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Chloride Threshold Ingress Evaluation of Corrosion Probability Using Concrete Electrical Resistivity and Half-Cell Potential Measurements

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Abstract

The application of Sticky gummy paste of anogeissus combretaceae exudates/resin extracted from tree extrudes was studied. It was used as an inhibitive material to control the manifestation corrosion effect on steel bars in built-in high salinity coastal areas. The extracted exudates/resin was coated to reinforcing steel and embedded in the concrete slab, exposed to corrosive media with high salt concentration. The results of maximum calculated percentile of the controlled sample value is -64.36% compared to the corroded and coated value of 154.98% and -60.05% and the controlled corrosion potential differential value is 1.19%, corroded 4.66% and coated 0.73% . The maximum yield of controlled and coated samples was -108.04mV and -122.85mV, which showed the relationship between corrosion potential and probability reference of $E_{\text{corr}} > -200\text{mV}$ as a reference range. For non-coated (corroded) samples, the maximum calculated value is -310.58mV; the result is within the reference value of the relationship between corrosion potential and probability of $-350\text{mV} \leq E_{\text{corr}} \leq -200\text{mV}$ value indicating a high value range close to 10% or an uncertain corrosion probability in comparison to the reference range. The maximum calculated percentile of the controlled sample concrete resistance is 141.67% compared to the corroded and coated value of -52.84% and 131.05% and the maximum percentile differential of control are 23.15% compared to the corroded and coated value of 3.87 % and 18.94%. The results of the controlled and layered concrete resistance samples obtained a maximum average value of 15.96kΩcm and 15.47kΩcm with a data value of $10 < \rho < 20$ (low) compared to a corrosion value of 7.28kΩcm with a specification of ($5 < \rho < 10$) and with the reference range of the relationship between concrete resistance and corrosion probability. The maximum percentile value calculated from the controlled yield strength is 9.96% against corroded sample and the coated value is -9.21% and 10.67% and the possible differentials value is 0.43% controlled 0.43% corroded and 0.52% coated. The calculated maximum values of the controlled tensile strength percentiles were 2.348% against corrosion and the coated values were -4.08% and 4. 27% and the potential differential values were 0.01% checked, 0.01%% corroded and 0 0.01% coated. The coated samples for yield strength, tensile strength and deformation ratio of the average, percentile and differential potential values of the control, plate samples. uncoated (corroded) and coated concrete had higher breaking loads compared to corroded specimens with reduced failure loads and low load bearing capacity and with average and percentile values compared to the reference range, whereas uncoated samples (corroded) indicated a low load-bearing capacity and reduced value compared to the reference range. The diameter of reinforcement after corrosion maximum calculated percentile value controlled 0.043% versus -1.11% corroded and 1.114% coated, the difference in percentage between corroded 0.121% versus 0.008% coated. The effect of corrosion attack on reinforcing steel embedded in the concrete slab and exposed to corrosion induced acceleration effect. The aggregate results show that the corrosion effect causes a weight reduction/weight reduction in the corroded samples compared to coatings with a percentage exposure and an average increase, resulting in a small increase in the volume of the coating thickness. This study shows the effectiveness and efficiency of exudates/resin as an inhibitor against the effects of corrosion on reinforcement embedded in samples of concrete slabs exposed to induced corrosion.

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

1.0 INTRODUCTION

Chloride attack is a major problem in reinforced concrete and can be obtained from the constituents of the concrete mixture itself or from the diffusion of chloride ions from the environment [1]. It can also be incorporated into the aggregate as an impurity. In developing countries where there is no easy access to clean water, seawater is used in the concrete mix, which brings chloride into the system. Chloride ions are responsible for the initiation of this reaction is then released back into the pore solution [2]. Stated that the hydroxide ions in the concrete continues to resist the efforts of chloride in the destruction of the passive layer through porous simulation, mathematical calculations and laboratory experiments with bare steel rods in a chloride contaminated concrete environment, the successes of breaking down chloride and passive film depends on the ratio of chloride ions to the hydroxide ions on steel-concrete interface. A concrete with a lower resistance makes it possible to transport more and faster than the hydroxyl ions from the cathode to the anode in an effort to measure the rate corrosion of de-passivated steel bar, embedded in concrete corrodes. Today the four-probe method (or methods Wenner) is the method most widely used and studied for the evaluation of in-situ concrete resistivity. The four probe resistivity meter, also known as a probe Wenner, contains four equally spaced electrodes that are positioned along a straight line.

Corrosion of steel reinforcement is one of the most common factors causing damage to concrete structures. Reinforcing steel has serious corrosion problems when in contact with water, salt (NaCl) and carbon dioxide (CO2). In industrial areas containing CO2, H2S, S and C, the corrosive types are more complex, thus complicating the corrosion mechanism [3-7]. Corrosion of the reinforcement not only damages the concrete, but also reduces the strength of the concrete. Typical forms of reinforcement corrosion are direct corrosion, galvanic corrosion and pitting. Black rust can also appear along the steel bars embedded in marine structures that occur constantly saturated. A steel bar embedded in a moist, chloride contaminated concrete environment, may also be susceptible to corrosion macrocell. Macrocell corrosion typically seen in moist, chloride contaminated concrete, where together the two conditions create electrolytes which can reduce the electrical resistance of the concrete that surrounds the embedded bar.

To ensure long-term operation, an integrated approach to selecting the right material to protect the reinforcing steel from corrosion is required. Among the various methods of protection, several advantages are ascribed to the use of inhibitors mixed in concrete. To avoid environmental problems, green corrosion inhibitors have become a promising key. Environmentally friendly inhibitors, compatible with all types of concrete and economically affordable. Therefore, research studies on green corrosion inhibitors are increasing rapidly. The beneficial properties of green inhibitors, or often referred to as organic inhibitors, are environmental and biodegradable [8, 9]. Green corrosion inhibitors are mainly made from natural plant extracts which are abundant in many countries. Most green inhibitors usually contain P, N, S, O. These atoms coordinate with metal ions to form a protective layer on the metal surface that inhibits further corrosion processes [9].

Stated that the mechanism is that onion cations are adsorbed on the cathode site of the metal surface to block the corrosion reaction. With further clarification, they suggested several inhibitory mechanisms, namely adsorption on metal surfaces, changes in anodic and/or catholic reactions, diffusion rates, and reduction of electrical resistance [10].

Investigating the corrosion potential, resistance of concrete and tensile tests of stainless, corrosion and coated reinforcing steel of slab concrete elements. Direct application of corrosion inhibitors to varying thicknesses of Dacryodes edulis resin coated with 12 mm diameter reinforcement, embedded in a concrete slab and exposed to a highly corrosive environment for 119 days for accelerated corrosion testing, half cell potential measurement, resistance measurement concrete and tensile test. 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% and shown in Figures 3.5 and 3.6 in the respective cases the weight reduction of 67.5% vs. 48.5% and 98.7% to 94.82%, the reduction of the cross-sectional diameter, both showed a decrease in the corrosion value compared to the coated samples [11].

Introduced garcinia cola exudates/resin extract as a corrosion inhibitor in reinforcing steel immersed in concrete slabs in a corrosive medium during an acceleration period of 150 days to induce surface changes, modifications and evaluate mechanical properties. The results showed a high final yield of corroded specimens for control samples and coated specimens due to the effect of corrosion on the mechanical properties of reinforcing steel. The results of the weight loss of steel showed a high percentile value compared to the control and coated samples due to the effect of corrosion on the mechanical properties of the steel [12].

