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Original Research Article

Electrochemical Mechanism of Reinforcing Steel Corrosion Current Measurement using Wenner Techniques

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Abstract

Environmental conditions include chloride penetration (eg de-icing salt or seawater) and carbonization of concrete. This protective effect may fail, but the provisional quantification of this process to assess the service life of reinforced concrete structures is an important task both in the planning stages of new buildings and in the context of renovation of existing buildings. The application of Boswellia dalzielii Hutch extruded viscous gummy paste (exudate/resin) obtained from the tree was studied in the research exudate/resin. Its utility as an inhibitive material in the curbing of corrosion effect on reinforcing steel built within the coastal region of high salinity. Extracted exudate/rein was coated to reinforcing steel and embedded into the concrete slab, exposed to corrosive media with a high concentration of salt. The experimental data of corrosion potential Ecorr, mV and concrete resistivity, kΩcm of maximum percentile value calculated from the concrete resistivity of the controlled sample concrete is 134.14% compared to the corroded and coated value of -31.11% and 88.07% and the maximum value of the percentile differential from the control is 49.97% compared to the corroded and coated value of 15.72% and 42.9%. The results of the controlled and coated concrete resistivity samples obtained of the maximum average values are 15.05kΩcm and 12.09kΩcm with a description of the value $10 < \rho < 20$ (low) compared to the corrosion value of 8.15kΩcm with Specifications $5 < \rho < 10$ (high) and with a reference range of dependence between concrete resistivity and corrosion probability significant corrosion probability ($\rho < 5$, $5 < \rho < 10$, $10 < \rho < 20$, $\rho > 20$) for very high, high, low to medium and low, for possible corrosion. The maximum calculated controlled percentile value was -66.02% compared to the corroded and coated values 171.66% and -62.28% and the controlled potential differential value was 1.7%, corroded 6.56% and coateded 0.91%. The maximum half-cell potential yields of controlled and coated samples were -107.1mV and -121.98 mV, which showed the relationship between corrosion potential and probability as a $E\text{corr} > -200\text{mV}$ as a reference range. The results of this corrosion potential Ecorr, mV result show that the controlled sample values and exudates/resin coated are low with a 90% probability that no corrosion of the reinforcement is observed at the time of measurement (10% corrosion risk, 10% or shows an uncertain corrosion probability for samples that uncoated, the maximum calculated value is -328.22mV, the result is within the reference value of the dependence between the corrosion potential and probability of the value $-350\text{mV} \leq E\text{corr} \leq -200\text{mV}$ indicates a high range of values, which is a corrosion probability of 10% or uncertain of the reference range (controlled) shows that the corrosion samples show corrosion as a result of accelerated corrosion induced as compared to the coated samples which show no corrosion. The maximum percentile calculated from the ultimate tensile strength is controlled by 2.99% in terms of corrosion and coating values are - 2.97% and 3 0.01% respectively and the potential differential value of 0.14% is controlled, 0.12% is corroded and 0.09% is coated. The calculated maximum percentile of the controlled yield strength is 9.08% relative to corrosion and coated values are -7.83% and 8.61% and the possible differential values are 1.42% controlled, 0.09% corroded and 4.29% coated. The maximum percentile value calculated to compare the strain ratio was checked at -7.21% against corroded 5.36% and coated -7.23%, and the maximum differential was checked for 0.08%, corroded 0.2% and coated 0.1%. The comparative results show that the low load carrying capacity is caused by the effect of corrosion attack on the uncoated (corroded) elements, which damage the reinforcing steel fibers, ribs and passive formation and surface modification. The observed mean values for the coated samples were associated with the corrosion resistivity potential to penetrate the reinforcing steel with the formation of a protective membrane; This attribute indicates the effectiveness of the exudate / resin as an inhibitor against corrosive effects of reinforced concrete structures exposed to heavy marine areas with high salt content. The maximum calculated percentile diameter of the reinforcement after corrosion was controlled 0.368% versus corroded - 0.903% and coated 0.796%, with a different percentile of corroded 0.011% versus 0.007% coated. For comparative, the results of the

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corroded samples showed a reduction and reduction value compared to the diameter of the reinforcement before and after the induction accelerated corrosion test with a percentile decrease in value from 0.368% to -0.903% and an average value in the range from 11.98mm to 11.94mm. The cross-sectional area differential in mean values and relative percentiles between coated and corroded samples ranged from 39.02% to -28.07%. The reduction 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 exudate/resin coated elements experience an increase in volume due to differentials in coating thickness differentials. The aggregate results show that the corrosion effect causes a reduction in weight/reduction of the corroded sample compared to the percentile layer and an increase in mean, resulting in a slight increase in volume around the layer thickness. This study shows the efficacy and effectiveness of exudates/resin as an anti-corrosion material in reinforcing steel embedded in samples of concrete slabs exposed to induced corrosion.

Keywords: Corrosion, Corrosion Inhibitors, Pull-Out Bond Strength, Concrete And Steel Reinforcement.

1.0 INTRODUCTION

Corrosion of reinforcement in RC structures (reinforced concrete) is one of the main problems that affect the structural properties of concrete structures that have been used for a long time. Since the yield strength and modulus of elasticity of corroded reinforcement affect the structural properties of reinforced concrete elements, it is important to know their condition in order to assess the performance of the rest of the reinforced concrete structure. In addition, if the corrosion is severe, the corroded reinforcing bars may fracture, leading to a sudden loss of load-bearing capacity or collapse of the reinforced concrete structure. Global environmental problems are on the rise and are likely to influence future selection of corrosion inhibitors. Environmental needs are still being built but some things have been established, Uhlig [1]. Some chemicals are excellent inhibitors, but they are toxic and easily absorbed into the skin [1]. The known harmful effects of many synthetic chemicals and restrictive environmental regulations have now led researchers to focus on the need to produce cheaper, inexpensive and toxic natural products such as corrosion inhibitors. Natural corrosion inhibitors has been widely reported by several authors [2-5]; Sethuraman and Raja [6-10]; Okafor *et al*., [11-17].

Examined the use of acacia senegal exudates / tree extract resins as corrosion inhibitors. Reinforcing steel were coated with varying thicknesses of exudates / resin paste and immersed in corrosive media for 150 days in an accelerated process. The results of percentile average potential E_{corr} corroded value are -230.4854% versus -69.7415% and -67.3178% for control and coated samples. The potential E_{corr} results ($-350mV \leq Ecorr \leq -200mV$) show that the values of the corroded specimens with the range are high, indicating an uncertain probability of 10% or corrosion. Concrete resistivity ρ, mean value of kΩcm percentiles are corroded -48.9081%, controlled 95.72572% and coated 114.8917%. The range of values for corrosion models indicated a significant corrosion (moderate) in controlled and coated samples over corroded [18].

Reported that concrete with 2% and 4% CN inhibitor based on cement weight showed no corrosion after 122 days when the concrete was immersed or exposed to saline water. In another study with reinforced concrete (w / c ratio = 0.50) that underwent 3.5% NaCl wetting / drying cycles for 3 years, 2.5% CN was effective in delaying corrosion [19]. However, another study found that CN was only effective in delaying corrosion but not effective after the onset of corrosion [20].

Investigated the corrosion potential, tensile tests and concrete resistivity of control, corroded and coated reinforcing steel of a concrete slab member with 12 mm diameter reinforcement, embedded in the concrete slab, undergoes severe corrosive weathering for 119 days for rapid corrosion testing of half-cell potential measurements, concrete resistivity measurement and tensile testing. Corroded specimens have an increased efficiency of 70.1% and decreased values of concrete resistivity by 38.8%, yield stress against ultimate strength 100%, nominal yield stress 100.95%, weight loss at 48.5% and 98.7% to 94.82% at 67.5%, Corrode samples showed decreased and reduction in values as compared to coated samples [21].

