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Original Research Article

Wenner Probe Technique Application in Electrical Resistivity and Corrosion Potential Measurements of Concrete Induced Chloride threshold Mechanism

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Abstract

The research evaluated Musanga cecropioides extrusion viscosity gummy paste (exudate/resin) obtained from trees as a corrosion inhibitor material to slow down the impact of corrosion on steel bars embedded in concrete and constructed in high-salinity coastal areas. The exudates/resin extracted is coated on the steel bar and embedded in the concrete slab, exposed to the corrosive medium with high salt concentration. The hardened concrete slab is completely immersed in a 5% aqueous sodium chloride (NaCl) solution, and the rapid corrosion process accelerated for 360 days with interval inspections and routine tests at 90 days, 180 days, 270 days, and 360 days for comparative evaluations for both uncoated and coated samples. The computed maximum control percentile value is -67.28% compared to the corroded and coated values 241.14% and -64.4% and the controlled potential difference value is 4.99%, corroded 60.25%, and coated 6.29%. The maximum yields of the controlled and coated samples were -105.1mV and -113.74mV, with the result obtained, this showed an indicative relationship between corrosion potential and probability as $E\text{corr} > -200\text{mV}$ as the reference range. These results of potential Ecorr results showed indication that the values of controlled and exudates/ resin coated specimens are low with the range of 90% probability that no reinforcing steel corrosion is occurring in that area at the time of measurement (10% risk of corrosion which indicates a 10% or uncertain probability of corrosion. For the non-coated sample, the maximum obtained computed value is -328.64mV, the results are within the range reference of dependence between potential and corrosion probability of the value $-350\text{mV} \leq E\text{corr} \leq -200\text{mV}$ indicating a high range of values, notifying a 10% or uncertain probability corrosion. The comparative results from the referencing range (controlled), showed that corroded samples exhibited corrosion presence resulting from the induced corrosion acceleration against coated samples that exhibited absence of corrosion. The exudates/resins exhibited inhibitory characteristics against corrosion attacks on reinforcing steel embedded in the concrete slab, exposed to corrosive media by the formation of the resistive coating. The maximum computed percentile of the controlled sample of concrete resistivity is 149.21% compared to the corroded and coated value of -59.26% and 153.52% and the maximum percentile difference of control is 5.38% compared to the corroded and coated value of 1.3 % and 8.09%. The results of the controlled and coated concrete resistivity samples obtained at an average maximum value of 15.85kΩcm and 16.23kΩcm with a data value of $10 < \rho < 20$ (low) compared to a corrosion value of 6.45kΩcm with specifications ($\rho < 5$, $5 < \rho < 10$, $10 < \rho < 20$, $\rho > 20$) and with the reference range of the relationship between concrete resistivity 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. The computed maximum percentile of the controlled yield strength is 8.96% compared to the corroded and coated values -7.83% and 9.08% and the possible difference values are 0.45% controlled, 0.49% corroded, and 0.59% coated. The maximum computed difference in values is 1.83MPa and 0.01% the controlled tensile strength is 3.478% against the corroded and coated values, respectively are -2.942% and 5.408% and the potential difference values 0.01% controlled, 0.01%% corroded and 0.01% coated. The yield strength, tensile strength, and strain ratio of the mean, percentile, and differential potential values of the control, uncoated (corroded) and coated concrete slab samples showed that coated samples had higher failure loads compared to corroded samples with reduced and decreased failure loads and low load-bearing capacity and with average values and percentiles to the reference range, while uncoated (corroded) samples recorded lower loads carrying capacity and reduced value compared to the reference range. The diameter of reinforcement after corrosion maximum computed percentile value is 0.039% as against -1.116% corroded and 1.128% coated; the difference in percentile is 0.005% corroded versus 0.008% coated. The results of the comparative of corroded samples show the reduction in values compared to the diameter of the reinforcement before and after the induction accelerated corrosion test with a percentile range for the reduction value from 0.039% to -1.116% and the average value in the range from 11.99mm to 11.94mm. The decrease/increase (diameter) in the cross-section of the minimum and maximum mean and percentile values were controlled 100%, with no decrease or increase in the description after 360 days of immersion in fresh water. The decrease in mean and percentile values indicates that the corrosion effect causes a reduction in diameter and cross-sectional area, fiber degradation, rib reduction, and surface modification, while the exudates/resin-coated elements show an increase in volume due to thickness differences in layers.

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

1.0. INTRODUCTION

Corrosion process does not occur directly but rather as a series of electrochemical reactions with the passage of an electric current. Corrosion also depends on the type and nature of the metal, immediate environment, temperature and other relevant factors. Corrosion is the damaging attacks of a metal with a chemical or electrochemical reaction with its environment. Steel in concrete is usually immune from corrosion due to the high alkalinity of concrete; pore water pH can be greater than 12.5, which protects embedded steel against corrosion. The alkalinity of concrete causes passivation of embedded reinforcement. A microscopic oxide layer, which is the film "passive" forms on steel surface due to the high pH, which prevents the dissolution of iron. The electrical resistivity of concrete is an important parameter to describe the resistivity of concrete structures and the risk of corrosion of reinforcement [1-4]. 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 region. Large potential gradients with low concrete resistivity therefore usually lead to high corrosion values, depending on the moisture content of the concrete, type of cement used, water/cement ratio (w/c), presence of chloride ions and carbonization [1, 5].

The most commonly used field test technique is Wenner's 4 sample techniques [6-8]. 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 conduction pathway may not be known with certainty.

Investigated the corrosion rate of embedded reinforcing steel in a concrete slab structure immersed in a corrosive environment, and assessed the corrosion potential using four Wenner- probe techniques and methods [9]. The non-coated sample value range shows significant corrosion potential probability due to the effect of corrosion on the mechanical properties of steel reinforcement; the results show a high yield and ultimate strength of the control sample and the coating sample. The results of the weight loss of steel showed a high percentile of values compared to the control and coating models because of the effect of corrosion on the mechanical properties of steel.

Evaluated the use of native eco-friendly inorganic exudates extracts from cola accumulator resins as a preventive measure against the corrosive effects of saltwater attack on reinforcing steel embedded in concrete structures with seawater, using an experimental application of half-cell corrosion potential and concrete resistivity to assess the surface modification of reinforcing steel immersed for 150 days in a corrosive environment with a rate range of 200mV to 1200 mV with a scanning speed of 1 mV/s. The results showed a high ultimate yield of the corrugated specimens to control and coating specimens due to the effect of corrosion on the mechanical properties of steel reinforcement. The results of the weight loss of steel showed a high percentile of values against the control and coating models due to the effect of corrosion on the mechanical properties of the steel[10].

Studied the effect of using steel reinforced concrete coated with Celtis zenkeri, embedded in concrete slabs with varying thicknesses by assessing corrosion potential and mechanical properties of reinforcing steel. The results showed a high ultimate yield of corroded specimens due to the effect of corrosion on the mechanical properties of steel reinforcement. The result of weight reduction of corroded steel shows a high percentile of value compared to the control and coated elements. The cross-sectional reduction results show a higher percentile of reduction due to the corrosive effect on the mechanical properties of the steel [11].

Evaluated the use of an inorganic exudates/resin extracted from the bark of Invincia gabonensis, coated to strengthen steel of various thicknesses, immersed in sodium chloride for corrosion acceleration for 150 days and compared to the uncoated and control sample[12]. The potential flow rate of 200 mV at 1200 mV with a scanning speed of 1 mV/s was adopted. The summary results of the exudates/resin coated samples showed no evidence of corrosive potential while non-coated samples showed corrosion potential probability. The cross-sectional reduction results show a higher percentile of reduction, because of fiber loss due to corrosion potential negative effect on the mechanical properties of the 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.

