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Original Research Article

Chemical Thermodynamics Determination of Corrosion Threshold Assessment of Reinforced Concrete Structures

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Abstract

The study evaluate the scourge of corrosion effects on reinforcing steel with the application Calotropis procera exudates / resin coated directly in different thicknesses to reinforcing steel, embedded into concrete slabs and exposed to coastal waters with a high concentration of salt to curb the rate and degree of corrosion. The hardened concrete slab is fully immersed in 5% sodium chloride (NaCl) solution for 360 days, with interval inspection and routine tests at 90 days, 180 days, 270 days and 360 days. The maximum calculated percentile control value is -59.22% compared to the corroded and coated values of 229.5% and -59.22% and the controlled potential difference value is 8.8%, 84.28% corroded and 10.43% coated. The maximum yields of the controlled and coated samples were -105.37mV and -122.66mV 6mV, which showed the relationship between corrosion potential and opportunity in the reference range $E_{corr} > -200\text{mV}$. Corrosion potential probability values of uncoated samples has maximum calculated range of -308.77mV, the result is within the reference value of dependence between corrosion potential and probability of value $-350\text{mV} \leq E_{corr} \leq -200\text{mV}$ indicates a high range of values, which is 10% or uncertain probability of corrosion. Results in comparison from the reference range (controlled), it is observed that show that non-coated samples showed corrosion potentials with higher values as a result of accelerated corrosion induced as compared to coated samples. The maximum value calculated from the concrete resistance of the controlled sample is 111.34% compared to the corroded and coated value of -54.53% and 135.59% and the maximum value of the percentile difference from the control is 19.17% compared to the corroded and coated value of 3 0.02% and 15.66%. The results of testing controlled samples coated with concrete resistance obtained the maximum average values of 15.28 kΩcm and 17.53kΩcm with a description of the value $10 < \rho < 20$ (low) compared to the corrosion value of 7.9kΩcm with specifications $5 < \rho < 10$ (high) and with a reference range of dependence between concrete resistance and corrosion probability at significant corrosion probability. The calculated maximum percentage of the controlled yield strength was 8.31% compared to the corroded and coated values -7.35% and 8.66% and the possible difference values of 0.45% controlled, 0.62% corroded and 0.72% coated. The calculated maximum percentage of the controlled of ultimate tensile strength is 1.99% relative to corroded value of -2.69% and the coated values of 2.78%% and with differential potential values of 0.01% controlled, 0.01% corroded and 0.01% coated. Comparatively, corroded samples exhibited high yielding to low load application representing the effect of corrosion on the mechanical properties of reinforcing steel that has resulted to low load carrying capacity, the corroded also recorded higher strain ratio as compared to the coated to the parameters above. The maximum calculated percentage was set at 0.929% versus corroded - 0.919% and coated at 1.043%, with a percentage difference in corrosion of 0.004% versus 0.067% coated. For comparison, the results of the corroded samples showed a reduction values compared to the diameter of the reinforcement before and after the induction accelerated corrosion test with a percentage decrease in value from 0.048% to -0.919% and an average value in the range from 11.96mm to 11.91mm. Comparatively, the results obtained show a reduction of the mean and percentile values for corroded from 0.07 kg to 0.05 kg and 35.19% to -23.61%. The summary results show that the corrosion effect on corroded samples causes a decrease in weight compared to coatings with percentile values and an increase in mean values, which causes a slight increase in volume with coating thickness.

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

1.0 INTRODUCTION

Steel corrosion in concrete is one of the main problems related to the durability of reinforced concrete structures. Most concrete structures work well in normal environments even after long periods of use. However, there are various reinforced concrete structures that are important to our infrastructure, particularly bridges and buildings that are showing early deterioration due to environmental impacts. In contrast to mechanical effects such as load, wind, environmental effects are irreversible and accumulate harmful components such as chloride ions in concrete.

The threshold value corresponds to the chloride content measured at the reinforcement surface, which causes the reinforcement to move locally. Thresholds have been shown to be influenced by a number of parameters, including the boundary between steel and concrete [1] pore solution pH [2, 3], and chemical [4], type of cement [5], the electrical potential of the steel surface [6], water and oxygen content in the pore solution of concrete [7] related to chloride compounds [8], the ability to binding to chloride [9] and threshold method. This causes the threshold value given in the literature to have a high dispersion in the range of 0.04-8.34 wt.

Concrete been a porous material with a strong alkaline pore solution, consisting mainly of sodium, potassium and calcium hydroxide, which are obtained by hydration of cement. Under normal conditions, the concrete pore solution maintains a pH in the range of 13.1-14. The pH of the pore solution depends on several factors including binder composition, cement content, water cement ratio, and chemical contaminants and additives absorption. Under these alkaline conditions, a passive layer forms around the steel. It is a solid film which, although present, can reduce corrosion [10].

Corrosion caused by chloride is the main cause of corrosion of reinforcing steel in concrete. Chloride can come from a variety of sources, such as diffusion into concrete from sea salt spray or de-icing salt. They can also become part of the concrete through the addition of a chloride-based accelerator such as calcium chloride or the use of an inert material contaminated with salt. The initial mechanism of chloride diffusion is suction, especially in dry concrete. The saltwater is absorbed and then the capillary movement of the saltwater occurs through the pores. This is followed by diffusion of chloride ions until the chloride reaches a concentration higher than the chloride threshold to initiate corrosion [11].

Electrical transport through the concrete closely resembles the ion current, because it is possible to classify the degree of corrosion bars embedded in concrete by measuring the electrical resistivity of the concrete surrounding [12]. Currently, concrete resistivity measurements can be performed in the field by using one of three methods: single-electrode method, the method of two probes, or a four-probe method of the three methods, two-probe is the most accurate and the most intensive work time [13]. This trend of corrosion effect on reinforcing steel has been researched by many as to curb the scourge and damaging effect with the use of corrosion inhibitors of both organic and inorganic origin.

Investigated the effect of Prosopis juliflora extract on steel corrosion in concrete at 3.5% NaCl [14]. Corrosion test was carried out after soaking the rebar for 30 days with and without inhibitor. Corrosion test showed that the corrosion inhibitor reached 91% effectiveness at the inhibitor concentration of 120 ppm. With a low inhibitor concentration (100 ppm) the effectiveness is 51%. The EIS study shows that there is a diffusion process and sedimentation effect of a solid layer of calcium hydroxide to form a protective layer at the boundary between steel and concrete. In addition, increasing the inhibitor concentration reduces the surface in homogeneity due to the adsorption of extract molecules on the surface of the embedded steel. The AFM image shows that the inhibitor molecules are absorbed by the reinforcement surface and form a protective layer that reduces the corrosion rate of the reinforcement.

Investigated the corrosion potential, concrete resistivity and tensile strength assessments of control, corroded and exudates/resin coated reinforcing steel and embedded into concrete slab member [15]. Direct application of corrosion inhibitor of dacryodes edulis exudates/resins of varying thicknesses coated on 12mm diameter reinforcement, embedded into the concrete slab and immersed into corrosive environment for 119 days for improved corrosion check, half cell potential measurements, concrete resistivity measurements, and tensile assessments. When in comparison to corroded samples, corroded has 70.1% increased values of corrosion potential over coated and 38.8% reduced values of concrete resistivity against coated samples. The yield and ultimate tensile strength in opposition to standard strength at in assessment to corrode as one 100% nominal yield stress reduced from 100.95% to 96.12% of corroded, weight reduction and cross-sectional diameter reduction, both confirmed decreased values of corroded compared to coated specimens. Inhibited specimen indicated a 10% or uncertain possibility of corrosion which indicates no corrosion presence or indicated a low possibility of corrosion or no corrosion indication.

Used Azadirachta indica (neem) powder and dehydrated aloe vera as inhibitors of steel corrosion in concrete [16]. Class M concrete with 20mm coarse aggregate is used. Concrete is immersed in a solution with a salt content of about 3.5% (35 g/L). Concrete with green corrosion of irreplaceable 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) in Hibia had better corrosion efficiency than aloe vera inhibitors.