Investigating the effect of chloride attack on reinforcement embedded in reinforced concrete structures constructed in a marine environment. The experimental work simulated a fast process through an accelerated process at uninhibited and inhibited reinforcing steel. The resin extracts with a polish thickness of 150µm, 250µm and 350µm, were coated to reinforcing steel and embedded into concrete slab and immersed in sodium chloride (NaCl) and accelerated for 119 days and the corrosion potential results were examined by the Wenner method with four probes. Compared with the sample, the corroded material has a 75.4% increase in the corrosion potential value of E_{corr}, mV and a 33.54% decrease in the resistance value of concrete, the stress at the yield point in comparison with corrosion with a nominal yield point of 100%, reduced from 108.38% to 90.25%, 69.3% weight loss compared to 43.98% and a reduction in cross-sectional diameter from 51.45% to 89.25%, both of which showed lower corrosion values compared to the coated samples [13].

Investigated the use of Senegalese acacia exudates/resin extract as a corrosion inhibitor. The reinforcing steel coated with exudates/resin paste of different thicknesses and immersed in a corrosive environment for 150 days in an accelerated process. The average potential value of the corroded percentile was -230.48% compared to -69.74% and -67.31% for the control and coated samples. The corrosion potential result showed that non-coated sample value is highly corroded values, indicating an uncertain 10% probability or corrosion. Concrete resistance, the average value of the percentile (kΩcm) -48.90%, 95.72% and 114.89% of the control and roof samples. The range of values for the corrosion model shows significant (moderate) corrosion [14].

Investigated the potential for estimating the probability of corrosion by measuring the corrosion potential of half cells, testing the strength of concrete and testing the tensile strength of reinforcing steel, the mechanical properties of paste reinforcement that is not corroded, corroded and retarded from Moringa oleifera coated resin made from extract wood. When comparing the samples, the corrosive samples had a 70.1% increase in the corrosion potential value of E_{corr}, mV and a 35.5% decrease in the resistance value of concrete. The average percentile of Ecorr potential, mV and concrete resistance are 29.9% and 68.74%, respectively. The results of the calculation of the percentile of the average value of tensile stress in relation to the maximum strength compared to corrosion at the nominal yield strength standard of 100% decreased from 105.75% to 96.12% and the weight loss was 67.5% compared to 48.5% and a reduction in diameter cross section from 48.34% to 94.82%, both of which showed lower corrosion values compared to the coated samples [15].

Experimentally evaluated the use of inorganic inorganic environmental exudates/resin extracted from the bark of Invincia gabonensis, inhibited to strengthen steel of various thicknesses, immersed in sodium chloride for corrosion testing in a 150-days rapid process and investigated the comparative performance of non-coated and coated samples with current flow rate from 200mV to 1200mV and a scan speed of 1mV/s. The summary results of exudates/resin-coated samples showed evidence of corrosion potential in the non-coated, while the results showed that invincia gabonensis exudate/resin was a good corrosion inhibitor. The results of the reduction in cross-section show a higher percentile reduction value in corroded samples with fiber loss due to corrosion potential e effect on the mechanical properties of steel. The results of the reduction in steel weight showed a high percentile value compared to the control and coating models because of the effect of corrosion on the mechanical properties of the steel [16].

Investigated the use of inorganic inhibitors and green inhibitors to assess corrosion potential using extract resin paste of Mangifera indica applied to reinforcing steel with coating thicknesses of 150 m, 250 m and 350 m. Compared with the corroded sample, the corroded sample had a 76.54% increase in the potential value of Ecorr, mV and a 38.8% reduction in the value of the concrete strength, the tensile stress relative to the final strength in summary and the average condition of the corroded slab with a nominal value of 100% and reduced. maximum strength from 105.36% to 96.12%, weight loss compared to reduction in cross-sectional diameter reduced due to sodium chloride attack from 64.8% to 44.45% and 46.76% to 86 and 43%, respectively . The average percentile of Ecorr potential, mV and concrete resistance are 26.57% and 61.25%, respectively [17].

Carried out an evaluation of the use of cola acuminate from natural inorganic environmental exudates/ resin extracts as a preventive measure against the corrosive effects of saltwater attack on reinforcing steel embedded in concrete structures with saltwater, using an experimental application of Ecorr, mV half cell potential, and concrete resistivity measurement to ascertain the effect of corrosion of concrete slab embedded with both non-coated and coated reinforcing member, immersed in corrosive media for 150 days and measured corrosion potential probability with current flow range of 200mV to 1200mV and a scanning speed of 1mV/S. The result showed that corroded sample has increased values of corrosion potential to coated and decreased values of concrete resistivity in comparison to the coated. The mechanical properties of reinforcing steel showed negative surface modification with the deformed ribs peeled off which resulted to low load application and high yield. The results of the weight reduction of steel showed a high percentile value compared to the control and coating models because of the effect of corrosion on the mechanical properties of the steel of an immersion and applied flow for 150 days in fast corrosive environment exudates/resin to monitor changes in surface condition, is in the [18].

2.1 MATERIALS AND METHODS

2.1.1 Aggregates

Fine and coarse aggregates purchased from the dumpsite, both met requirements of [19].

2.1.2. Cement

Grade 42.5 limestone cement is used for all concrete mixes. The cement meets the requirements of [20].

2.1.3. Water

Water samples were taken from the laboratory of the Department of Civil Engineering, Kenule Beeson Saro-Wiwa, Bori, Rivers. Water meets the requirements of [21].

2.1.4 Steel Structure Reinforcement

The steel bar was purchased directly from Port Harcourt Market, meets [22].

2.1.5 Corrosion Inhibitors (Resins / Exudates) Anogeissus (Combretaceae)

Gum exudation/resins were extracted from the wounded stem of the tree. Samples were obtained from Arku in Dambam Local Government of Bauchi State, Nigeria.

2.2 Experimental procedure

2.2.1 Experimental method

2.2.2 Prepare Samples for Reinforcement with Coated Exudate/Resin

The application of Sticky gummy paste (exudates/resin) extracted from tree extrudes was studied. It is used as an inhibitor material to inhibit the corrosion effect of steel bars in built-in high salinity coastal areas.

The extracted exudates/resin is coated with reinforcing steel and embedded in the concrete slab, exposed to corrosive media with high salt concentration. The manifestation process of corrosion is long-term. However, the artificial introduction of sodium chloride (NaCl) accelerates the corrosion rate and its performance occurs in a short time. By estimating the quantification of the current density and corrosion rate obtained or obtained from the polarization curve, the destructive effect and destructive force of the corrosion rate is measured.

The slabs used in this study were made of concrete mixtures distributed by material weight using a manual mixing method with a standard concrete ratio of 1.2.4 and a water-cement ratio of 0.65. The studied concrete slab is designed of 100 mm × 500 mm × 500 mm (thickness, width, and length) and is cast into a metal mold, compacted in air and without voids, and reinforced with 10 numbers of steel bar of 12 mm in diameter spaced at 100mm c / c (top and bottom) with concrete cover of 10 mm thick and was de-molded after 72 hours, and cure at standard room temperature for 28 days to set. The hardened concrete slab is fully immersed in a 5% aqueous sodium chloride (NaCl) solution and accelerated for 360 days with on routine tests for 90 days, 180days, 270 days, and 360 days and ascertained comparative performances between uncoated and coated samples.