Investigated rebar with the introduction of milicia excelsa exudates / resins to reduce surface changes and mechanical properties of reinforcing steel in concrete structures in a saltwater environment. The accelerated corrosion process lasted for 150 days and the corrosion potential was determined. Corrosion properties of peeling and cracking of uncoated elements indicated the negative effect of corrosion on the mechanical properties of reinforcing steel which resulted to the presence of corrosion potentential [13].

2.1. MATERIALS AND METHODS

2.1.1 Aggregate

Both (fine and coarse) aggregate purchased and meets the requirements of [14]

2.1.2. Cement

Grade 42.5 limestone cement is used in all concrete mixtures. The cement meets the requirements of [15]

2.1.3. Water

Water samples were taken from the laboratory of the Department of Civil Engineering, Kenule Beeson Saro-Wiwa Polytechnic, Bori, Rivers State. The water meets the requirements of [16].

2.1.4. Structural Steel Reinforcement

Purchased directly from the market and meets the requirements of [17].

2.1.5. Corrosion Inhibitors (Resins/ Exudates) Musanga cecropioides

The natural gummy exudates were extracted from the tree's trunk and gotten from Uyanga Village in Akamkpa Village bush of Cross – Rivers State of Nigeria.

2.2. Experimental procedure

2.2.1. Experimental method

2.2.2. Preparation of Exudates/Resin-Reinforced Coating Sample

The research evaluated Musanga cecropioides extrusion viscosity gummy paste (exudate/resin) obtained from trees as a corrosion inhibitor material to slow down the impact of corrosion on steel bars embedded in concrete and constructed in high-salinity coastal areas. The exudate/resin extracted is coated on the steel bar and embedded in the concrete slab, exposed to the corrosive medium with high salt concentration. The corrosion activities process is long-term, however, the artificial introduction of sodium chloride (NaCl) accelerates the corrosion rate and its performance occurs in a short time. The effect of corrosion rate and destructive damage is measured by estimating the current density or quantification of the corrosion rate obtained. The concrete slab in this study is made in batches according to the weight of the material using the manual mixing method with a standard concrete ratio of 1.2.4 and a water-cement ratio of 0.65, cat into a metal mold of 100mm × 500mm × 500mm (thickness, width, and length), with 10mm concrete cover, compacted to void and air free, reinforced 10 numbers of steel bars of 12 mm diameter and spaced at 100 mm c/c (to and bottom) and de-molded after 72 hours, cured at standard room temperature for 28 days to harden. The hardened concrete slab is completely immersed in a 5% aqueous sodium chloride (NaCl) solution, and the rapid corrosion process is accelerated for 360 days with interval inspections and routine tests at 90 days, 180 days, 270 days, and 360 days for comparative evaluations for both 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 corrode the steel bars embedded in the concrete and accelerates the increase in corrosion. To test the corrosion resistivity of concrete, an experimental method was developed to accelerate the corrosion process and maximize the corrosion resistivity of concrete. Accelerated corrosion test is an impress current technology, it is an effective technology, it can check the corrosion process of steel bars in concrete and evaluate the damage of the concrete protective layer to the steel bars. To construct structural elements and corrosion resistivity, as well as to select suitable materials and protection systems, accelerated corrosion tests were carried out to obtain quantitative and qualitative information about corrosion.

2.4 Corrosion current measurement (Half-Cell Potential Measurement)

The classification of the corrosion severity of steel bars is shown in Table 2.1. If the potential measurement results show that the possibility of active corrosion is high, the degree of corrosion can be assessed by measuring the resistivity of the concrete. However, care must be taken when using this data because it is assumed that the corrosion rate is constant over time. The measurement of average potential is an indirect method to estimate the likelihood of corrosion. Recently, there has been great interest in developing tools for electrochemical measurements of steel perturbations to obtain direct estimates of corrosion rates (Stem and Geary [18].

Table-2.1: Dependence between potential and corrosion probability [19]

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
$-350\text{mV} \leq Ec_{orr} \leq -200\text{mV}$	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 ofmeasurement (10% risk of corrosion

2.5 Test to Measure the Resistivity of Concrete

There is an indication of different measurements and values are obtained at different points on the surface of the concrete. 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. This location is chosen on the side of the panel because special resistivity measurements can be made with water on the top of the panel. 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 concrete changes with time. For this reason, these four probes directly contact the concrete of the reinforced rail. From now on, this measure will be referred to as the "dry" measure. 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 floor, 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 [20]

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 the Steel Bars

To ascertain the yield and ultimate tensile strength of reinforcing steel bars, the studied concrete slab is reinforced with 10 numbers of steel bars with a diameter of 12 mm in the direction Y-X directions of top and bottom of coated and uncoated reinforced steel, subjected to pressure in Universal Testing Machine (UTM) to failures and the remaining cut parts were used for the tests 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), and the weight of the steel bar (after corrosion), check other weight-loss parameters

3.0 TEST RESULTS AND DISCUSSION

For ease of explanation, the results of the half-cell potential measurement are plotted against concrete resistivity. It is used to indicate very high, high, low to medium probability, and low severe corrosion. At another measurement point, the possibility of corrosion 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 possibility of corrosion is low within a certain range (<-350mV), there is a 95% probability of corrosion. Resistivity research data indicates whether certain states can help reduce ion movement, leading 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	**MCS**	**MCS1**	**MCS2**	**MCS3**	**MCS4**	**MCS5**	**MCS6**	**MCS7**	**MCS8**	**MCS 9**	**MCS 10**	**MCS 11**
	Time Intervals after 28 days curing											
Sampling and Durations	**Samples 1 (28 days)**			**Samples 2 (28 Days)**			**Samples 3 (28 Days)**			**Samples 4 (28 Days)**		
Potential Ecorr, mV	-106.5	-110.8	-105.9	-104.5	-106.2	-103.8	-112.3	-108.2	-103.6	-108.8	-109.8	-104.3
Concrete Resistivity ρ, kΩcm	15.72	15.72	15.71	15.70	15.70	15.86	15.86	15.85	15.84	15.84	15.78	15.70
Yield Strength, fy (MPa)	456.74	459.74	455.74	456.04	456.74	460.97	458.97	459.27	457.97	459.36	455.87	459.70
Ultimate Tensile Strength, fu (MPa)	614.71	612.66	614.34	610.12	613.65	614.07	613.87	614.67	613.27	614.82	614.32	614.18
Strain Ratio	1.38	1.36	1.36	1.35	1.36	1.36	1.35	1.36	1.36	1.36	1.36	1.35
Rebar Diameter Before Test (mm)	11.99	11.97	11.98	12.00	11.97	11.99	11.99	11.97	11.97	11.97	11.97	11.98
Rebar Diameter at 28 days(mm)	11.99	11.97	11.98	12.00	11.97	11.99	11.99	11.97	11.97	11.97	11.97	11.98
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rebar Weights- Before Test	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
Rebar Weights- After at 28 days (Kg)	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
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

	Corroded Concrete slab Specimens											
Sampling and Durations	**Samples 1 (90 days)**			**Samples 2 (180 Days)**			**Samples 3 (270 Days)**			**Samples 4 (360 Days)**		
Potential Ecorr, mV	-326.2	-331.4	-328.3	-320.6	-330.4	-337.9	-371.3	-378.5	-382.6	-385.8	-390.1	-388.2
Concrete Resistivity ρ, kΩcm	**6.05**	**6.23**	**7.06**	**6.07**	**6.84**	**6.40**	**6.02**	**6.57**	**6.61**	**6.21**	**6.38**	**6.39**
Yield Strength, fy (MPa)	420.77	423.77	419.77	420.07	420.77	420.00	423.00	423.30	422.00	423.39	419.90	423.73
Ultimate Tensile Strength, fu (MPa)	620.73	618.68	620.36	616.14	619.67	620.09	619.89	620.69	619.29	620.84	620.34	620.20
Strain Ratio	1.48	1.46	1.48	1.47	1.47	1.48	1.47	1.47	1.47	1.47	1.48	1.46
Rebar Diameter Before Test (mm)	11.99	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)	11.95	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)	0.04	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)	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
Rebar Weights- After Corrosion (Kg)	0.82	0.82	0.83	0.82	0.83	0.83	0.83	0.83	0.83	0.82	0.83	0.83
Weight Loss /Gain of Steel (Kg)	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06