Investigated corrosion degree likelihood assessment through half cell corrosion potential, concrete resistivity test, and tensile strength test mechanical residences of control, corroded and inhibited reinforcement with moringa oleifera lam resin paste of plant extract [17]. When as compared to corroded samples, corroded has 74.8% values of corrosion potential E_{corr}, mV, and 37.9% reduced values of concrete resistivity over coated samples. Results of computed of percentile average values of yield stress strength, whilst in comparison to corrode as 100% nominal yield stress decreased from 105.75 % to 96.12% and weight loss at 67.5% towards 48.5% and 48.34% to 94.82%, cross-sectional diameter reduction, both showed reduced values of corroded in comparison to lined specimens.

Investigated rice husk powder for steel corrosion in concrete [18]. They added rice husk extract to the concrete using the American method of designing a mix (ACI 211) with strength of 30 MPa at 28 days of age. The rebar were sealed 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 averages that the corrosion reduction is 30% or 81%.

Investigated the effectiveness of green inhibitors from orange peel waste. They extracted dried orange peel with methanol extract during immersion for 6 hours in methanol at pressures (60 mbar) and 40 °C [19]. From experimental data with electrochemical polarization measurements and analysis of weight loss during anchor diving for 7 days, this inhibition showed similar 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.

Characterized Phyl-lannthus muellerianus as an inhibitor to reduce steel reinforcement corrosion in powder media [20]. They used 0.5 M H2SO4 medium to simulate the 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.

investigated the usage of inorganic inhibitors and Greener technique inhibitors to assess the assessment of corrosion effect using Mangifera indica resins paste extracts coated to reinforcing steel with coated thicknesses of 150µm, 250µm, and 350µm. When compared to corroded samples, corroded has 73.18% increased corrosion potential values E_{corr}, mV over coated samples and 38.8% reduced values of concrete resistivity, corroded samples recorded weight loss and cross-sectional area(diameter) reduction resulting from the effects of corrosion attacks on the reinforcing steel with surface modifications[21].

2.1 MATERIALS AND METHODS

2.1.1 Aggregate

Fine aggregate and coarse aggregate are bought in the sandbox. Both meet the requirements of [22].

2.1.2. Cement

Cement (lime) 42.5 is used for all concrete mixes. Cement meets the requirements of [23].

2.1.3 Water

Water samples were taken from Civil Engineering Laboratory, Kenule Beeson Polytechnic, Bori Rivers State. The water meets the requirements of [24].

2.1.4 Structural Steel Reinforcement

Reinforcement is purchased directly from the Port Harcourt market. Meet the requirements of [25]

2.1.5 Corrosion Inhibitors (Resins / Exudates) Calotropis procera

Exudates were extracted from the root and fruit with toxic milky sap of gluey coating properties. It was obtained from Abiya Village bush in Bogoro Local Government Area of Bauchi State, Nigeria.

2.2. Samples prepared to be reinforced with coating

The exudate / resin obtained was coated directly in different thicknesses to reinforcing steel, embedded into concrete slabs and exposed to coastal waters with a high concentration of salt. Naturally, the corrosion behavior of reinforced materials, metals and related materials is a long-term process that takes several years. However, the artificial introduction of sodium chloride (NaCl) can accelerate the corrosion rate and corrosion will occur in a short time. The corrosion rate can be calculated by estimating the current density and the quantification rate of the degree of corrosion obtained or obtained from the polarization curve. Using the manual mixing method, with a standard concrete ratio of 1.2.4 and a water-cement ratio of 0.65, the concrete mix is batched according to the weight of the material. A concrete slab of 100 mm x 500 x 500 mm (thickness, width and length) with a thickness of 10 mm concrete cover is cast into a metal mold, compacted to eliminate air and reinforced with 10 numbers of steel bars with a diameter 12 mm at a distance of 100 mm c / c (top and bottom), and demold after 72 hours, cure at standard room temperature for 28 days until set. The hardened concrete slab is fully immersed in water, and then a 5% sodium chloride (NaCl) solution is immersed for 360 days, and it is accelerated by interval inspection and routine tests at 90 days, 180 days, 270 days and 360 days.

2.3 Accelerated corrosion test

The corrosion process is a natural phenomenon, it takes decades to appear, this is a long-term process, but the use of artificial sodium chloride substances (NaCl), accelerated corrosion process makes the corrosion process fast, and possible. Corrosion of steel bars embedded in concrete can simulate the increased corrosion that will occur in a short period of decades. To test the corrosion resistance of concrete, experimental procedures was designed to accelerate the corrosion process and maximize the corrosion resistance of concrete. Accelerated corrosion testing is a current impressed technique and an effective technique that can be used to check the corrosion process of steel in concrete and assess damage to the outer layer of concrete. The laboratory acceleration process helps distinguish the effects of various factors that may affect chloride corrosion. Therefore, in order to design structural elements and corrosion resistance, as well as select suitable materials and suitable protection systems, it is necessary to carry out accelerated corrosion tests to obtain quantitative and qualitative information about corrosion.

2.4 (Measurement of Half-Cell Potential)

The corrosion severity degree and level of steel bar is shown in Table 2.1. If potential measurements indicate a high probability of active corrosion, concrete resistivity measurements can be used to assess the degree of corrosion. However, care must be taken when using this data because it is assumed that the corrosion rate is constant over time. The half-potential measurement is an indirect method to estimate the possibility of corrosion. However, there has recently been research into the development of a tool to perform electrochemical measurements of interference on the steel itself to obtain a direct estimate of the corrosion rate [26]. Corrosion rate is related to electrochemical measurement, firstly based on data

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

Potential E_{corr}	**Probability of Corrosion**
Ecorr < −350mV	Greater than 90% probability that reinforcing steel corrosion is occurring in that area at the time of measurement
−350mV ≤ E_{corr} ≤ −200mV	Corrosion activity of the reinforcing steel in that area is uncertain
E_{corr} > −200mV	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

To measure the resistivity of concrete took different readings at different positions on the concrete surface. After applying water to the surface of the slab, the resistivity of the concrete is measured at a reference point every day to determine its saturation state. Slab saturation is controlled by measuring the resistivity of the concrete, which is directly related to the moisture content of the concrete. Time limitation is the main challenge for all experimental measurements, because the saturation state of concrete changes with time. To do this, the four probes directly contact the concrete on the steel rail. Before pouring water on the slab, measure the resistivity of the concrete at certain locations in the dry state. After the concrete reaches the saturated state, the resistivity will be constant.

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 steel bars

In order to determine the elastic limit and tensile strength of steel bars, a tensile test was carried out on the concrete slabs reinforced with 10 numbers of 12mm diameter (top and bottom direction) of uncoated and coated reinforcing steel and tested under stress in an Instron Universal testing machine (UTM) to failure. A digitalized and computerized system records the results of yield strength, ultimate tensile strength, and strain ratio. To ensure stability, the remaining cut portions are used for other parameters examinations of rebar diameter before the test, rebar diameter - after corrosion, cross-sectional area reduction/increase, rebar weights- before the test, rebar weights- after corrosion, weight loss /gain of steel.

