Original Research Article

ASSESSMENT OF OIL PAINTS FOR CORROSION PROTECTION OF REINFORCING STEEL BARS IN CONCRETE

Abstract

Corrosion becomes a threat to reinforced concrete structural integrity during the service life of the structural member. This situation has become a global concern because of the economic and safety implications. Hence, many corrosion inhibition techniques including coating with materials (organic and inorganic) were used to prevent its devastating effects. The present study used three oil paint brands (mat, red-oxide and gloss Leyland oil paints in Ghana) to variedly coat reinforcing steel bars to ascertain their corrosion protection capacity in concrete. There were zero, one, two and three paintcoats of average film thickness, 72 μm, 129 μm and 220 μm respectivelyexplored. An Electrochemical process involved simulated concrete pore solution made of 10% sodium chloride (NaCl) in distilled water with three electrode systems to represent a corrosion medium was used to determine corrosion protection capacity of the paints. The results indicate over 90% corrosion resistance of the paints used. Comparing the corrosion rates of the coated and uncoated reinforcing steel bars, while it would take a one coat steel bar 342.5 years and 237 years respectively for spraying and manual brushing modes to reduce in diameter by 0.616mm, it would take only one year for an uncoated steel bar to reduce by this same 0.616mm. The protection capacity proved better with increasing coats on all corrosion variables for the selected paints used. The implication is that the selected oil paint brands are capable of protecting reinforcing steel bars in concrete against corrosion and therefore recommended for application to reduce maintenance cost. Statistically, no significant difference existed between coating mode, number of coatings, paint type and steel type on the corrosion variables for the coated steel bars. However, a further study about the durability of the coating in the concrete during its service time is recommended.

Keywords: *corrosion, reinforcing steel bar, concrete, oil paint coating, corrosion protection capacity.*

1.0 Introduction

Reinforced concrete is a composite product of steel bars and concrete used to build structures like bridges, buildings, airport runway pavements, water tanks, among others. These two materials act as a composite material through the bond between them to resist applied loads. However, corrosion of the reinforcing steel bar becomes a threat to the integrity of the reinforced concrete structure during the period of its service life.

A good number of studies show that bonding characteristics reduce when reinforcing bars begin to corrode.Charles et al. (2018) found that the corrosion of reinforcingsteel bar in concrete as one of the foremost influences to failure of steel and concrete, leading to the use of epoxy and resin/exudate to prevent corrosion effect on reinforcing steel. Similarly, Tobi et al. (2021) conducted a study in Nigeria in which corrosion inhibitor (resins / exudates) from boswelliadalzielii hutch was used to coat reinforcing steel. The coating thickness of 150μm, 300μm, 450μm, and 600μm was applied before corrosion testing by subjecting specimens to 5% NaCl solution up to 360days in a lab. The result showed thatexudate/resin has a corrosion-resistant effect because of its waterproofing quality that prevented corrosion causing agents entry and attack. They also found that interaction between the concrete and the reinforcing steel was greater in controlled and coated specimens than that of corroded samples. However, the exudates and the epoxy employed to prevent reinforcing steel corrosion are not common on the local market inWest Africa. Earlier, Auyeung et al. (2000) indicated from their study that bond strength dilapidation of an unconstrained concrete specimen with a corroded reinforcing steel of 2% could result in a bond loss of 80%. According to them steel corrosion is much more critical to cross-sectional loss. That is devastating effect of corrosion of reinforcing steel has been alasting concern(Rodrigues, et al., 2021;Biparva, A., 2019). The concrete itself being a stone-like material contains capillaries, air voids and pores that encourage relative humidity intrusion under the right temperature. The condition at a certain threshold leads to reaction or exchange of ions between chlorides, moisture, oxygen and irons as well as carbonation of the concrete elements(Bowman, J. 2019;Biparva, A., 2019; Qiao, et al., 2023). The situation is very common especially with structures alongcoastalregions, acid rain regions, industrial zones, water-containing structures and structures spanning over river bodies. In some cases, the reinforcing steel bars start to corrode on shelve before they are brought to the site.

Many building projects take not less than two years to complete especially in Ghana. Some projects take decades to complete; and what happens is that the exposedprojected rebars start to corrode before the building is continued to completion. This may undermine the bond strength between the concrete and the reinforcing steel bars andhencethe safety of the structure. The effects of the abovepracticeandaction include early deterioration of structural elements – cracking due to expansion of the corroded rebars; reduction in tensile strength; and reduction in bond. This condition, if not prevented could lead to huge economic losses, since the resulting remedial works could be very expensive and negativelyimpact on thenational GDP. In 2018, the corrosion protection industry alonewas estimated to be around USD 2.5 trillion to over USD 3 trillion by the end of the year (Prasad, 2021; Wang et al., 2012). Over a decade ago, it was also reported thatcorrosion of metals cost the U.S. economy almost USD 300 billion per year at 1995 prices although some of these are preventable(Holbrook, 1996).

Some earlier studies in this area concentrated on prevention of corrosion of reinforcing steel bars and projected their use in concrete without testing the bonding characteristics and cost effectiveness. For example, Joycee et al. (2021) concluded from polarization and alternating current (AC) impedance spectra studies that in the presence of paint coating (using Asian guard red paint) the corrosion resistance of mild steel immersed in simulated concrete pore solution increased. Exudates/resins were used to coat reinforcing steel to prevent corrosion (Tobi et al., 2021; Benjamin et al., 2021; Charles et al., 2018;Vigdorovich et al., 2016). Other prevention measures like application of epoxypigment, galvanization and sand blasting are expensive and require heavy machinery and energy to achieve, with sand blasting producing a lot of pollution (Buchheit, 2018; Nguyen and Nguyen, 2018;Popov, 2015;Safiuddin, 2005, 2016). This study therefore aimed at demonstrating the use of local Leyland oil paint brands (red-oxide, mat black and gloss green) produced in Ghana to preventordelay corrosion of reinforcing steel bars in concrete without compromising good bond for structural integrity and safety. Thepaper focused on the corrosion protection capacity of the selected paints to both mild steel and high yieldsteelbars before and after coating.

1.1 Corrosion Process in Steel-Reinforced Concrete

Corrosion of steel is an electrochemical process in reinforced concrete comprising electrons transfer or movement of current (Hearn, 1996;Biparva, 2019). The electrical potential difference in between finite areas on the steel reinforcing bars is the contributing force for corrosion. This is usually caused by steel composition variation, presence of impurities along a steel bar or electrically linked steel system and unpredictable corrosive environment (AGA, 2002). The corrosion process of steel reinforcement depends on the following four conditions (West, 1999; Basheer et al., 1994; Safiuddin, 2005: 2016;Qiao, et al., 2023;Bowman, 2019;Biparva, 2019)

1. **Anode**: a location for anodic reaction is needed for driving metal ions into solution and releasing electrons.
2. **Cathode**: a location for cathodic reaction is required for consuming electrons in presence of oxygen and water.
3. **Electrolyte**: a conductive medium must be present to allow the movement of electron between anode and cathode.
4. **Conductor**: steel reinforcing bar must permit transfer of electrons from anode to cathode (see figure 1).