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

	Musanga cecropioides 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	-115.5	-118.2	-117.7	-117.9	-114.9	-118.2	-116.3	-120.5	-116.5	-111.6	-111.3	-118.5
Concrete Resistivity ρ, kΩcm	15.63	15.78	16.06	16.19	15.88	16.17	16.12	16.27	16.30	15.77	15.66	15.51
Yield Strength, fy (MPa)	455.95	458.95	459.25	457.95	457.18	460.18	460.48	459.18	460.57	457.08	460.91	456.62
Ultimate Tensile Strength, fu (MPa)	614.91	612.86	614.54	610.32	613.85	614.27	614.07	614.87	613.47	615.02	614.52	614.38
Strain Ratio	1.35	1.34	1.34	1.33	1.34	1.34	1.33	1.34	1.33	1.35	1.33	1.35
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)	0.05	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)	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
Rebar Weights- After Corrosion (Kg)	0.96	0.96	0.96	0.97	0.96	0.96	0.96	0.97	0.96	0.96	0.96	0.96
Weight Loss /Gain of Steel (Kg)	0.07	0.08	0.08	0.08	0.07	0.08	0.07	0.08	0.07	0.07	0.07	0.08

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

Sampling and Durations	Control Concrete slab Specimens				Corroded Concrete slab Specimens				Musanga cecropioides 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 Musanga cecropioides Exudate / Resin Coated Specimens			
Potential Ecorr, mV	-107.5	-105.1	-107.7	-107.9	-328.6	-329.5	-377.6	-388.2	-117.6	-116.6	-117.7	-113.4
Concrete Resistivity ρ, kΩcm	15.72	15.75	15.85	15.77	6.45	6.44	6.40	6.33	15.82	16.08	16.23	15.64
Yield Strength, fy (MPa)	457.41	457.92	458.74	458.31	421.44	420.28	422.77	422.34	458.05	458.44	460.08	458.20
Ultimate Tensile Strength, fu (MPa)	613.91	612.62	613.94	614.44	619.92	618.63	619.95	620.46	614.10	612.81	614.13	614.64
Strain Ratio	1.37	1.36	1.36	1.36	1.47	1.47	1.47	1.47	1.34	1.34	1.34	1.34
Rebar Diameter Before Test (mm)	11.98	11.99	11.98	11.97	11.99	11.99	11.98	11.98	11.99	12.00	11.99	11.98
Rebar Diameter- After Corrosion(mm)	11.98	11.99	11.98	11.97	11.95	11.95	11.94	11.94	12.04	12.05	12.04	12.03
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05
Rebar Weights- Before Test(Kg)	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
Rebar Weights- After Corrosion (Kg)	0.89	0.89	0.89	0.89	0.83	0.83	0.83	0.83	0.96	0.97	0.97	0.96
Weight Loss /Gain of Steel (Kg)	0.00	0.00	0.00	0.00	0.06	0.06	0.06	0.06	0.08	0.08	0.08	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				Musanga cecropioides 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 Musanga cecropioides Exudate / Resin Coated Specimens			
Potential Ecorr, mV	-67.28	-68.11	-71.40	-72.27	180.89	182.49	220.61	241.14	-64.40	-64.60	-68.81	-70.69
Concrete Resistivity ρ, kΩcm	143.83	144.73	147.63	149.21	-59.26	-59.96	-60.56	-59.54	145.43	149.73	153.52	147.17
Yield Strength, fy (MPa)	8.54	8.96	8.51	8.52	-7.99	-8.32	-8.11	-7.83	8.69	9.08	8.83	8.49
Ultimate strength (N/mm2)	3.468	3.478	3.478	3.478	-2.942	-2.952	-2.952	-2.952	5.398	5.408	5.408	5.408
Strain Ratio	-7.14	-7.81	-7.57	-7.62	9.69	10.10	9.81	9.55	-8.84	-9.17	-8.94	-8.71
Rebar Diameter Before Test (mm)	0.037	0.035	0.036	0.036	0.034	0.038	0.035	0.039	0.035	0.036	0.035	0.038
Rebar Diameter- After Corrosion(mm)	0.437	0.404	0.414	0.414	-1.116	-1.131	-1.194	-1.237	1.128	1.121	1.120	1.121
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.000	0.000	0.000	0.000	-22.596	-21.399	-21.693	-21.986	30.486	30.774	30.476	30.812
Rebar Weights- Before Test(Kg)	0.429	0.432	0.430	0.431	0.425	0.434	0.430	0.434	0.432	0.430	0.429	0.432
Rebar Weights- After Corrosion (Kg)	7.52	7.64	7.50	7.64	-14.24	-14.51	-14.30	-14.15	16.61	16.97	16.69	16.49
Weight Loss /Gain of Steel (Kg)	0.00	0.00	0.00	0.00	-17.33	-19.48	-18.42	-15.07	20.97	24.19	22.58	17.74

3.1 Results of Potential Ecorr, mV, and Concrete Resistivity ρ, kΩcm on Concrete Slab Members

The electrical resistivity of concrete plays an important role in assessing the condition of the concrete structure and the condition of the corrosion protection of reinforcement [21-24]. Concrete resistivity as a parameter is also used to indicate the state of concrete damage. Water in concrete acts as a medium for the transfer of free ions such as chloride. For this reason, total moisture content, chloride concentration in pore water and pore structure of concrete are the three most important factors for the electrical resistivity of concrete. Understanding the relationship between concrete resistivity and these factors has attracted attention in the study of concrete strength for many years ([25], [26]). The corrosion potential E_{corr} mV and concrete resistivity, kΩcm results are obtained from Tables 3.1-3.3 and summarized into the mean 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, which are the determining reference range, 12 samples non-coated (corroded) and 12 samples with exudates/resin coated samples.