3.0. TEST RESULTS AND DISCUSSION

The half-cell potential measurement results in Table 1 are plotted against the resistance in Table 3 for easy explanation. 2. It is used to represent the significant corrosion probability of extremely high, extremely high, extremely low to moderate and extremely low corrosion probability (ρ 20). At another measurement point, the correction potential is very high (–350 mVEcorr≤–200 mV), which averages that the probability of corrosion is 10% or uncertain. The measurement results of concrete strength are shown in Table 2. It has been shown that when there is a low corrosion potential (<-350 mV) within a certain range, there is a 95% possibility of corrosion. Concrete strength is usually measured using the fourelectrode method. The data from the resistance study indicates whether certain conditions will cause less ion movement, which leads to more 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	**CPS**	**CPS1**	**CPS2**	**CPS3**	**CPS4**	**CPS5**	**CPS6**	**CPS7**	**CPS8**	**CPS9**	**CPS10**	**CPS11**
	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	-109.7	-110.4	-106.1	-104.7	-107.1	-104.1	-112.6	-108.2	-103.8	-106.1	-110.4	-104.3
Concrete Resistivity ρ, kΩcm	15.16	15.15	15.14	15.14	15.13	15.30	15.29	15.28	15.28	15.27	15.21	15.13
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)	623.90	621.85	623.53	619.31	622.84	623.26	623.06	623.86	622.46	624.01	623.51	623.37
Strain Ratio	1.37	1.36	1.37	1.36	1.37	1.36	1.36	1.36	1.36	1.36	1.37	1.36
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	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Rebar Weights- After at 28 days (Kg)	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
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	-306.3	-311.5	-308.4	-300.8	-310.6	-317.6	-351.5	-358.7	-362.8	-385.9	-409.1	-417.4
Concrete Resistivity ρ, kΩcm	**7.04**	**7.06**	**7.89**	**8.20**	**7.98**	**7.53**	**7.35**	**7.71**	**7.74**	**7.34**	**6.72**	**7.53**
Yield Strength, fy (MPa)	421.77	424.77	420.77	421.07	421.77	421.00	424.00	424.30	423.00	424.39	420.89	424.73
Ultimate Tensile Strength, fu (MPa)	611.79	609.74	611.42	607.20	610.73	611.15	610.95	611.75	610.35	611.90	611.40	611.26
Strain Ratio	1.45	1.44	1.45	1.44	1.45	1.45	1.44	1.44	1.44	1.44	1.45	1.44
Rebar Diameter Before Test (mm)	11.96	11.94	11.95	11.97	11.94	11.96	11.96	11.94	11.95	11.95	11.94	11.95
Rebar Diameter- After Corrosion(mm)	11.91	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)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Rebar Weights- Before Test(Kg)	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Rebar Weights- After Corrosion (Kg)	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
Weight Loss /Gain of Steel (Kg)	0.05	0.05	0.05	0.06	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 Calotropis procera 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	-124.6	-127.0	-126.4	-126.6	-123.0	-127.1	-125.3	-129.7	-125.6	-120.2	-120.7	-126.9
Concrete Resistivity ρ, kΩcm	16.93	17.08	17.36	17.49	17.18	17.47	17.42	17.57	17.60	17.07	16.96	16.81
Yield Strength, fy (MPa)	457.41	457.71	456.41	455.64	458.64	458.94	457.64	459.03	455.54	459.37	455.07	456.51
Ultimate Tensile Strength, fu (MPa)	628.72	626.67	628.35	624.13	627.66	628.08	627.88	628.68	627.28	628.83	628.33	628.19
Strain Ratio	1.37	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)	11.97	11.95	11.96	11.98	11.95	11.97	11.97	11.95	11.95	11.95	11.95	11.96
Rebar Diameter-After Corrosion(mm)	12.03	12.01	12.02	12.04	12.01	12.03	12.03	12.01	12.01	12.01	12.01	12.02
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)	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Rebar Weights-After Corrosion (Kg)	0.95	0.95	0.95	0.95	0.95	0.95	0.96	0.96	0.95	0.95	0.95	0.96
Weight Loss /Gain of Steel (Kg)	0.07	0.07	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 Exudates/Resin Coated (specimens Average Potential Ecorr, after 28 days curing and 360days

Sampling and Durations	Control Concrete slab Specimens				Corroded Concrete slab Specimens				Calotropis procera 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 Calotropis procera Exudate / Resin Coated Specimens			
Potential Ecorr, mV	-108.8	-105.3	-108.2	-106.8	-308.7	-309.6	-357.6	-404.1	-125.9	-125.5	-126.6	-122.6
Concrete Resistivity ρ, kΩcm	15.15	15.19	15.28	15.20	7.33	7.90	7.60	7.19	17.12	17.38	17.53	16.95
Yield Strength, fy (MPa)	455.75	456.26	457.08	456.66	422.43	421.28	423.76	423.34	457.17	457.74	457.40	456.98
Ultimate Tensile Strength, fu (MPa)	623.09	621.80	623.13	623.63	610.99	609.70	611.02	611.52	627.91	626.62	627.94	628.45
Strain Ratio	1.37	1.36	1.36	1.37	1.45	1.45	1.44	1.45	1.37	1.37	1.37	1.38
Rebar Diameter Before Test (mm)	11.95	11.96	11.95	11.94	11.95	11.96	11.95	11.95	11.96	11.97	11.96	11.95
Rebar Diameter-After Corrosion(mm)	11.95	11.96	11.95	11.94	11.91	11.91	11.90	11.90	12.02	12.02	12.01	12.01
Cross- sectional Area Reduction/Increase (Diameter, mm)	0.00	0.00	0.00	0.00	0.055	0.057	0.055	0.059	0.061	0.064	0.066	0.063
Rebar Weights-Before Test(Kg)	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Rebar Weights-After Corrosion (Kg)	0.88	0.88	0.88	0.88	0.83	0.83	0.83	0.83	0.95	0.95	0.96	0.95
Weight Loss /Gain of Steel (Kg)	0.00	0.00	0.00	0.00	0.05	0.06	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				Calotropis procera 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 Calotropis procera Exudate / Resin Coated Specimens			
Potential Ecorr, mV	-64.76	-65.97	-69.74	-73.56	145.22	146.61	182.36	229.50	-59.22	-59.45	-64.58	-69.65
Concrete Resistivity ρ, kΩcm	106.67	92.17	101.08	111.34	-57.19	-54.53	-56.65	-57.55	133.62	119.93	130.67	135.59
Yield Strength, fy (MPa)	7.89	8.31	7.86	7.87	-7.60	-7.97	-7.35	-7.36	8.22	8.66	7.94	7.95
Ultimate strength (N/mm2)	1.98	1.99	1.98	1.98	-2.70	-2.70	-2.69	-2.69	2.77	2.78	2.77	2.77
Strain Ratio	-5.46	-5.81	-5.48	-5.47	5.32	5.70	5.03	5.09	-5.05	-5.39	-4.79	-4.84
Rebar Diameter Before Test (mm)	0.044	0.046	0.047	0.048	0.043	0.045	0.048	0.045	0.043	0.044	0.048	0.049
Rebar Diameter-After Corrosion(mm)	0.446	0.446	0.443	0.446	-0.926	-0.919	-0.952	-0.986	0.929	0.925	0.928	0.929
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.00	0.00	0.00	0.00	-15.79	-15.79	-15.79	-15.79	18.75	18.75	18.75	18.75
Rebar Weights-Before Test (Kg)	0.410	0.413	0.411	0.412	0.406	0.415	0.411	0.415	0.413	0.411	0.410	0.413
Rebar Weights-After Corrosion (Kg)	8.53	8.65	8.51	8.65	-13.31	-13.31	-13.28	-13.31	11.66	11.37	11.32	11.56
Weight Loss /Gain of Steel (Kg)	0.00	0.00	0.00	0.00	-26.03	-23.61	-26.03	-26.03	35.19	30.91	35.19	35.19

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

The electrical resistivity of concrete is an important parameter to describe the resistance of concrete structures and the risk of corrosion of reinforcement [10, 29, 30, 31]. In addition, this property is very important for the design of electrochemical repair systems and for monitoring repair efficiency. The corrosion rate is controlled by the ease with which ions can pass through the concrete from the cathode to the anode area. Therefore, the large potential gradient compared to the low resistance of the concrete usually results in high corrosion rates. The obtained computed results of corrosion potential $E_{corr,mV}$, and concrete resistivity, kΩcm, from Tables 3.1 - 3.3 and summarized into average and percentile values in Tables 3.4 and 3.5, represented graphically in Figures 3.1-3.7b, are the results of controlled samples, the reference range from which all other results are determined from, non-coated (corroded).) and coated for 36 concrete slabs, divided into 3 sets of 12 controlled samples, which are the determinant reference range, 12 uncoated (corroded) samples and 12 exudates/resin coated samples.