These actions could be prevented or retarded through various means to prolong the service life of rebars in concrete. Barrier coating is one of the easiest and cheapest ways to prevent corrosion (Joycee et al., 2021). Paints are commonly-used method for corrosion protection and control of metals from damage especially outside concrete.

The created protective film on the metal surface by the paint tends to prevent cathodicand anodic reactions responsible for corrosion (Mayne, 2010;Joycee et al., 2021Buchheit, 2018; Popov, 2015). The types of pigments, thickness of film, concentration of electrolyte, temperaturevariation, and types of solvents are used todetermine the resistance of the polymer films formed on the metal surface to definethe performance of the paint (Mayne, 2010).

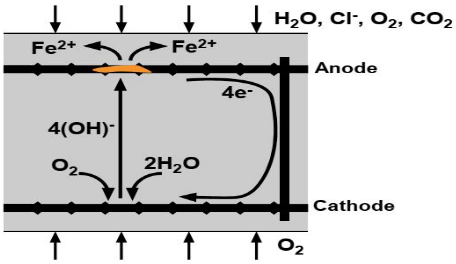

Figure 1: Simplified model for corrosion process in reinforced concrete (West, 1999Safiuddin, 2005;Qiao, et al., 2023;Bowman, 2019; Biparva, 2019).

When the barrier is created to prevent corrosion that may not be one stop since the protective material may succumb to some environmental corrosive conditions. Nguyen and Nguyen (2018) investigated effect of incorporating nanoparticles on the corrosion resistance of epoxy-coated steel rebar by linear potentiodynamic polarization and electrochemical impedance spectroscopy. Two kinds of nanoparticles (nano-SiO_2 and nano-Fe_2O_3) coated on steel rebar embedded in a chloride contaminated cement mortar. NaCl was added to the fresh Portland cement paste (at 0.3% and 0.5% by weight of cement) to simulate the chloride contamination at the critical level. For the 0.3 wt.% chloride mortars, the electrochemical monitoring of the coated steel rebars during immersion for 56 days in 0.1 M NaOH solutions suggested the beneficial role of nano-Fe_2O_3 particles in significantly improving the corrosion resistance of the epoxy-coated rebar. After 56 days of immersion, the nano-Fe_2O_3 reduced the corrosion current of epoxy-coated rebar by a factor of 7.9. When the chloride concentration in the cement mortar was 0.5 wt.%, the incorporation of nanoparticles into the epoxy matrix did not enhance the corrosion resistance of epoxy coating for the rebar. At this critical level, chloride ions initiated rebar corrosion through nanoparticles at the epoxy/rebar interface. Hence, limit of protection of the protective coating needs to be monitored periodically.

2.0 Materials, Tools and Methods

2.1 Materials and Tools

The materials used in this study included reinforcing steel bars of 12mm diameter (both mild and high tensile steels) produced in Ghana and were coated for the study. The coating materials used were Leylac mat, Leylac red-oxide (guard) and Leylac gloss oil base paints from the local market (Table 1). These were oil paintbrands of Leyland Company Ghana Limited. They were chosen because mat finish is not shiny and therefore may improve bond while the red oxide is normally used as priming coat against corrosion, but produces a shiny finish. On the other hand, gloss gives a shiny finish and may not bond well in concrete but may protect against corrosion. The simulated concrete pore solution (SCPS) was made of 10% sodium chloride (NaCl) in distilled water while the tools included Electrochemical Workstation, brush, spraying gun, rag, tape measure, hacksaw and digital veneer caliper.

2.2 Methods

2.2.1 Materials Preparation

The steel bar was cut into 40mm lengths. The steel bars in the prescribed lengths, were pretreated in conformity with ASTM A 775/A 775M – 01, by cleaning with metal brush and thinner to remove dirt, grease/oil substance and metal oxide form on the surface of the steel bar. They were then cleaned with safe water, wiped with cotton rag and dried in readiness for coating.

The coating was done with brush and spraying gun. For each case, the coating was 0, 1, 2, and 3 groups. The control specimens received no coating at all after the surface preparation. However, the other test specimens received 1, 2, or 3 coats of the various paint types either by brush or spraying. Apart from the quest to ascertain the corrosion protection capacity of the various types of paint, the study also tested the effect of the coating mode and number of coatings applied to the steel bar surface on protection capacity. After selecting the control specimens, all the test specimens received one coat each in their various groups and allowed to dry for 24 hours. Then one coat specimens were taken out and the rest received second coat and allowed to dry for 24 hours. The same step was repeated for the third coat and they were cured under room temperature for 14 days before chemical test was conducted on them.

The physical properties were taken to determine the coating thickness with digital veneer caliper. Average thickness taken from the web were 72 µm, 129 µm and 220 µm for one, two and three coats respectively in accordance to ASTM A775/A775 M, section A 1.2 (coating requirement) for brush coating; while that of spraying produced 60 µm, 77 µm and 91 µm for one, two and three coats respectively. However, this was contrary to current standard specification for epoxy-coated steel reinforcing bars (ASTM A775/A775M) that allows epoxy coating thicknesses between 175 to 400 µm. The varied thicknesses were chosen because coating thickness has effect on bond strength. Hence, that would guide suitable thickness of coating to recommend.

2.2.2 Electrochemical Studies

The environment or medium used to achieve the corrosion protective capacity of the paint coats on the reinforcing steel bars was simulated concrete pore solution (SCPS) thatwasmade of 10% sodium chloride (NaCl) in distilled water,which was far more than the 3.5% NaCl content in sea water. This was to determine the behaviour of the coating material under a more severe condition other than coastal environment.

Corrosion resistance testing of steel could be measured by polarization (stable polarizationwhere electrode potential remains relatively constant over time with changes in current density) and AC impedance spectra among others(Joycee et al., 2021Sharanya et al., 2016). However, this study used only Polarization study. The CorrTest Electrochemical Workstation (Model CS350, China) was used for the corrosion protectiontesting (Fig 3d). Three electrode system including counter electrode-graphite, reference electrode-Ag/AgCl, and test electrode -steel barspecimens (eithercoated or uncoated) was employed for the scan in the corrosion medium at a scan rate (V/s) of 0.01. The corrosion parameters including techniques used to measure polarization resistance - linear polarization resistance (LPR), corrosion current (I_{corr}), corrosion potential (E_{corr}), corrosion rate and Tafel slope values (anodic = b_a and cathodic = b_c) were recorded, refined and presented in Tables 2a-2d; and Figures 4a-f for analysis. The Tafel slope is a term that characterizes electrode kinetic of the anode and cathode (Qiao, et al., 2023;Joycee et al., 202.