The mean, percentile, minimum, maximum, and differential values of the half-cell potential measurements computed from the controlled sample were -107.97mV and -105.1 mV (-72.27% and -67.28%) with potential differences (2.87mV and 4.99%), the corroded samples were -388.02 mV and -328.64 mV (180.89% and 241.14%) and the difference in values were 59.38 mV and 60.25%, and the coated samples were -117.76 mV and -113.74mV (-70.69 % and -64.4%) and the potential difference is 4.02 mV and 6.29%, respectively. The computed maximum control percentile value is -67.28% compared to the corroded and coated values 241.14% and -64.4% and the controlled potential difference value is 4.99%, corroded 60.25% and coated 6.29%. The maximum yields of the controlled and coated samples were -105.1mV and -113.74mV, with the result obtained, this showed an indicative relationship between corrosion potential and probability as $E_{corr} > -200$mV as the reference range. These results of potential E_{corr} results showed indication that the values of controlled and exudates/ resin coated specimens are low with the range of 90% probability that no reinforcing steel corrosion is occurring in that area at the time of measurement (10% risk of corrosion which indicates a 10% or uncertain probability of corrosion. For the non-coated sample, the maximum obtained computed value is -328.64mV, the results are within the range reference of dependence between potential and corrosion probability of the value $-350\text{mV} \leq E_{corr} \leq -200\text{mV}$ indicating a high range of values, notifying a 10% or uncertain probability corrosion. The comparative results from the referencing range (controlled), showed that corroded samples exhibited corrosion presence resulting from the induced corrosion acceleration against coated samples that exhibited absence of corrosion. The exudates/resins exhibited inhibitory characteristics against corrosion attacks on reinforcing steel embedded in the concrete slab, exposed to corrosive media by the formation of the resistive coating. On the other hand, the resistivity of concrete directly affects the corrosion process of steel reinforcement by controlling the corrosion potential and corrosion current [27]. Therefore, for an accurate evaluation of the resistivity of concrete under different environmental conditions, it is important to evaluate the corrosion potential protection for concrete reinforcement. The average value and the minimum and maximum percentile of concrete resistivity with a controlled sample potential difference are 15.72kΩcm and 15.85kΩcm (143.83% and 149.21%) and the difference values are 0.13kΩcm and 5.38%. Corroded samples were 6.33kΩcm and 6.45kΩcm (-60.56% and -59.26%) and the difference values were 0.12kΩcm and 1.3%, coated samples were 15.64kΩcm and 16.23kΩcm (145.43 % and 153.52%) and the difference values of 0.59 mV and 8.09%. The maximum computed percentile of the controlled sample of concrete resistivity is 149.21% compared to the corroded and coated value of -59.26% and 153.52% and the maximum percentile difference of control is 5.38% compared to the corroded and coated value of 1.3 % and 8.09%. The results of the controlled and coated concrete resistivity samples obtained at an average maximum value of 15.85kΩcm and 16.23kΩcm with a data value of $10 < \rho < 20$ (low) compared to a corrosion value of 6.45kΩcm with specifications ($\rho < 5$, $5 < \rho < 10$, $10 < \rho < 20$, $\rho > 20$) and with the reference range of the relationship between concrete resistivity 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 obtained of the coated and corroded samples, the maximum value obtained in both samples clearly shows that the value of the coated sample with a range of $10 < \rho < 20$, which classifies the range of values from low to moderate, with a significant indication of the possibility of corrosion. The maximum value of the corroded sample is in the range of $5 < \rho < 10$ which indicates high, signs indicating the presence of corrosion probability, as related and validated in studies of [10-13]. From the results obtained it can be compared that the effect of corrosion attack was observed in uncoated samples, which resulted to in depth effect on the mechanical properties of reinforcing steel while samples with exudates/resin with anti-corrosion properties with highly resistant and water-resistant membranes that prevented corrosion of the reinforcing steel embedded in concrete slabs exposed to induced accelerated corrosion media.

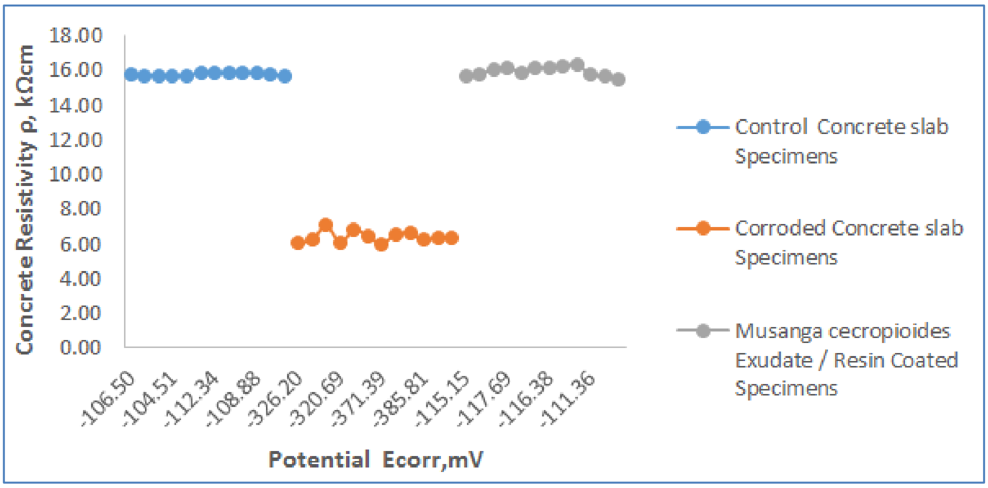

Fig-3.1: Concrete Resistivity ρ, kΩcm versus Potential Ecorr,mV Relationship

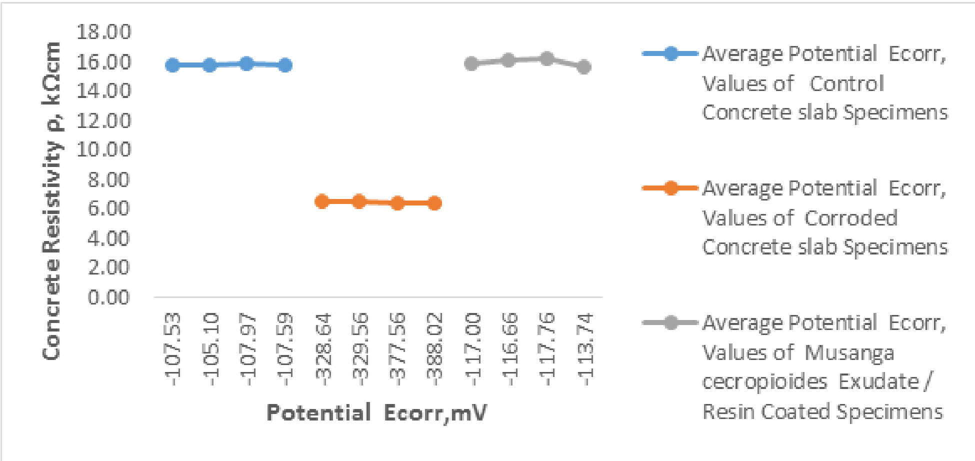

Fig-3.1: Concrete Resistivity ρ, kΩcm versus Potential E_{corr}, mV Relationship

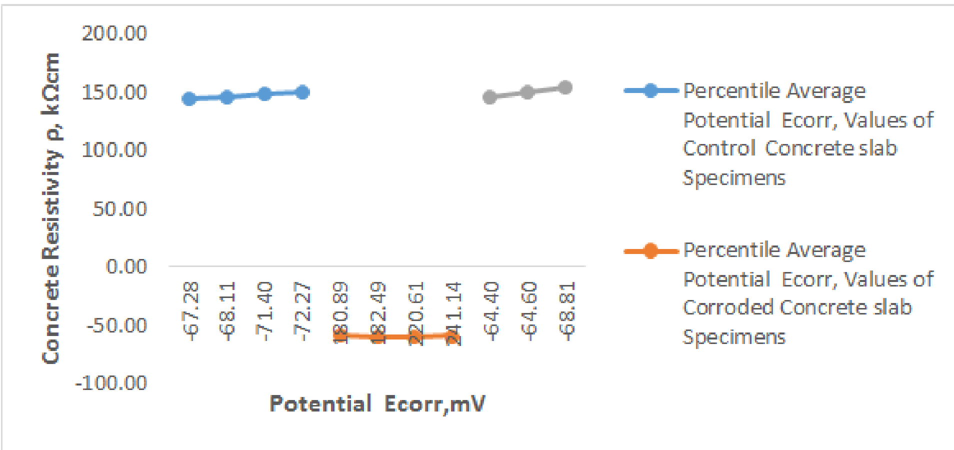

Fig-3.1B: Average Percentile Concrete Resistivity versus Potential Relationship

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

The Tensile strength of reinforcing steel behavior of corroded beams is very important to assess the load bearing capacity of corroded reinforced concrete structures. Reduction in the effective diameter of steel bars has significant impact on the tensile strength of reinforced concrete structures. The results show an inverse relationship between the corrosion rate and the true tensile strength of the controlled, corroded and coated samples. The degree of corrosion according to [28] is inversely related to rail capacity; i.e. increasing the corrosion rate decreases the tensile strength. The results of the mean, percentile, and the difference between the minimum and maximum density limits, fy (MPa) of the controlled sample were 457.41MPa and 458.74MPa (8.51% and 8.96%), and the difference values of 1.33MPa and 0.45%, the corroded samples were 420.28MPa and 422.77MPa (-8.32% and -7.83%) and the difference value was 2.49MPa and 0.49%, the coated sample value was 458.05 MPa and 460.08MPa (8.49% and 9.08%) and the difference value is 2.03 MPa and 0.59%. The computed maximum percentile of the controlled yield strength is 8.96% compared to the corroded and coated values -7.83% and 9.08% and the possible difference values are 0.45% controlled, 0.49% corroded and 0.59% coated. The mean, percentile, and the difference between the minimum and maximum tensile strength, fu (MPa) of the controlled samples were 612.62MPa and 614.44MPa (3.468% and 3.478%) and the difference values were 1.82MPa and 0.01%, which corroded were 618.63MPa and 620.46MPa (-22.952MPa and -2.942%) and the difference is 1.83MPa and 0.01%, coated of 612.81MPa and 614.64MPa (5.398% and 5.408%). The maximum computed difference in values are 1.83MPa and 0.01% the controlled tensile strength is 3.478% against the corroded and coated values, respectively are -2.942% and 5.408% and the potential difference values 0.01% controlled, 0.01%% corroded and 0.01% coated.