2.3 Accelerated Corrosion Test

The occurrence of corrosion is a long-term process, but the rapid induction and accelerated corrosion process using sodium chloride (NaCl) solution causes steel bars embedded in concrete to corrode and they can accelerate the appearance of corrosion in a short-period. To test the corrosion resistance of concrete, an experimental method was developed to accelerate the corrosion process and maximize the corrosion resistance of concrete. Accelerated corrosion test is an impressive technique, it is an effective technique to check the corrosion process of steel in concrete and evaluate the protective layer of concrete for steel reinforcement. For the structure and corrosion resistance of the structural elements, as well as the selection of suitable materials and suitable protection systems, accelerated corrosion tests were carried out to obtain quantitative and qualitative information on corrosion.

2.4 Corrosion Current Measurement (Half Cell Potential Measurement)

The corrosion severity classification of steel bars 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 the corrosion rate is assumed to be constant over time. Measurement of the average potential is an indirect method to estimate the possibility of corrosion. Recently, there has been a great interest in developing tools for the electrochemical measurement of disturbances in the steel as to obtain direct estimates of corrosion rates [23].

Table 2.1: Dependence between potential and corrosion probability [24]

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
$-350\text{mV} \leq E\text{c}_{orr} \leq -200\text{mV}$	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 Concrete Resistivity Test

The different measured values are measured at different points on the concrete surface. After the water is applied to the surface of the slab, the resistivity of the concrete is measured at a reference point every day to determine its saturation state.

The reason for choosing this position is that water can be added to the top of the panel for special resistivity measurement. Slab saturation is controlled by measuring the resistivity of the concrete, which is directly related to the moisture content of the concrete. Once one plate reaches saturation, the water will flow out while the other plate remains closed.

Time limitation is the main challenge for all experimental measurements because the saturation state of the concrete will change with time. For this reason, these four probes directly contact the concrete of the reinforced rail. Because each plate has a different water-cement ratio, the time required to saturate each plate is not the same. Before applying water to the slab, measure the resistivity of the concrete in certain places in a dry state. Once the concrete reaches saturation, the resistivity will remain constant.

Table 2.2: Dependence between concrete resistivity and corrosion probability [25]

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 The Tensile Strength of Steel Bars

It is to determine the yield strength and maximum points of the maximum tensile strength of steel bars. 10 numbers of steel bars were reinforced to concrete slabs with a diameter of 12mm (up and down direction) are used to test coated and uncoated reinforced steel. The Universal Testing Machine (UTM) was pressure tested to check for failure. To ensure stability, the remaining cut part is used 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 testing), the weight of the steel bar (after corrosion, check other parameters of weight loss).

3.0 TEST RESULTS AND DISCUSSION

For ease of explanation, plot the results of the half-cell potential measurement in Table 1 with the resistivity in Table 3. It is used to indicate the possibility of severe corrosion of very high corrosion, high, low to moderate, and low (ρ20). At another measurement point, the possibility of correction is high (-350 mV$\leq E$corr$\leq$ -200 mV), indicating that the probability of corrosion is 10% or uncertain. It has been shown that if the corrosion potential is low within a certain range (<-350mV), the chance of corrosion is 95%. Resistivity research data indicates whether certain states can help reduce ion movement, leading to increased corrosion.

Table 3.1: Potential Ecorr, after 28 days curing and 360days Accelerated Periods of Control Concrete slab Specimens

	Control Concrete slab Specimens											
Sample Numbers	ACS	ACS 1	ACS 2	ACS 3	ACS 4	ACS 5	ACS 6	ACS 7	ACS 8	ACS 9	ACS 10	ACS 11
	Time Interval 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	-112.43	-113.11	-108.84	-107.44	-109.85	-106.82	-115.27	-110.95	-106.50	-108.81	-112.80	-106.96
Concrete Resistivity ρ, kΩcm	15.93	15.92	15.91	15.91	15.90	16.07	16.06	16.05	16.05	16.04	15.98	15.90
Yield Strength, fy (MPa)	455.09	458.09	454.09	454.39	455.09	459.32	457.32	457.62	456.32	457.71	454.22	458.05
Ultimate Tensile Strength, fu (MPa)	619.90	617.85	619.53	615.31	618.84	619.26	619.06	619.86	618.46	620.01	619.51	619.37
Strain Ratio	1.36	1.35	1.36	1.35	1.36	1.35	1.35	1.36	1.36	1.36	1.36	1.35
Rebar Diameter Before Test (mm)	11.96	11.94	11.95	11.97	11.94	11.96	11.96	11.94	11.94	11.94	11.94	11.95
Rebar Diameter at 28 days(mm)	11.96	11.94	11.95	11.97	11.94	11.96	11.96	11.94	11.94	11.94	11.94	11.95
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	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
Rebar Weights- After at 28 days (Kg)	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
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	-310.29	-315.49	-312.39	-304.78	-314.58	-321.58	-355.48	-362.68	-366.78	-389.90	-413.10	-421.36
Concrete Resistivity ρ, kΩcm	**6.30**	**6.32**	**7.15**	**7.46**	**7.23**	**6.79**	**6.61**	**6.96**	**7.00**	**6.60**	**5.97**	**8.27**
Yield Strength, fy (MPa)	415.44	418.44	414.44	414.74	415.44	414.67	417.67	417.97	416.67	418.06	414.57	418.40
Ultimate Tensile Strength, fu (MPa)	605.79	603.74	605.42	601.20	604.73	605.15	604.95	605.75	604.35	605.90	605.40	605.26
Strain Ratio	1.46	1.44	1.46	1.45	1.46	1.46	1.45	1.45	1.45	1.45	1.46	1.45
Rebar Diameter Before Test (mm)	11.96	11.94	11.95	11.97	11.94	11.96	11.96	11.94	11.94	11.94	11.94	11.95
Rebar Diameter-After Corrosion(mm)	11.92	11.90	11.91	11.93	11.90	11.92	11.92	11.90	11.90	11.90	11.90	11.91
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	0.92	0.91	0.91	0.92	0.92	0.92	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	0.86	0.86	0.86	0.86
Weight Loss /Gain of Steel (Kg)	0.05	0.05	0.06	0.05	0.06	0.05	0.05	0.05	0.05	0.06	0.05	0.06

Table 3.3: Potential Ecorr, after 28 days curing and 360days Accelerated Periods of Anogeissus (Combretaceae) 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	-121.5	-124.4	-124.7	-124.4	-120.4	-124.5	-122.7	-126.5	-123.1	-117.7	-118.1	-124.4
Concrete Resistivity ρ, kΩcm	15.02	15.17	15.45	15.58	15.27	15.56	15.51	15.66	15.69	15.16	15.05	14.90
Yield Strength, fy (MPa)	458.89	459.19	457.89	457.12	460.12	460.42	459.12	460.51	457.02	460.85	456.56	457.99
Ultimate Tensile Strength, fu (MPa)	631.54	629.49	631.17	626.95	630.48	630.90	630.70	631.50	630.10	631.65	631.15	631.01
Strain Ratio	1.38	1.37	1.38	1.37	1.37	1.37	1.37	1.37	1.38	1.37	1.38	1.38
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 (specimensAverage Potential Ecorr, after 28 days curing and 360days

