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Original Research Article

Electrochemical Techniques Assessment of Chloride Threshold for Reinforcing Steel Corrosion in Concrete Structures

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Abstract

Corrosion of steel reinforcement in reinforced concrete is one of the most significant problems affecting structures and infrastructure worldwide, especially coastal structures. This study investigated the direct application of exudates/resin extract of Lannea coromandelica as a potential inhibitive material to control and prevent the corrosion of steel bars embedded in concrete structures and exposed to high salinity and acidic prone environments. The extruded exudates / resin is extracted from the tree and layered to reinforcing steel of different thicknesses. The hardened concrete slab **is** completely immersed in a 5% sodium chloride (NaCl) aqueous solution for 360 days with routinely checks, monitors and tested for 90 days, 180 days, 270 days, and 360 days of accelerated and corrosion process for comparative evaluation of both uncoated and coated samples. The maximum corrosion potential yields from the controlled and coated samples were -109.24mV and -114.16mV, indicating the relationship between corrosion potential and corrosion probability in the reference range $E\text{corr} > -200\text{mV}$. For non-coated samples, the calculated maximum value is -333.97mV, the result is within the reference value of the relationship between corrosion potential and corrosion probability of $-350\text{mV} \leq E\text{corr} \leq -200\text{mV}$ indicates a high value range of 10% or less. The maximum calculated value of the controlled sample concrete resistance is 138.35% compared to the corroded and coated values of -56.56% and 153.43% and the maximum value of the control percentile difference is 24.97% compared to the corroded and coated value of 3.98% and 23.22%. The results of the controlled and layered concrete resistance samples obtained a maximum average value of 15.01kΩcm and 16.17kΩcm with a value of $10 < \rho < 20$ (low) compared to a corrosion value of 7.01kΩcm with a specification of $5 < \rho < 10$ (high) and with a reference range of the relationship between concrete resistance and corrosion probability and significant corrosion probability. The maximum computed percentile values of yield strength of controlled are 9.42% against corrode and coated values -8.03% and 9.57% respectively and the potential differential values of 0.71% controlled 0.71% corroded and 0.84% coated. The maximum computed percentile values of ultimate tensile strength of controlled are 1.68% against corrode and coated values -2.98% and 3.07% respectively and the potential differential values of 0.01% controlled, 0.00%% corroded, and 0.01% coated. Comparatively, the results of corroded samples showed reduction and decreased values in comparison of rebar diameter before and after induced accelerated corrosion test with values reduction percentile range from 0.038% to -0.895% and average ranges values from 11.98mm to 11.93mm. The reduction in average and percentile values showed that corrosion effects caused diameter reduction and cross-sectional area, fibre degradation, ribs reduction, and surface modifications whereas, exudates/resin coated members showed volumetric increase resulting from varying coating thicknesses. ***Conclusion:*** Summarized results showed that the effect of corrosion caused weight reduction/decreased in corroded samples as compared to coated with an exhibition of percentile and average value increase resulting in a volumetric minute increase from coating thicknesses.

Keywords: Corrosion, Corrosion inhibitors, corrosion potential, concrete resistivity and Steel Reinforcement.

1.0 INTRODUCTION

Corrosion retardation in steel reinforcement in concrete is caused by aggressive agents in the environment which affect the durability of the structure and increase premature deterioration. Some of the causes of damage to reinforced concrete are chloride,

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acid and sulfate attacks, the reaction of alkaline pore solutions with carbon dioxide in the atmosphere [1]. The decomposition of the thin protective oxide layer around the reinforcement and steel reinforcement is susceptible to corrosion [2]. When the corrosion process begins, corrosion products expand inward in the form of rust, causing cracks, dents, and poor load bearing capacity. Structural measures to increase the service life of concrete reinforcement are carried out by coating epoxy resin, waterproofing, reducing the water/cement ratio, increasing the reinforcing layer, commercial chemicals, cathodic protection, penetrating sealant [2]. One of the most economical and new control techniques available. Recently used or slowed corrosion of reinforcement in concrete is a corrosion inhibitor. Inhibitors can be applied to reinforced concrete structures while the concrete is being mixed or to the surface of existing reinforced concrete structures for repair work [3]. Inhibitors can be organic or inorganic depending on their use. Organic inhibitors include plant extracts. The advantages of green inhibitors compared to chemical inhibitor analogues are their availability, are less toxic, biodegradable, do not contain heavy metals, are environmentally friendly and are easily renewable [4].

Corrosion of reinforcement occurs when concrete is exposed to harsh environments such as high acidity, high Carbon dioxide content, and high human environment [5]. Concrete with a high pH value (around 12-13) usually forms a passive layer on the surface of the reinforcing steel. In this condition the steel is in a corrosion resistant condition [6]. However, the pH can drop if corrosive species get into the pores of the concrete. Types of corrosion such as Carbon dioxide and hydrogen sulphide and chloride that penetrate the pores of the concrete react with the reinforcing steel strips and cause corrosion of the steel. Corrosion products in the form of iron oxide / hydroxide increase the volume of steel up to 3 to 6 times the volume of the original steel, which can cause cracks in the concrete [7]; Asmara *et al.*, [8].

Corrosion affects the society in so many that has led to too expenses in repair of affected structures, too wasteful of natural resources during times of further concern for the damages to the environment and its environment causes serious human suffering and sometimes loss of life. Industrial metal corrosion is one of the oldest problems that its cost is enormous and translates into billions of dollars. However it can be considered as indicative of the order of protection as well added prevention of the cost of damage due to corrosion [9].

Investigated the corrosion potential, concrete resistivity, and tensile strength assessments of control, corroded, and coated reinforcing steel of concrete slab member with the direct application of corrosion inhibitor of dacryodes edulis resins of varying coating thicknesses to 12mm diameter reinforcement, embedded into the concrete slab and uncovered to extreme corrosive surroundings for 119 days for increased corrosion check, half-cell potential measurements, concrete resistivity measurement, and tensile assessments. When compared to corroded samples, corroded has 70.1% expanded values ability and 38.8% reduced values of concrete resistivity, yield and tensile strength of reinforcing decreased in corroded samples which resulted to the effect of corrosion on the reinforcing steel, followed by cross-section area reductions and weight loss. The controlled and coated samples exhibited standard load carrying capacity against the corroded [10].

Studied the effectiveness of calcium stearate as an inhibitor. They include carbon steel in the normal Portland cement standard IS: 456-2000. The results showed that the effectiveness of the inhibitor at concentrations of 3% and 5% for a 60-day trial with 3.5% NaCl was 90% and 93%, respectively. According to previous studies, these inhibitors reduce the corrosion rate of steel by blocking aerated concrete to limit the penetration of chloride ions [11].

Characterized Phyl-lannthus muellerianus as an inhibitor to reduce the corrosion of steel reinforcement in a powder environment. They used 0.5 M H2SO4 medium to simulate industrial/microbial medium. At a concentration of 6.67 g/l this inhibitor reduces the valve corrosion rate by up to 90%. At a concentration of 1.67%, the corrosion rate decreased by 78%. The results showed that the leaves of Phyllanthus muellerianus and Euphorbiaceae contain components of tannins, flabatanins, saponins, flavoids, terpenoids, and alkaloids P Mullerianus [12].

Investigated the effectiveness of green inhibitors made from orange peel waste. They extracted dried orange peel with methanol extract at an immersion time of 6 hrs in methanol at a pressure (60 mbar) and 40 °C. From the experimental data with electrochemical polarization measurements and weight loss assay for an anchor immersion time of 7 days, this inhibition showed good results in 3.5 wt.-% aqueous NaCl solution. Steel reinforcement showed that the degree of corrosion of reinforcement decreased to 0.02 mm/year at a concentration of 3% inhibitor [13].

Used Azadirachta indica (neem) powder and dehydrated aloe vera as corrosion inhibitors for steel in concrete. M class concrete is used with 20 mm coarse aggregate. Concrete is immersed in a solution with a salt content of about 3.5% (35 g/L). Concrete with green corrosion of non-removable inhibitors reduces the corrosion rate of steel in concrete from 0.3 mm / year to 0.22 mm / year. The inhibitor of aloe vera extract showed that the corrosion rate decreased to 0.27 mm/year. The inhibitor results showed that aza-dirachta indica (neem) had better corrosion efficiency than aloe vera inhibitor in hibiscus [14].

Investigated the effect of calcium palmitate alone and in combination with calcium nitrite on the corrosion of steel in concrete. The results showed that calcium palmitate was an effective inhibitor. After 90 days of exposure in 3.5% NaCl solution, the inhibitor offers 91 to 92% effectiveness. It has been shown that the inhibitor does not affect the mechanical strength of cement and concrete. Petrographic examination shows that calcium palmitate clogs the pores and reduces the corrosion rate of the steel. Further studies showed that calcium palmitate inhibits corrosion through an adsorption mechanism. The inhibitor forms a film on the steel surface through the polar carboxylate groups blocking the pores and forming an insoluble hydrophobic iron stearate salt [15].