The average and minimum, maximum and differential values of the calculated measurements of the half-cell potentials of the controlled sample were -108.8 mV and -105.37 mV (-73.56% and -64.76%) with potential differences (3.43mV and 8.8%), the corroded samples were -404.17 mV and -308.77mV (145.22% and 229.5%) and the difference values were 95.42mV and 84.28%, and the coated samples were -126.68 mV and -122.66 mV (-69.65% and -59.22%) and the potential differences are 4.02 mV and 10.43%, respectively. The maximum calculated percentile control value is -59.22% compared to the corroded and coated values of 229.5% and -59.22% and the controlled potential difference value is 8.8%, 84.28% corroded and 10.43% coated. The maximum yields of the controlled and coated samples were -105.37mV and -122.66mV 6mV, which showed the relationship between corrosion potential and opportunity in the reference range $E_{corr} > -200$mV. The results of these potential E_{corr} results indicate that the controlled and exudates/resin-coated sample values are low with a 90% probability that no corrosion of reinforcing steel is observed at the time of measurement (10% or uncertain). Corrosion potential probability values of uncoated samples has maximum calculated range of -

308.77mV, the result is within the reference value of dependence between corrosion potential and probability of value $-350\text{mV} \leq E_{\text{corr}} \leq -200\text{mV}$ indicates a high range of values, which is 10% or uncertain probability of corrosion. Results in comparison from the reference range (controlled), it is observed that show that non-coated samples showed corrosion potentials with higher values as a result of accelerated corrosion induced as compared to coated samples which show no corrosion presence and attack on reinforcing steel embedded in concrete slab, and exposed corrosive environment with high saline level. Coated samples exhibited inhibitory properties with the formation of resistive coating to corrosion dissemination.

The durability of concrete is a function of the water content of the concrete, the type of cement used, the water/cement ratio (w/c), the presence of chloride ions and the carbonization state of the concrete [10, 32]. The most commonly used field testing technique is the 4-sample Wenner technique [33-35]. The probe is placed on the surface of the tested concrete and an alternating current is changed between the two outer electrodes, while the voltage is recorded at the two inner electrodes. The disadvantage of this technique is that the exact conduction route may not be known.

The average values and the specific minimum and maximum percentages of resistance with the controlled sample potential difference were 15.15kΩcm and 15.28kΩcm (92.17% and 111.34%) and the difference values were 0.13kΩcm and 19.17%. The corroded samples were 7.19kΩcm and 7.9kΩcm (-57.55% and -54.53%) and the difference values were 0.71kΩcm and 3.02%, the portion of the sample covered was 16.95kΩcm and 17.53kΩcm (119.93% and 135.59%) and the difference values of 0.58 mV and 15.66%, respectively. The maximum value calculated from the concrete resistance of the controlled sample is 111.34% compared to the corroded and coated value of -54.53% and 135.59% and the maximum value of the percentile difference from the control is 19.17% compared to the corroded and coated value of 3 0.02% and 15.66%. The results of testing controlled samples coated with concrete resistance obtained the maximum average values of 15.28 kΩcm and 17.53kΩcm with a description of the value $10 < \rho < 20$ (low) compared to the corrosion value of 7.9 kΩcm with specifications $5 < \rho < 10$ (high) and with a reference range of dependence between concrete resistance and corrosion probability at 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 of $5 < \rho < 10$, which indicates high, signs indicating the possibility of corrosion, as in the works [15, 17, 21].

From the results obtained, it can be compared that the effect of corrosion attack was observed in uncoated samples, while samples with exudates/resin coating had anti-corrosion properties with highly resistant and water-resistant membranes that prevented corrosion of reinforcing steel embedded in concrete structures and exposed to high salinity media of induced corrosion.

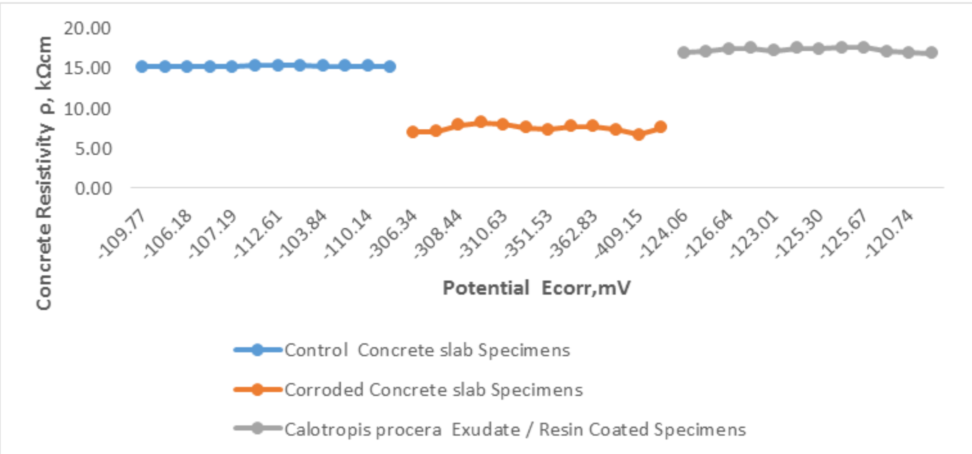

Fig-3.1: Concrete Resistivity ρ, kΩcm versus Potential Ecorr, mV Relationship

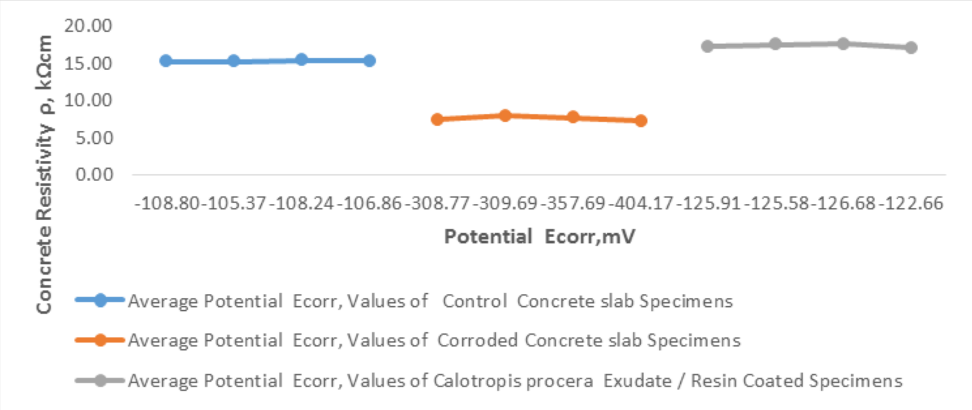

Fig-3.1A: Average Concrete Resistivity versus Potential Relationship

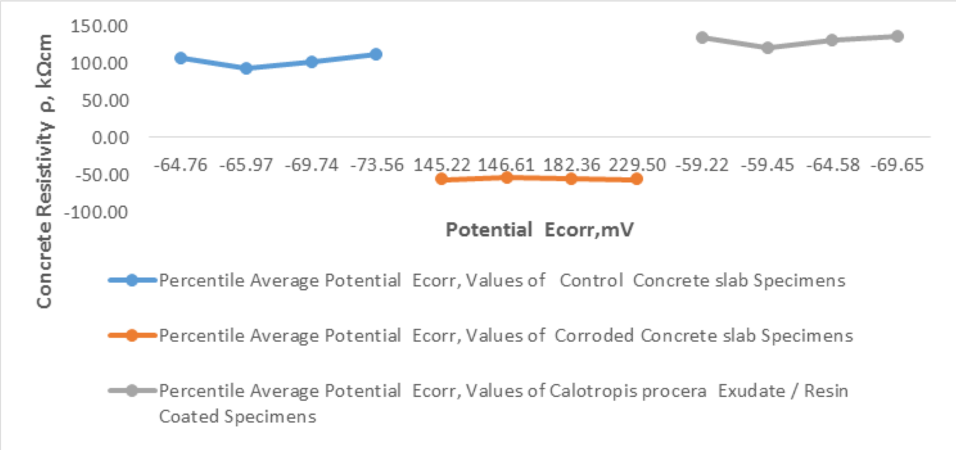

Fig-3.1B: Average Percentile Concrete Resistivity versus Potential Relationship

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

The degradation of reinforced concrete structures by chloride reinforced concrete infrastructure is affected by corrosion which worsens especially exposed to coastal/sea water under severe and corrosive conditions. In chloride-containing media, as a result of expansion-contraction and hydration-dehydration cycles, resulting from seasonal fluctuations in temperature and humidity which leads to the initiation and spread of corrosion of reinforcement, which leads to cracking, decay and loss of load bearing capacity of reinforced concrete structures. In order to protect reinforcing steel from corrosion, the mechanism of chloride entry into concrete and the factors that influence it must be understood and limited through the use of inhibitors.