From electrochemical measurement, the corrosion rate is estimated from the extrapolation in equation one:

Corrosion rate = (B I_{corr}) / (n F A) ………………………………. Eq 1

where:

- B is a constant related to the Tafel slope (electro kinetic of cathode and anode)

- I_{corr} is the corrosion current obtained from the Tafel plot (graphical presentation for analyzing electro kinetics)

- n is the number of electrons involved in the corrosion reaction

- F is Faraday's constant

- A is the surface area of the corroding metal

On the other hand, the computation of the corrosion rate from linear polarization resistance (LPR) is done using equation 2 as follows:

Corrosion rate = (K R_p) / (A ρ) ………………………………………… Eq 2

where:

- K is a constant related to the electrochemical system
- R_p is the polarization resistance obtained from the LPR measurement
- A is the surface area of the corroding metal
- ρ is the density of the corroding metal

The determination of corrosion potential (E_{corr}) and current (I_{corr}) from the Tafel plot(graphical presentation for analyzing electro kinetics) is by tracing the values of the intersection of thetangent to anodic and cathodic polarization curves to thex-axis and y-axis for I_{corr} and E_{corr} in that order as demonstrated in fig. 2

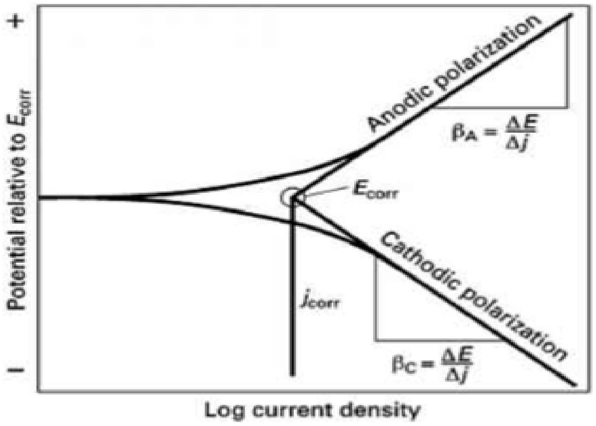

Fig. 2 Tafel plot reading guide for I_{corr} and E_{corr}

According to ASTM C876-09, a corrosion potential of -0.564 mV or higher indicates a 90% probability that no reinforcing steel bar has corroded. On the other hand, corrosion potentialsthatare more negative than -0.564 mV are assumed to have a greater than 90% likelihood of corrosion occurrence. Similarly, a decreased corrosion current signifies no corrosion and the vice-versa.

Fig. 3: a- Rebar before, b – Selected paints, c – Rebar after coat, d - Model CS350 station setup

Table 1: FP analysis result of the selected paints

Component (%)	Gloss	Redox	Matex
Mg	0.0883	0.0364	1.42
Al	0.0421	0.0102	0.0488
Si	0.0873	0.0299	1.18
S	0.0073	0.006	0.0092
Cl	0.429	0.0027	0.012
K	0	0	0.0054
Ca	0.167	0.13	11.8
Ti	0.419	0.0012	0.0031
V	0.0025	0	0
Cr	0	0.0001	0
Mn	0	0	0.0035
Fe	0.0038	0.237	0.074
Co	0.0236	0.0191	0.0131
Cu	0.0464	0.0002	0.0004
Zn	0.0008	0	0.0004
Br	0.0009	0	0
Rb	0.0017	0.0016	0.0002
Sr	0.141	0.151	0.0804
Sn	0.002	0.0019	0.0063
Te	0.0017	0.0017	0.0015
Hf	0.0011	0	0
Ta	0	0	0.0001
U	0.0077	0.0093	0.0009
Oil	94.6	99.2	85.2
Na	3.77	0	0
Zr	0.115	0.114	0.16

Lab result 2024

2.2.3 Statistical Studies

Differences were expected in the means of the effectofvarious variables such as paint type, steel type, number of coatings and coating mode on corrosion rate, corrosion current(I_{corr}), linear polarization resistance(LPR) and corrosion potential(E_{corr}). Hence, the one-way ANOVA was used to establish the differences with SPSS software.

3.0 Results and Discussions

The electrochemical results of the stablepolarization used to determine the corrosion protection capacity of the various coatings adopted in this study; namely, Leyland mat, Leyland red-oxide (guard) and Leyland gloss oil base paints. The number of coatings applied and the mode of coating were considered. In addition, the type of reinforcing steel bar in terms of mild and high yield steels were factors for consideration. The outcome of the experiment provided information and gave confidence in the chosen paint brands to be used in concrete to protect reinforcing steel bars against corrosion; and hence, encouraged progression for other fitness tests such as bond and flexural characteristics in concrete (to be considered in subsequent publications). Theresults from Tafelextrapolation (graphical presentation of electro kinetics values) and linearpolarization outcomes as well as statistical analysis were evaluated and interpreted in the sections that follow.

3.1 Electrochemical Analysis

3.3.1 Potentiodynamic Polarization Analysis

Polarization helps to detect protective film formation on metal surface. The formation of aprotective film on the surface ofa metal would indicate the signs of the linear polarization resistance (LPR) increasing while corrosion current (I_{corr}) is decreasing (Joycee.et al., 2021) which is the main purpose of this section of the study to determine corrosion resistance capacity of the coatings and methods used. The polarization curves or Tafel plots of the steel specimens immersed in the test solution (SCPS) are shown graphically as Figures 5a-5f to enable visual interpretation of corrosion protection capacity of the selected paints. Other corrosion parameters such as Tafel slope (b_c = cathodic, b_a = anodic), linear polarization resistance (LPR); corrosion potentials (E_{corr}), corrosion rate and corrosion current (I_{corr}) are summarized in Tables 2a – 2d.

Interpreting the results, a more negative or lower corrosion current (I_{corr}) and a more positive corrosion potential (E_{corr}) indicate high corrosion resistance. Similarly, a higher linear polarization resistance (LPR) signifies a more corrosion resistance capacity. Table 2a, presents Tafel extrapolation and linear polarization results for mild steel coated by spraying of various levels of coating and paint types (example MA1-M = mild steel automated/spray coated with one (1) coat of mat paint; MB1-M = mild steel brush coated with one (1) coat of mat paint; and CM-1 = uncoated mild steel)

Table 2a: Tafel extrapolation and linear polarization results of mild steel coating by spraying

Coating	E_{corr} mV	b_a mV/decade	b_c mV/decade	LPR Ohm*cm^2	I_{corr} A/cm^2	Corrosion rate (mm/a)
CM-1	-0.618	169.36	49.71	342.99	5248 x10^{-8}	0.61564
MA1-R	-0.492	404.66	251.10	11.71x10^{4}	15.40 x10^{-8}	18.04 x10^{-4}
MA2-R	-0.458	385.76	346.28	30.14x10^{4}	5.97 x10^{-8}	7.01 x10^{-4}
MA3-R	-0.470	144.11	136.22	66.98 x10^{4}	2.69 x10^{-8}	3.15 x10^{-4}
MA1-M	-0.408	80.58	160.16	12.43 x10^{4}	14.50 x10^{-8}	17.00 x10^{-4}
MA2-M	-0.430	79.84	116.59	31.30 x10^{4}	5.75 x10^{-8}	6.75 x10^{-4}
MA3-M	-0.628	1227.30	921.53	214.34 x10^{4}	0.84 x10^{-8}	0.99 x10^{-4}
MA1-G	-0.485	445.96	324.28	38.95 x10^{4}	4.62 x10^{-8}	5.42 x10^{-4}
MA2-G	-0.464	687.14	524.77	86.84 x10^{4}	2.07 x10^{-8}	2.43 x10^{-4}
MA3-G	-0.458	218.95	200.96	129.68 x10^{4}	1.39 x10^{-8}	1.63 x10^{-4}

LPR = Linear polarization resistance, I_{corr} = Corrosion current, E_{corr} = Corrosion potential, b_a = anode, b_c cathode. Lab result 2023