Investigated rice husk powder for steel corrosion in concrete. They added rice husk extract to the concrete using the American method of designing a mixture (ACI 211) with strength of 30 MPa at 28 days of age. The fittings were compacted in tap water for 30 days by immersion in a 3.5% NaCl solution. Corrosion tests were carried out on solutions with different concentrations of inhibitors (1%, 2% and 3%). The data showed that the corrosion currents were 41.3 A/cm2 for solutions without inhibitor and 28.5 A/cm2 and 7.8 A/cm2 for solutions with 1% and 3% rice husk powder, respectively. This means that the corrosion reduction is 30% or 81% [16].

Investigated the electrochemical treatment that causes electron transfer during the corrosion process of steel reinforcement in a harsh marine environment with a high chloride content. The average comparison results show an increase in values from 70.1% compared to 27.2% of potential control and from 87.8% to 38.8% decrease in values for concrete resistance, tensile stress related to final strength in summary and average conditions of corroded slab with nominal 100% value and reduced maximum strength from 100.68% to 96.12%, weight loss compared to reduction in cross-sectional diameter reduced from 67.1% to 48.5% and from 98.2 % due to sodium chloride attack 94.82%. Compared with the corroded sample, the corroded has a 70.1% increase in the potential value of E_{corr}, mV and 38.8% reduce the value of the concrete strength, the tensile stress relative to the maximum force compared to corrosion, because the nominal yield strength from 100% from 103.06% to 96, a decrease of 12% and a decrease in weight of 67.5% versus 48.5% and a reduction of 47.80% to 94.82% in the cross-sectional diameter, both of which showed a reduced corrosion value compared to the sample with the cover [17].

Investigated the corrosion potential, resistance of concrete and control tests for tensile, corrosion and reinforcing steel coatings of slab concrete elements. Direct application of corrosion inhibitors to Dacryodes edulis resins of various thicknesses is applied to reinforcement with a diameter of 12 mm, which is embedded in a concrete slab and exposed to a highly corrosive environment for 119 days, for accelerated corrosion tests, half cell potential measurements, concrete resistance measurements and tests. Pull. Compared with the corroded sample, the corroded has a 70.1% increase in potential value and 38.8% decrease in the resistance value of concrete, the limit of tensile strength compared to corrosion, because the nominal tensile stress of 100% decreased from 100.95% to 96.12%. The weight loss in each case was 67.5% against 48.5% and 98.7% to 94.82%, the diameter reduction in cross-section, both showed higher corrosion values lower than that of the coated sample [18].

Investigating the effect of chloride attack on reinforcement embedded in reinforced concrete structures constructed in marine environments. Experimental work simulating a fast process through an accelerated process with uninhibited and unimpeded strengthening of Acardium occidental l. The resin extracts with a polish of varying thickness were immersed in a concrete slab and immersed in sodium chloride and accelerated for 119 days by the Wenner method with four probes. Compared with the corroded sample, the corroded has a 75.4% increase in the potential value of E_{corr}, mV and 33.54% reduced concrete resistance value, the yield and ultimate strength values decreased in corroded as compared to coated, also weight loss and cross-sectional area reduction also witnessed in corroded samples [19].

2.1 MATERIALS AND METHODS

2.1.1 Aggregates

Fine and coarse aggregates are purchased from sand piles. Both meet the requirements of [20].

2.1.2 Cement

Cement (limestone) 42.5 is used for all concrete mixtures. The cement meets the requirements [21].

2.1.3 Water

Water samples were obtained from the laboratory of the Civil Engineering Department of Kenule Beeson Polytechnic, Bori, Rivers State Bori. The water meets the requirements of [22].

2.1.4 Structural Steel Reinforcement

The structural steel reinforcement met [23] requirements, it was purchased from the market.

2.1.5 Corrosion Inhibitors (Resins / Exudates) Lannea coromandelica

The light-dark brown exudates are obtained from the wounded tree trunk. Exudates are liquid but change to solid states with time. They are obtained from

Aba Adetipe in Ife North Local Government Area of Osun state, Nigeria.

2.2 Experimental Procedure

2.2.1 Experimental method

2.2.2 Prepare Samples for Reinforcement with Coated

This study investigated the direct application of exudate/resin extract of Lannea coromandelica as a potential inhibitive material to control and prevent the corrosion of steel bars embedded in concrete structures and exposed to high salinity and acidic prone environments. The extruded exudate / resin is extracted from the tree and layered to reinforcing steel of different thicknesses. It is worth noting that the corrosion performance process is a long-term effect, spanning several decades until it fully surfaced, but the introduction of sodium chloride speeds up the corrosion rate and accelerated the corrosion rate in a short period. The degree of the corrosion rate is measured by estimating the current density obtained by the polarization curve and the degree of quantification of the corrosion rate. The concrete slabs for this investigation were prepared in batches according to the material weight using the manual mixing method with a standard concrete ratio of 1.2.4and a cement-to-water ratio of 0.65. By gradually adding cement, gravel (fine sand and coarse sand), and water to obtain a uniform color, standard concrete was obtained. The concrete slab has (thickness, width, and length) of 100mm×500mm×500mm, concrete is cast into a metal mold, compacted to air and void free, with 10mm cover to reinforcement, and reinforced with 10 numbers of 12mm diameter steel bars with a diameter at spacing of 100mm c / c (top and bottom, de-molded after 72 hours, cured at standard room temperature for 28 days to harden. The hardened concrete slab is completely immersed in a 5% sodium chloride (NaCl) aqueous solution for 360 days with routinely checks, monitors and tested for 90 days, 180 days, 270 days, and 360 days of accelerated and corrosion process for comparative evaluation of both uncoated and coated samples**.**

2.3 Accelerated Corrosion Test

The corrosion process is a natural phenomenon and requires decades to manifest fully. This is a long-term process, but the rapidly accelerated corrosion process using sodium chloride (NaCl) corrodes the steel bars embedded in the concrete and can simulate the intensification of corrosion that occurs within a short period of decades. To test the corrosion resistance of concrete, an experimental method has been developed to accelerate the corrosion process and maximize the corrosion resistance of the concrete. The accelerated corrosion test is an impressive latest technology. It is an effective technology that can check the reinforcement corrosion process in concrete and evaluate the damage of the concrete protective layer to steel bars. The laboratory acceleration process helps to distinguish the effects of various factors that may affect chloride corrosion. To construct structural elements and corrosion resistance, as well as to select suitable materials and suitable protection systems, accelerated corrosion tests were carried out to obtain quantitative and qualitative information about corrosion.

2.4 Corrosion current measurement (Half-Cell Potential Measurement)

The classification of steel reinforcement corrosion severity is shown in Table 2.1. If the potential measurement results show that the possibility of corrosion is high, the degree of corrosion can be assessed by measuring the resistivity of the concrete. However, care must be taken when using this data because it is assumed that the corrosion rate is constant over time. Practical experience has also proved this point [24, 25]. The measurement of average potential is an indirect method to estimate the likelihood of corrosion. Recently, there has been a great interest in the development of tools for the electrochemical measurement of the interference of the steel itself to obtain a direct estimate of the corrosion rate (Stem and Geary [26]). Corrosion rate refers to electrochemical measurements, first based on data.

Table 2.1: Dependence between potential and corrosion probability [27]

Potential E_{corr}	**Probability of Corrosion**
$E\text{corr} < -350\text{mV}$	Greater than 90% probability that reinforcing steel corrosion is occurring in that area at the time of measurement
$-350\text{mV} \leq E_{corr} \leq -200\text{mV}$	Corrosion activity of the reinforcing steel in that area is uncertain
$E_{corr} > -200\text{mV}$	90% probability that no reinforcing steel corrosion is occurring in that area at the time of measurement (10% risk of corrosion

2.5 Test for measuring the Resistivity of concrete

Thisobtains different measured values at different points on the surface of the concrete. After the water is applied to the surface of the board, the resistivity of the concrete is measured at a reference point every day to determine its saturation state. This location is chosen on the side of the panel because special resistivity measurements can be made with water on the top of the panel. In this study, the hearing aid was recorded as the final resistivity measurement. The saturation of the slab is controlled by measuring the resistivity of the concrete.

The resistivity is directly related to the moisture content of the concrete. Once one plate reaches saturation, water will flow out while the other plate remains closed. The time limit is a huge challenge for all experimental measurements because the saturation state of concrete will change over time. This study used the Wenner method with four probes. To this end, the four probes directly contact the concrete of the reinforced rail.Since the water cement ratio of each plate is different, the time required to saturate each plate is also different. Before applying water to the slab to measure the resistivity of the concrete in certain places in a dry state. Once the concrete reaches saturation, the resistivity immediately becomes a constant value.