The minimum and maximum mean, percent and strain ratio values of the controlled sample are 1.36 and 1.37 (-7.81% and -7.14%) with a difference value of 0.01 and 0.67%, the corroded sample is 1.47 and 1.47 (9.55 and 10.1%) and the difference values of 0.00 and 0.55%, the coated samples were 1.34 and 1.34 (-9.17% and -8.71 %) and the difference between 0.00 and 0.46%. 10.1% and -8.71% coverage and differential peak controlled up to 0.67%, 0.55% corroded and 0.46% coated, as related and validated in studies of [10-13]. From the calculation results, which are summarized in Tables 3.4 and 3.5 and shown graphically in Figures 3.1-3.8, the yield strength, tensile strength and strain ratio of the mean, percentile and differential potential values of the control, uncoated (corroded) and coated concrete slab samples showed that coated samples had higher failure loads compared to corroded samples with reduced and decreased failure loads and low load bearing capacity and with average values and percentiles to the reference range, while uncoated (corroded) samples recorded lower loads carrying capacity and reduced value compared to the reference range. The comparative results show that the low load carrying capacity is caused by the effect of corrosion attack on the exposed (corroded) elements, which affects the reinforcing steel fibers, ribs and passive formation and surface modification. The preserved value of the coated samples in the two average values is due to the potential for resistivity 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 the effects of corrosion of reinforced concrete structures in high salinity coastal marine areas.