Investigated the effects of chloride attack on reinforcing steel embedded in reinforced concrete structures constructed in the marine environment. The results of the potential Ecorr, mv, concrete resistivity and tensile strength of the acardium occidental were recorded. The constrained model indicates the 10% or uncertain probability of corrosion, which indicates the presence or probability of corrosion, and the low likelihood of concrete resistivity corrosion [22].

Investigated the corrosion level probability estimation by means of a half-cell potential corrosion measurement, concrete resistivity test, and tensile strength test of control, reinforced and coated with moringa oleifera lam resin paste of tree extract. The mean percentile results of potential Ecorr, MV and concrete resistivity were 29.9% and 68.74%, respectively. Compared to the corrugated specimens, the decreased values of the potential Ecorr, MV, and concrete resistivity decreased by 35.5% with increasing values of 72.1%. The results of the computed percentile average values of yield stress against ultimate strength at nominal yield stress decreased from 105.75% to 96.12% and weight loss decreased by 67.5% to 48.5% and 48.34% to 94.82%, cross-sectional diameter reduction, compared to both coated and control specimens [23].

Investigated the use of inorganic inhibitors and greener approach inhibitors to estimate corrosion potential using layered mangifera indica resins paste extracts to reinforce steel with. The mean percentile results of potential E_{corr},MV and concrete resistivity were 26.57% and 61.25%, respectively. Compared to corroded specimens with 69.8% increased values of potential E_{corr}, MV, and 38.8% concrete resistivity decreased, in essence the ultimate strength of the slab, and the mean strength 105.36% due to attack from 44.45% and 46.76% to 86.43% from 96.12% weight loss and cross-sectional diameter reduction [24].

Investigated the degree of deterioration of reinforcement embedded in concrete slab structures submerged in hazardous environments, and the use of Weneer accelerated four-probe experimental methods in assessing coated and non-coated concrete slab structures. Results showed a high yield of non-coated versus controlled and coating members [25].

Evaluated of the impact of reinforced steel mechanical properties due to corrosion attack in concrete members of Celtic zinc exudates/resins paste coated and non-coated reinforcing steel. Weight loss results of non-coated steel showed higher percentile values against control and coated members. The cross-sectional reduction results showed the percentiles loss due to the impact of corrosion on the mechanical properties of steel [26].

Investigated the extraction of environmentally friendly mineral exudates/resins of Invincia gabonensis, coated with reinforcing steel of different finish thickness and non-coated, immersed in sodium chloride for a 150-days rapid operation. The cross-sectional area reduction results showed higher percentile reduction values because the fiber loss in the mechanical properties of the steel as a result of corrosion energy is negative. Steel weight loss results showed higher percentile values against control and coating samples due to the effect of corrosion on the mechanical properties of steel. The results showed high yields and coating patterns of the coating samples to control the mechanical properties of the steel reinforcement [27].

Investigated an eco-friendly exudates/resins extract from Olibanum, coated with varying thickness to reinforcing steel and that of non-coated members, embedded in a concrete slab and pooled in a corrosive environment for 150 days with a potential test rate of 1200mV to -200 mV and compared to control samples potential flow rate. High yield results were recorded of non-coated (corroded) specimens as opposed to coated specimens due to the attack on the mechanical properties of steel reinforcement. The results of the weight loss of steel indicated a high percentile of values against the control and coated members, which resulted in reductions of the fiber / ribbed properties of the steel and thus strengthening the surface. The cross-sectional expansion of the corroded sample results showed higher percentile reduction values due to the effect of corrosion on the mechanical properties of steel [28].

Investigated the passive loss of reinforcing steel with the use of natural inorganic exudates/resins paste of milicia excelsa with a coating thickness of 150µm, 300µm, and 450µm. The coated and uncoated members are embedded in the concrete slab and immersed in a partially fast-flowing media with fast application currents from 1200mV to -200 mV, with a scan rate of 1mV and a half scan rate for the non-coated. The half -cell corrosion potential, concrete resistivity, and tensile strength. Cross-sectional area reduction leads to a coating-free pattern that leads to higher corrosion values due to the effect of corrosion on the mechanical properties of steel reinforcement. Due to the effect of fiber / ribbed removal from the surface attack and the effect of corrosion on the mechanical properties of the steel, the non-coated members showed higher percentile values against the control and coating samples. High-end yield and coating patterns of non-coated samples with low-load application lead to corrosion on the mechanical properties of steel reinforcement [29].

2.1 MATERIALS AND METHODS

2.1.1 Aggregates

Fine and coarse aggregates are purchased and both meet the requirements of [30].

2.1.2 Cement

Limestone cement grade 42.5 was used for all concrete mixes. The cement meets the requirements of [31].

2.1.3 Water

Water samples were taken from the Department of Civil Engineering laboratory at Kenule Beeson Polytechnic, Bori, Rivers State. Water meets [32] requirements.

2.1.4 Structural steel reinforcement

Purchased directly from the market at Port Harcourt, Conformed to (BS4449: 2005 + A3) [33].

2.1.5Corrosion Inhibitors (Resins / Exudates) Boswellia dalzielii Hutch

The tree barks yielded whitish gummy Exudates / Resins. They are gotten from tree trunks by tapping from Ardo-Kola Village in Ardo Kola Local Government of Taraba State, Nigeria

2.2 Experimental Procedure

2.2.1 Experimental method

2.2.2 Prepare samples for reinforcement with coated exudates/resin

The application of Boswellia dalzielii Hutch extruded viscous gummy paste (exudate/resin) obtained from the tree was studied in the research exudates/resin. Its utility as an inhibitive material in the curbing of corrosion effect on reinforcing steel built within the coastal region of high salinity. Extracted exudate/rein was coated to reinforcing steel and embedded into the concrete slab, exposed to corrosive media with a high concentration of salt. The process of corrosion manifestation is long-term. However, the artificial introduction of sodium chloride (NaCl) accelerates the rate of corrosion, and its manifestations occur in a short time. The effect and devastating damage of corrosion rate measured by estimating the current density obtained or obtained from the polarization curve and the degree of quantification of the corrosion rate. The slabs for this research are achieved with concrete mixes were batched by material weight with the manual mixing method using a standard concrete ratio of 1.2.4, and a water-cement ratio of 0.65. Concrete slabs of 100 mm × 500 mm × 500 mm (thickness, width, and length) coated of 10 mm are cast into a metal mold, compacted to air and void-free, and reinforced by 10 pieces of reinforcing steel with a diameter of 12 mm, at 100 mm c / c (top and bottom) are placed and de-molded after 72 hours, cured for 28 days at standard room temperature to harden. The hardened concrete slabs are wholly immersed in 5% sodium chloride (NaCl) solution to water and accelerated for a rapid corrosion process for 360 days with interval checks and routine tests of 90 days, 180 days, 270 days, and 360 days for record documentation of comparative.

2.3 Accelerated Corrosion Test

The occurrence of corrosion is a long-term process, but the fast induced and accelerated corrosion process using sodium chloride (NaCl) solution allows reinforcement embedded in concrete to undergo corrosion and can quicken the increase in corrosion that will occur over decades in a short time. To test the corrosion resistivity of concrete, experimental processes were developed that accelerate the corrosion process and maximize the corrosion resistivity of concrete. The accelerated corrosion test is an impressed current technique, an effective technique for examining the corrosion process of steel in concrete and for assessing damage to the concrete coated protection to the steel bar. For the construction of structural elements and corrosion resistivity as well as for the selection of suitable materials and suitable protection systems, an accelerated corrosion test is carried out to obtain quantitative and qualitative information on corrosion.