Table 2.2: Dependence between Concrete Resistivity and Corrosion Probability [28]

Concrete resistivity ρ, kΩcm	**Probability of corrosion**
$\rho < 5$	Very high
$5 < \rho < 10$	High
$10 < \rho < 20$	Low to moderate
$\rho > 20$	Low

2.6 Tensile Strength of Reinforcement

The determination of that the yield point and the maximum ultimate tensile strength peak point of the reinforcing steel bar, the concrete slab is reinforced with 10 numbers of 12 mm diameter reinforcing steel for each for both coated and uncoated steel and subjected with pressure to failure state using Instron universal testing machine (UTM) for results validation. The digital and computerized system records the results of the yield strength, the maximum tensile strength, and the strain ratio. To ensure stability, use the remaining cut part for the diameter of the steel bar before the test, the diameter of the steel bar after corrosion, the reduction/increase of the cross-sectional area after corrosion, the weight of the steel bar (before the test), and the weight of the steel bar (after corrosion), and checks other parameters of weight loss and gain.

3.0 TEST RESULTS AND DISCUSSION

For ease of explanation the measurement of the half-cell potential is plotted graphically against concrete resistivity. It is used to indicate the significant corrosion probability (ρ 20) of extremely high, extremely high, extremely low to medium and extremely low corrosion probability. At another measurement point, the correction potential is very high ($-350\ \text{mV} \le E\text{corr} \le -200\ \text{mV}$), indicating that the probability of corrosion is 10% or uncertain. The measurement results of the concrete resistivity are shown in Table 2.2. Facts have proved that if the corrosion potential is low (<-350 mV) within a certain range, the probability of corrosion is 95%. The electrical resistivity of concrete is usually measured using the four-electrode method. Data from resistivity studies indicate whether certain states will cause less ion movement, which leads to more corrosion.

Table 3.1: Potential E_{corr}, after 28 days curing and 360days Accelerated Periods of Control Concrete slab Specimens

Sample Numbers	**LCS**	**LCS 1**	**LCS 2**	**LCS 3**	**LCS 4**	**LCS 5**	**LCS 6**	**LCS 7**	**LCS 8**	**LCS 9**	**LCS 10**	**LCS 11**
	Time Intervals after 28 days curing											
Sampling and Durations	**Samples 1 (28 days)**			**Samples 2 (28 Days)**			**Samples 3 (28 Days)**			**Samples 4 (28 Days)**		
Potential Ecorr,mV	-113.6	-114.3	-110.4	-108.6	-111.5	-108.2	-116.4	-112.1	-107.7	-110.1	-114.0	-115.6
Concrete Resistivity ρ, kΩcm	14.98	14.97	14.96	14.96	14.95	15.12	15.11	15.10	15.10	15.09	15.03	14.95
Yield Strength, fy (MPa)	457.65	460.65	456.65	456.95	457.65	456.88	459.88	460.18	458.88	460.27	456.78	460.61
Ultimate Tensile Strength, fu (MPa)	620.66	618.61	620.29	616.07	619.60	620.02	619.82	620.62	619.22	620.77	620.27	620.13
Strain Ratio	1.36	1.34	1.36	1.35	1.35	1.36	1.35	1.35	1.35	1.35	1.36	1.35
Rebar Diameter Before Test (mm)	11.99	11.97	11.98	12.00	11.97	11.99	11.99	11.97	11.97	11.97	11.97	11.98
Rebar diameter at 28 days(mm)	11.99	11.97	11.98	12.00	11.97	11.99	11.99	11.97	11.97	11.97	11.97	11.98
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rebar Weights- Before Test	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
Rebar Weights- After at 28 days (Kg)	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
Weight Loss /Gain of Steel (Kg) at 28 days	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 3.2: Potential Ecorr, after 28 days curing and 360days Accelerated Periods of Corroded Concrete slab Specimens

Sampling and Durations	**Samples 1 (90 days)**			**Samples 2 (180 Days)**			**Samples 3 (270 Days)**			**Samples 4 (360 Days)**		
Potential Ecorr, mV	-326.2	-339.4	-336.3	-328.7	-338.5	-345.5	-379.4	-386.6	-390.7	-413.8	-419.2	-427.8
Concrete Resistivity ρ, kΩcm	5.91	6.05	6.88	7.19	6.96	6.52	6.34	6.69	6.73	6.33	5.70	8.00
Yield Strength, fy (MPa)	417.18	418.18	421.18	421.48	420.18	419.41	422.41	422.71	421.41	422.80	419.31	423.14
Ultimate Tensile Strength, fu (MPa)	610.45	608.40	610.08	605.86	609.39	609.81	609.61	610.41	609.01	610.56	610.06	609.92
Strain Ratio	1.46	1.46	1.45	1.44	1.45	1.45	1.44	1.44	1.45	1.44	1.46	1.44
Rebar Diameter Before Test (mm)	11.98	11.97	11.98	12.00	11.97	11.99	11.99	11.97	11.97	11.97	11.97	11.98
Rebar Diameter- After Corrosion(mm)	11.94	11.92	11.93	11.95	11.92	11.94	11.94	11.92	11.93	11.93	11.92	11.93
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Rebar Weights- Before Test (Kg)	0.91	0.92	0.91	0.91	0.91	0.92	0.92	0.92	0.92	0.91	0.92	0.92
Rebar Weights- After Corrosion (Kg)	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
Weight Loss /Gain of Steel (Kg)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Table 3.3: Potential Ecorr, after 28 days curing and 360days Accelerated Periods of Lannea coromandelica Exudate / Resin Coated Specimens

Sampling and Durations	**Samples 1 (90 days)**			**Samples 2 (180 Days)**			**Samples 3 (270 Days)**			**Samples 4 (360 Days)**		
	150µm (Exudate/Resin) coated			**300µm (Exudate/Resin) coated**			**450µm (Exudate/Resin) coated**			**600µm (Exudate/Resin) coated**		
Potential Ecorr, mV	-112.81	-115.78	-115.38	-115.35	-111.75	-115.86	-114.04	-117.81	-114.41	-109.01	-109.49	-115.71
Concrete Resistivity ρ, kΩcm	15.72	15.87	16.15	16.28	15.97	16.26	16.21	16.36	16.39	15.86	15.75	15.60
Yield Strength, fy (MPa)	458.27	461.27	457.27	457.57	458.27	457.50	460.50	460.80	459.50	460.89	457.40	461.23
Ultimate Tensile Strength, fu (MPa)	629.15	627.10	628.78	624.56	628.09	628.51	628.31	629.11	627.71	629.26	628.76	628.62
Strain Ratio	1.37	1.36	1.38	1.37	1.37	1.37	1.36	1.37	1.37	1.37	1.38	1.36
Rebar Diameter Before Test (mm)	12.00	11.98	11.99	12.01	11.98	12.00	12.00	11.98	11.98	11.98	11.98	11.99
Rebar Diameter- After Corrosion(mm)	12.05	12.03	12.04	12.06	12.03	12.05	12.05	12.03	12.03	12.03	12.03	12.04
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Rebar Weights- Before Test (Kg)	0.91	0.93	0.91	0.92	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Rebar Weights- After Corrosion (Kg)	0.99	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Weight Loss /Gain of Steel (Kg)	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07

Table 3.4: Average Potential Ecorr, after 28 days curing and 360days Accelerated Periods (Control, Corroded and Exudate/Resin Coated (specimens)

Sampling and Durations	**Control Concrete slab Specimens**				**Corroded Concrete slab Specimens**				**Lannea coromandelica Exudate / Resin Coated Specimens**			
	Average Potential Ecorr, Values of Control Concrete slab Specimens				**Average Potential Ecorr, Values of Corroded Concrete slab Specimens**				**Average Potential Ecorr, Values of Lannea coromandelica Exudate / Resin Coated Specimens**			
Potential Ecorr, mV	-112.6	-111.0	-109.9	-109.2	-333.9	-334.8	-334.5	-337.5	-114.6	-115.5	-114.1	-114.3
Concrete Resistivity ρ, kΩcm	14.97	14.96	14.96	15.01	6.28	6.71	7.01	6.89	15.92	16.10	16.14	16.17
Yield Strength, fy (MPa)	458.32	458.08	457.08	457.16	418.85	420.28	420.95	420.36	458.94	458.70	457.70	457.78
Ultimate Tensile Strength, fu (MPa)	619.85	618.32	618.65	618.56	609.65	608.12	608.45	608.36	628.34	626.81	627.14	627.05
Strain Ratio	1.35	1.35	1.35	1.35	1.46	1.45	1.45	1.45	1.37	1.37	1.37	1.37
Rebar Diameter Before Test (mm)	11.98	11.98	11.98	11.98	11.98	11.98	11.98	11.98	11.99	11.99	11.99	11.99
Rebar Diameter- After Corrosion(mm)	11.98	11.98	11.98	11.98	11.93	11.94	11.94	11.94	12.04	12.05	12.05	12.05
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.04	0.06	0.06	0.06	0.06
Rebar Weights- Before Test (Kg)	0.86	0.86	0.86	0.86	0.92	0.92	0.91	0.91	0.92	0.92	0.92	0.92
Rebar Weights- After Corrosion (Kg)	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.99	0.99	0.99	0.99
Weight Loss /Gain of Steel (Kg)	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.07	0.07	0.07	0.07