Sampling and Durations	**Control Concrete slab Specimens**				**Corroded Concrete slab Specimens**				**Anogeissus (Combretaceae) 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 Anogeissus (Combretaceae) Exudate / Resin Coated Specimens**			
Potential Ecorr, mV	-111.4	-109.8	-108.7	-108.0	-312.7	-310.8	-310.5	-313.6	-123.3	-124.2	-122.8	-123.1
Concrete Resistivity ρ, kΩcm	15.92	15.91	15.91	15.96	6.59	6.98	7.28	7.16	15.22	15.40	15.44	15.47
Yield Strength, fy (MPa)	455.76	455.52	454.52	456.27	416.11	415.87	414.87	414.95	458.66	458.07	458.38	459.22
Ultimate Tensile Strength, fu (MPa)	619.09	617.56	617.89	617.80	604.98	603.45	603.78	603.69	630.74	629.21	629.54	629.45
Strain Ratio	1.36	1.36	1.36	1.35	1.45	1.45	1.46	1.46	1.38	1.37	1.37	1.37
Rebar Diameter Before Test (mm)	11.95	11.95	11.95	11.96	11.95	11.95	11.95	11.96	11.99	11.99	11.99	11.99
Rebar Diameter-After Corrosion(mm)	11.95	11.95	11.95	11.96	11.91	11.91	11.91	11.92	12.04	12.02	12.05	12.03
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.00	0.00	0.00	0.00	0.044	0.046	0.043	0.044	0.069	0.066	0.067	0.068
Rebar Weights-Before Test (Kg)	0.874	0.876	0.972	0.878	0.923	0.928	0.931	0.928	0.927	0.921	0.925	0.902
Rebar Weights-After Corrosion (Kg)	0.874	0.876	0.872	0.878	0.869	0.864	0.869	0.864	0.997	0.997	0.993	0.994
Weight Loss /Gain of Steel (Kg)	0.00	0.00	0.00	0.00	0.06	0.06	0.06	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**				**Anogeissus (Combretaceae) 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 Anogeissus (Combretaceae) Exudate / Resin Coated Specimens**			
Potential Ecorr, mV	-64.36	-64.68	-65.00	-65.55	153.53	150.32	152.81	154.98	-60.56	-60.05	-60.45	-60.78
Concrete Resistivity ρ, kΩcm	141.67	128.16	118.52	122.86	-56.71	-54.72	-52.84	-53.72	131.00	120.85	112.06	116.09
Yield Strength, fy (MPa)	9.53	9.53	9.56	9.96	-9.28	-9.21	-9.49	-9.64	10.23	10.15	10.49	10.67
Ultimate strength (N/mm2)	2.33	2.34	2.34	2.34	-4.08	-4.09	-4.09	-4.09	2.26	2.27	2.25	2.29
Strain Ratio	-6.60	-6.55	-6.60	-6.94	5.75	5.60	5.97	6.13	-6.43	-6.31	-6.64	-6.77
Rebar Diameter Before Test (mm)	0.443	0.441	0.442	0.442	0.440	0.444	0.441	0.445	0.441	0.442	0.441	0.444
Rebar Diameter-After Corrosion(mm)	0.443	0.410	0.420	0.420	-1.11	-1.125	-1.188	-1.231	1.134	1.1262	1.126	1.127
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0	0	0	0	-24.945	-23.748	-24.042	-24.335	34.346	34.634	34.336	34.672
Rebar Weights-Before Test (Kg)	0.452	0.455	0.453	0.454	0.448	0.457	0.453	0.457	0.455	0.453	0.452	0.455
Rebar Weights-After Corrosion (Kg)	9.05	9.93	9.16	9.05	-12.55	-12.48	-12.82	-12.87	14.15	14.45	14.579	14.73
Weight Loss /Gain of Steel (Kg)	0.00	0.00	0.00	0.00	-18.57	-17.39	-18.31	-23.94	22.81	21.05	22.41	31.48

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

Corrosion of steel bars is a major problem for the durability of reinforced concrete structures [26]. The development and spread of corrosion depends on the parameters of the concrete's resistance (porosity, diffusion, absorption, permeability). However, evaluating these parameters on-site is time-consuming, expensive and/or requires destructive testing. Resistance is increasingly seen as a reliable strength index to evaluate the long-term performance of concrete structures [27]. The E_{corr} potential yields, mV and concrete resistance, kΩcm, obtained from Tables 3.1 - 3.3 and summarized into average and percentile values in Tables 3.4 and 3.5, plotted graphically in Figures 3.1-3.8b, are the results of controlled samples, non-coated (corroded), and coated for 36 concrete slabs, divided into 3 sets of 12 controlled samples, representing the determining reference range, 12 samples without coating (corroded) and 12 samples with exudates/resin coating.

The average and minimum, maximum and differential values of the calculated measurements of the half-cell potential of the controlled sample were -111.46mV and -108.04mV with representative percentile values of (-65.55% and -64.36%) with a differential corrosion potential values of 3.42 mV and 1.19%, the corroded samples were -313.65mV and -310.58mV, having percentile ranges of (150.32% and 154.98%) and differential obtained values of 3.07mV and 4.66%, and the coated samples were -124.2mV and -122.85mV with range percentile values of (-60.78% and -60.05%) and the potential differentials was 1.35mV and 0.73%. The maximum calculated percentile of the controlled sample value is -64.36% compared to the corroded and coated value of 154.98% and -60.05% and the controlled corrosion potential differential value is 1.19%, corroded 4.66% and coated 0.73% . The maximum yield of controlled and coated samples was -108.04mV and -122.85mV, which showed the relationship between corrosion potential and probability reference of $\boldsymbol{E_{corr}} > -200$mV as a reference range. The results of these corrosion potential E_{corr} results indicate that the values of controlled samples and exudates/resin coated samples are low, with a 90% probability, with indications of no rebar corrosion in these areas during the measurement (10% corrosion risk, indicating a 10% or uncertain corrosion probability. For non-coated (corroded) samples, the maximum calculated value is -310.58mV; the result is within the reference value of the relationship between corrosion potential and probability of $-350\text{mV} \leq E_{corr} \leq -200$mV value indicating a high value range close to 10% or an uncertain corrosion probability in comparison to the reference range, (controlled) shows that the corrosion samples as a result of the acceleration of the induced corrosion compared to the coated samples which show no corrosion presences and attack. The embedded reinforcing steel in concrete slab possessed inhibitive and coating membrane that resisted the effect of corrosion attacks.

The average value and the minimum and maximum percentile of concrete resistance with the potential differential from the controlled sample are 15.91kΩcm and 15.96kΩcm (118.52% and 141.67%) and the differential value is 0.05kΩcm and 23.15 %. Corroded samples were 6.59kΩcm and 7.28kΩcm (-56.71% and -52.84%) and the differential values were 0.69kΩcm and 3.87%, coated samples were 15.22kΩcm and 15.47kΩcm (112.06% and 131%) and the differential in values of 0.25 kΩcm and 18.94%. The maximum calculated percentile of the controlled sample concrete resistance is 141.67% compared to the corroded and coated value of -52.84% and 131.05% and the maximum percentile differential of control are 23.15% compared to the corroded and coated value of 3.87 % and 18.94%. The results of the controlled and layered concrete resistance samples obtained a maximum average value of 15.96kΩcm and 15.47kΩcm with a data value of $10 < \rho < 20$ (low) compared to a corrosion value of 7.28kΩcm with a specification of ($5 < \rho < 10$) and with the reference range of the relationship between concrete resistance and corrosion probability, the significant corrosion probability ($\rho < 5$, $5 < \rho < 10$, $10 < \rho < 20$, $\rho > 20$) was very high, high, low to medium and low, for corrosion probability. From the comparative results of coated and corroded samples, the maximum value of the two samples clearly shows that the value of the coated sample lies in the range of $10 < \rho < 20$, which classifies the range of values from low to medium and with an indication of the possibility of significant corrosion. The maximum value of the corroded sample is in the range of $\mathbf{5} < \rho < 10$, which indicates high, signs indicating the possibility of corrosion, as in the works of [12, 14, 15, 18]. From the results obtained, it can be compared that the effect of corrosion attack was observed in samples without coating material, while samples with exudates/resin formed anti-corrosion properties with highly resistant and water-resistant membranes that prevented corrosion of reinforcing steel embedded in the concrete slab and exposed to induced accelerated corrosion media.