2.4 Corrosion current measurement (Half-Cell Potential Measurement)

The classification of the severity of reinforcing steel corrosion is shown in Table 2.1. If the potential measurement results indicate a high probability of active corrosion, then the degree of corrosion can be assessed by measuring the resistivity of the concrete. However, care must be taken when using these data as it is assumed that the corrosion rate is constant over time. Measurement of half potential is an indirect method of estimating the probability of corrosion. Recently, there has been much interest in developing tools for carrying out electrochemical measurements of disturbances on the steel itself to obtain a direct estimate of the corrosion rate, Stem and Geary [34].

Table 2.1: Dependence between potential and corrosion probability [35]

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

Tests for Measuring the Resistivity of Concrete

Different measured values are measured at different points on the concrete surface. After the water has been applied to the slab surface, the resistivity of the concrete is measured daily at the reference point to determine its saturation state. This position was chosen on the side of the panel because special measurements of electrical resistivity can be made with water on top of the panel. The level of slab saturation is monitored by measuring the electrical resistivity of the concrete, which is directly related to the moisture content of the concrete. As soon as one plate reaches a saturated state, water can flow out while the other plate remains closed. The time limit is a major challenge for all experimental measurements because the saturation state of the concrete changes over time. For this purpose, the four probes touch the concrete of the reinforcing steel rail directly. From now on this measurement will be referred to as the "dry" measurement. Because each slab has a different water-cement ratio, the time required to saturate each slab not the same. Before water is applied to the slab, the electrical resistivity of the concrete is measured at certain points in the dry state. The electrical resistivity becomes constant as soon as the concrete reaches saturation.

Table 2.2: Dependence between concrete resistivity and corrosion probability [36]

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

2.6 Tensile Strength of Reinforcement

To determine the yield strength and ultimate tensile strength peak point of the reinforcing steel bar, 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. 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 results of the half-cell potential measurements are plotted against the resistivity for ease of interpretation. It is used as an indication of the probability of significant corrosion (ρ <5, 5 <ρ <10, 10 <ρ <20, ρ> 20) for very high, high, low to a moderate and low probability of corrosion. At another measurement point, the potential for correction was high (–350 mV ≤ *E*corr ≤ –200 mV), indicating a corrosion probability of 10% or uncertainty. It is proven that if the potential for corrosion is low (<-350 mV) within a certain range, there is a 95% chance of corrosion. Resistivity study data show whether certain states are conducive to lower ion movement, leading to greater and more corrosion.

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

Sample Numbers	**BD HS**	**BDH S1**	**BDH S2**	**BDH S3**	**BDH S4**	**BDH S5**	**BDH S6**	**BDH S7**	**BDH S8**	**BDHS 9**	**BDHS 10**	**BDHS 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	-114.9	-112.7	-107.9	-106.5	-108.9	-105.8	-114.3	-110.1	-105.5	-107.8	-111.8	-113.2
Concrete Resistivity ρ, kΩcm	15.02	15.01	15.00	15.00	14.99	15.16	15.15	15.14	15.14	15.13	15.07	14.99
Yield Strength, fy (MPa)	452.14	449.14	452.14	452.44	451.14	450.37	453.37	453.67	452.37	453.76	450.27	454.10
Ultimate Tensile Strength, fu (MPa)	609.31	607.26	608.94	604.72	608.25	608.67	608.47	609.27	607.87	609.42	608.92	608.78
Strain Ratio	1.35	1.35	1.35	1.34	1.35	1.35	1.34	1.34	1.34	1.34	1.35	1.34
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	0.92	0.92	0.92	0.92	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Rebar Weights- After at 28 days (Kg)	0.92	0.92	0.92	0.92	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92
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	-320.4	-333.6	-330.5	-322.9	-332.7	-339.7	-273.6	-280.8	-284.9	-308.7	-313.7	-321.5
Concrete Resistivity ρ, kΩcm	**7.78**	**7.92**	**8.75**	**6.46**	**6.43**	**6.39**	**8.21**	**6.56**	**6.60**	**7.20**	**6.57**	**7.87**
Yield Strength, fy (MPa)	420.01	419.52	417.62	413.64	412.26	415.34	420.23	413.75	415.63	416.45	417.54	417.56
Ultimate Tensile Strength, fu (MPa)	600.92	606.52	601.52	603.12	605.82	599.32	602.75	604.35	607.05	600.55	603.20	599.32
Strain Ratio	1.43	1.45	1.44	1.46	1.47	1.44	1.43	1.46	1.46	1.44	1.45	1.44
Rebar Diameter Before Test (mm)	11.98	11.96	11.97	11.99	11.96	11.98	11.98	11.96	11.97	11.97	11.96	11.97
Rebar Diameter- After Corrosion(mm)	11.94	11.92	11.93	11.95	11.92	11.94	11.94	11.92	11.93	11.93	11.92	11.93
Cross- sectional Area Reduction/Increase (Diameter, mm)	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Rebar Weights- Before Test(Kg)	0.91	0.92	0.91	0.91	0.91	0.92	0.92	0.92	0.92	0.91	0.92	0.92
Rebar Weights- After Corrosion(Kg)	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
Weight Loss /Gain of Steel (Kg)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Table 3.3: Potential Ecorr, after 28 days curing and 360days Accelerated Periods of Boswellia dalzielii Hutch 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	-123.6	-123.2	-123.7	-119.5	-123.6	-121.8	-125.6	-122.2	-116.8	-117.3	-114.5
Concrete Resistivity ρ, kΩcm	11.64	11.79	12.07	12.20	11.89	12.18	12.13	12.28	12.31	11.78	11.67	11.52
Yield Strength, fy (MPa)	455.62	455.13	453.23	449.25	447.87	450.95	450.84	449.36	451.24	452.06	453.15	453.17
Ultimate Tensile Strength, fu (MPa)	623.61	622.56	620.24	626.02	619.55	619.97	619.77	620.57	619.17	618.72	624.22	622.08
Strain Ratio	1.37	1.37	1.37	1.39	1.38	1.38	1.38	1.38	1.37	1.37	1.38	1.37
Rebar Diameter Before Test (mm)	12.00	11.98	11.99	12.01	11.98	12.00	12.00	11.98	11.98	11.98	11.98	11.99
Rebar Diameter- After Corrosion(mm)	12.05	12.03	12.04	12.06	12.03	12.05	12.05	12.03	12.03	12.03	12.03	12.04
Cross- sectional Area Reduction/Increase (Diameter, mm)	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Rebar Weights- Before Test(Kg)	0.91	0.92	0.91	0.91	0.91	0.92	0.92	0.92	0.92	0.91	0.92	0.92
Rebar Weights- After Corrosion(Kg)	0.99	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Weight Loss /Gain of Steel (Kg)	0.07	0.07	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 Exudate/Resin Coated (specimens)

