified protective potential of specimen

Fig. 1 shows corrosion rates of unprotected specimens submerged in different-resistivity samples of the metropolitan soil after 40 days. From the figure it can be observed that corrosion rates of the specimens range from 0.061 to 0.165mm/yr for the entire resistivity spectrum of the soil. The highest rate of 0.165mm/yr occurred in soil sample of resistivity 31.9 Ohm-m. This value decreases with increase in resistivity to about 0.061mm/yr in soil sample of resistivity 152.9 Ohm-m. According to John Tarilonye Afa and Felix Opuama Ngobia [23], John Howard [24] and Guma *et al* [6]; soil resistivity is inversely related to corrosivity. It is thus clear that this trend of resistivity-corrosivity relationship is also attested by results for the metropolitan soil.

Fig. 2 on the other hand shows effects of exposure duration on corrosion rates of unprotected specimens submerged in different-resistivity samples of the soil for various durations up to 40 days. From the figure, it is apparent that corrosion rates of the specimens increased with exposure duration up to about the 24th day and thereafter decrease minimally to about 0.159, 0.069 and 0.051 Ohm-m in soil samples of resistivities 31.9 Ohm-m, 90.7 Ohm-m and 152.9 Ohm-m respectively. Several previous studies showed that corrosion rate generally decrease with time due to corrosion product formation and resulting in various levels of passivation of the corrosion [25]. The decrease in corrosion rates after the 24th day can thus be attributed to passivation according to Callister [7].

Fig. 3-5 show effects of exposure time on corrosion rates of specimens protected by the zinc, magnesium alloy and pure magnesium anodes in the test soil samples of 31.9, 90.7 and 152.9 Ohm-m resistivities. From the figures, it can be clearly observed that specimens protected by the zinc anode had highest corrosion rates while those by pure magnesium anode had the least rates in the soil samples for the same exposure durations. This indicates that pure magnesium anode is most suitable for the metropolitan soil because its protection spans the soil resistivity spectrum with relatively smaller corrosion rates compared to the zinc and magnesium alloy anodes. The corrosion rates generally turned to decrease to more or less constant values towards the 40th day of exposure except for specimens protected by the zinc anode in soil sample of resistivity 152.9 Ohm-m which increased with exposure duration as can be observed from Figures 3-5. The corrosion rates for each case of protection by the anodes are however minimal compared to those of the unprotected specimens as can be observed in Figures 3-5 in tandem with Figure 2. This shows that each of the three anodes can provide protection to the study steel, the level of which however depends on the anode size and prevailing resistivity. For the same size of anode, pure magnesium alloy anode exhibits outstanding protection performance in all the soil samples. Zinc anode exhibits relatively lowest protection performance in the 31.9 Ohm-m resistivity soil while pure magnesium the lowest in the 152.9 Ohm-m resistivity soil.

Fig. 6-8 shows effects of exposure duration on the polarized potentials of protected specimens by the anodes in the soil samples. For each figure and soil resistivity, the potentials increased steadily to higher values with increase in exposure duration as can be observed. This indicates that the specimens were protected. Loto and Popoola [1] observed similar trend of behavior for mild steel specimens protected by zinc and aluminum anodes in sea water and sulphuric acid. Scantlebury *et al* [26] studied corrosion of mild steel in marine environments under cathodic protection. His electrochemical studies at the two protection potential namely: -780 and -1100mV were examined by different techniques. DC polarization experiments was carried out for mild steel in natural sea water and 18.5g/L NaCl solution to evolve corrosion current density. He concluded that mild steel does not corrode under the protection potentials, viz., -780 and -1100mV. It can thus be observed the polarized potentials presented in Figures 6-8 more or less fall in this range so indicate reasonable protection of the specimens. It can however be observed that the pure magnesium anode proved more effective as sacrificial anode for the test steel because the polarized potential of the steel by it has the widest range of about -1.6 to -0.8 compared to those of the other anodes. The bigger the anode or its area, more electrons are supplied to protect the cathode and the longer time it takes for replacement. The potentials of pure magnesium, magnesium alloy (6%Al, 3%Zn and 0.15%Mn), zinc, and low carbon steel with respect to Cu/CuSO₄ in a neutral Ph environment are: -1.75V, -1.6V, -1.1V and -0.2 to -0.8V respectively [27]. This also shows that pure magnesium has the most negative potential, so is most suitable of the three anodes for delivering higher current per unit mass where needed such as high-resistivity soils. The differences in the protective performances can thus be attributed to their capacities to deliver protective current per unit mass. Moreover In high-resistivity environments, corrosion rates are controlled largely by electrolytic resistance rather than by polarization alone [20].