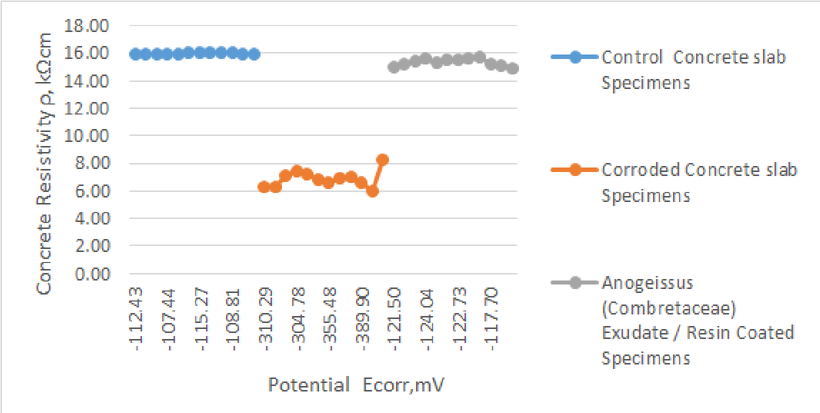

Figure 3.1: Concrete Resistivity ρ, kΩcm versus Potential Ecorr,mV Relationship

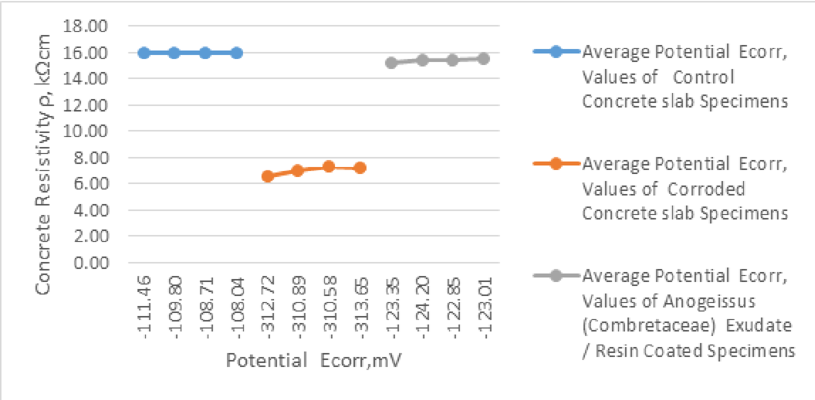

Figure 3.1A: Average Concrete Resistivity versus Potential Relationship

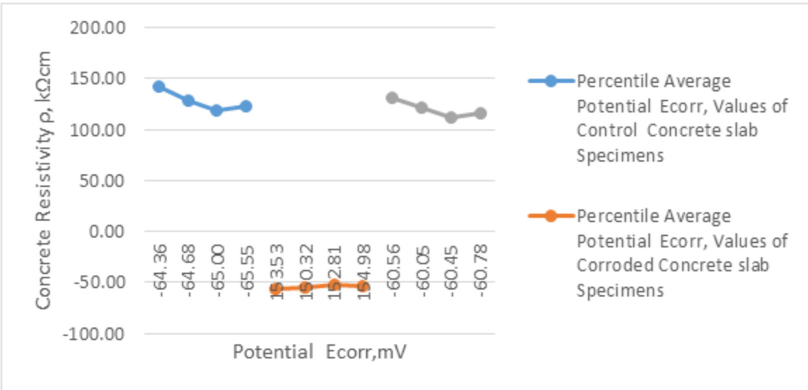

Figure 3.1B: Average Percentile Concrete Resistivity versus Potential Relationship

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

Tensile behavior of corroded bars is very important to assess the load bearing capacity of corroded reinforced concrete structure. Reduction in the effective diameter of steel bars has a significant impact on the tensile strength of reinforced concrete structures. The results show an inverse correlation between the degree of corrosion and the true tensile strength. The degree of corrosion according to [28] is inversely related to steel capacity; that is, increasing the corrosion rate will decrease the tensile strength, which is consistent with this study. The results of the average, percentile, and the differential between the minimum and maximum yield strength limits, fy (MPa) obtained of the controlled samples were 454.52MPa and 456.27MPa with percentile variations of (9.53% and 9.96%), and the differential values of 1.75MPa and 0.43%, the corroded sample was 414.87MPa and 416.11MPa with percentile value ranges of (-9.64% and -9.21%) and the differential value was 1.24MPa and 0.43%, the coated sample values are 458.07MPa and 459.22MPa, and with percentile values of (10.15% and 10.67%) and the differential value of 1.15MPa and 0.52%. The maximum percentile value calculated from the controlled yield strength is 9.96% against corroded sample and the coated value is -9.21% and 10.67% and the possible differentials value is 0.43% controlled 0.43% corroded and 0.52% coated.

The average, percentile, and the differential between the minimum and maximum tensile strength, fu (MPa) of the controlled sample were 617.56 MPa and 619.09MPa (2.33% and 2.34%) and the differential value was 1.53MPa and 0.01%, corrosion is 603.45MPa and 604.98MPa (-4.09 MPa and -4.08%) and the differential is 1.53MPa and 0.01%, coated is 629.21MPa and 630.74MPa (4.26% and 4.27%) and the differential value is 1.53MPa. The calculated maximum values of the controlled tensile strength percentiles were 2.348% against corrosion and the coated values were -4.08% and 4. 27% and the potential differential values were 0.01% checked, 0.01%% corroded and 0 0.01% coated.

The minimum and maximum average values, percent and differential in deformation of the controlled sample are 1.35 and 1.36 (-6.94% and -6.55%) with a differential of 0.01 and 0.39%, the corroded sample is 1.45 and 1.46 (5.6 and 6.13%) and the differential values of 0.01 and 0.53%, the coated samples were 1.37 and 1.38 (-6.77% and -6.31%) and differential values of 0.01 and 0.46%. 6.13% and coverage -6.31% and differential peak controlled by 0.39%, corroded by 0.53% and coated by 0.46%, as in the works [12, 14, 15, 18]. The obtained computed results, which are summarized in Tables 3.4 and 3.5 and shown graphically in Figures 3.1-3.8, show the coated samples for yield strength, tensile strength and deformation ratio of the average, percentile and differential potential values of the control, plate samples. uncoated (corroded) and coated concrete had higher breaking loads compared to corroded specimens with reduced breaking loads and low load bearing capacity and with average and percentile values compared to the reference range, whereas uncoated samples (corroded) indicated a low load-bearing capacity and reduced value compared to the reference range. The comparison results show that the low load carrying capacity is caused by the effect of corrosion attack on the uncoated (corroded) elements, which damage the reinforcing steel fibers, ribs and passive formation and surface modification. The preserved value of the coated samples on both averages is due to the potential for resistance when corrosion penetrates the reinforcing steel with the formation of a protective membrane; these attributes indicate the effectiveness and efficiency of exudates/resin as an inhibitor against corrosion, the influence of reinforced concrete structures from high salinity heavy territorial sea areas. This indicates that a higher percentage reduction in area leads to a reduction in tensile stress.