Sampling and Durations	**Control Concrete slab Specimens**				**Corroded Concrete slab Specimens**				**Boswellia dalzielii Hutch 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 Boswellia dalzielii Hutch Exudate / Resin Coated Specimens**			
Potential Ecorr,mV	-111.5	-108.8	-107.7	-107.1	-328.2	-329.0	-328.7	-331.8	-123.8	-123.3	-121.9	-122.1
Concrete Resistivity ρ, kΩcm	15.01	15.00	15.00	15.05	8.15	7.71	7.21	6.43	11.83	12.02	12.05	12.09
Yield Strength, fy (MPa)	451.14	451.24	451.91	451.32	419.05	416.93	414.51	413.75	454.66	452.53	450.11	449.35
Ultimate Tensile Strength, fu (MPa)	608.50	606.97	607.30	607.21	602.99	603.72	603.49	602.76	622.14	622.94	621.94	621.85
Strain Ratio	1.35	1.35	1.34	1.35	1.44	1.45	1.46	1.46	1.37	1.38	1.38	1.38
Rebar Diameter Before Test (mm)	11.98	11.98	11.98	11.98	11.98	11.98	11.98	11.98	11.99	11.99	11.99	11.99
Rebar Diameter-After Corrosion(mm)	11.98	11.98	11.98	11.98	11.93	11.94	11.94	11.94	12.04	12.05	12.05	12.05
Cross- sectional Area Reduction/Increase (Diameter, mm)	0.00	0.00	0.00	0.00	0.044	0.042	0.044	0.046	0.064	0.066	0.065	0.068
Rebar Weights-Before Test(Kg)	0.924	0.922	0.915	0.918	0.922	0.921	0.919	0.915	0.921	0.919	0.917	0.922
Rebar Weights- After Corrosion(Kg)	0.924	0.922	0.915	0.918	0.861	0.862	0.861	0.864	0.995	0.998	0.992	0.995
Weight Loss /Gain of Steel (Kg)	0.00	0.00	0.00	0.00	0.054	0.056	0.056	0.053	0.075	0.076	0.079	0.072

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**				**Boswellia dalzielii Hutch 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 Boswellia dalzielii Hutch Exudate / Resin Coated Specimens**			
Potential Ecorr,mV	-66.02	-66.92	-67.22	-67.72	165.10	166.82	169.50	171.66	-62.28	-62.52	-62.89	-63.19
Concrete Resistivity ρ, kΩcm	84.17	94.64	107.92	134.14	-31.11	-35.86	-40.15	-46.83	45.17	55.90	67.07	88.07
Yield Strength, fy (MPa)	7.66	8.23	9.02	9.08	-7.83	-7.87	-7.91	-7.92	8.50	8.54	8.59	8.61
Ultimate strength (N/mm2)	2.99	2.85	2.89	2.94	-3.08	-3.09	-2.97	-3.07	2.92	3.01	2.96	2.95
Strain Ratio	-7.25	-7.21	-7.29	-7.27	5.19	5.16	5.36	5.28	-7.33	-7.27	-7.28	-7.23
Rebar Diameter Before Test (mm)	0.368	0.359	0.365	0.367	0.358	0.366	0.358	0.361	0.363	0.367	0.359	0.361
Rebar Diameter-After Corrosion(mm)	0.368	0.359	0.365	0.367	-0.914	-0.905	-0.903	-0.907	0.791	0.796	0.791	0.789
Cross- sectional Area Reduction/Increase (Diameter, mm)	0.00	0.00	0.00	0.00	-28.07	-28.07	-28.07	-28.07	39.02	39.02	39.02	39.02
Rebar Weights-Before Test(Kg)	0.407	0.410	0.408	0.409	0.403	0.412	0.408	0.412	0.410	0.408	0.407	0.410
Rebar Weights-After Corrosion(Kg)	6.27	6.27	6.29	6.28	-12.85	-12.85	-12.88	-12.87	9.75	9.75	9.79	9.77
Weight Loss /Gain of Steel (Kg)	0.00	0.00	0.00	0.00	-26.03	-26.03	-26.03	-26.03	35.19	35.19	35.19	35.19

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

Steel corrosion in concrete follows the electrochemical mechanism of metal corrosion in the electrolyte, RILEM, [37, 38]. Chemical thermodynamics determines whether a metal is susceptible to corrosion in a given environment as stated in [35, 36]. The half-cell potential measurements are especially suitable for reinforced concrete structures exposed to the costal marine environment with high saline water. The method (measurement and interpretation) is approved and used regardless of the depth of the concrete layer and the size and detail of the reinforcement. Half-cell potential measurements show corrosive reinforcement not only at the outermost reinforcement layer compared to the reference electrode, but also at a greater depth.

The experimental data of corrosion potential E_{corr},mV and concrete resistivity, kΩcm, computed from Tables 3.1 - 3.3 and summarized into mean and percentile values in Tables 3.4 and 3.5, plotted graphically in Figures 3.1-3.8b, are the results of controlled , uncoated (corroded), and coated samples. The experimental samples are made up of 36 concrete slabs of 3 sets, 12 controlled samples, which is the determinant reference range, 12 samples uncoated (corroded) and 12 samples coated with exudates / resin.

The average value and the minimum and maximum percentile of concrete resistivity with controlled sample potential differential are 15.0kΩcm and 15.05kΩcm (84.17% and 134.14%) and the differential value is 0.05kΩcm and 49.97%. The corrosion samples were 6.43kΩcm and 8.15kΩcm (-46.83% and -31.11%) and the differential values were 1.72kΩcm and 15.72%. The coated sample values were 11.83kΩcm and 12.09kΩcm (45.17% and 88.07%) and the differential values were 0.26kΩcm and 42.9%. The maximum percentile value calculated from the concrete resistivity of the controlled sample concrete is 134.14% compared to the corroded and coated value of -31.11% and 88.07% and the maximum value of the percentile differential from the control is 49.97% compared to the corroded and coated value of 15.72% and 42.9%.

The results of the controlled and coated concrete resistivity samples obtained of the maximum average values are 15.05kΩcm and 12.09kΩcm with a description of the value $10 < \rho < 20$ (low) compared to the corrosion value of 8.15kΩcm with Specifications $5 < \rho < 10$ (high) and with a reference range of dependence between concrete resistivity and corrosion probability significant corrosion probability ($\rho < 5$, $5 < \rho < 10$, $10 < \rho < 20$, $\rho > 20$) for very high, high, low to medium and low, for possible corrosion. From the comparative results of coated and corrosion samples, the maximum values obtained for both samples clearly show the value of coated samples with a range of $10 < \rho < 20$ which classifies the range of values as low to moderate, with information as a significant corrosion probability. The maximum value of the corroded sample was in the range of $5 < \rho < 10$, indicating high, signs suggesting possible corrosion, confirmed in the studies of [23, 25, 28, 29, 21].

From the results obtained it can be compared that the effect of corrosion attack was observed in the uncoated samples, while the samples with exudates/resin coating showed anti-corrosion properties with highly resistant and water-resistant membranes, which prevented corrosion of reinforcing steel embedded in the concrete slab from the induced accelerated corrosion medium is exposed.

The mean and percentile of minimum, maximum and differential of the calculated potential measurements from the half-cell potential of controlled were -111.52mV and -107.1mV (67.72% and -66.02%) with a potential differential of 4.42mV and 1.7%, the corroded samples were -331.81 mV and -328.22mV (165.1% and 171.66%) and the differential values were 3.59mV and 6.56%, and samples coated are -123.81 mV and -121.98mV (-63.19% and -62.28%) and the potential differential is 1.83mV and 0.91%, respectively. The maximum calculated controlled percentile value was -66.02% compared to the corroded and coated values 171.66% and -62.28% and the controlled potential differential value was 1.7%, corroded 6.56% and coateded 0.91%. The maximum half-cell potential yields of controlled and coated samples were -107.1mV and -121.98 mV, which showed the relationship between corrosion potential and probability as a $E_{\text{corr}} > -200\text{mV}$ as a reference range. The results of this corrosion potential E_{corr}, mV result show that the controlled sample values and exudates/resin coated are low with a 90% probability that no corrosion of the reinforcement is observed at the time of measurement (10% corrosion risk, 10% or shows an uncertain corrosion probability for samples that uncoated, the maximum calculated value is -328.22mV, the result is within the reference value of the dependence between the corrosion potential and probability of the value $-350\text{mV} \leq E_{\text{corr}} \leq -200\text{mV}$ indicates a high range of values, which is a corrosion probability of 10% or uncertain of the reference range (controlled) shows that the corrosion samples show corrosion as a result of accelerated corrosion induced as compared to the coated samples which show no corrosion as stated in the studies of [23, 25, 28, 29, 21]. The exudates/resin exhibits properties against the corrosive attack of reinforcing steel embedded in concrete slab, which is exposed to the corrosive medium through formation of a resistivity layer.