Table 3.5: Average Percentile Potential Ecorr, after 28 days curing and 360days Accelerated Periods (Control, Corroded and Exudate/Resin Coated (specimens)

	Control Concrete slab Specimens				**Corroded Concrete slab Specimens**				**Lannea coromandelica Exudate / Resin Coated Specimens**			
	Percentile Average Potential Ecorr, Values of Control Concrete slab Specimens				**Percentile Average Potential Ecorr, Values of Corroded Concrete slab Specimens**				**Percentile Average Potential Ecorr, Values of Lannea coromandelica Exudate / Resin Coated Specimens**			
Potential Ecorr, mV	-66.27	-66.85	-67.14	-67.64	191.28	189.86	193.00	195.28	-65.67	-65.50	-65.87	-66.13
Concrete Resistivity ρ, kΩcm	138.35	123.18	113.38	117.81	-60.54	-58.36	-56.56	-57.40	153.43	140.18	130.21	134.71
Yield Strength, fy (MPa)	9.42	8.99	8.58	8.75	-8.74	-8.38	-8.03	-8.17	9.57	9.14	8.73	8.90
Ultimate strength (N/mm2)	1.67	1.68	1.68	1.68	-2.98	-2.98	-2.98	-2.98	3.07	3.07	3.07	3.07
Strain Ratio	-7.14	-6.70	-6.37	-6.50	6.36	5.85	5.47	5.62	-7.38	-6.53	-7.19	-6.82
Rebar Diameter Before Test (mm)	0.038	0.035	0.036	0.037	0.038	0.035	0.037	0.039	0.038	0.038	0.035	0.036
Rebar Diameter- After Corrosion(mm)	0.335	0.353	0.354	0.361	-0.895	-0.902	-0.906	-0.957	1.043	0.996	1.015	1.028
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.00	0.00	0.00	0.00	-28.07	-28.07	-28.07	-28.07	39.02	39.02	39.02	39.02
Rebar Weights- Before Test(Kg)	0.396	0.399	0.397	0.398	0.392	0.401	0.397	0.401	0.399	0.397	0.396	0.399
Rebar Weights- After Corrosion (Kg)	8.93	8.93	9.04	8.93	-12.85	-12.85	-12.88	-12.87	14.75	14.75	14.79	14.77
Weight Loss /Gain of Steel (Kg)	0.00	0.00	0.00	0.00	-22.86	-21.74	-23.94	-23.94	29.63	27.78	31.48	31.48

3.1 Results of Potential E_{corr}, mV, and Concrete Resistivity ρ, kΩcm on Concrete Slab Members

The half-cell potential monitoring method is the most widely used quality method for detecting the corrosion of reinforcing steel. It was introduced in the 1970s [29]. This technique was standardized by ASTM in 1980 as C876 "Standard Method for Testing the Half-Cell Potential of Uncoated Reinforced Steel in Concrete".

The E_{corr}, mV potentialand kΩcm, concrete resistivity yields obtained fromthe data presented in Tables 3.1 - 3.3 and summarized into mean and percentile values in Tables 3.4 and 3.5,and graphically represented in Figures 3.1-3.7b, are the results of36 concrete slab samples of12 controlled samples, 12non-coated (corroded), and 12 exudates / resin coated samples in which the controlled samples were determinant reference range in which all other computed values are referenced from as the bases.

The obtained results ofthe derived and computed mean and percentileminimum, maximum and differential values of the calculated measurements of the corrosionpotential of the controlled sample were -112.66mV and -109.24mV (-67.64% and -66.27%) with a potential difference of 3.42mV and 1.37%, the corroded samples were -337.56mV and -333.97mV (189.86% and 195.28%) and the difference values were 3.59mV and 5.42%, and the samples coated are -115.51mV and -114.16mV (-66.13% and -65.5%) and the potential difference is 1.35mV and 0.63%, respectively. The maximum calculated controlled percentile value is -66.27% compared to the corroded and coated values of 195.28% and -65.5% and the controlled potential difference value is 1.37%, corroded 5.42% and coated 0.63% . The maximum corrosion potential yields from the controlled and coated samples were -109.24mV and -114.16mV, indicating the relationship between corrosion potential and corrosion probability in the reference range $E_{corr} > -200\text{mV}$. The results of these potential E_{corr} results indicate that the values of controlled samples and exudates/resin coated samples are low with a 90% probability that no corrosion of the reinforcement is observed at the time of measurement (10% corrosion risk, 10% or indicates an uncertain corrosion probability. For non-coated samples, the calculated maximum value is -333.97mV, the result is within the reference value of the relationship between corrosion potential and corrosion probability of $-350\text{mV} \leq E_{corr} \leq -200\text{mV}$ indicates a high value range of 10% or less. The obtained differential computed comparative results of the reference range of (controlled) show that corrosion samples exhibited non- inhibitory corrosion properties as a result of accelerated induced corrosion compared to coated samples showing no corrosion/resin exhibiting inhibitory properties against corrosion attack on steel reinforcement exposed to corrosive environments through the formation of a resistance layer as related to the studies of [10, 17, 19].The resistance layers provided a thick membrane that repels the scourge of corrosion attacks on the embedded exudates coated reinforcing steel in the concrete slab.

The average value and the minimum and maximum percentile of concrete resistivity with controlled sample corrosion potential difference are 14.96kΩcm and 15.01kΩcm (113.38% and 138.35%) and the difference value is 0.05kΩcm and 24.97%. The corrosion samples were 6.28kΩcm and 7.01kΩcm (-60.54% and -56.56%) and the difference values were 0.73 kΩcm and 3.98%. The coated sample values were 15.92kΩcm and 16.17kΩcm (130.21% and 153.43%) and the difference values were 0.25kΩcm and 23.22% respectively. The maximum calculated value of the controlled sample concrete resistance is 138.35% compared to the corroded and coated values of -56.56% and 153.43% and the maximum value of the control percentile difference is 24.97% compared to the corroded and coated value of 3.98% and 23.22%. The results of the controlled and layered concrete resistance samples obtained a maximum average value of 15.01kΩcm and 16.17kΩcm with a value of $10 < \rho < 20$ (low) compared to a corrosion value of 7.01kΩcm with a specification of $5 < \rho < 10$ (high) and with a reference range of the relationship between concrete resistance and corrosion probability and significant corrosion probability ($\rho < 5$, $5 < \rho < 10$, $10 < \rho < 20$, $\rho > 20$)for very high, high, low to moderate and low , for possible corrosion. From the comparison results obtained with the coated and corroded samples, the maximum values obtained for the two samples clearly indicate that the value of the coated samples lies in the range of $10 < \rho < 20$, which classifies the range of values from lowest to moderate, with information as significant corrosion probability. The maximum value of the corroded sample is in the range $5 < \rho < 10$, which indicates high, signs indicating the possibility of corrosion, as in the works [10, 17, 19]. From the results obtained, it can be compared that the effect of corrosion attack was observed in uncoated samples, while samples with exudate/resin coating had anti-corrosion properties with highly resistant and water-resistant membranes that prevented corrosion of concrete. -the reinforcing steel plate is embedded and exposed to the induced accelerated corrosion medium.