The results of the mean, percentile and the difference between the minimum and maximum yield strength (limits), fy (MPa) of the controlled sample were 455.75MPa and 457.08MPa (7.86% and 8.31%) and the difference in values are 1.33MPa and 0.45%, the corroded samples were 421.28MPa and 423.76MPa (-7.97% and -7.35%) and the difference in value are 2.48MPa and 0.62%, the coated sample value were 457.74MPa and 457.74MPa (7.94% and 8.66%) and the difference value are 0.76MPa and 0.72%. The calculated maximum percentage of the controlled yield strength was 8.31% compared to the corroded and coated values -7.35% and 8.66% and the possible difference values of 0.45% controlled, 0.62% corroded and 0.72% coated.

The mean, percentile, and the difference between the minimum and maximum tensile strength, fu (MPa) of the controlled sample were 621.8MPa and 623.63MPa (1.98% and 1.99%) and the difference in value was 1.83MPa and 0.01%, corroded 609.7MPa and 611.52MPa (-2.7MPa and -2.69%) and the difference is 1.82MPa and 0.01%, the coated is 626.62MPa and 628.45MPa (2.77% and 2.78%) and the difference values are 1.83 MPa and 0.01%, the calculated maximum percentage of the controlled of ultimate tensile strength is 1.99% relative to corroded value of -2.69% and the coated values of 2.78%% and with differential potential values of 0.01% controlled, 0.01% corroded and 0.01% coated.

The strain ratio of the mean minimum and maximum, percentile and difference values of the controlled samples were 1.36 and 1.37 (5.81% and -5.46%) with a difference value of 0.01 and 0.35%, the corroded value samples were 1.44 and 1.45 (5.03% and 5.7%) and the difference in values are 0.01 and 0.67%, the coated samples were 1.37 and 1.38 (-5.39% and - 4 .79%) and the difference value of 0.01 and 0.6%. The maximum calculated percentage for comparison checked are -5.46% against corrosion 5.7% and coated - 4.79%, and differential maximum computed values 0.35% controlled, and 0.67% corroded and 0.6% coated, as confirmed in works [15, 17, 21].

From the calculation results obtained, which are summarized in Tables 3.4 and 3.5 and shown graphically in Figures 3.1 - 3.7b, the yield strength, ultimate tensile strength and strain ratio deformation average and percentile values computed from data as presented in the tables and represent in figures of controlled, corroded and coated samples of 36 concrete slab showed the differential parameters existed among the tested samples. The controlled samples remained the reference range for which comparative results are drawn from the corroded and the coated samples.

Comparatively, corroded samples exhibited high yielding to low load application representing the effect of corrosion on the mechanical properties of reinforcing steel that has resulted to low load carrying capacity, the corroded also recorded higher strain ratio as compared to the coated to the parameters above. The results obtained showed that coated samples maintained closed values range to that of controlled samples having the attributes that exudates/resin coated samples exhibited the potential of inhibition against corrosion attacks on reinforcing steel embedded in concrete structures and exposed to corrosive media with the formation of watertight and resistive membrane. These attributes showed the effectiveness of Calotropis procera exudates/resin as an anti-corrosive agent and can be used as an inhibitor in curbing the scourge and the damaging effects of corrosion to reinforced concrete structures built within the coastal region with high level of salinity.