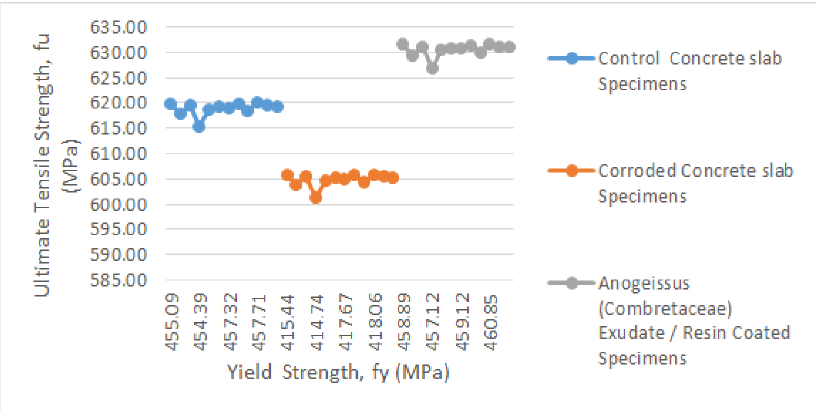

Figure 3.2: Yield Strength versus Ultimate strength

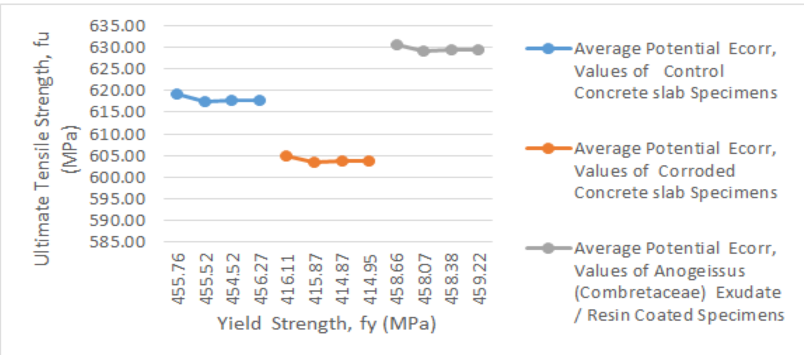

Figure 3.2A: Average Yield Strength versus Ultimate Tensile Strength

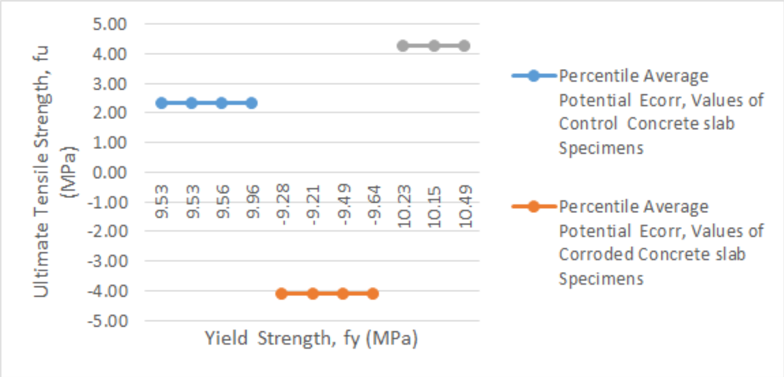

Figure 3.2B: Average Percentile Yield Strength versus Ultimate Tensile Strength

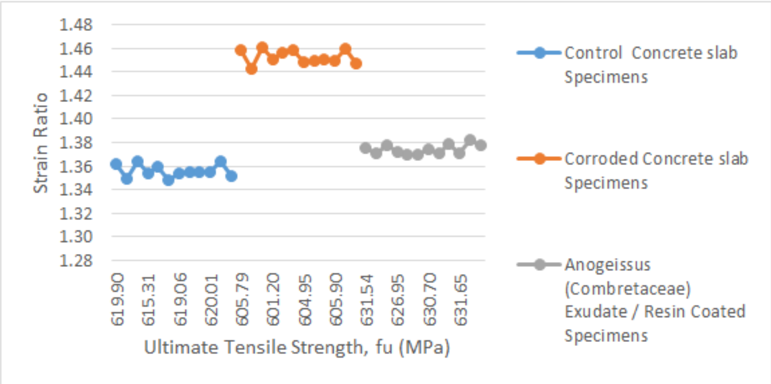

Figure 3.3: Ultimate Tensile Strength versus Strain Ratio

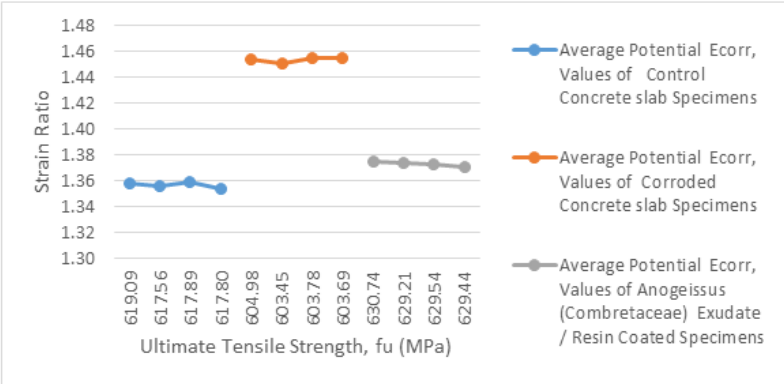

Figure 3.3A: Average Ultimate Tensile Strength versus Strain Ratio

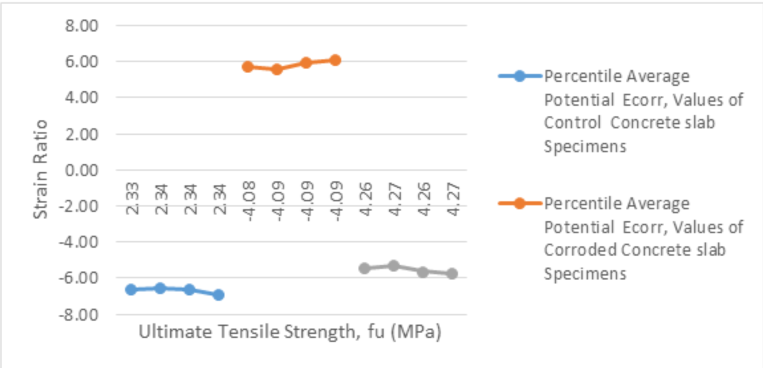

Figure 3.3B: Average percentile Ultimate Tensile Strength versus Strain Ratio

3.3 Results of Mechanical Properties of Rebar Diameter, Cross -Sectional Area and Weight Loss/Increase of Embedded Reinforcing Steel in Concrete Slab