Table 2b: Tafel extrapolation and linear polarization results of mild steel coated by brushing

Coating	E_{corr} mV	b_a mV/decade	b_c mV/decade	LPR Ohm*cm^2	I_{corr} A/cm^2	Corrosion rate (mm/a)
CM-1	-0.618	169.36	49.707	342.99	5248 x10^{-8}	0.61564
MB1-R	-0.499	668.79	369.99	8.24x10^{4}	21.80 x10^{-8}	25.63 x10^{-4}
MB2-R	-0.647	842.01	207.54	88.64 x10^{4}	2.03 x10^{-8}	2.38 x10^{-4}
MB3-R	-0.542	440.89	230.74	116.60 x10^{4}	1.54 x10^{-8}	1.81 x10^{-4}
MB1-M	-0.519	431.05	348.76	5.71 x10^{4}	31.50 x10^{-8}	36.95 x10^{-4}
MB2-M	-0.597	570.59	169.72	218.26 x10^{4}	0.83 x10^{-8}	0.97 x10^{-4}
MB3-M	-0.628	1227.3	921.53	214.34 x10^{4}	0.84 x10^{-8}	0.99 x10^{-4}
MB1-G	-0.560	359.53	259.91	0.47 x10^{4}	384 x10^{-8}	450.50 x10^{-4}
MB2-G	-0.53076	555.54	378.56	7.81 x10^{4}	23.0 x10^{-8}	27.03 x10^{-4}
MB3-G	-0.67769	467.61	287.68	203.04 x10^{4}	0.89 x10^{-8}	1.04 x10^{-4}

LPR = Linear polarization resistance, I_{corr} = Corrosion current, E_{corr} = Corrosion potential, b_a = anode, b_c cathode. Lab result 2023

3.3.2 Linear Polarization Analysis

It can be seen from Table 2a that, the LPR for uncoated mild steel (CM-1) is 342.99 Ohm*cm^2, corrosion potential and corrosion current were -0.618 mV and 5248 x 10^{-8} A/cm^2 respectively while corrosion rate was 0.616mm/a. This shows atendency of over 90% chance of the reinforcing steel bar tocorrode without coating. It implies that under the same corrosion environment, a 12mm reinforcing steel bar would reduce in diameter by 0.616mm in a year without coating or corrosion protection. However, from Tables 2a and 2b alike, when the mild steel was coated with red-oxide paint by automation (spraying) and brush (manual), even for a single coat, the results for LPR, E_{corr} and I_{corr}were (11.71x10^{4}, 8.24x10^{4} Ohm*cm^2), (-0.492, -0.499mV) and (15.40 x10^{-8}, 21.80 x10^{-8} A/cm^2) respectively. The corresponding corrosion rates were 18.40 x10^{-4}, 25.63 x10^{-4} mm/a, which implied over 90% of corrosion resistance. Thus, comparing the corrosion rates, the same 12mm diameter reinforcing steel bar would take 342.5 years or 237 years to reduce by 0.616mm when given one coat of red-oxide oil paint by spraying or by manual brushing respectively, under the same aggressive corrosion environment. It could also be seen from Table 2a and 2b under corrosion rate that the rate of corrosion decreased tremendously with increasing coating thickness to a more negligible value state making the corrosion rate rather almost non-existent. Similarly, LPR increased with increasing coating thickness while I_{corr} decreased with increasing coating thickness for the various paint types and modes of coating used. This is an indication that the selected paint proved to be corrosion resistant and is consistent with the findings of Joycee et al. (2021), Mayne,

(2010) and Tobi et al. (2021). The condition was not different in the case of mat and gloss paints either coated by spraying or brushing as illustrated in the Table 2a-2d.

Table 2c: Tafel extrapolation and linear polarization results high tensile steel coated by spraying

Coating	E_{corr} (mV)	b_a (mV/decade)	b_c (mV/decade)	LPR (Ohm.cm^2)	I_{corr} (A/cm^2)	Corrosion rate (mm/a)
CHT-1	-0.486	305.42	121.53	0.0008×10^5	22060×10^{-8}	2.5876
HA1-R	-0.386	94.62	245.69	0.23×10^5	77.23×10^{-8}	9.06×10^{-4}
HA2-R	-0.444	72.37	141.16	4.73×10^5	3.81×10^{-8}	0.45×10^{-4}
HA3-R	-0.499	420.15	276.95	9.17×10^5	1.96×10^{-8}	0.23×10^{-4}
HA1-M	-0.367	105.65	176.82	1.63×10^5	10.65×10^{-8}	1.30×10^{-4}
HA2-M	-0.446	1492.90	651.50	4.06×10^5	4.43×10^{-8}	0.52×10^{-4}
HA3-M	-0.432	327.37	235.51	3.52×10^5	5.11×10^{-8}	0.60×10^{-4}
HA1-G	-0.585	196.75	122.58	0.01×10^5	128.00×10^{-8}	150.12×10^{-4}
HA2-G	-0.469	254.38	207.22	9.26×10^5	1.94×10^{-8}	0.23×10^{-4}
HA3-G	-0.493	530.12	320.96	8.78×10^5	2.05×10^{-8}	0.24×10^{-4}

LPR = Linear polarization resistance, I_{corr} = Corrosion current, E_{corr} = Corrosion potential, b_a = anode, b_c cathode. Lab result 2023

Table 2d: Tafel extrapolation and linear polarization results of high tensile steel coated by brushing

Coating	E_{corr} mV	b_a mV/decade	b_c mV/decade	LPR Ohm*cm^2	I_{corr} A/cm^2	Corrosion rate (mm/a)
CHT-1	-0.486	305.42	121.53	0.0008×10^5	22060×10^{-8}	25876×10^{-4}
HB1-R	-0.572	213.09	132.68	0.18×10^5	985×10^{-8}	1155.3×10^{-4}
HB2-R	-0.468	258.62	257.69	14.38×10^5	1.25×10^{-8}	1.47×10^{-4}
HB3-R	-0.584	209.89	128.99	0.01×10^5	1320×10^{-8}	1544.5×10^{-4}
HB1-M	-0.485	712.43	416.58	12.65×10^5	1.42×10^{-8}	1.67×10^{-4}
HB2-M	-0.585	213.03	124.57	0.02×10^5	1060×10^{-8}	1242×10^{-4}
HB3-M	-0.596	187.97	113.36	0.01×10^5	1500×10^{-8}	1763×10^{-4}
HB1-G	-0.523	408.75	247.85	1.50×10^5	12.00×10^{-8}	14.04×10^{-4}
HB2-G	-0.514	557.67	200.99	22.44×10^5	0.80×10^{-8}	0.94×10^{-4}
HB3-G	-0.602	181.10	106.73	0.01×10^5	1540×10^{-8}	1801.7×10^{-4}

LPR = Linear polarization resistance, I_{corr} = Corrosion current, E_{corr} = Corrosion potential, b_a = anode, b_c cathode. Lab result 2023

These values even for asingle coating (in both coating modes and paint types) indicate an increase in LPR and E_{corr},but a decrease in I_{corr} and corrosion rate, meaning the coats resisted corrosion in the corrosion environment used in this study. It therefore follows that coatings and paints can be applied to protect surfaces against corrosion, even if they are relatively thin (Buchheit, 2018). The same trend indicating a better protection capacity could be seen for 2 coats and 3 coats of the selected paints used. The results indicated that increasing coats facially showed a more resistance capacity to the corrosion media used for all the paints. Hence, it is evident that the selected local paints could be used as corrosion protection for reinforcing steel bars in concrete.