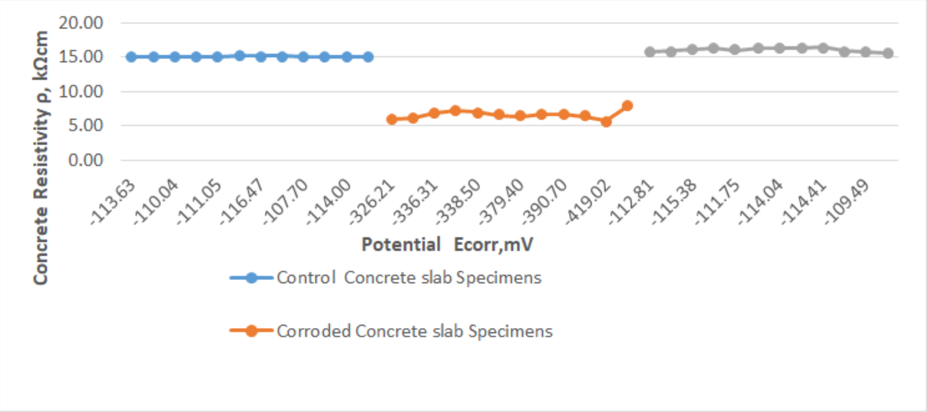

Figure 3.1: Concrete Resistivity ρ, kΩcm versus Potential E_{corr},mV Relationship

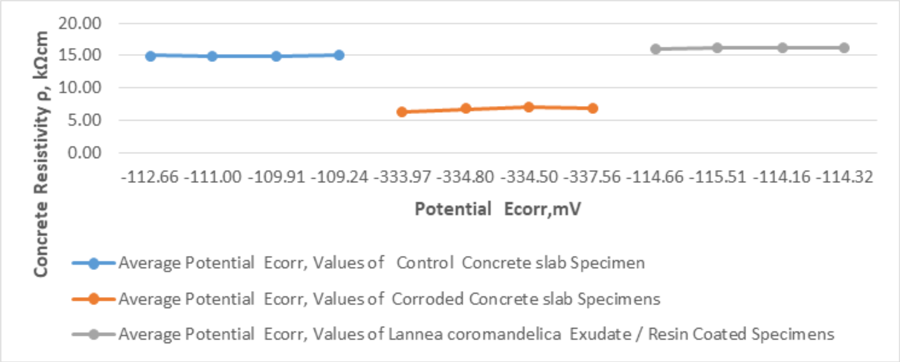

Figure 3.1A: Average Concrete Resistivity versus Potential Relationship

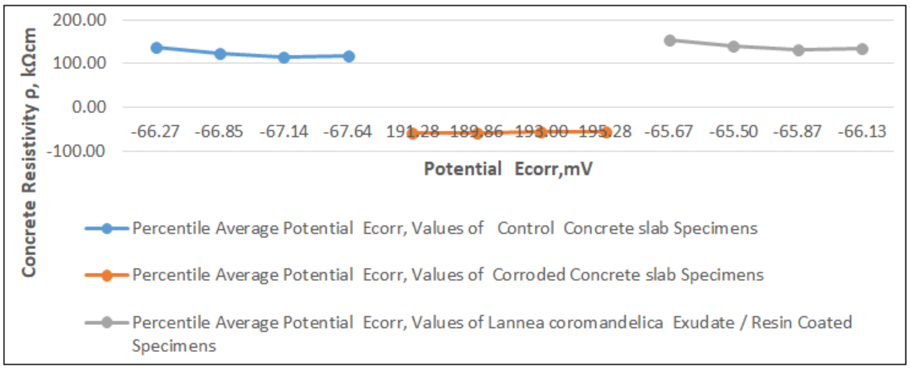

Figure 3.1B: Average Percentile Concrete Resistivity versus Potential Relationship

3.2 Results of Mechanical Properties of Yield Strength, Ultimate Strength and Strain Ratio of Embedded Reinforcing Steel in Concrete Slab

The results of the average, percentile, and differential values of minimum and maximum yield strength, fy (MPa) of controlled samples are 457.08MPa and 458.32MPa (8.58% and 9.42%) and the differential values are 1.24MPa and 0.84%, the corroded samples are 418.85Mpa and 420.95Mpa (-8.74% and -8.03%) and differential values of 2.1MPa and 0.71%, the coated sample values are 457.7MPa and 458.94MPa (8.73% and 9.57%) and differential values of 1.24MPa and 0.84%. The maximum computed percentile values of yield strength of controlled are 9.42% against corrode and coated values -8.03% and 9.57% respectively and the potential differential values of 0.71% controlled 0.71% corroded and 0.84% coated.

The average, percentile and differential values of minimum and maximum ultimate tensile strength, fu (MPa) of controlled samples are 618.32MPa and 619.85MPa (1.67% and 1.68%) and differential values of 1.53MPa and 0.01%, the corroded are 608.12MPa and 609.65MPa (-2.98MPa and -2.98%) and differentials of 1.53MPa and 0.0%, the coated are 626.81MPa and 628.34Mpa (3.07% and 3.07% and differential values are 1.53MPa and 0.01%. The maximum computed percentile values ofultimate tensile strength of controlled are 1.68% against corrode and coated values -2.98% and 3.07% respectively and the potential differential values of 0.01% controlled, 0.00%% corroded, and 0.01% coated.

The strain ratio minimum and maximum average, percentile and differential values of controlled samples are 1.35 and 1.35(-7.14 % and -6.37%) with differential values of 0.00 and 0.77%, the corroded sample values are 1.45 and 1.46(5.47 and 6.36%) and differential values of 0.01 and 0.89%, the coated samples are 1.37 and 1.37(-7.38% and -6.53%) and differential values of 0.00 and 0.85%. The maximum computed percentile values for comparison are controlled -6.37% against corroded 6.36% and coated -6.53% and the differential peak values are controlled 0.77%, corroded 0.89% and coated 0.85% as validated in the works of (Charles *et al*., [10]; Charles *et al*., [17]; Charles *et al*., [19].

From the computed obtained results summarized in tables 3.4 and 3.5 and presented graphically in figures 3.1 – 3.8, of yield strength, ultimate tensile strength, and strain ratio of the average, percentile, and differential potential values of the controlled, non-coated(corroded), and coated concrete slab samples, the coated samples recorded higher failure load over corroded samples with decreased failure load and low load carrying capacity and having average and percentile values to the reference range while the non-coated (corroded) recorded low carry capacity and decreased values as compared to the reference ranges. The comparative results showed that the low load-carrying capacity was attributed to the effect of corrosion attacks on the non-coated (corroded) members that affected the reinforcing steel fibre, ribs, and formation of passivity and surface modification. The coated samples maintained values in both at average was attributed to the resistive potential to corrosion entrance into the reinforcing steel with the formation of protective membrane, these attributes showed the effectiveness and the efficiency of exudates/resin as an inhibitive material against corrosion effect of reinforced concrete structures exposed to the severe coastal marine regions with high salinity.