The mechanical properties of a corroded reinforced concrete structure depend on the cross section of the reinforcement area size and corrosion rate. The active cross-section of the steel decreases in proportion to the degree of corrosion, with changes in mechanical properties. The reduction in steel area is linearly correlated with the actual tensile strength. It is evident that the tensile strength of corroded reinforcement is more strongly affected by the reduction in cross-sectional area. Thus, the tensile strength of the bar, calculated by the actual cross section, changes significantly [29]. The minimum and maximum anchorage diameters before testing (mm) the mean and percentage values were controlled from 11.95mm and 11.96mm (0.041% and 0.043%) with a difference of 0.01 mm and 0.002%, the corroded sample was 11.95mm and 11.96mm (0.04% and 0.045%) and the difference values were 0.01mm and 0.005%, and the coated sample values were 11.99mm and 11.99mm (0.041% and 0.054%) and calculated differentiation values of 0.00mm and 0.013%. The cut weight of the rebar before the corrosion test shows a negligible difference due to the product and shape of the firm and by-products used in the production process. The mean, percentile and difference in diameter of reinforcement after corrosion (mm) minimum and maximum obtained for the controlled sample were 11.95mm and 11.96mm (0.041% and 0.043%) with a difference of 0.01mm and 0.002%, maintaining the reference value is 100%, the corroded sample values are 11.91mm and 11.92mm (-1.231% and -1.11%) and the difference is 0.01 mm and 0.112%, The coated sample values are 12.02 mm and 12 0.05mm (1.126% and 1.134%) and the difference between 0.03mm and 0.008%. The diameter of reinforcement after corrosion maximum calculated percentile value controlled 0.043% versus -1.11% corroded and 1.114% coated, the difference in percentage between corroded 0.121% versus 0.008% coated. The results obtained in Tables 3.4 and 3.5, which are summarized in Tables 3.1, 3.2 and 3.3 and shown graphically in Figures 3.3-3.6b, show the effect of corrosion attack on reinforcing steel embedded in the concrete slab and exposed to corrosion induced acceleration effect. For comparison, the results of corroded samples showed a decrease and decrease in value compared to the diameter of the reinforcement before and after the induction accelerated corrosion test with a percentile range to reduce the value from 0.043% to -1.11% and the average value in the range of 11.96 mm to 11.92mm.

The decrease/increase (diameter) in the cross section of the minimum and maximum mean and percentile values was controlled 100%, with no decrease or increase in the description after 360 days of immersion in fresh water. Corroded sample values were 0.043mm and 0.046mm with percentile computed values of (-24.945% and -23.748%) and the difference was 0.003% and 1.197% for corroded, coated sample values were 0.066mm and 0.069mm (34.336% and 34.672%) and the difference is 0.003mm and 0.336%. The average and relative percentage difference between coated and corroded samples ranged from 34.672% to -23.748%. The decrease in mean and percentile values indicates that the corrosion effect has led to a reduction in diameter and cross-sectional area, fiber degradation, rib reduction and surface modification, whereas resin-coated exudates/elements show an increase in volume due to different coating thicknesses developed in the work ([12]; [14];[15];[18]) were validated. .

It can be concluded that the exudates/resin has inhibitory properties against corrosive effects on reinforcing steel embedded in the concrete slab sample, which is induced in a high salinity environment. Rebar weights - before testing (kg), the mean and minimum, maximum and differential percentiles of the controlled samples were 0.874kg and 0.972kg (6.42% and 6.542%), and the differences were 0.098% and 0.122%, samples were corroded the weight is 0.923kg and 0.931kg (6.422% and 6.504%) and the difference is 0.008% and 0.082%, the coated samples are 0.902 kg and 0.927 kg (6.246% and 6.54%) with a difference of 0.025% and 0.294%, respectively.

The average and percentage of reinforcement weight after corrosion (Kg) and the general difference values of the minimum and maximum values of the controlled samples were 0.874kg and 0.972kg (6.42% and 6.542%). and the difference values of 0.098% and 0.122%, the corroded samples were 0.864kg and 0.869kg (-12.87% and -12.48%) and the difference was 0.005% and 0.39%, the coated sample values were 0.993 kg and 0.997kg (14.15% and 14.73%) and the difference between 0.004% and 0.58%. Average and percentage loss/gain of minimum and maximum weight of steel (Kg) and percentage difference in comparison controlled 100% of values held as a result of aggregation in freshwater tanks with no trace of corrosion potential compared to corroded sample values of 0.05 kg and 0.06 kg (-23.94% and -17.39%), and coverage of 0.07kg and 0.07kg (21.05% and 31.48%). The calculation results obtained from Table 3.1-3.3 and summarized in 3.4-3.5 and plotted graphically in Figure 3.7-3.87 show the effect of corrosion on uncoated (corroded) and coated reinforcing steel and check the weight of the pieces of reinforcement before and after the corrosion test as well. For comparison, the results obtained showed a decrease and increase in the average and percentage values with 0.07 kg coating to 0.06 kg and 31.48% to -17.39% corrosion, as in the work [12, 14, 15, 18]. The aggregate results show that the corrosion effect causes a weight reduction/weight reduction in the corroded samples compared to coatings with a percentage exposure and an average increase, resulting in a small increase in the volume of the coating thickness. This study shows the effectiveness and efficiency of exudates/resin as an inhibitor against the effects of corrosion on reinforcement embedded in samples of concrete slabs exposed to induced corrosion.

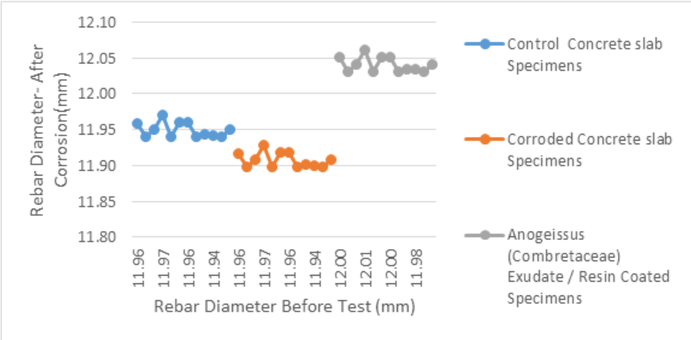

Figure 3.4: Rebar Diameter Before Test (mm) versus Rebar Diameter- After Corrosion(mm)

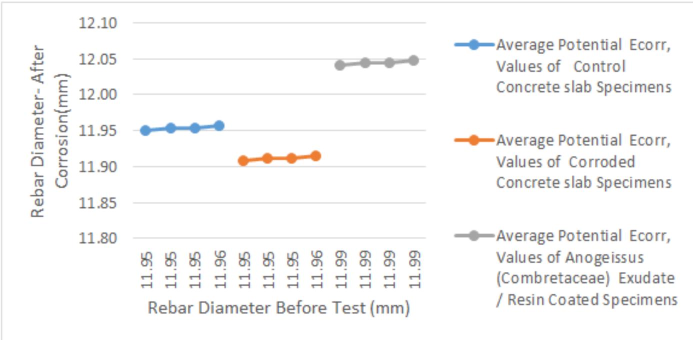

Figure 3.4A: Average Rebar Diameter Before Test(mm) versus Rebar Diameter- After Corrosion (mm)

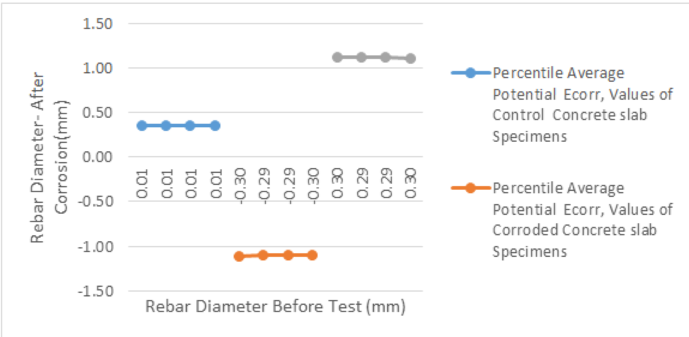

Figure 3.4B: Average Percentile Rebar Diameter Before Test (mm) versus Rebar Diameter- After Corrosion (mm)