Apart from the red-oxide, the rest of the paint brands -Mat and Gloss - also showed similar protective capacity against corrosion. However, 3 coats of Mat by spraying showed thehighest linear polarization resistance to corrosion. The results can be found from Tables 2a – 2d for details of the various coating conditions. Further, the charts of Figures 4a-4f indicate graphical presentations of the corrosion currents and corrosion potentials for the various coating conditions and non-coated reinforcing steel bars in the corrosion medium used as described in Tables 2a – 2d.

From Figures 4a – 4f, the curves or Tafelplots indicate that the curves for coated specimens together with number of coatings moved more towards negative direction on the X-axis from the uncoated specimens (CHT-1 & CMS-1) resulting in a more negative corrosion current (I_{corr}) values. Similarly, more movement of the curvestoward thepositive direction can be seen on the Y-axis, resulting in a more positive corrosion potential (E_{corr}) values of the coated reinforcing steel bars in their various coating modes (automated or brush) and the number of coats as well as steel bar types (high yield steel or mild steel) compared to the uncoated specimens.

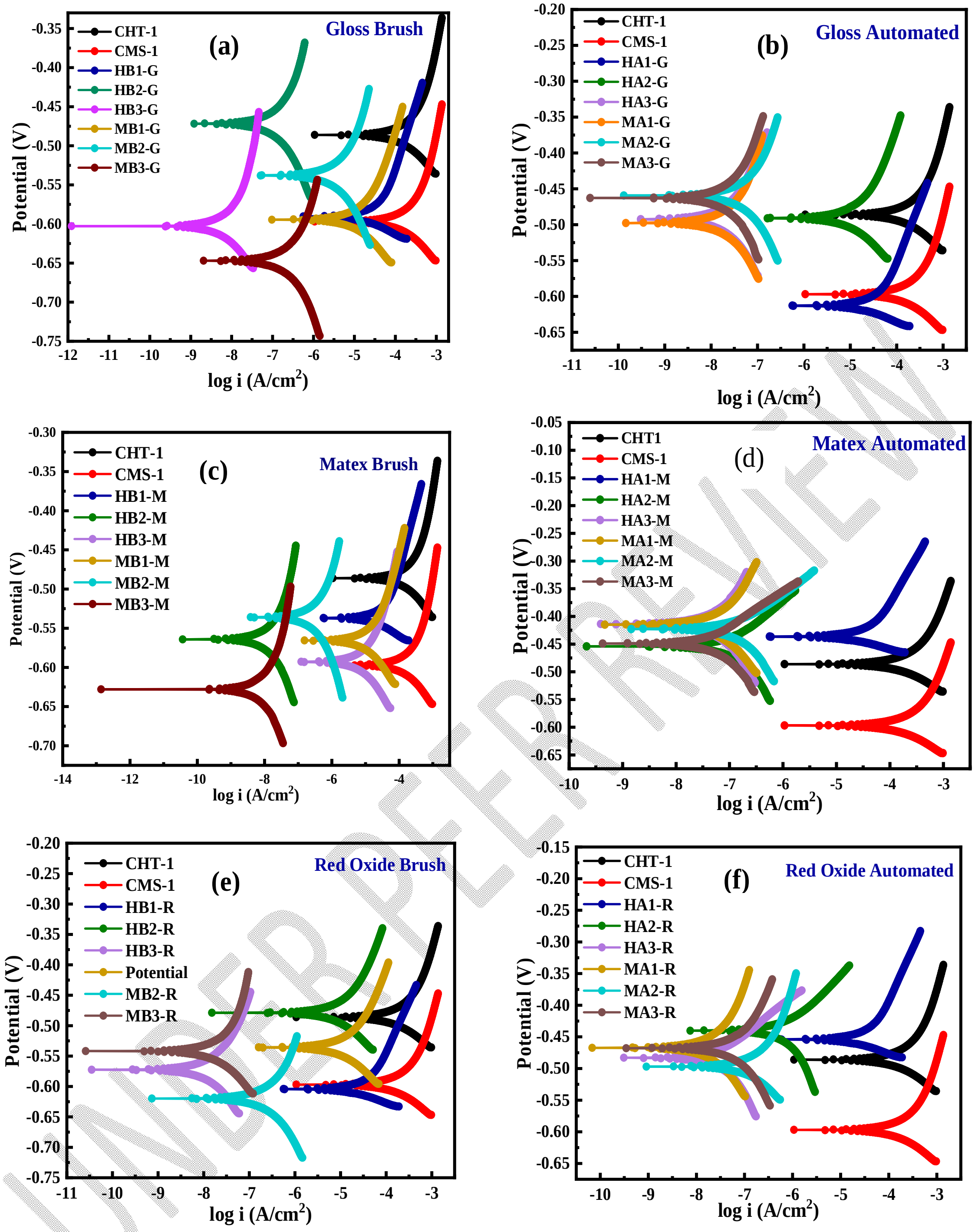

Fig. 4: Tafel plot for the selected paints and coating mode

(*Note: CHT-1 = high tensile steel control; CMS-1 = mild steel control; HA1-R = high tensile 1coat red-oxide by automation; HB1-R = high tensile red-oxide 1 coat by brushing; MA1-R mild steel 1 coat-red-oxide by automation; MB2-R mild steel 2 coats red-oxide by brush*)

For example, from Figures 4e & f, it can be seen that the corrosion potential(E_{corr}) is -0.61814 and -0.48617 Volts while the corrosion current (I_{corr})is $5.248x10^{-5}$ and $2.206x10^{-4}$ A/cm$^{\mathbf{2}}$ for mild steel and high yield steel uncoated (control) reinforcing steel bars(CMS-1 & CHT-1), respectively.

However, forthe coated steel bar specimens (withone coat of red-oxide) for both mild and high yield steels, the corrosion potentials (E_{corr} = -0.49169 and -0.3856) increase towards a positive region while the corrosion current(I_{corr} = $1.54x10^{-7}$and $2.18x10^{-7}$) decreased towardsthe negative region. This trend could be seen mostly in a better order from one coat to three coats accordingly for all the coating materials as well as the coating mode and type of steel in the corrosion medium used. This further proves that the paint coatings explored in this study develop good corrosion resistance capacity against the corrosion medium.

Furthermore, from Table 2a, the Tafel slope (b_a and b_c) - Anodic and Cathodic potentials - of the control or non-coated reinforcing bars for mild steel and high yield steel were b_a = 169.36, b_c = 49.71 mv/ decade and b_a =305.42, b_c = 121.53 mV/decade, respectively. Among the coated steel bars, even for one coat, a red-oxide- brush coated reinforcing steel bars (both mild steel and high yield steel), an increase occurred in the both cases to b_a =668.79, b_c = 369.99 mV/decade and b_a = 213.09 (less) andb_c = 132.69 respectively. These results indicate that corrosion resistance capacity of the paints was high. The trend remained same for higher coats and the other types of paints used except in a few cases where adecrease was seen in the b_a and b_c slopes which may be due to human error in the laboratory experiments. The various Tables 2a – 2d indicate all the details for the red-oxide, mat and gloss paints brands used as well as the coating modes and levels.