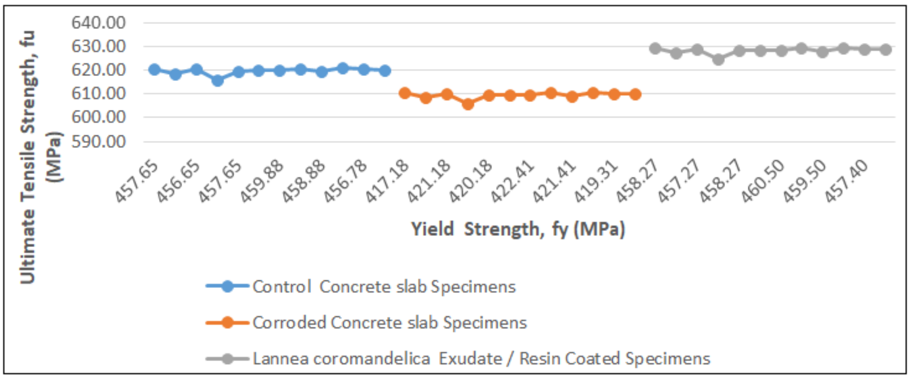

Figure 3.2: Yield Strength versus Ultimate strength

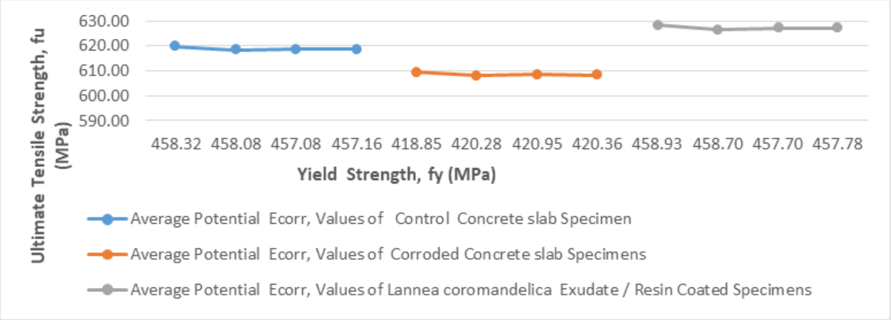

Figure 3.2A: Average Yield Strength versus Ultimate Tensile Strength

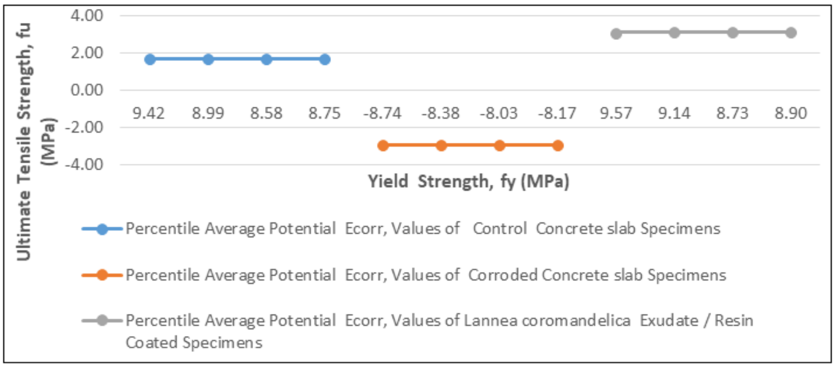

Figure 3.2B: Average Percentile Yield Strength versus Ultimate Tensile Strength

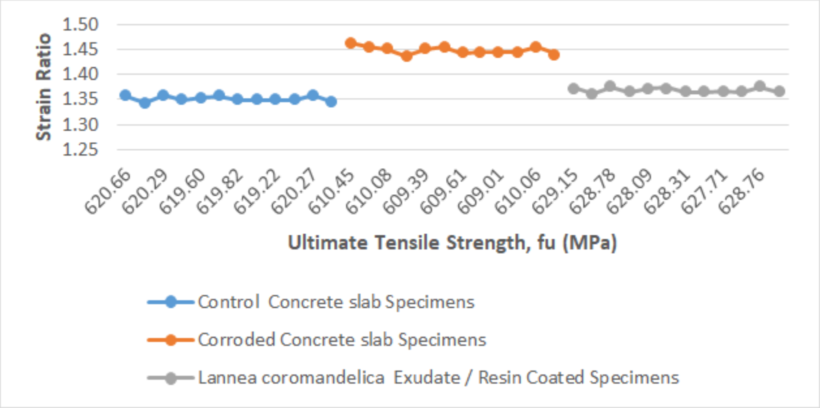

Figure 3.3: Ultimate Tensile StrengthversusStrain Ratio

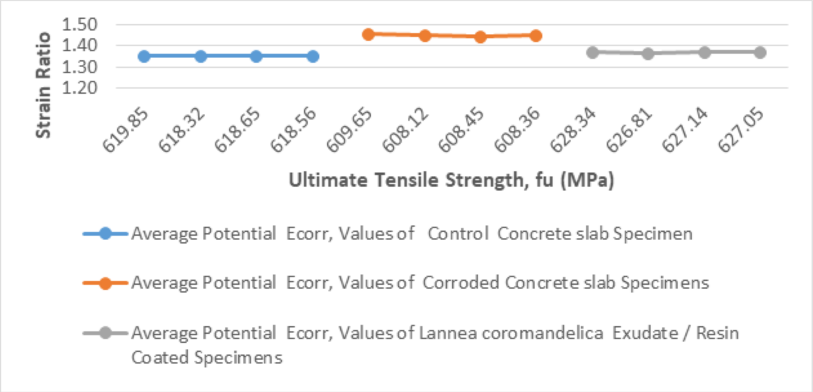

Figure 3.3A: Average Ultimate Tensile Strength versus Strain Ratio

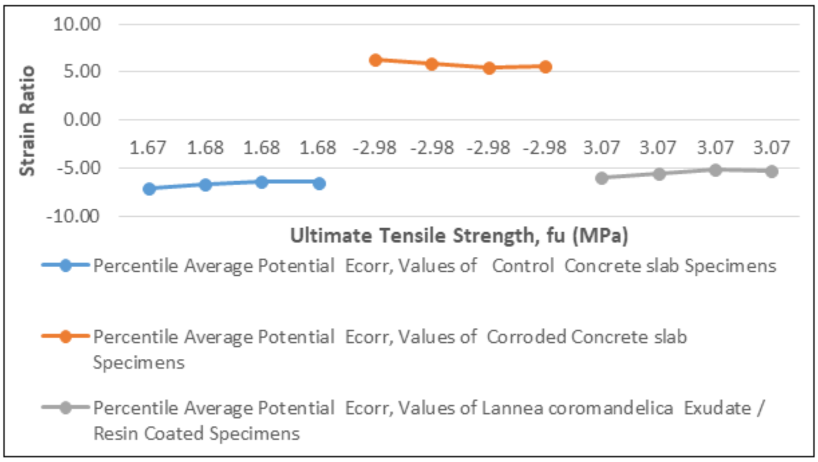

Figure 3.3B: Average percentile Ultimate Tensile Strength versusStrain Ratio

3.2 Results of Mechanical Properties of Yield Strength, Ultimate Strength and Strain Ratio ofEmbedded Reinforcing Steel in Concrete Slab

The rebar diameter before test (mm) minimum and maximum average and percentile values are controlled 11.98mm and 11.98mm (0.035% and 0.038%) with differential values of 0.00mm and 0.003%, the corroded sample values are 11.98mm and 11.98mm (0.035% and 0.039%) and differential values of 0.00mm and 0.004% and the coated sample values are 11.99mm and 11.99mm (0.035% and 0.038%) and differentially computed values of 0.01mm and 0.003%. The unit weight of rebar before the corrosion test exhibited infinitesimal differences based on product and company molds as well as the byproducts used in the manufacturing processes. The minimum and maximum obtained average, percentile and differential values of rebar diameter-after corrosion (mm) for controlled samples are 11.98mm and 11.98mm (0.035% and 0.038%) with differential values of 0.00mm and 0.003%, having 100% maintained reference value, the corroded sample values are 11.93mm and 11.94mm (-0.957% and -0.895%) and differentials of 0.01mm and 0.062%, the coated samples values are 12.04mm and

12.05mm (0.996% and 1.043%) and differentials of 0.01mm and 0.047%. The rebar diameter-after corrosion (mm maximum computed percentile values are controlled 0.038% against corroded -0.895% and coated 1.043%, the percentile difference is corroded 0.062% against 0.047% coated. The results obtained in tables 3.4 and 3.5 as summarized from tables 3.1, 3.2, and 3.3, and represented graphically in figures 3.3-3.6b showed the effects of corrosion attacks on the reinforcing steel embedded in the concrete slab and exposed to induced corrosion acceleration activities. Comparatively, the results of corroded samples showed reduction and decreased values in comparison of rebar diameter before and after induced accelerated corrosion test with values reduction percentile range from 0.038% to -0.895% and average ranges values from 11.98mm to 11.93mm.

The cross-sectional area reduction/increase (diameter) minimum and maximum average and percentile values are controlled 100%, no reduction or increased notice after 360 days immersion in freshwater. The corroded sample values are 0.04mm and 0.04mm(-28.07% and -28.07%) and differentials of 0.00% and **0.00**% at corroded, the coated sample values are 0.06mm and 0.06mm (39.02% and 39.02%) and differentials of 0.00mm and 0.00%. The comparatively results cross-sectional area reduction/increase average and percentile value differences between of coated and corroded samples are with the ranges of 39.02% to -28.07%. The reduction in average and percentile values showed that corrosion effects caused diameter reduction and cross-sectional area, fibre degradation, ribs reduction, and surface modifications whereas, exudates/resin coated members showed volumetric increase resulting from varying coating thicknesses as validated in the works of (Charles *et al*., [10]; Charles *et al.*, [17]; Charles *et al*., [19]. It can be summarized that exudates/resin exhibited inhibitive characteristics against corrosion influences on reinforcing steel embedded in concrete slab samples that were induced in a highly salinity environment. The rebar weights -before test (Kg) results of minimum, maximum and differential average and percentile values of controlled samples are 0.86kg and 0.86kg (6.385% and 6.708%) and differentials are 0.00% and 0.323%, the corroded sample are 0.91kg and 0.92kg (6.387% and 6.469%) and differentials of 0.01% and 0.082%, the coated samples are 0.92kg and 0.92kg (6.211% and 6.505%) with differentials of 0.00% and 0.294%.

The rebar weights-after corrosion(Kg) average and percentile results and the summarized differential values of the minimum and maximum values of controlled samples are 0.86kg and 0.86kg (6.385% and 6.708%) and differentials are 0.00% and 0.323%, the corroded samples are 0.86Kg and 0.86Kg (-12.88% and -12.85%) and differentials of 0.00% and 0.03%, the coated sample values are 0.99kg and 0.99kg (14.75% and 14.79%) and differentials of 0.00% and 0.04%. The average and percentile minimum and maximum unit weight loss /gain of steel (Kg) and the percentile differences in comparison are controlled 100% maintained values resulting from pooling in a freshwater tank with no traces of corrosion potentials against the corroded sample values of 0.05kg and 0.05kg (-23.94% and -21.74%) and the coated are 0.07kg and 0.07kg (27.78% and 31.48%). The computed results obtained from tables 3.1-3.3 and summarized in 3.4 - 3.5, and graphically plotted in figures 3.7-3.87 enumerated the effect of corrosion on non-coated (corroded) and coated reinforcing steel and the examination of unit weight of rebar before and after corrosion test and as well as the weight loss/gain. Comparatively, obtained rebar weights-after corrosion(Kg) results showed average and percentile values reduction / decreased and increased with coated with 0.07kg to 0.05Kg and 31.48% to -21.74% corroded, as validated in the works of [10, 17, 19]. Summarized results showed that the effect of corrosion caused weight reduction/decreased in corroded samples as compared to coated with an exhibition of percentile and average value increase resulting in a volumetric minute increase from coating thicknesses. The investigated study showed the effectiveness and efficiency of exudates/resin as an inhibitory material against corrosion effects on reinforcing steel embedded in concrete slab samples exposed to the induced corrosion.