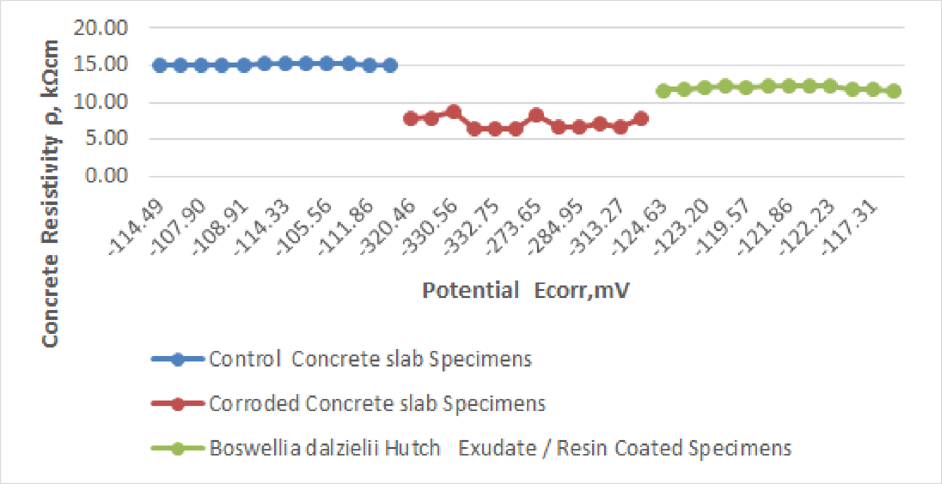

Figure 3.1: Concrete Resistivity ρ, kΩcm versus Potential Ecorr,mV Relationship

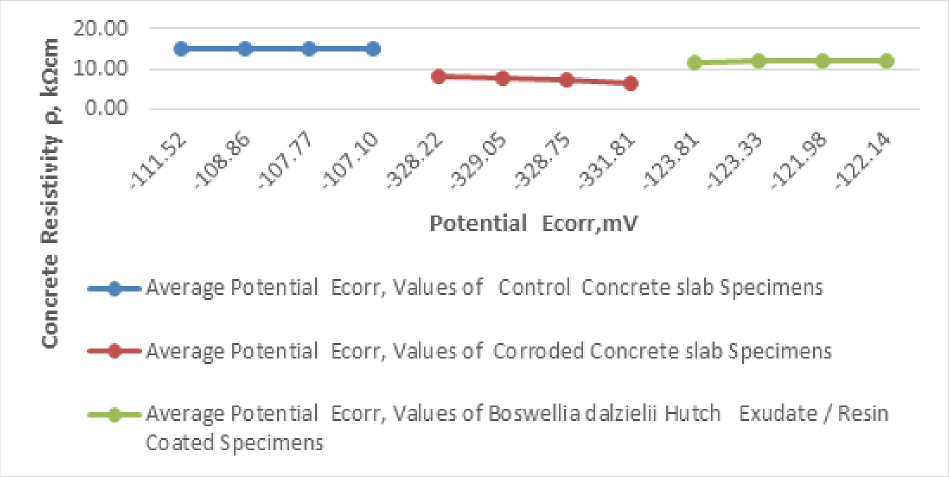

Figure 3.1A: Average Concrete Resistivity versus Potential Relationship

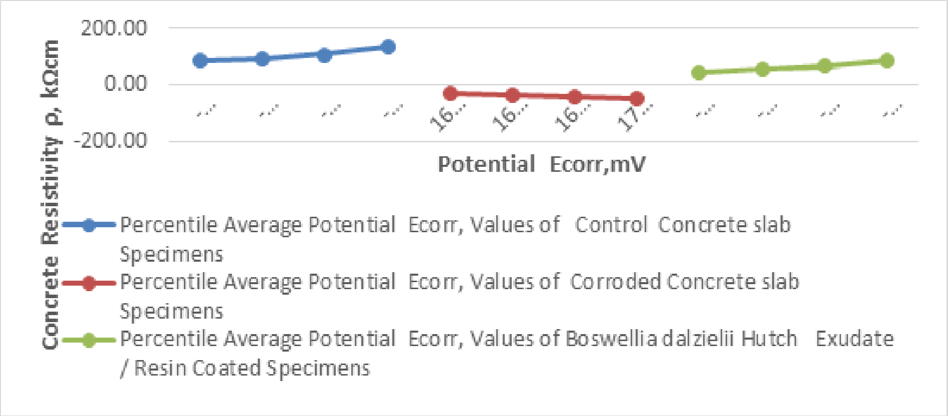

Figure 3.1B: Average Percentile Concrete Resistivity versus Potential Relationship

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

For reinforcement concrete design, ACI-318-14 (2014) has 3 limitations: value of yield strength, tensile and yield strength ratio, and elongation of steel reinforcing bars which used in reinforcement concrete. One of three limitations based on ACI-318-14 (2014), tensile and yield strength ratio, limited should not less than 1.25. The requirement is based on the assumption that a capability of a structural member to develop inelastic rotation capacity is a function of the length of the yield region [39].

The mean, percentile, and the differential between the minimum and maximum tensile strength, fu (MPa) of the controlled sample were 606.97MPa and 608.5MPa (2.85% and 2.99%) and the differential values were 1.53MPa and 0.14%, corroded 602.76MPa and 603.72MPa (-3.09% and -2.97%) and a differential of 0.96MPa and 0.12%, coated are 621.85MPa and 622.94MPa (2.92% and 3.01%) and the differential values of 1.09MPa and 0.09%, the maximum percentile calculated from the ultimate tensile strength is controlled by 2.99% in terms of corrosion and coating values are - 2.97% and 3 0.01% respectively and the potential differential value of 0.14% is controlled, 0.12% is corroded and 0.09% is coated as confirmed in the studies of [29, 21, 23, 24, 28].

The results of the mean, percentile and the value of the differential between the minimum and maximum yield strength, fy (MPa) of the controlled sample were 451.14MPa and 451.91MPa (7.66% and 9.08%) and the differential value was 0.77MPa and 1.42%, the corroded samples were 413.75MPa and 419.05 MPa (-7.92% and -7.83%) and the differential values were 5.3MPa and 0.09%, the coated sample values were 449.35MPa and 454.66MPa (8.5% and 8.61%) and the differential value is 5.31MPa and 4.29%. The calculated maximum percentile of the controlled yield strength is 9.08% relative to corrosion and coated values are -7.83% and 8.61% and the possible differential values are 1.42% controlled, 0.09% corroded and 4.29% coated.