The conclusion from the above results is that the Leyland oil paint brands – red-oxide, mat and gloss - are capable of protecting reinforcing steel bars in concrete against corrosion.

3.2 Statistical Analysis

The above discussions concentrated on the stable polarization interpretation results as to how the paints used are capable of protecting reinforcing steel bars against corrosion. The generated values were used for the various variables tested for and which informed decisions in the discussion. However, there were variations in the results in terms of paint type, steel type, mode of coating and the number of coatings. In order to ascertain the variations, one-way analysis of variance (ANOVA) was conductedon the data. Largely, the resultsshow that significant difference existed between the corrosion protection resistance capacity of the paints used with regard to types,number of coats, mode of coating in comparison to the control specimens which were not coated, but not between the number of coats, coating mode or steel type (on corrosion rate, current, potential and LPR). This means that the differences observed visually in the values between these variables based on paint type, mode of coating, number of coating and steel type, were not significant enough to determine superiority in protecting capacity. Hence, these differences seen were due to chance. Thus, even though two coats proved more protective than one coat, and three coats proved more protective than one coat and two coats, the differences were not significant at 0.05 level of significance. Hence, all the coat types could perform approximately the same in terms of corrosion resistance to the reinforcing steel bars to which they were coated when the coat was damage-free. The details of the condition of significant difference are discussed next.

Three paint types/brands were employed for this study to establish their corrosion protection capacities. The paints included Leyland gloss, mat and red-oxideas against no paint coating.

Table 3a: Mean and standard deviation of the corrosion rate for paint types

Group	N	Mean	sd
No Paint	4	2.9493	2.7992
Gloss	12	0.0632	0.1130
Mat	12	0.0472	0.1035
Red-oxide	12	0.0472	0.1015
Total	**40**	**0.3422**	**1.1776**

Source: Lab result 2023 *sd = standard deviation*

From Table 3a, the means of values derived for corrosion rate from electrochemical test for the various paint types vary in face value. Thus, $M_{(4)} = 2.9493 > M_{(12)} = 0.0632 > M_{(12)} = 0.0472 > M_{(12)} = 0.0472$, respectivelyfor No Paint (control), Gloss, Red-oxide and Mat paints. However, to ascertain whether these differences are not due to chance, theone-way ANOVA result from Table 3b is nextconsidered.

Table 3b: One-way ANOVA summary of corrosion rate (mm/a) for paint types

Group	Sum of squares	df	Mean square	F	p-value	p
Between Groups	30.209	3	10.070	15.182	0.000	<0.05
Within Groups	23.877	36	0.663			
Total	**54.087**	**39**				

Source: Lab result 2023

As shown in Table 3b, the result $F_{(3, 39)} = 15.182$, $P < 0.05$ indicates that a significant difference exists between at least two of the means of the paint types used on corrosion rate retardation. Nonetheless, where the difference exists can be seen from the post hoc analysis Table 3c.

Table 3c: Post hoc summary of corrosion rate (mm/a) for paint types

Paint Type	1	2	3	4
No Paint				
Gloss	2.886*			
Mat	2.902*	0.016		
Red-oxide	2.902*	0.016	0.000	

Source: Lab result 2023 ** means significant at 0.05*

From the post hoc analysis results in Table 3c, the mean difference values $M_d = 0.016$, $P > 0.05$; $M_d = 0.016$, $P > 0.05$ and $M_d = 0.000$, $P > 0.05$ indicate that there is no significant difference between the mean corrosion rate of Gloss, Mat and Red-oxide paints used at 0.05 level of significance. Therefore, the differences seen between their means could be due to chance. Hence, they were about the same level in corrosion rate retardation, and the assumption that variation might exist in the corrosion rate protection of the various paint types used in the study was not confirmed. However, the result $M_d = 2.886^*$, 2.902^* and 2.902^* indicated a significant difference between the control (uncoated steel) and all other paints used at 0.05 level of significance. This shows that the paints used in the study have the capacity to significantly retard the rate of corrosion in acorrosion environment. The results shown in Fig. 5a on the mean plot for corrosion rate as the performance of all the paint types indicated about the same corrosion protection capacity. This trend was seen for corrosion current, linear polarization resistance (LPR) as well as the corrosion potential.

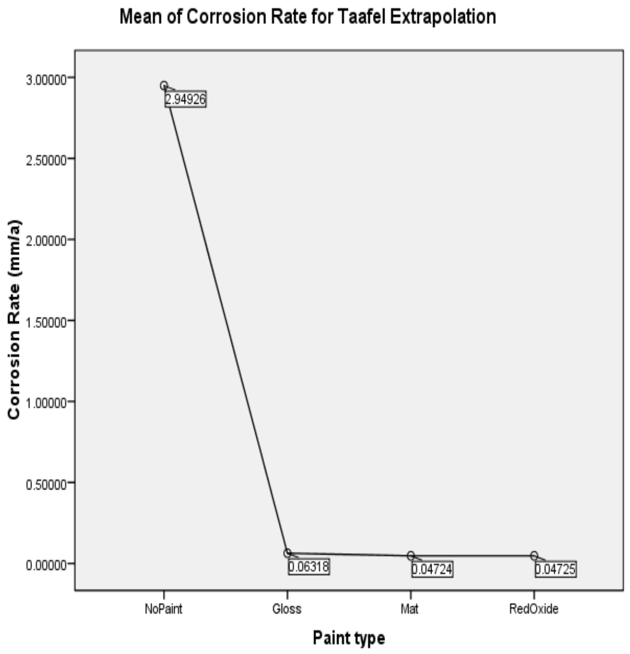

Fig. 5a: Mean corrosion rate for paint types

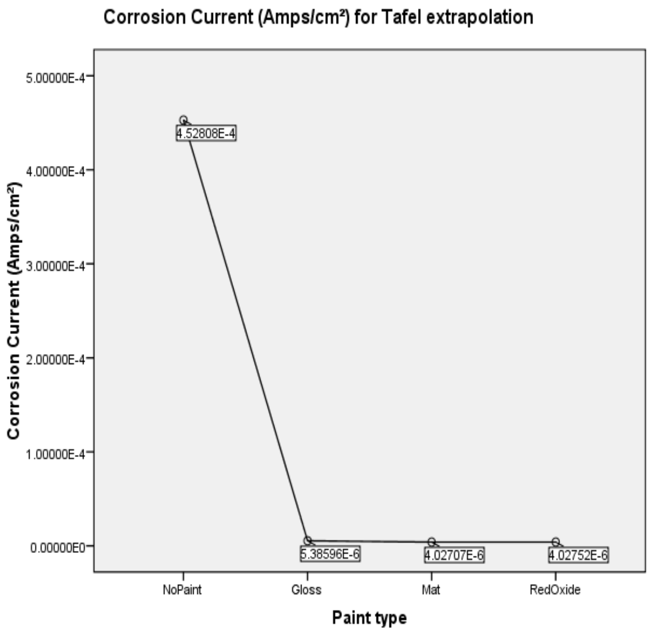

Fig. 5b: Mean corrosion current for paint types

Table 4a: Mean and standard deviation of the corrosioncurrent (Amps/cm^2) for painttypes