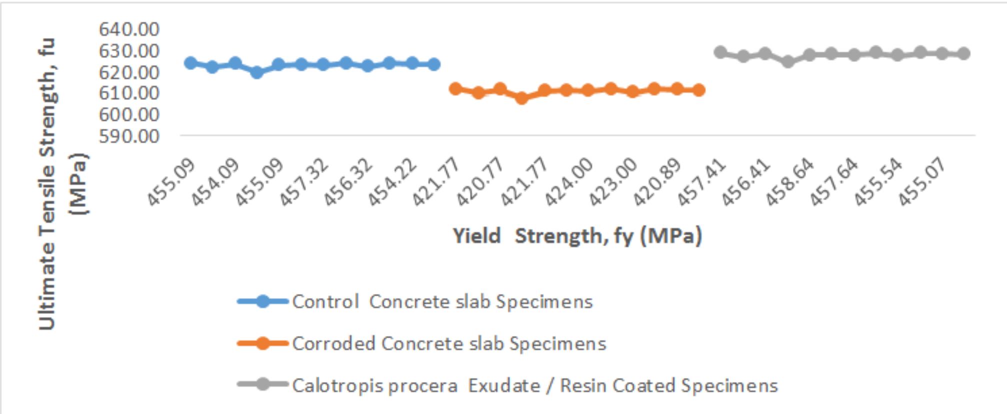

Fig-3.2: Yield Strength versus Ultimate strength

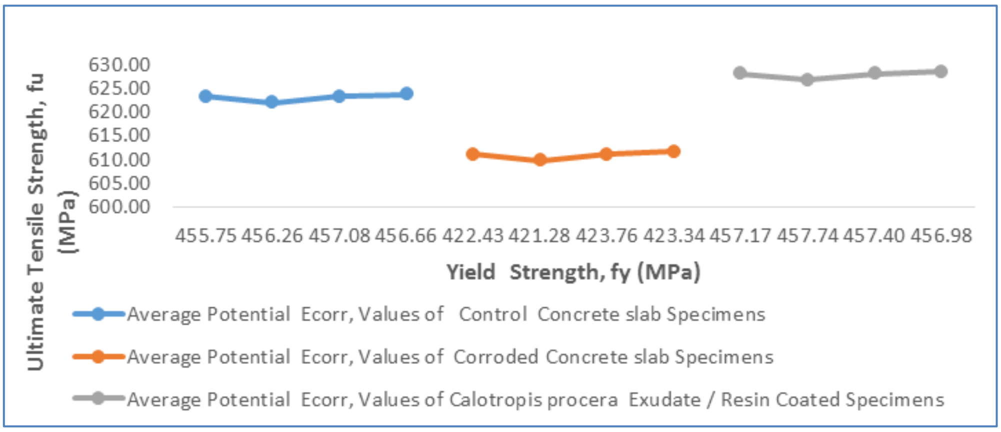

Fig-3.2A: Average Yield Strength versus Ultimate Tensile Strength

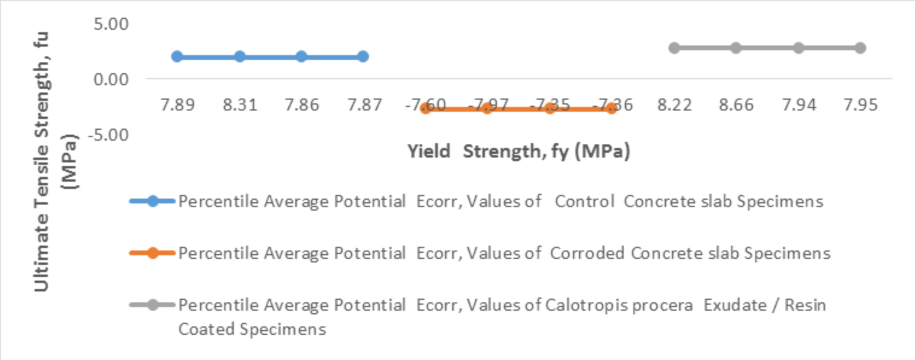

Fig-3.2B: Average Percentile Yield Strength versus Ultimate Tensile Strength

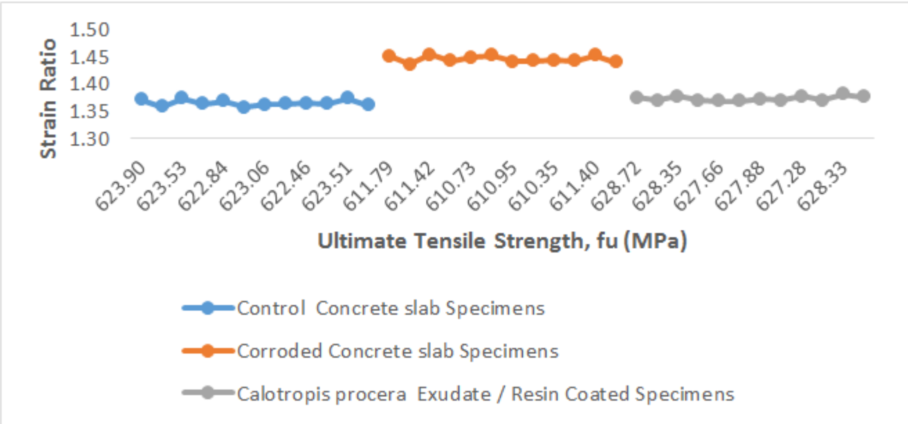

Fig-3.3: Ultimate Tensile Strength versus Strain Ratio

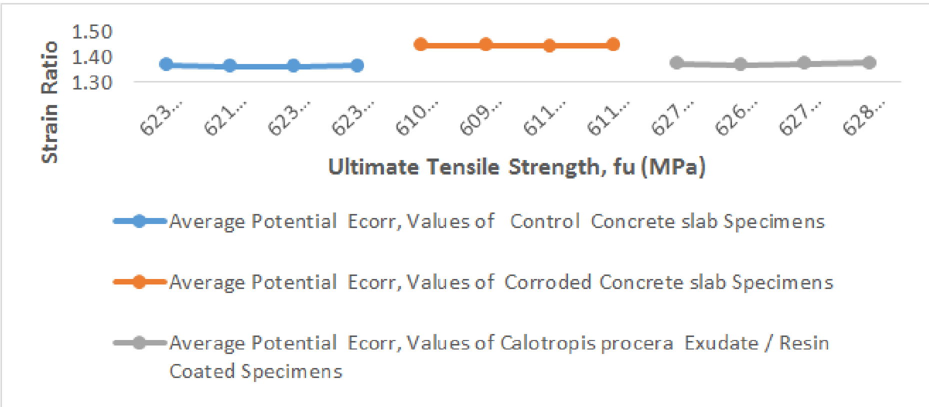

Fig-3.3A: Average Ultimate Tensile Strength versus Strain Ratio

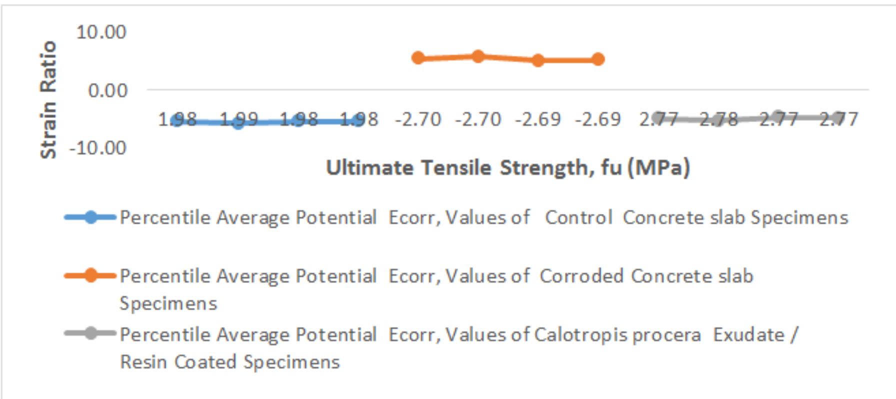

Fig-3.3B: Average percentile Ultimate Tensile Strength versus Strain Ratio

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

Corrosion affects the structural integrity of the concrete structure, leading to a decrease in the mechanical properties of reinforcement [36, 37]. An aggravating effect of corrosion is the reduction of the usable cross-sectional area of the reinforcing structural elements [38, 39].

The obtained values of diameter before testing (mm) of the minimum and maximum average and percentile values were controlled samples 11.94mm and 11.96mm (0.044% and 0.048%) with a difference of 0.02 mm and 0.004%, the corroded value, was 11.95mm and 11.96mm (0.043% and 0.048%) and the difference values of 0.01 mm and 0.005% and the values of the coated samples were 11.95mm and 11.97mm (0.043% and 0.049%) and the deferential computed values are 0.02mm and 0.006%.

The unit rebars weight before the corrosion test showed very small differences due to the product and shape of the company as well as the by-products used in the production process. The minimum and maximum mean values obtained, percentiles and the value of the difference in the diameter of the reinforcement after corrosion (mm) for the controlled sample were 11.94 mm and 11.96 mm (0.044% and 0.048%) with a difference of 0.02 mm and 0.004%, respectively, maintaining 100% reference value, corroded sample values were 11.9mm and 11.91mm (-0.986% and -0.919%) and the difference was 0.01mm and 0.067%, sample of coated values were 12.01 mm and 12.02 mm (0.925% and 0.929%) and the difference between 0.01mm and 0.004%. The maximum calculated percentage was set at 0.929% versus corroded - 0.919% and coated at 1.043%, with a percentage difference in corrosion of 0.004% versus 0.067% 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, which is exposed to induced corrosion-accelerating activity. For comparison, the results of the corroded samples showed a reduction values compared to the diameter of the reinforcement before and after the induction accelerated corrosion test with a percentage decrease in value from 0.048% to -0.919% and an average value in the range from 11.96mm to 11.91mm.

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 loss of the steel cross-sectional area is the destruction of the steel to its original state, namely rusting. Rust, a product of corrosion, increases the original volume of steel by 3 to 5 times. Due to expansion, this causes internal stresses between the concrete surfaces and eventually leads to cracking of the concrete cover [40].

The cross-sectional area decrease/increase (diameter) minimum and maximum mean and percentile values were controlled up to 100%, with no decrease or increase after 360 days of immersion in fresh water. Corroded sample values are 0.05 mm and 0.059 mm (-15.79% and -15.79%) and the difference between 0.004% and 0.00% for the corroded, coated sample values are 0.061 mm and 0.066 mm, 75 % and 18.75%) and the difference between 0.005 mm and 0.00%. The relative mean and difference in percentage values between coated samples and corrosion range from 18.75% to -15.79%. 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 [36].

The decrease in mean and percentage values indicates that the corrosion effect causes a reduction in diameter and cross-sectional area, fiber degradation, rib reduction and surface modification, whereas exudates/resin-coated elements confirm an increase in volume as the difference in coating thickness as affirmed by the studies of [15, 17, 21].

In summary it can be said that the exudates/resin has inhibitory properties against corrosive effects on reinforcing steel embedded in the concrete slab sample, which is induced in an environment with high salt content.

The rebar unit Weight - Before Test (kg), of the mean and percentage results of the minimum, maximum, and differential of the controlled samples were 0.88 kg and 0.88 kg (6.429% and 6.551%) and the difference was 0.00% and 0.122 %, corroded samples were 0.88 kg and 0.88 kg (6.431% and 6.513%) and the difference was 0.00% and 0.082%, coated samples were 0.88 kg and 0.88 kg (6.255% and 6.549%) with a difference of 0.00% and 0.294%.