The average ratio of the minimum and maximum strain ratio percentile and differential values of the controlled samples were 1.34 and 1.35(-7.21% and -7.22%) with a differential value of 0.01% and 0.08%, the corroded sample value was 1.44 and 1.46 (5.16% and 5.36%) and the differential values of 0.02% and 0.2%, coated samples were 1.37 and 1.38 (-7.33% and -7.23%) and the differential value of 0.01 and 0.1%.

The maximum percentile value calculated to compare the strain ratio was checked at -7.21% against corroded 5.36% and coated -7.23%, and the maximum differential was checked for 0.08%, corroded 0.2% and coated 0.1%, confirmed in the studies of [23, 25, 28, 29, 21].

The calculated results, which are summarized in Tables 3.4 and 3.5 and shown graphically in Figures 3.1-3.8, were used to determine the yield strength, tensile strength and deformation ratio of the mean, percentile and differential potential values of the control, sampled concrete slab. uncoated (corroded) and coated, coated samples reported higher damage loads compared to rusted samples with reduced breakdown loads and low load bearing capacities and with average and percentile values to the reference range, whereas without coating (corroded)) low load-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 uncoated (corroded) elements, which damage the reinforcing steel fibers, ribs and passive formation and surface modification. The observed mean values for the coated samples were associated with the corrosion resistivity potential to penetrate the reinforcing steel with the formation of a protective membrane; This attribute indicates the effectiveness of the exudate / resin as an inhibitor against corrosive effects of reinforced concrete structures exposed to heavy marine areas with high salt content.