Group	N	Mean	sd
No Paint	4	$4.528\mathrm{x}10^{-4}$	$6\mathrm{x}10^{-6}$
Gloss	12	$5.386\mathrm{x}10^{-6}$	$9.63\mathrm{x}10^{-6}$
Mat	12	$4.027\mathrm{x}10^{-6}$	$8.82\mathrm{x}10^{-6}$
Red-oxide	12	$4.028\mathrm{x}10^{-6}$	$8.65\mathrm{x}10^{-6}$
Total	**40**	**$4.931\mathrm{x}10^{-5}$**	**$13.65\mathrm{x}10^{-5}$**

Source: Lab result 2023

From Table 4a, the statistical means for the various paint types vary superficially in face value for corrosion current. Thus, $M_{(4)} = 4.528\text{x}10^{-4} > M_{(12)} = 5.386\text{x}10^{-6} > M_{(12)} = 4.028\text{x}10^{-6} > M_{(12)} = 4.027\text{x}10^{-6}$, for No-Paint (Control), Gloss, Red-oxide and Mat paints respectively. However, to ascertain whether these differences were not due to chance, the one-way ANOVA analysis in Table 4b is presented for the discussion.

Table 4b: One-way ANOVA summary of corrosion current (Amps/cm^2) for paint types

Group	Sum of squares	df	Mean square	F	p-value	p
Between Groups	0.000	3	10.070	3093	0.000	<0.05
Within Groups	0.000	36	0.663			
Total	**0.000**	**39**				

Source: Lab result 2023

The result $F_{(3,\ 39)} = 3093$, $P < 0.05$ from Table 4b indicates that a significant difference exists between at least two of the means of the paint types used on corrosion current. The post hoc analysis presented in Table 4c identifies the existence of the difference.

Table 4c: Post hoc summary of corrosion current (Amps/cm^2) for paint types

Paint Type	1	2	3	4
No Paint				
Gloss	0.004*			
Mat	0.004*	0.000		
Red-oxide	0.004*	0.000	0.000	

Source: Lab result 2023 ** means significant at 0.05*

From the post hoc results in Table 4c, the mean difference values $M_d = 0.000$, $P > 0.05$; $M_d = 0.000$, $P > 0.05$ and $M_d = 0.000$, $P > 0.05$ indicate that there is no significant difference between the mean corrosion current of Gloss, Mat and Red-oxide paints used at 0.05 level of significance. Therefore, the differences seen between their means were due to chance. Hence, they were about the same level of retarding corrosion current, and the assumption that variation may exist in the corrosion current retardation of the various paint type used in the study could not be established. However, the resultsM_d = 0.004*, 0.004* and 0.004* indicate a significant difference between the control (No-Paint) and all the paints used at 0.05 level of significance. This shows that the paints used in the study have the capacity to retard significantly the corrosion current in corrosion environment compared to the control specimens. Thus, the uncoated steel bar had higher corrosion current indicating high corrosion tendency while a very low corrosion current values were recorded for the coated steel bars, indicating low/no corrosion tendency. The mean plot for corrosion current is also presented in Fig. 5b.

Table 5a: Mean and standard deviation of the corrosionrate (mm/a) for number of coats

Group	N	Mean	sd
Zero-coat	4	2.9493	2.7992
One-coat	12	0.0612	0.1005
Two-coats	12	0.0219	0.0669
Three-coats	12	0.0746	0.1332
Total	**40**	**0.3422**	**1.1776**

Source: Lab result 2023

From Table 5a and Fig.7, the means for the various number of coats vary superficially in value with the uncoated steel showing higher corrosion rate than the coated reinforcing steel bars. Thus $M_{(4)} = 2.9493 > M_{(12)} = 0.0746 > M_{(12)} = 0.0612 > M_{(12)} = 0.0219$, respectively for control (uncoated), three-coats, one-coat, and two-coats. However, in order to ascertain whether these differences are not due to chance, theone-way ANOVA result from Table 5b is next presented for consideration.

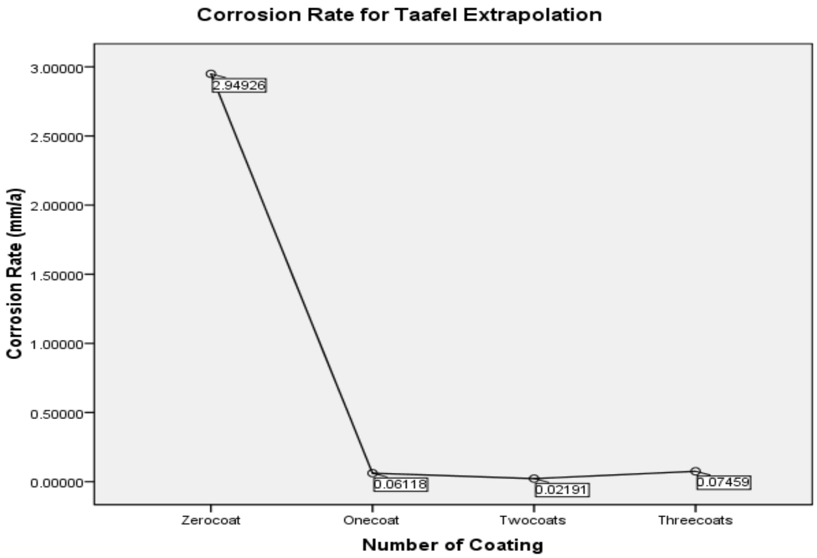

Fig. 6: Corrosion rate for number of coating

Table 5b: One-way ANOVA summary of corrosion rate (mm/a) for number of coats

Group	Sum of squares	df	Mean square	F	p-value	p
Between Groups	30.225	3	10.075	15.200	0.000	<0.05
Within Groups	23.861	36	0.663			
Total	54.087	39				

Source: Lab result 2023

The result $F_{(3, 39)} = 15.200$, $P < 0.05$ from Table 5b indicates thata significant difference exists between at least two of the means of the number of coats to the reinforcing steel bar on corrosion rate retardation. Post hoc analysis identifies the possible existence of any difference in the results of corrosion rate and number of coats in Table 5c.