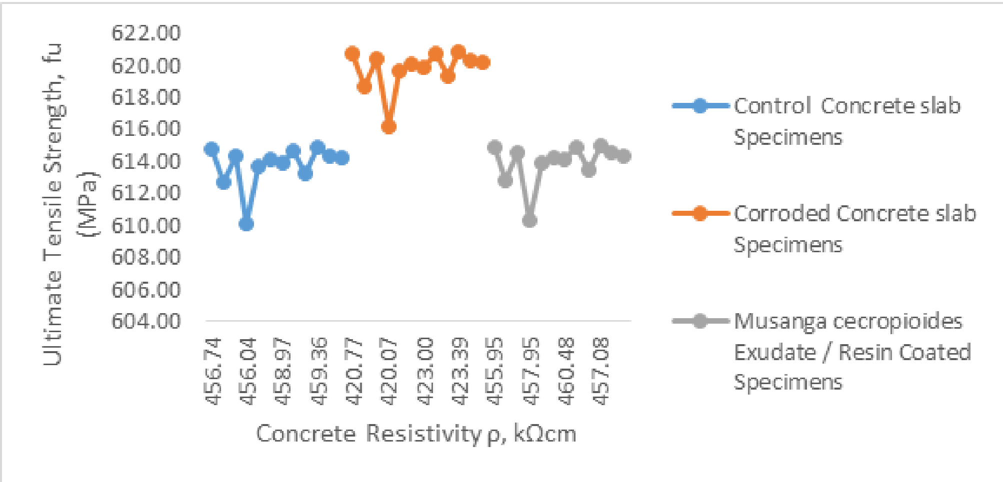

Fig-3.2: Yield Strength versus Ultimate strength

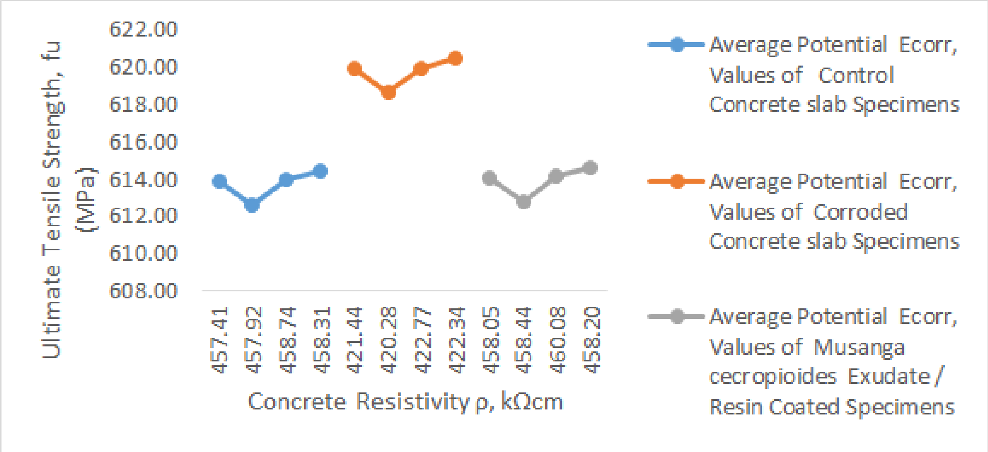

Fig-3.2A: Average Yield Strength versus Ultimate Tensile Strength

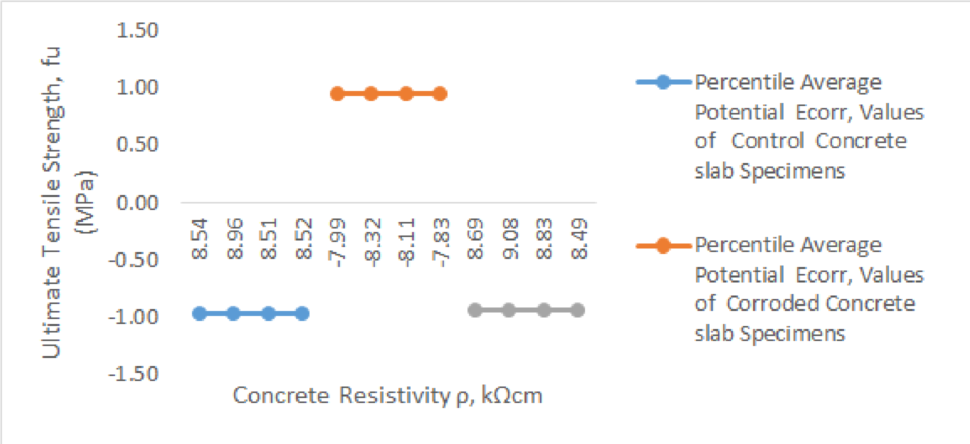

Fig-3.2B: Average Percentile Yield Strength versus Ultimate Tensile Strength

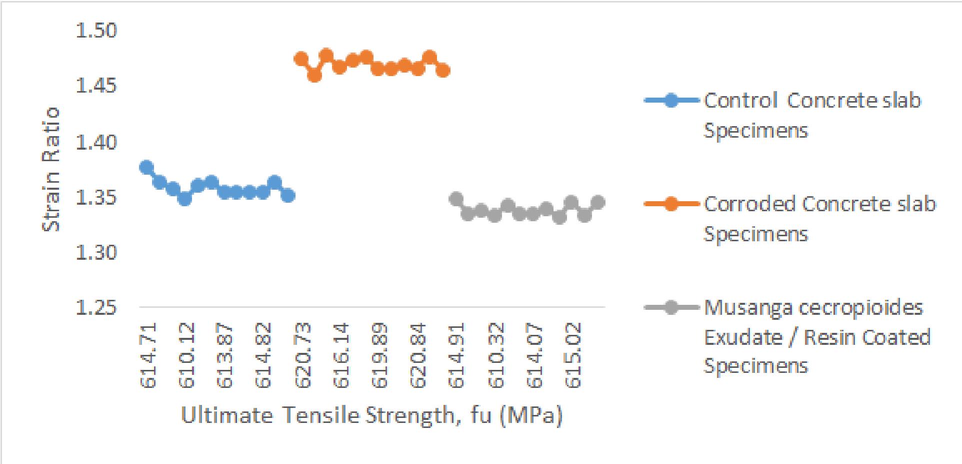

Fig-3.3: Ultimate Tensile Strength versus Strain Ratio

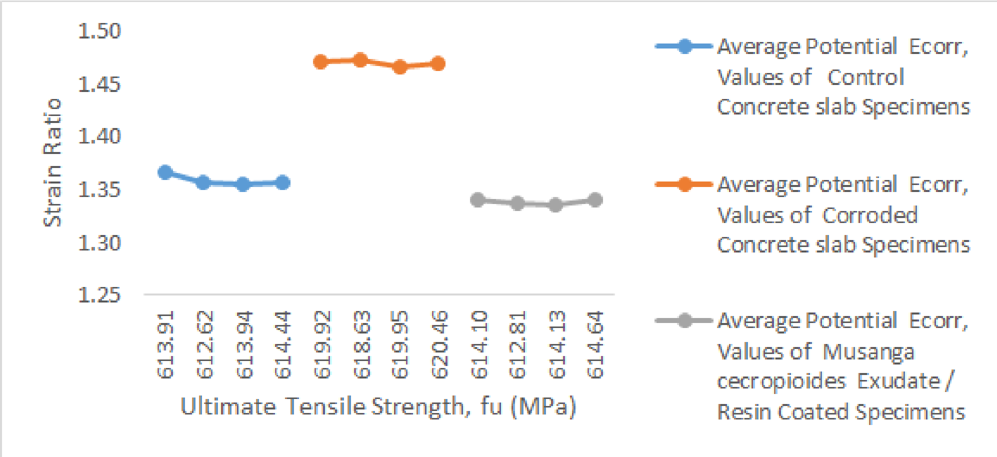

Fig-3.3A: Average Ultimate Tensile Strength versus Strain Ratio

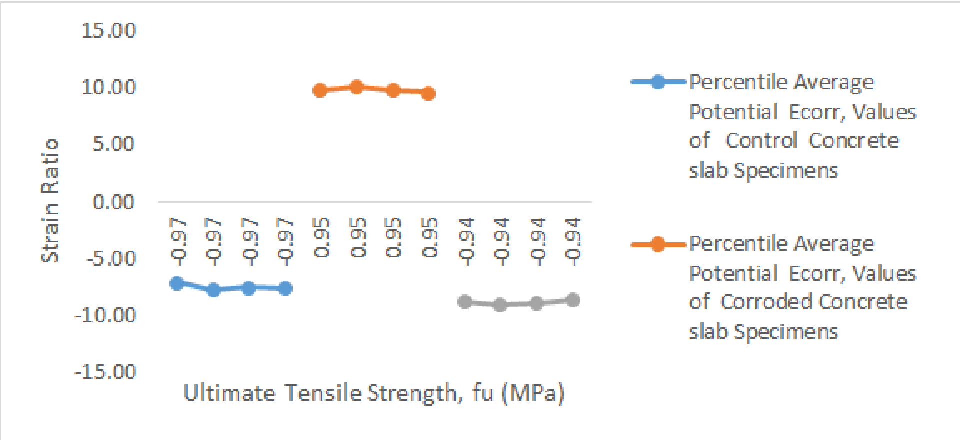

Fig-3.3B: Average percentile Ultimate Tensile Strength versus Strain Ratio

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

The mechanical properties of corroded reinforced concrete structures depend on the cross section, the size of the reinforcement area and the corrosion rate. The active cross-section of the steel decreases in proportion to the corrosion rate, as the mechanical properties change. Reduction of the cross-sectional area of steel significantly affects the mechanical properties of corroded steel reinforcement. The tensile strength of corroded reinforcement is greatly affected by the reduction in the cross-sectional area of the steel. The diameter of the valve before testing (mm), the minimum and maximum mean and percentile values were controlled from 11.97 mm and 11.99 mm (0.035% and 0.037%) with a difference value of 0.02 mm and 0.002%, the corroded sample was 11 .98 mm and 11.99 mm (0.034% and 0.039%) and the difference values were 0.01 mm and 0.005%, and the coated sample values were 11.98 mm and 12 mm (0.035% and 0.038%)) and the computed values differentially 0.02 mm and 0.003%. 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 of the minimum and maximum diameter of reinforcement after corrosion (mm) obtained for the controlled sample are 11.98mm and 11.99mm (0.034% and 0.039%) and the difference value is 0.01mm and 0.005% with the value 100% reference is maintained, the corroded sample is 11.94mm and 11.95mm (-1.237% and -1.116%) and a difference of 0.01mm and 0.121%, the values of the coated samples were 12.03mm and 12.05mm (1.12% and 1.128%) and the difference was 0.02 mm and 0.008%. The diameter of reinforcement after corrosion maximum computed percentile value is 0.039% as against -1.116% corroded and 1.128% coated; the difference in percentile is 0.005% of corroded versus 0.008% coated. The results obtained in Tables 3.4 and 3.5, which are summarized from 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 concrete slabs, which are subjected to induced corrosion-accelerating activities. The results of the comparative of corroded samples show the reduction in values compared to the diameter of the reinforcement before and after the induction accelerated corrosion test with a percentile range for the reduction value from 0.039% to -1.116% and the average value in the range from 11.99mm to 11.94mm. 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 0.04mm and 0.04mm (-18.37% and -18.37%) and the difference was 0.00% and 0.00% for corroded, coated sample values were 0.05mm and 0 .05mm (22.5% and 22.5%) and a difference of 0.00 mm and 0.00%. The relative mean and difference in percentile values between coated and corroded samples ranged from 22.5% to -18.37%. The decrease in mean and percentile values indicates that the corrosion effect causes a reduction in diameter and cross-sectional area, fiber degradation, rib reduction and surface modification, while the exudates/resin-coated elements show an increase in volume due to thickness differences layers as related and validated in studies of [10-13]. 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. Weight of rebar - before testing (kg), the mean and minimum, maximum and differential percentile results of the controlled samples were 0.89 kg and 0.89kg (12.09% and 13.25%) and the difference was 0 0.00% and 1.16%, samples corroded 0.89kg and 0.89kg (14.56% and 12.24%) and the difference between 0.00% and 2.32%, coated samples 0.89kg and 0.89 kg (17.29% and 20.49%) with a difference of 0.00% and 0.386%.

The mean and percentile of reinforcement weight after corrosion (Kg) and the aggregate difference values of the minimum and maximum values of the controlled samples were 0.89kg and 0.89kg (12.09% and 13.25%) and the difference was 0.00% and 1.16%, the samples corroded 0.83kg and 0.83kg (-14.51% and -14.15%) and the difference was 0.00% and 0.36%, the closed sample values were 0.96 kg and 0.97kg (16.49% and 16.97%) and the difference between 0.001% and 0.48%. Average and percentile decrease/increase in minimum and maximum weight of steel (kg) and percentile difference compared to values complied with 100% as a result of aggregation in freshwater tanks with no trace of corrosion potential controlled corroded sample value 0.06kg and 0.06kg (-19.48% and -15.07%) and coverage of 0.07kg and 0.08kg (17.74% and 24.19%). The computed results obtained from Tables 3.1-3.3 and summarized in 3.4-3.5 and shown graphically in Figure 3.7-3.8b show the effect of corrosion on uncoated (corroded) and coated steel and check the weight of the pieces of reinforcement before and after the corrosion test. For comparative, the results obtained show a decrease and increase in the average and percentile values with 0.08 kg coating to 0.06kg and 24.19% to 15.07% corrosion, as related and validated in studies of ([10]; [11]; [12]; [13]).The aggregate results show that the corrosion effect causes a reduction in weight/weight reduction in the corroded samples compared to coatings with a percentile 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.