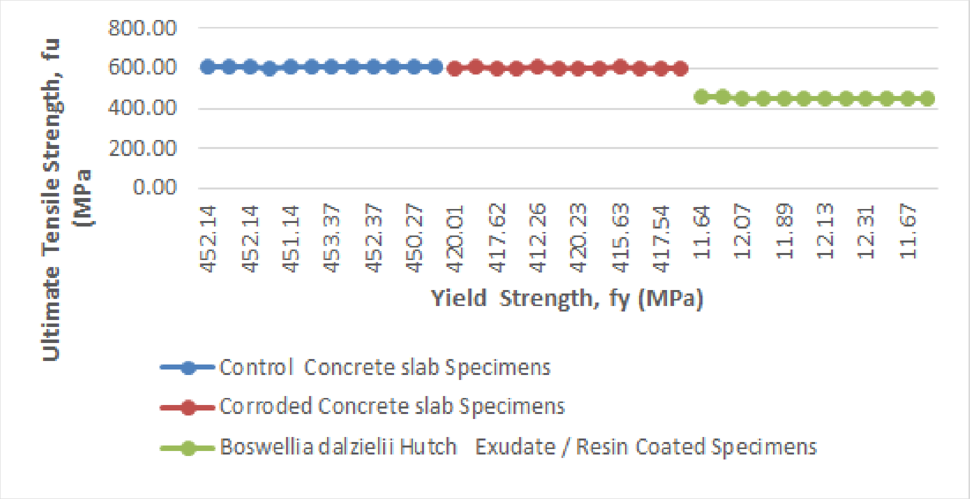

Figure 3.2: Yield Strength versus Ultimate strength

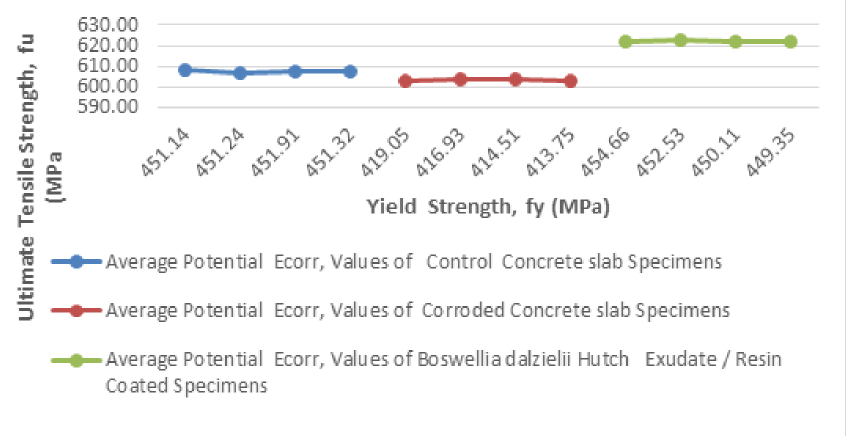

Figure 3.2A: Average Yield Strength versus Ultimate Tensile Strength

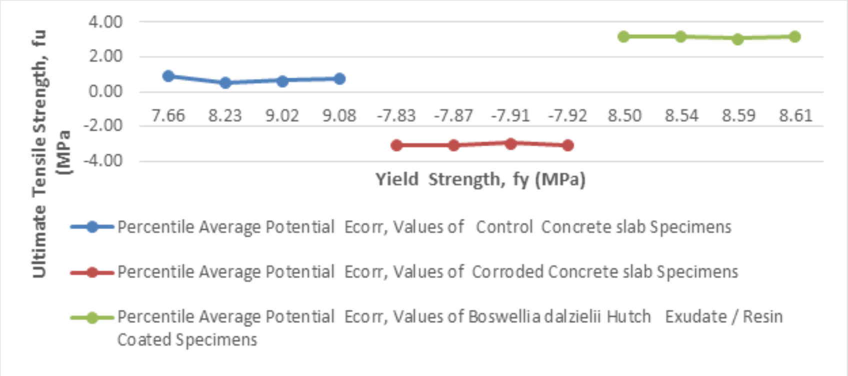

Figure 3.2B: Average Percentile Yield Strength versus Ultimate Tensile Strength

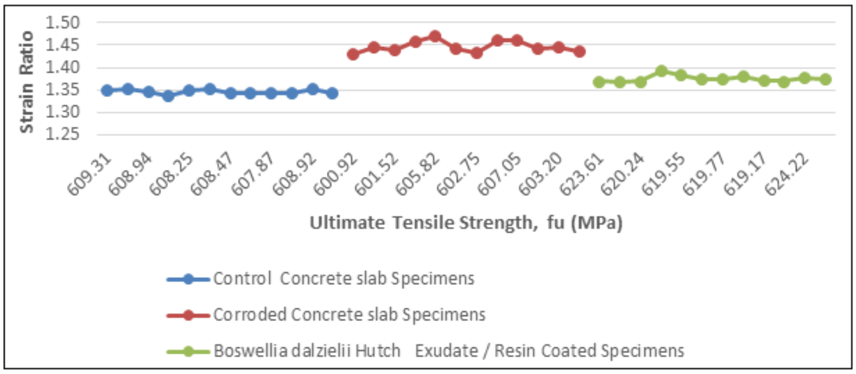

Figure 3.3: Ultimate Tensile Strength versus Strain Ratio

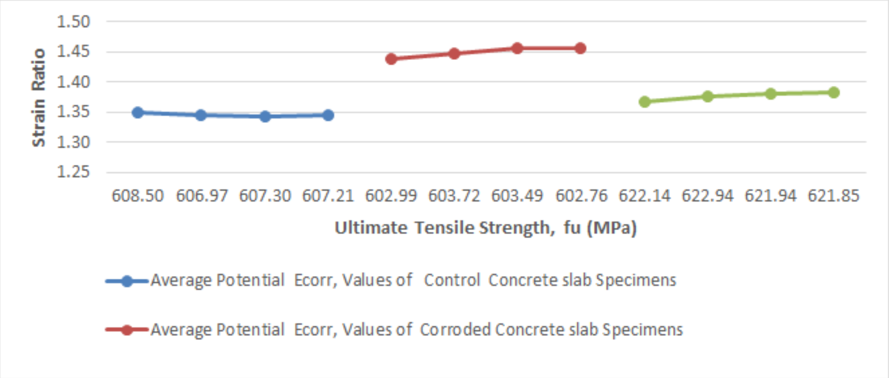

Figure 3.3A: Average Ultimate Tensile Strength versus Strain Ratio

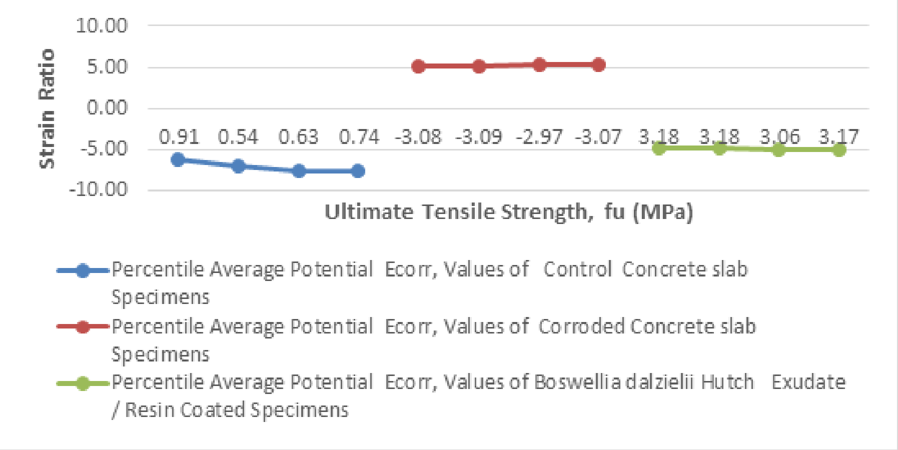

Figure 3.3B: Average percentile Ultimate Tensile Strength versus Strain Ratio

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

The geometry of the steel reinforcement makes a significant contribution to the strength of the joint. It has been observed that deformed stems have better properties than smooth stems. The results of reinforcing steel diameter before testing (mm) average values, the minimum and maximum percentiles were 11.98mm and 11.98mm (0.359% and 0.368%) with a differential of 0.00mm and 0.009%, corroded and controlled samples values were 11.98 mm and 11.98mm (0.358% and 0.366%) and the differential values are 0.00 mm and 0.008% and the coated sample values are 11.99mm and 11.99mm (0.359% and 0.367%) and differential values calculated from 0.00mm and 0.008%. The unit weight of the reinforcing steel before the corrosion test showed small differentials based on the shape of the product and company, as well as by-products used in the production process.

The mean, percentile and the value of the differential in the diameter of the reinforcement after corrosion (mm) for the controlled sample were 11.98 mm and 11.98mm (0.359% and 0.368%) with a differential of 0.00mm and 0.009%, with 100% reference value, which is maintained, the corroded values of the sample are 11.93mm and 11.94mm (-0.914% and -0.900%) and the differential between 0.01mm and 0.011% is the value of the coated samples 12.04mm and 12.05mm (0.789% and 0.796%) and the differential between 0.01mm and 0.007%.

The maximum calculated percentile diameter of the reinforcement after corrosion was controlled 0.368% versus corroded - 0.903% and coated 0.796%, with a different percentile of corroded 0.011% versus 0.007% 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 effects of corrosion attack on reinforcing steel embedded in the concrete slab and exposed to activity-induced corrosion acceleration. For comparative, the results of the corroded samples showed a reduction and reduction value compared to the diameter of the reinforcement before and after the induction accelerated corrosion test with a percentile decrease in value from 0.368% to -0.903% and an average value in the range from 11.98mm to 11.94mm.

Decrease/increase (diameter) in cross-sectional area, 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 were 0.042 mm and 0.046 mm (-28.07% and -28.07%) and the % differential in corrosion, coated sample values were 0.064 mm and 0.068 mm (39.02% and 39 0.02%)) and the differential between 0.00mm and 0.00%. The cross-sectional area differential in mean values and relative percentiles between coated and corroded samples ranged from 39.02% to -28.07%. The reduction 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 exudate/resin coated elements experience an increase in volume due to differentials in coating thickness differentials confirmed in the studies of ([23]; [25]; [28]; [29]; [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), the minimum, maximum, and differential mean and percentile of controlled samples were 0.915kg and 0.924kg (0.416% and 0.419%) and the differential was 0.009% and 0.003%, corroded samples 0.915kg and 0.922 kg (0.412% and 0.421%) and the differential between 0.007% and 0.009%, the coated samples were 0.917kg and 0.922kg (0.416% and 0.419%) with a differential of 0.005% and 0.003%.

The average value and percentile of the weight of the rebar after corrosion (Kg) and the general differential values of the minimum and maximum values of the samples examined were 0.915kg and 0.924kg (0.416% and 0.419%), and a differential of 0.009% and 0.003%, the corroded samples are 0.861kg and 0.864kg (-12.88% and -12.85%), and the differential was 0.003% and 0.03%, the value of the coated sample was 0.992kg and 0.998kg (9 0.75% and 9.79%) and the differential between 0.006% and 0.04%.

The mean and minimum and maximum unit loss/gain steel (Kg) percentiles and percentile differentials in comparative are values maintained at 100% as a result of aggregation in freshwater tanks without any trace of corrosion potential of being corroded, for the controlled sample, values obtained were 0.053kg and 0.056kg (-26.03% and -26.03%), and coated were 0.072kg and 0.079kg (35.19% and 35.19%). The computed results from Tables 3.1-3.3 and in 3.4 - 3.5 are summarized and plotted graphically in Figures 3.7-3.8b showing the effect of corrosion on uncoated (corroded) and coated reinforcing steel, and an investigation of the unit weight of reinforcement before and after corrosion and decreasing/increasing weight. For comparative, the results obtained show a reduction of the mean and percentile values for the coating from 0.079kg to 0.056kg and corroded 35.19% to 26.03%, as also seen in the studies of [23, 25, 28, 29, 21]. The aggregate results show that the corrosion effect causes a reduction in weight/reduction of the corroded sample compared to the percentile layer and an increase in mean, resulting in a slight increase in volume around the layer thickness. This study shows the efficacy and effectiveness of exudates/resin as an anti-corrosion material in reinforcing steel embedded in samples of concrete slabs exposed to induced corrosion.

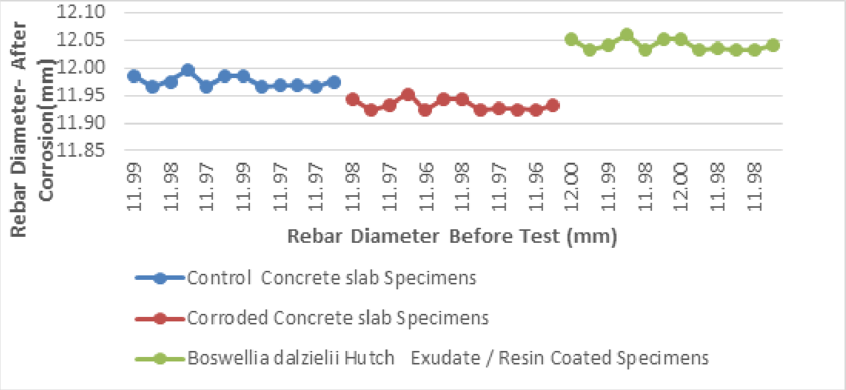

Figure 3.4: Rebar Diameter Before Test(mm) versus Rebar Diameter- After Corrosion(mm)