Table 5c: Post hoc summary of corrosionrate (mm/a) for number of coats

Paint Type	1	2	3	4
No coat				
One coat	2.888*			
Two coats	2.927*	0.039		
Three coats	2.875*	-0.013	0.053	

Source: Lab result 2023 ** means significant at 0.05*

From the post hoc results in Table 5c, the mean differences $M_d = 0.039$, $P > 0.05$; $M_d = 0.013$, $P > 0.05$ and $M_d = 0.053$, $P > 0.05$ shows that there is no significant differenceat0.05 level of significance between the mean corrosion rate of one-coat, two-coats and three-coats of paints used, thus the differences seen between their means were due to chance. Hence, they were about the same level in corrosion rate retardation, and therefore, the assumption that variation might exist in the corrosion rate of the reinforcing steel bar due to thenumbers of paint coats was not confirmed. However, the result M_d = 2.888*, 2.927* and 2.875* indicated a significant difference between the zero-coat (Control), and all the different numbers of coatings used at 0.05 level of significance. This shows that each number of paint coatings used in the study has the capacity to retard significantly the rate of corrosion in corrosion environment. Hence, any number of coatings, either one-coat, two-coats or three-coats of the paints used in the study has very high (over 98%) corrosion protection capacity compared to the control. This trend was seen for corrosion current, linear polarization resistance (LPR) as well as the corrosion potential for number of coats (Figures 7a and 7b)

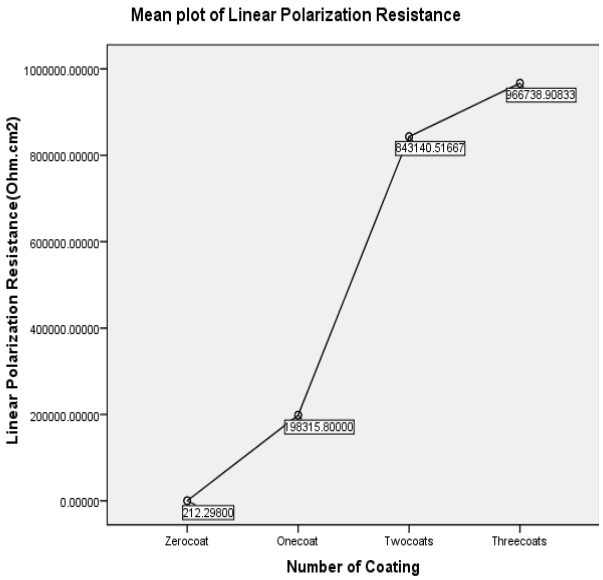

Fig. 7a: Corrosion LPR for number of coating

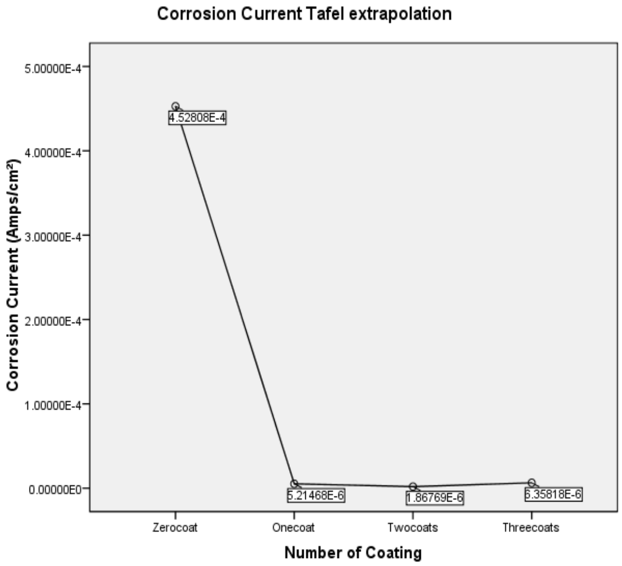

Fig.7b: Corrosion current for number of coating

Table 6a: Mean and standard deviation of corrosion rate for steel type

Group	N	Mean	sd
Mild Steel	20	0.0641	0.1617
High Tensile	20	0.6203	1.6302
Total	40	0.3422	1.1776

Source: Lab result 2023

It was intended to know if the type of steel could affect corrosion rate. From Table 6a, the means for the two types of steel used vary superficially in face value with regards to the coated reinforcing steel bars; that show corrosion rate values as $M_{(20)} = 0.0641 < M_{(20)} = 0.6203$ for mild and high tensile steels respectively. Nevertheless, in order to establish whether this variation was not due to chance, theone-way ANOVA result from Table 6b is nextconsidered and discussed.

Table 6b: One-way ANOVA summary of corrosion rate for steel type

Group	Sum of squares	df	Mean square	F	p-value	p
Between Groups	3.093	1	3.093	2.305	0.137	>0.05
Within Groups	50.993	38	1.342			
Total	54.087	39				

Source: Lab result 2023

From Table 6b, the value$F_{(1,\ 39)} = 2.305$, $P > 0.05$ indicates that no significant difference exists between the means of the coated steel types with regard to corrosion rate retardation. The difference seen between the means was not significant at 0.05 level of significance, and this means that the type of steel does not affect corrosion rate when coated with paint for corrosion protection. The trend was the same for corrosion current, LPR and corrosion potential.

Table 7a: Mean and standard deviation of corrosion rate for coating mode

Group	N	Mean	sd
Brush	20	0.3734	1.1867
Automated	20	0.3111	1.1985
Total	**40**	**0.3422**	**1.1776**

Source: Lab result 2023

Two modes of coating – manual by use of brush and automation by use ofspraying machine – were employed in coating the steel specimens for the study. From Table 7a, the means for the various coating modes used vary superficially in value with the coated reinforcing steel bars on corrosion rate; that is, $M_{(20)} = 0.3734 > M_{(20)} = 0.3111$ for brushing and automation respectively. However, to establish whether this variance was not due to chance, theone-way ANOVA result as presented in Table 7b is next considered.

Table 7b: One-way ANOVA summary of corrosion rate for coating mode

Group	Sum of squares	df	Mean square	F	p-value	p
Between Groups	0.039	1	0.039	0.027	0.870	>0.05
Within Groups	54.048	38	1.422			
Total	54.087	39				

Source: Lab result 2023

The result $F_{(1,\ 39)} = 0.027$, $P > 0.05$ in the table means that no significant difference exists between the means of the coating modes (brush and automation) on corrosion rate. The difference seen between the means is not significant at 0.05 level of significance. Thisresult means that the mode of coating does not influence corrosion rate of steel reinforcement coated with paint (with particular reference to the paints used in this study) for corrosion protection. It implies that irrespective of the coating mode or method used either by means of manualbrushing or automated spraying, the corrosion protection capacity of the paints used was the same and alsonot dependent on the steel type. However, it must be noted that as much as possible, pinholes should be avoided to achieve the level of perfection needed. This trend remains the same for LPR and corrosion current, but the reverse for corrosion potential.

Though thestatistical means of values did not show significant difference in number of coatings, paint type, coating mode and steel type on corrosion rate, current, potential and LPR, it could still guide the choice of method of coating, paint type, number of coating and or steel type during implementation of findings herein.

4.0 Conclusion

Stable polarization electrochemical test was conducted to determine the corrosion protection capacity of selected oil paint brands (made by Leyland in Ghana) to reinforcing steel in concrete. Varied coats, mode of coating and steel types were used to enable preference and specificity in practice or implementation of outcome of the study. The outcomes of the experimental tests are as follows:

- The Leyland paint brands – red-oxide, mat and gloss - are capable of protecting reinforcing steel bars in concrete against corrosion in concrete and therefore recommended for application.

- The paint coats, even one coat, showed decreased corrosion rate and corrosion current, andincreased linear polarization resistance (LPR) and corrosion potential; thus potency of protection against corrosion is indicated.
- Facially, protection capacity increased with increasing number of coats where 2 and 3 coats of mat paint indicated superiority over the others.
- Significant difference was seen between the mean values of the control/uncoated specimen and test specimens with reference tothe various corrosion parameters in favour of the selected paint brands; irrespective of number of coats, mode of coat, and or the steel on which they were applied.
- However, significant difference was not seen between number of coats, paint type, steel type and coating mode on corrosion rate, corrosion current, linear polarization resistance (LPR) and corrosion potential.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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