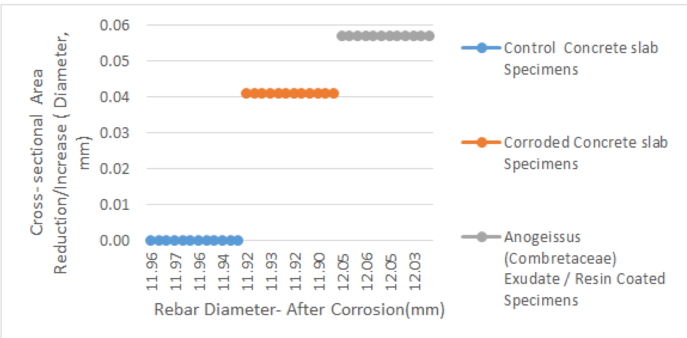

Figure 3.5: Rebar Diameter- After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

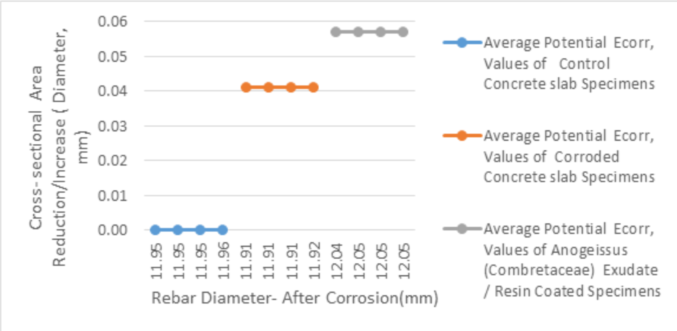

Figure 3.5A: Average Rebar Diameter- After Corrosion(mm) versus Cross- Section al Area Reduction/Increase (Diameter, mm)

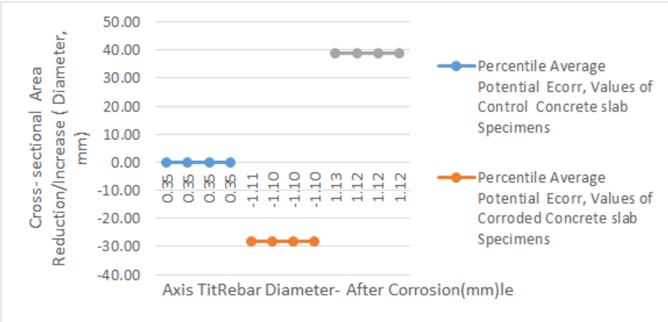

Figure 3.5B: Average Percentile Rebar Diameter- After Corrosion(mm) versus Cross- Sectional Area Reduction/Increase (Diameter, mm)

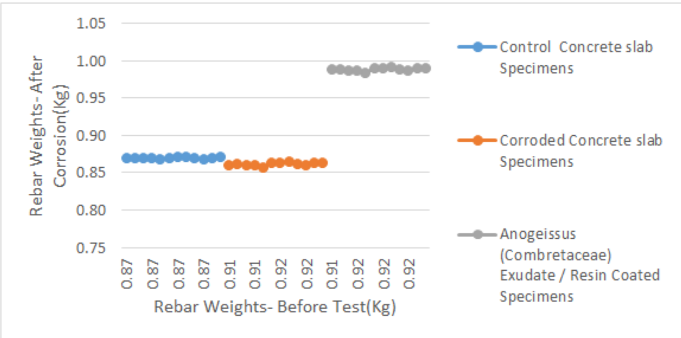

Figure 3.6: Rebar Diameter - After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

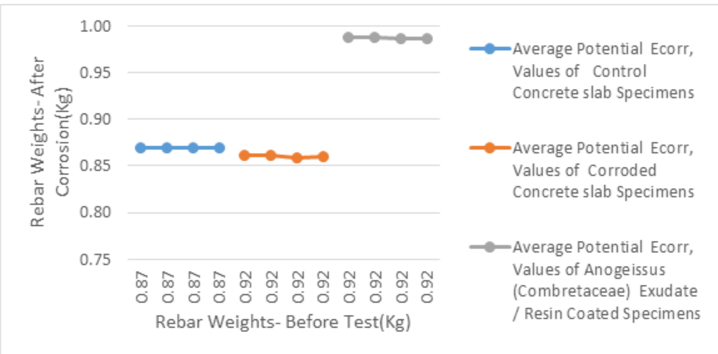

Figure 3.6A: Average Rebar Diameter - After Corrosion(mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

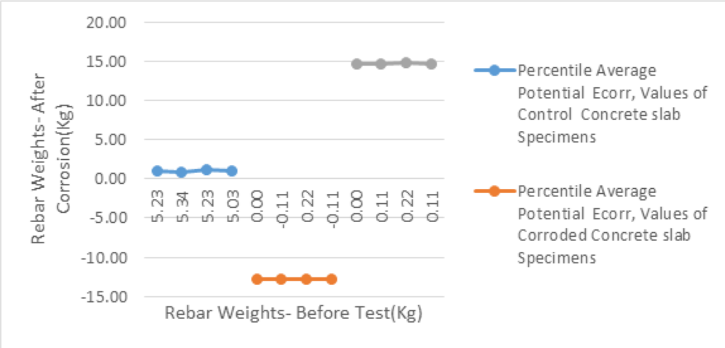

Figure 3.6B: Average Percentile Rebar Diameter - After Corrosion(mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

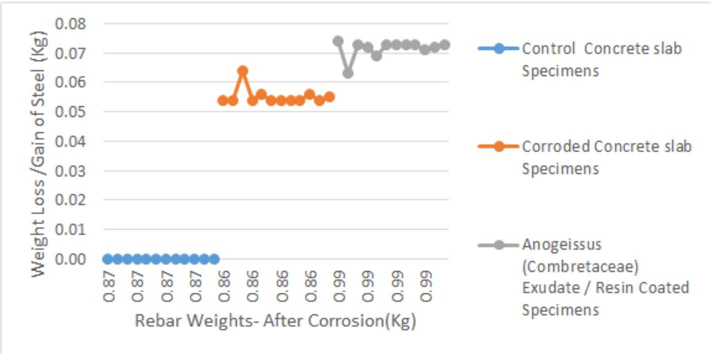

Figure 3.7: Rebar Weights- After Corrosion (Kg) versus Weight Loss /Gain of Steel (Kg)

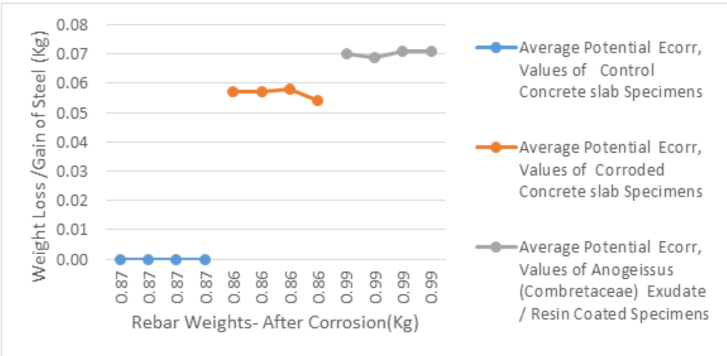

Figure 3.7A: Average Rebar Weights- After Corrosion (Kg) versus Weight Loss /Gain of Steel (Kg)

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:

i. Coated reinforcing steel showed no indications of corrosion presence
ii. Anogeissus (Combretaceae) exudates / resins showed an inhibitory properties against corrosion attacks
iii. Reduction in diameter and cross-sectional areas were noticed in corroded samples
iv. Weight loss was witnessed in corroded samples while inhibited samples exhibited minute volumetric increase.
v. Yield strength and ultimate tensile strength reduction was noticed in corroded samples resulting from corrosion effect
vi. The corroded sample maximum value is within the range of $5 < \rho < 10$ indicating high, the signs showed the presence of corrosion probability

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