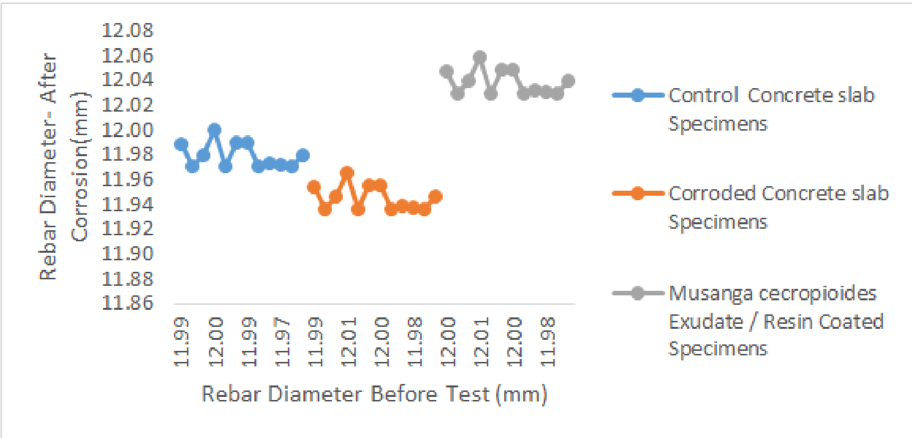

Fig-3.4: Rebar Diameter before Test (mm) versus Rebar Diameter- After Corrosion (mm)

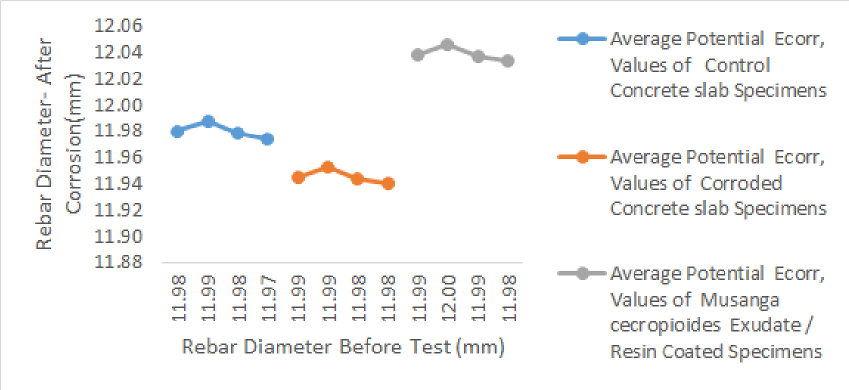

Fig-3.4A: Average Rebar Diameter before Test (mm) versus Rebar Diameter- After Corrosion (mm)

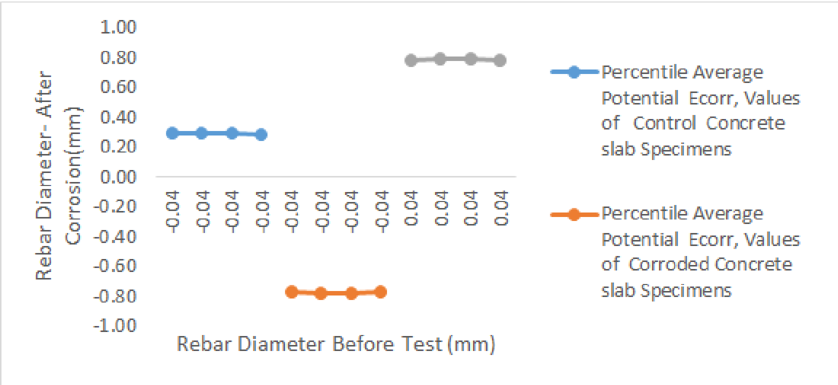

Fig-3.4B: Average Percentile Rebar Diameter before Test (mm) versus Rebar Diameter- After Corrosion (mm)

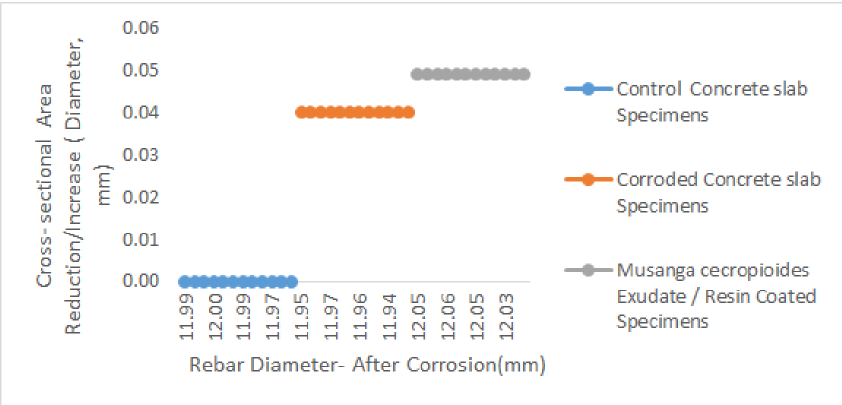

Fig-3.5: Rebar Diameter- after Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

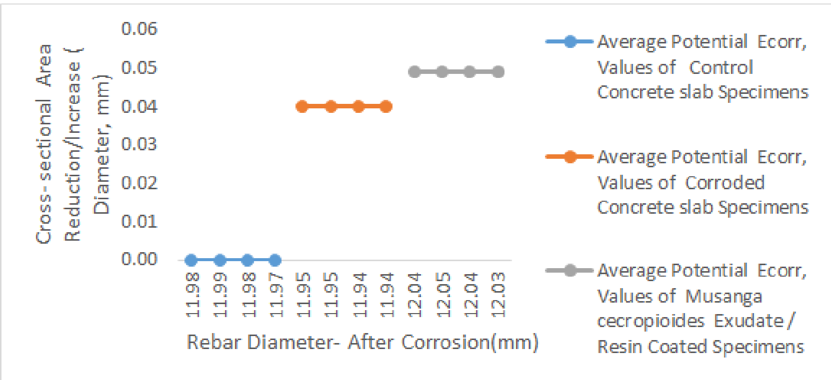

Fig-3.5A: Average Rebar Diameter- after Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

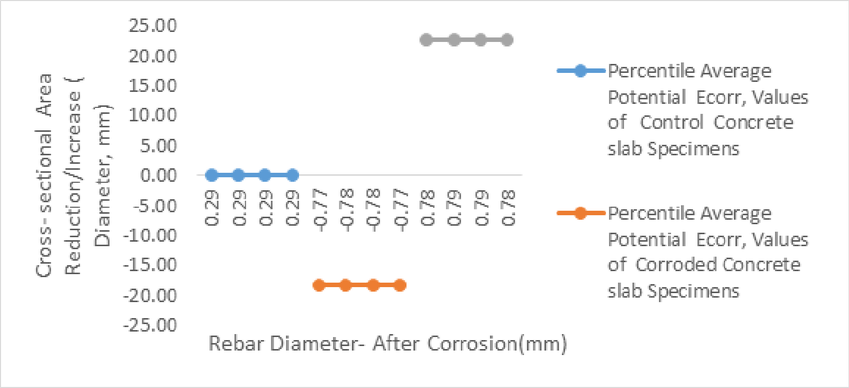

Fig-3.5B: Average Percentile Rebar Diameter- after Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