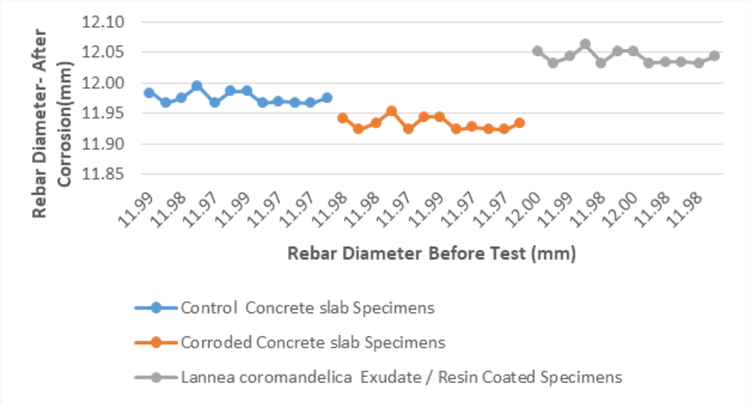

Figure 3.4: Rebar Diameter Before Test (mm) versus Rebar Diameter- After Corrosion (mm)

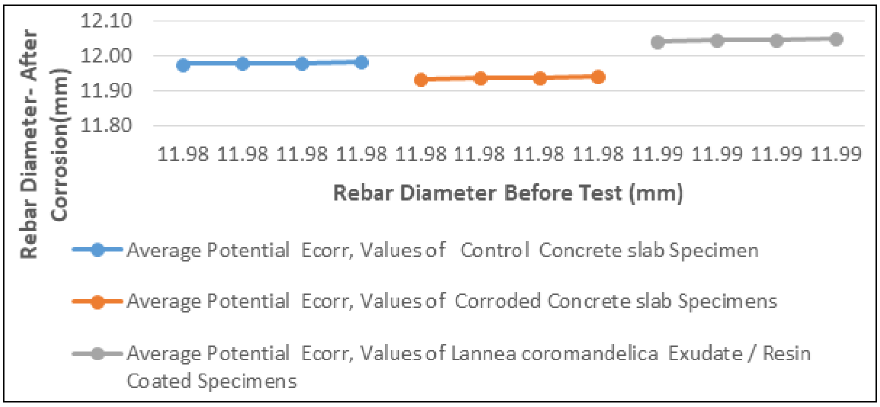

Figure 3.4A: Average Rebar Diameter Before Test (mm) versus Rebar Diameter- After Corrosion (mm)

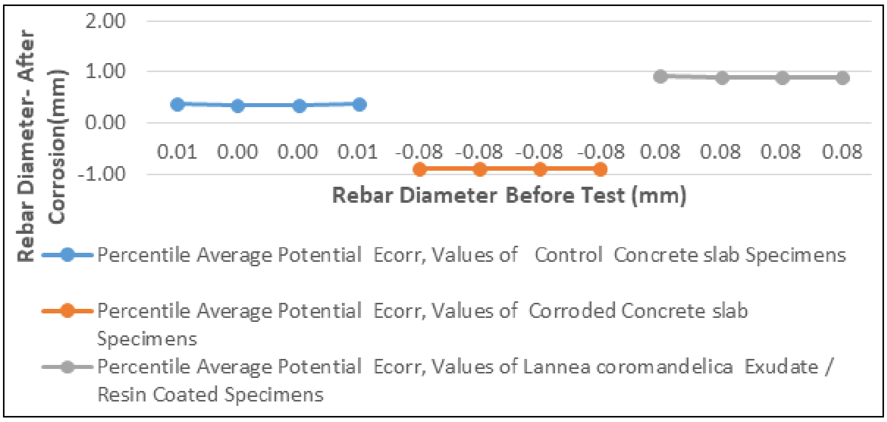

Figure 3.4B: Average Percentile Rebar Diameter Before Test(mm) versus Rebar Diameter- After Corrosion (mm)

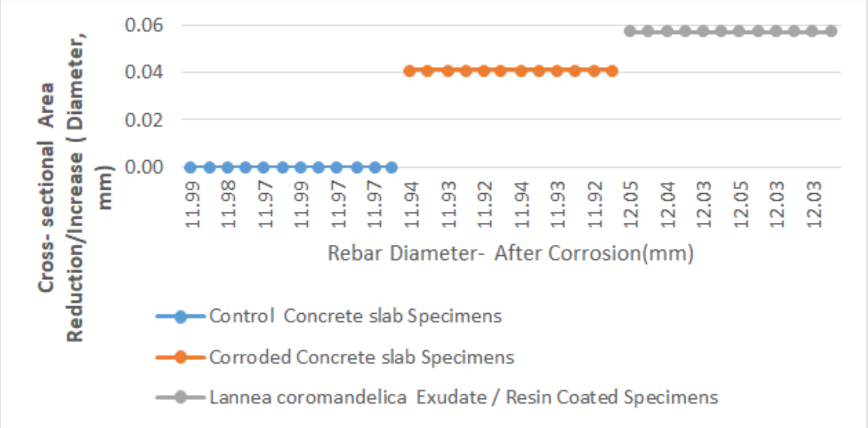

Figure 3.5: Rebar Diameter- After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

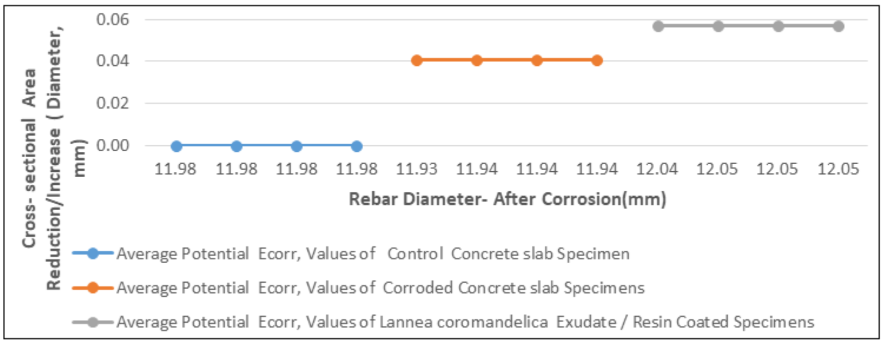

Figure 3.5A: Average Rebar Diameter- After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

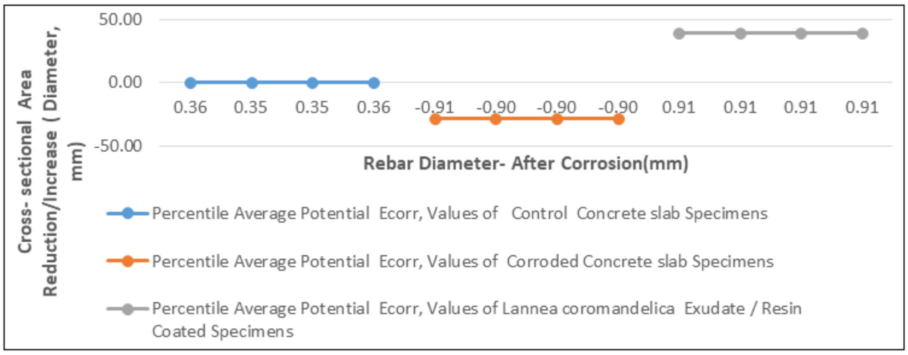

Figure 3.5B: Average Percentile Rebar Diameter- After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

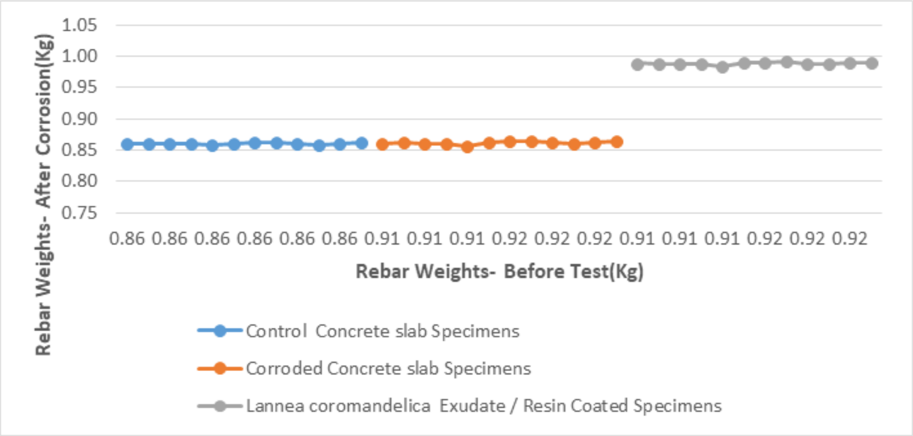

Figure 3.6: Rebar Diameter - After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