The results of the average value and percentage of rebar weight after corrosion (Kg) and the generalized difference value from the minimum and maximum values of the controlled sample were 0.88 kg and 0.88 kg (6.429% and 6.551%), and the difference is 0.00% and 0.122%, corroded samples 0.83 kg and 0.83kg (-13.31% and -13.28%) and the difference between 0.00% and 0.03%, the value of coated samples is 0.95kg and 0.96kg (11.32% and 11.66%) and the difference between 0.01% and 0.34%. Average and percentage losses/gains of minimum and maximum units of steel (kg) and percentage difference in comparison are controlled values which are kept at 100% as a result of aggregation in fresh water tanks with no trace of corrosion potential relative to a corrosion sample value of 0.05kg and 0.06kg (-26.03% and -23.61%) and coverage of 0.07 kg and 0.07 kg (30.91% and 35.19%). The calculation results from Tables 3.1-3.3 and in 3.4 - 3.5 are summarized and plotted graphically in Figures 3.7-3.7b, the listing effects of corrosion on non-coated (corroded) and coated reinforcing steel and checking the weight of reinforcement before and after corrosion testing and reduction/increase weight. Comparatively, the results obtained show a reduction of the mean and percentile values for corroded from 0.07 kg to 0.05 kg and 35.19% to -23.61%, as affirmed by works of [15, 17, 21].The summary results show that the corrosion effect on corroded samples causes a decrease/decrease in weight compared to coatings with percentile loading and an increase in mean values, which causes a slight increase in volume with coating thickness. This study shows the efficacy and effectiveness of exudates/resin as an inhibitor against the effects of corrosion on reinforcement embedded in samples of concrete slabs exposed to induction corrosion.

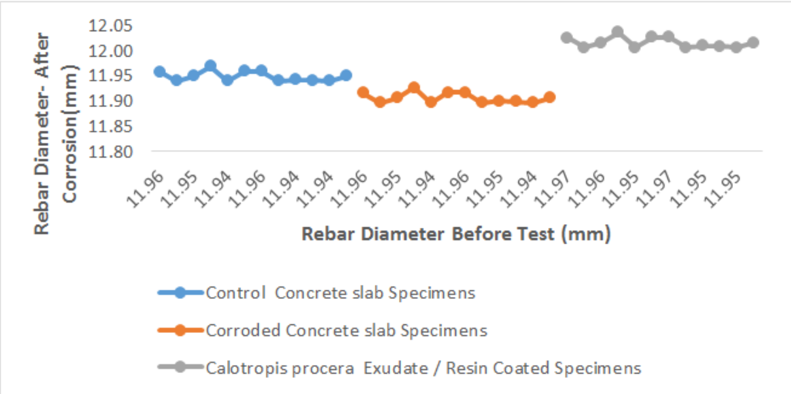

Fig-3.4: Rebar Diameter before Test (mm) versus Rebar Diameter- After Corrosion (mm

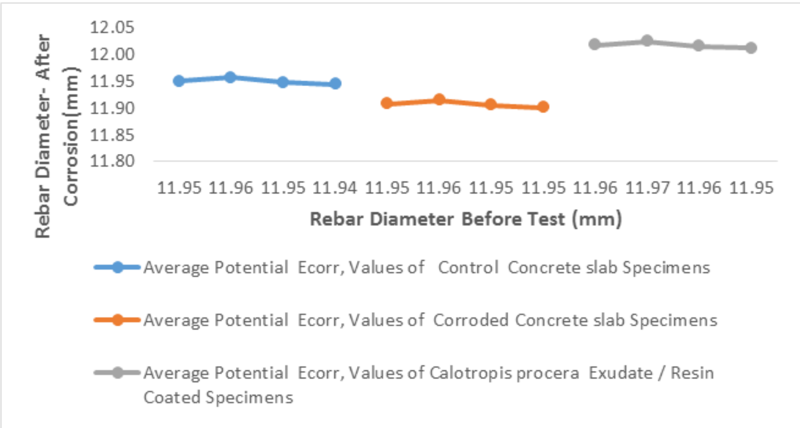

Fig-3.4A: Average Rebar Diameter before Test (mm) versus Rebar Diameter- After Corrosion (mm)

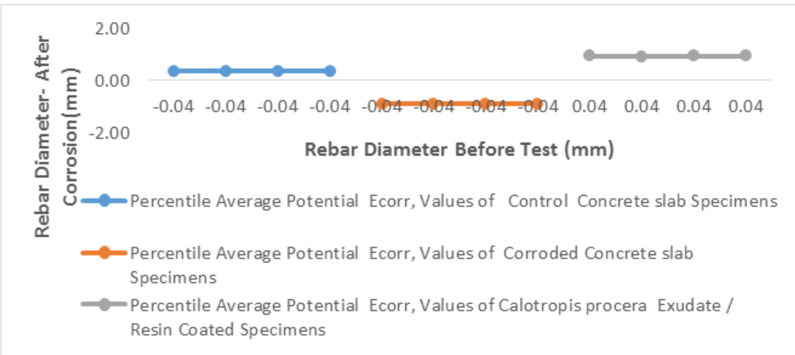

Fig-3.4B: Average Percentile Rebar Diameter before Test (mm) versus Rebar Diameter- After Corrosion (mm)

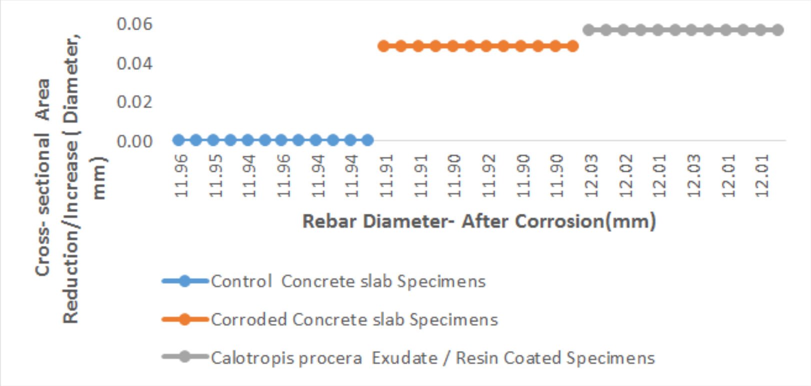

Fig-3.5: Rebar Diameter- after Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

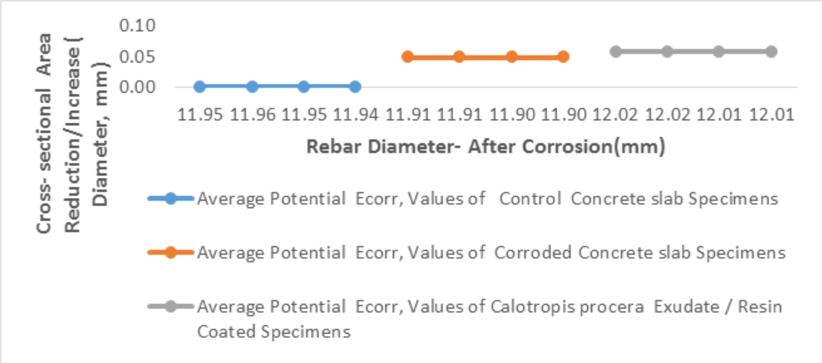

Fig-3.5A: Average Rebar Diameter- after Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

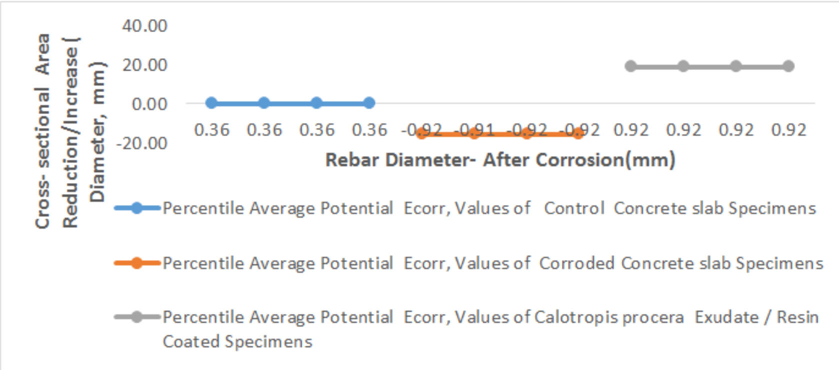

Fig-3.5B: Average Percentile Rebar Diameter- after Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