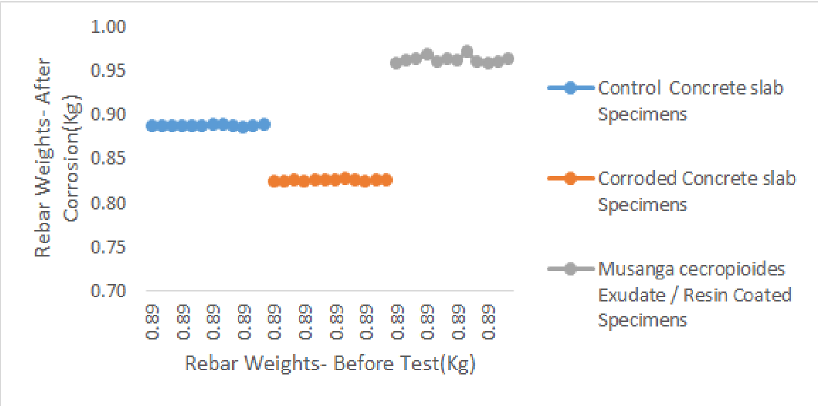

Fig-3.6: Rebar Diameter - After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

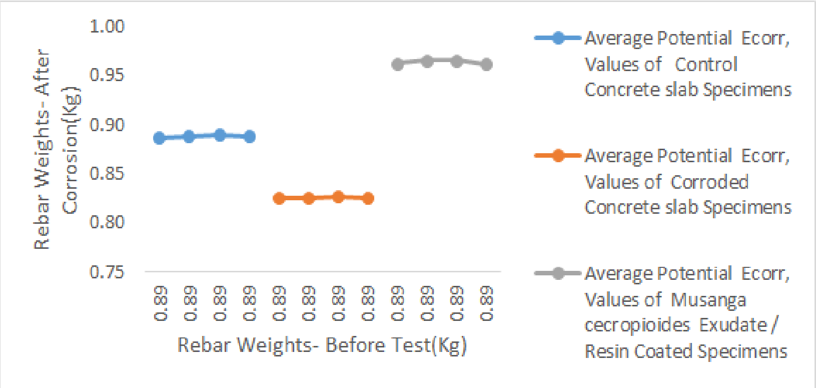

Fig-3.6A: Average Rebar Diameter - After Corrosion(mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

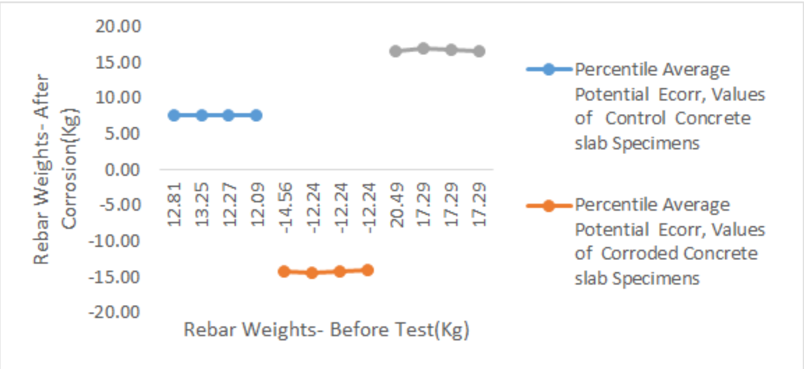

Fig-3.6B: Average Percentile Rebar Diameter - After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

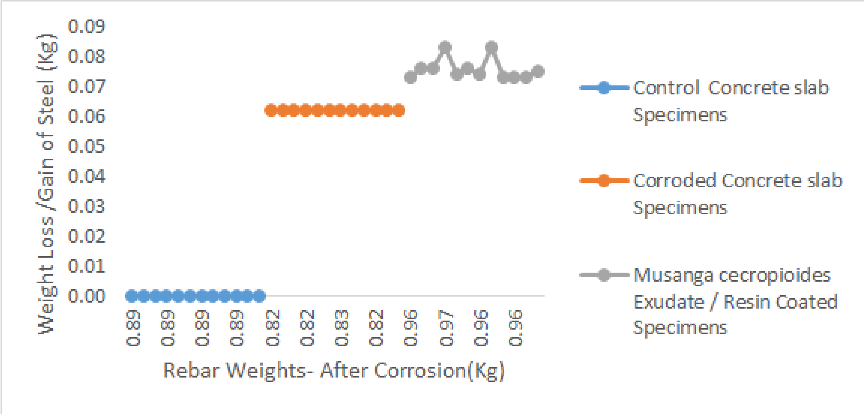

Fig-3.7: Rebar Weights- After Corrosion (Kg) versus Weight Loss /Gain of Steel (Kg)

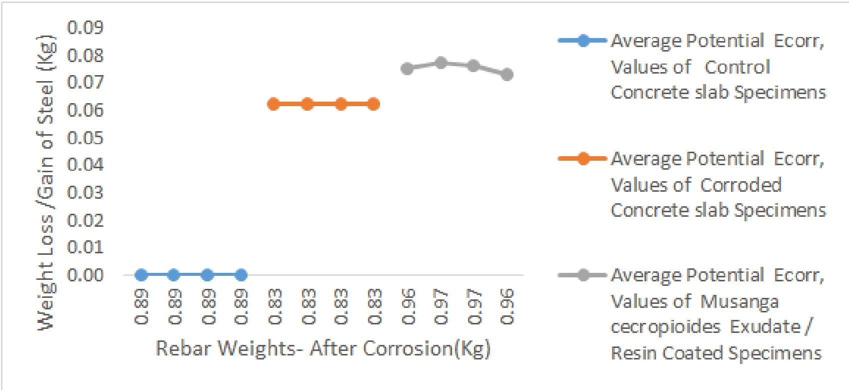

Fig-3.7A: Average Rebar Weights- After Corrosion (Kg) versus Weight Loss /Gain of Steel (Kg)

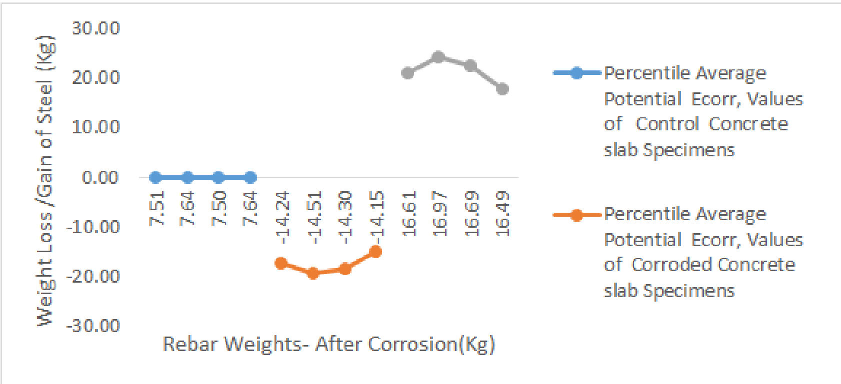

Fig-3.7B: Average Percentile Rebar Weights- After Corrosion (Kg) versus Weight Loss /Gain of Steel (Kg)

4.0 CONCLUSION

The experimental results show the following conclusions:

1. Uncoated samples exhibited higher corrosion potential values as a result of accelerated corrosion caused by coated samples showing no corrosion and no attack on reinforcing steel embedded in concrete slabs and exposed to a highly corrosive environment from saline solutions .
2. The coated sample exhibits inhibitory properties with the formation of a layer that is resistant to the spread of corrosion.
3. The effect of corrosion attack was observed in the uncoated samples, whereas the exudates/resin coated samples had anti-corrosion properties with a highly resistant and water-resistant membrane which prevented the corrosion of reinforcing steel embedded in the concrete structure and exposed to high salinity from corrosion induction.
4. Corroded samples show high yield strength at low load, which indicates the effect of corrosion on the mechanical properties of reinforcing steel, which causes low load bearing capacity, corroded also shows a higher deformation ratio compared to coating in the above parameters.
5. The results obtained indicate that the coated samples maintain a closed range of values compared to the controlled samples, which has the property that the exudates/resin-coated samples have the potential to inhibit corrosion attack on

reinforcing steel embedded in the concrete structure and exposed corrosive media to form a membrane. waterproof and resistant.

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