Fig. 9 shows the effects of polarized potential of specimens by the anodes on corrosion rates. From the figure, it very clear that corrosion rate of specimens decreased from about 0.12mm/yr at the -0.65 potential to negligible rate at the -0.85V potential and zero rate as potentials became more negative with respect to Cu/CuSO₄. According to Zuhair [27] and Collins [28] a CP potential reading with respect to Cu/CuSO₄ of between -0.5 to -0.6 represents intense corrosion, -0.6 to -0.7 corrosion, -0.7 to -0.8 slow corrosion, -0.8 to -0.9 cathodic protection, -0.9 to -1.1 overprotection and -1.1 to -1.4 severe overprotection in soil environments. Also, previous work in low resistivity environments by Schwerdtfeger [20] and other investigators has shown that corrosion can be reduced to a negligible degree by polarizing a steel structure to -0.85 volts (protective potential) with reference to a copper-copper sulphate electrode. However, this required protective potential tends to shift to more negative value from the -0.85V as soil corrosivity level drastically increases. For example, the protective potential of -1.1 to -1.4V has been reported by Zuhair [27] to be more satisfactory for Saudi's Aramco highly corrosive. For steel in anaerobic electrolyte of nearly neutral pH, a commonly accepted protection potential is -0.85V; when exposed to sulphate-reducing bacteria a potential of -0.95V with reference to copper/copper sulphate electrode would be required. These show that if the environment is particularly different in nature such as corrosivity level, the potential may change significantly [16].

From these it is clear that the test protective criteria of -0.85V for the Kaduna metropolitan area also meet the general criteria used by engineers for CP of steel structures for soils of usual corrosivity.

Fig. 10 shows effect of varying the surface area of the cathode relative to a unit surface area of the anode on the least negative protective potential of the cathode in the soil. From the figure it is indicative that at the optimum protective potential of -0.85V , a unit area of anodes can protect up to about 1200 unit area of the specimen. Tai-Ming Tsai [25] studied the performance of aluminum alloys used as sacrificial anodes for protection of steel in seawater. His results showed that steel can be protected under area ratio up to 4000-5000 with -0.85V protective potential [25]. This shows that less surface area of a steel structure in the metropolitan soil can be protected compared to the sea water environment. One reason attributable to this is that the resistivity of the sea water was lower than about $31.9\ \Omega\text{-m}$ for the soil.

IV. SUMMARY AND CONCLUSION

Cathodic protection is one of the most effective and economical methods of durably preventing corrosion of engineering systems or structures in aqueous environments if properly designed installed and maintained. One important requirement of CP is that it should be applied in the most economical way. Proper CP design therefore requires careful study with regard to complexity of variables that affect it such as environmental corrosivity, type of material to be protected, nature and surface area of the material, type and size of anode to be used or amount of current to be applied so as to establish conditions for optimal mitigation of corrosion in specific environments or localities. The paper sought laboratory information on relative merits of zinc, magnesium alloy and pure magnesium as cheap and locally available galvanic anodes for suitable CP of underground engineering steel structures in the metropolitan area of Kaduna-a top city in Nigeria. Obtained information show that the -0.85V protective potential generally accepted by the engineering community as adequate for CP of bare steel in soil environments is also met for the metropolitan soil. Corrosion of underground engineering steel structures in the soil can therefore be reduced to negligible rate by polarizing them to the protective potential using the anodes. A unit surface area of the anodes can protect up to nearly 1200 units of the structure with the -0.85V protective potential depending on the anode type. The pure magnesium has been found to be most suitable out of the three anodes for CP of the structures in term of economical size and outstanding effectiveness that spans resistivity spectrum of the soil.

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