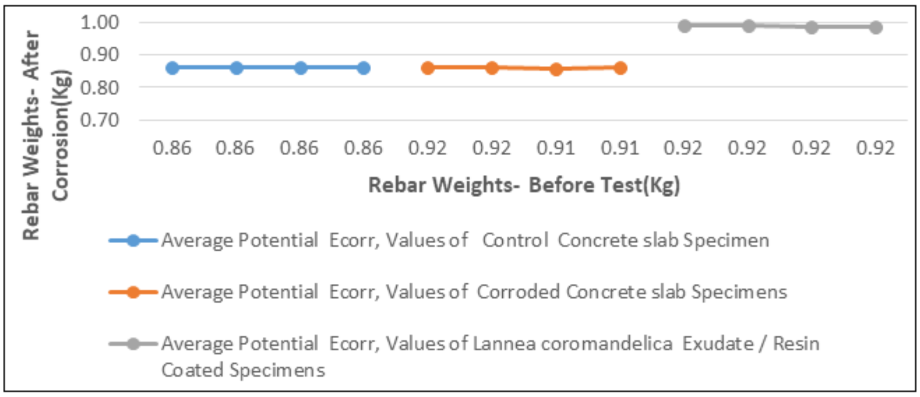

Figure 3.6A: Average Rebar Diameter - After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm

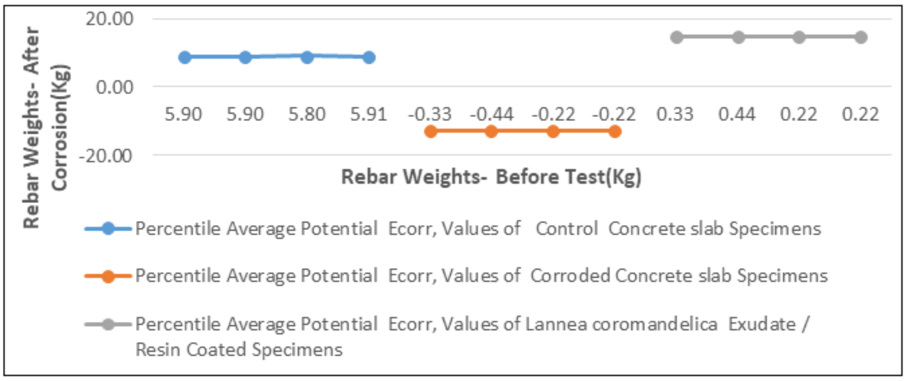

Figure 3.6B: Average Percentile Rebar Diameter - After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

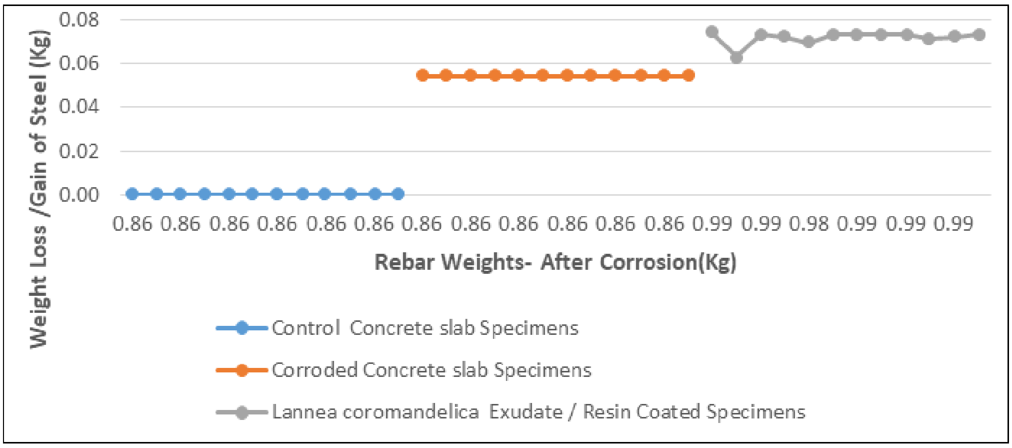

Figure 3.7: Rebar Weights- After Corrosion (Kg) versus Weight Loss /Gain of Steel (Kg)

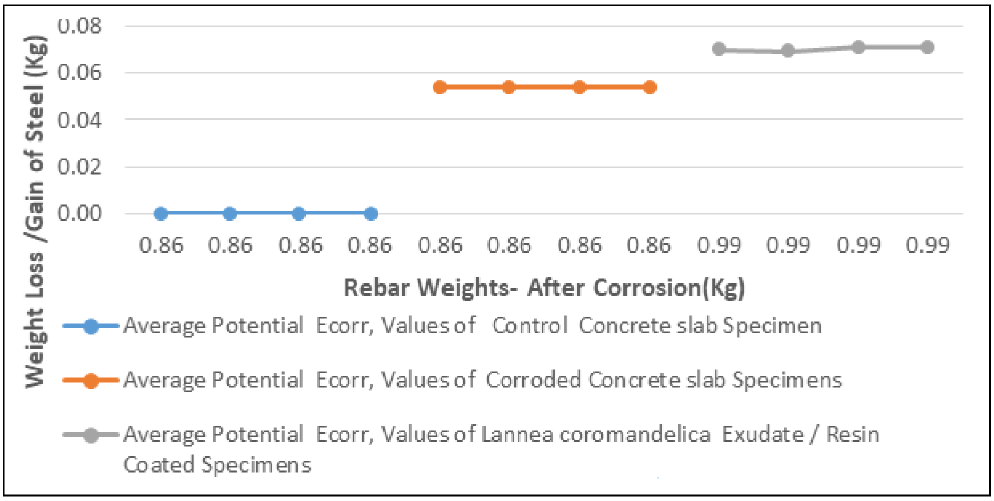

Figure 3.7A: Average Rebar Weights- After Corrosion (Kg) versus Weight Loss /Gain of Steel (Kg)

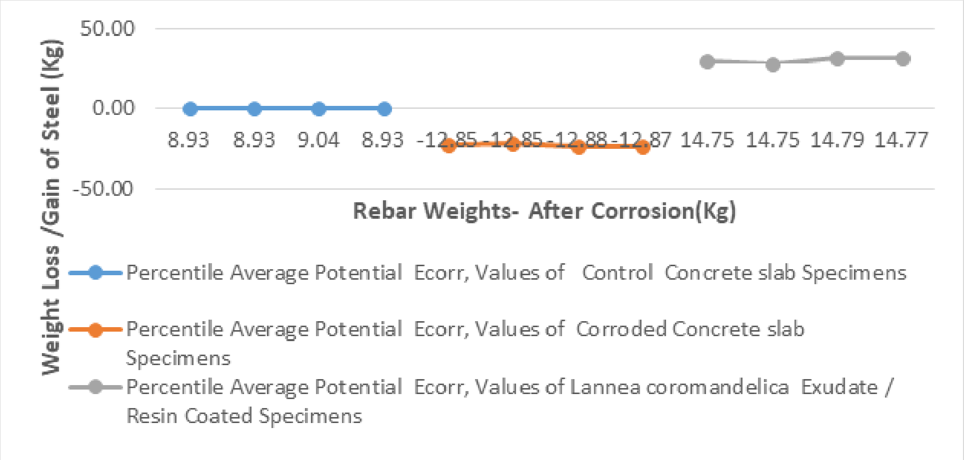

Figure 3.7B: Average Percentile Rebar Weights- After Corrosion (Kg) versus Weight Loss /Gain of Steel (Kg)

4.0 CONCLUSION

Experimental results showed the following conclusions:

1. The obtained differential computed comparative results of the reference range of (controlled) show that corrosion samples exhibited non- inhibitory corrosion properties as a result of accelerated induced corrosion compared to coated samples
2. Comparatively, the results of corroded samples showed reduction and decreased values in comparison of rebar diameter before and after induced accelerated corrosion test compared to coated with an exhibition of percentile and average value increase resulting in a volumetric minute increase from coating thicknesses.

3. The investigated study showed the effectiveness and efficiency of exudates/resin as an inhibitory material against corrosion effects on reinforcing steel embedded in concrete slab samples exposed to the induced corrosion
4. The reduction in average and percentile values showed that corrosion effects caused diameter reduction and cross-sectional area, fibre degradation, ribs reduction, and surface modifications whereas, exudates/resin coated members showed volumetric increase resulting from varying coating thicknesses.
5. The comparative results showed that the low load-carrying capacity was attributed to the effect of corrosion attacks on the non-coated (corroded) members that affected the reinforcing steel fibre, ribs, and formation of passivity and surface modification.

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