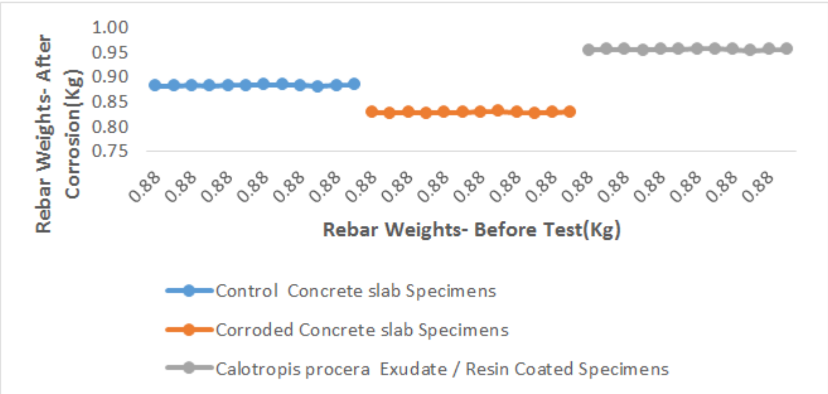

Fig-3.6: Rebar Diameter - After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

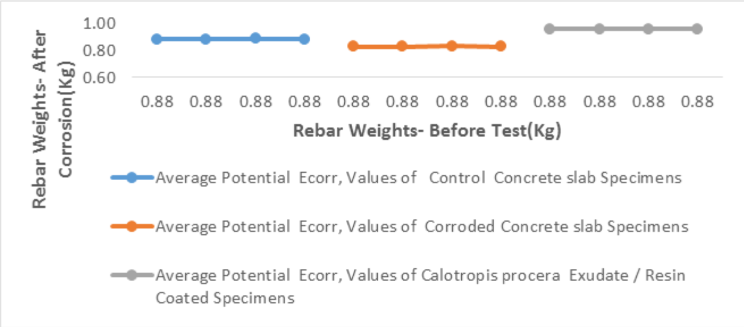

Fig-3.6A: Average Rebar Diameter - After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

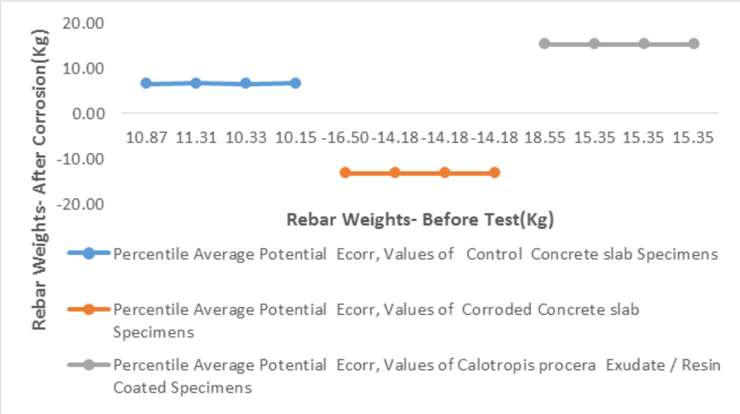

Fig-3.6B: Average Percentile Rebar Diameter - After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

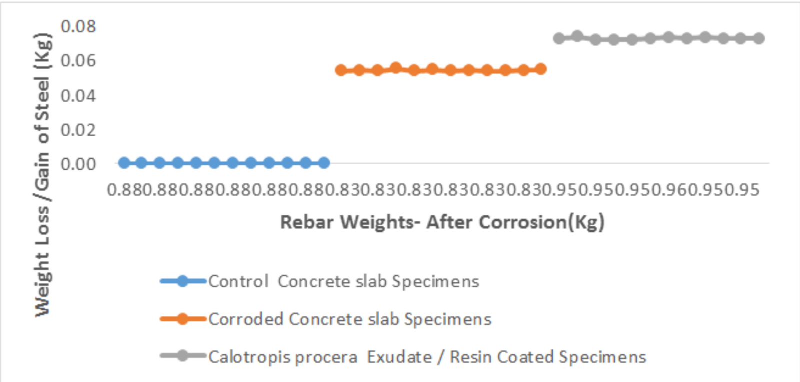

Fig-3.7: Rebar Weights- After Corrosion (Kg) versus Weight Loss /Gain of Steel (Kg)

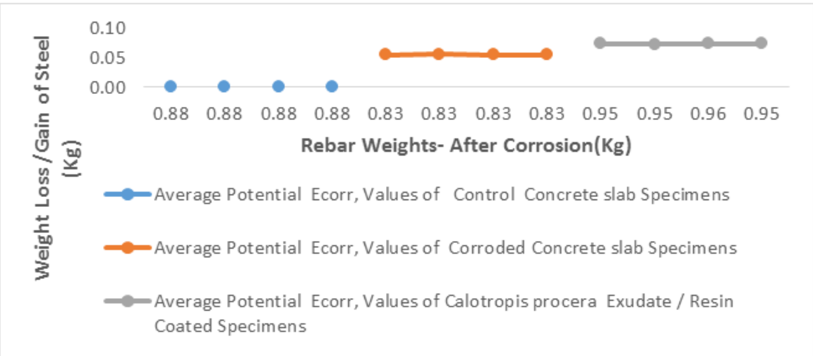

Fig-3.7A: Average Rebar Weights- After Corrosion (Kg) versus Weight Loss /Gain of Steel (Kg)

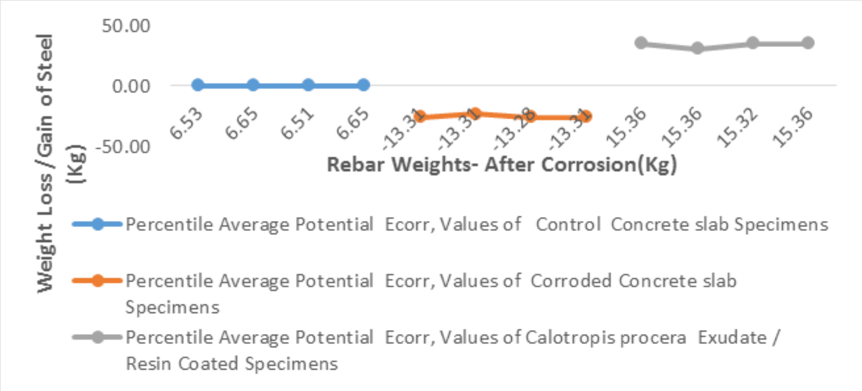

Fig-3.7B: Average Percentile Rebar Weights- After Corrosion (Kg) versus Weight Loss /Gain of Steel (Kg)

4.0. CONCLUSION

Experimental results showed the following conclusions

1. Non-coated samples showed corrosion potentials with higher values as a result of accelerated corrosion induced as compared to coated samples which show no corrosion presence and attack on reinforcing steel embedded in concrete slab, and exposed corrosive environment with high saline level.
2. Coated samples exhibited inhibitory properties with the formation of resistive coating to corrosion dissemination.
3. Effect of corrosion attack was observed in non-coated samples, while samples with exudates/resin coating had anti-corrosion properties with highly resistant and water-resistant membranes that prevented corrosion of reinforcing steel embedded in concrete structures and exposed to high salinity media of induced corrosion.
4. Corroded samples exhibited high yielding to low load application representing the effect of corrosion on the mechanical properties of reinforcing steel that has resulted to low load carrying capacity, the corroded also recorded higher strain ratio as compared to the coated to the parameters above.
5. The results obtained showed that coated samples maintained closed values range to that of controlled samples having the attributes that exudates/resin coated samples exhibited the potential of inhibition against corrosion attacks on reinforcing steel embedded in concrete structures and exposed to corrosive media with the formation of watertight and resistive membrane.

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