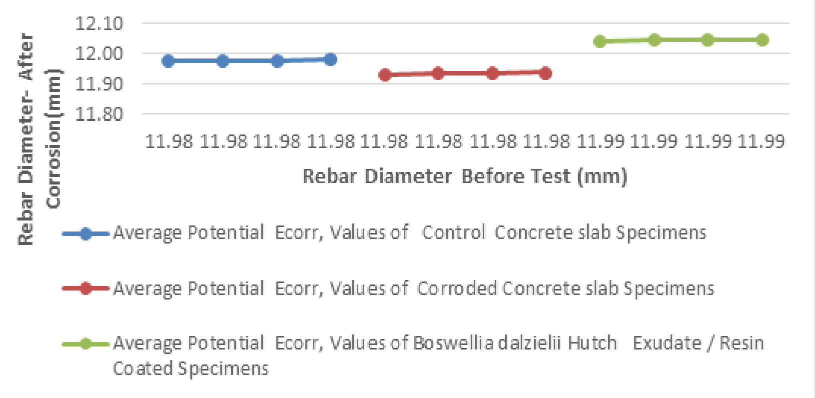

Figure 3.4A: Average Rebar Diameter Before Test(mm) versus Rebar Diameter- After Corrosion(mm)

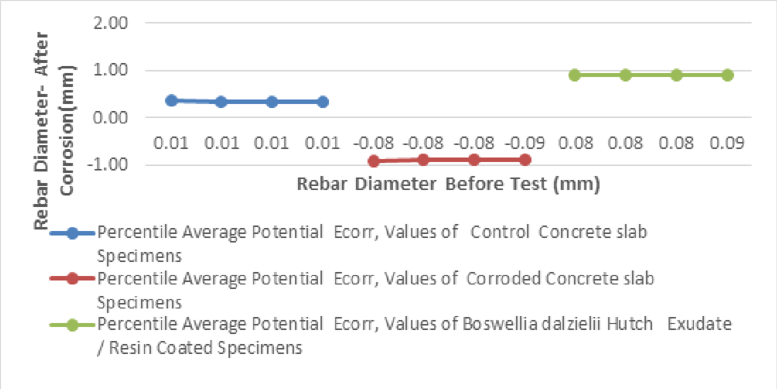

Figure 3.4B: Average Percentile Rebar Diameter Before Test (mm) versus Rebar Diameter- After Corrosion(mm)

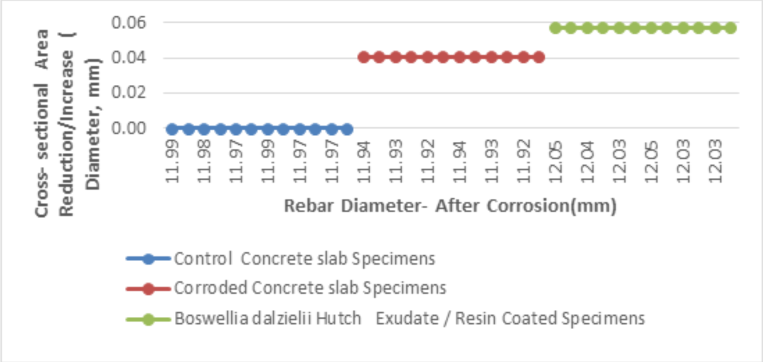

Figure 3.5: Rebar Diameter- After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

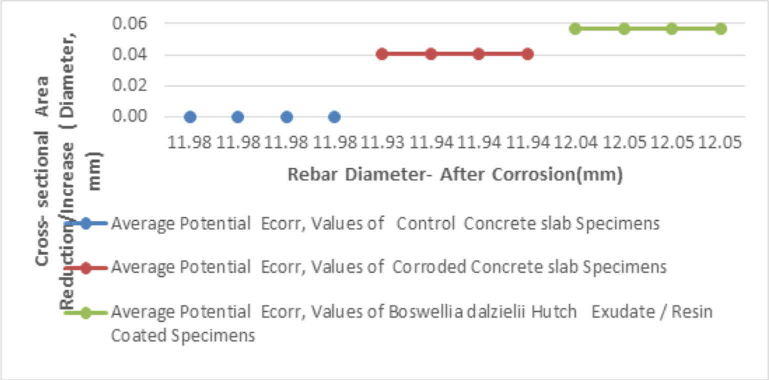

Figure 3.5A: Average Rebar Diameter- After Corrosion (mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

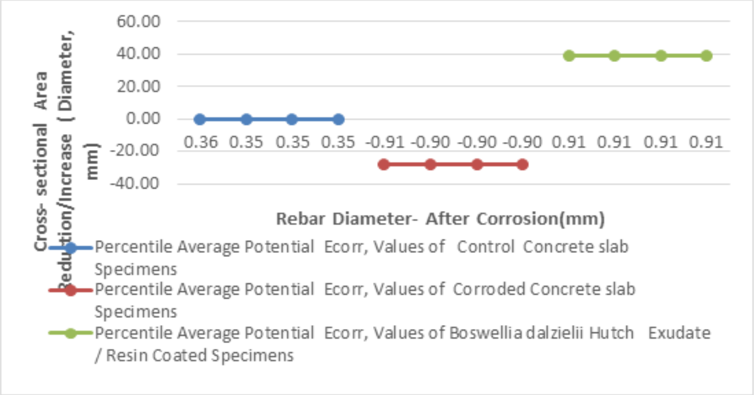

Figure 3.5B: Average Percentile Rebar Diameter- After Corrosion(mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

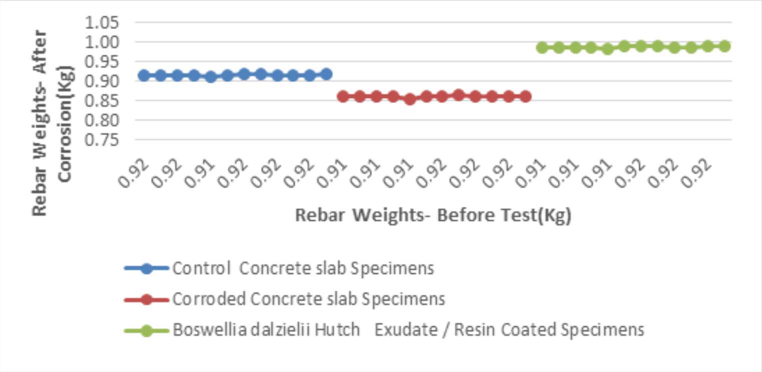

Figure 3.6: Rebar Diameter - After Corrosion(mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

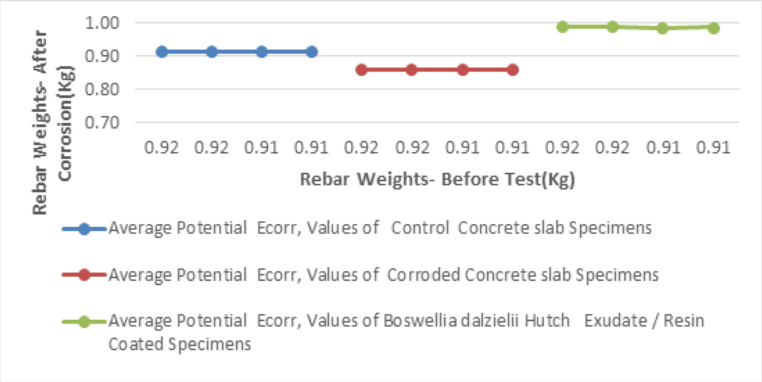

Figure 3.6A: Average Rebar Diameter - After Corrosion(mm) versus Cross- section Area Reduction/Increase (Diameter, mm

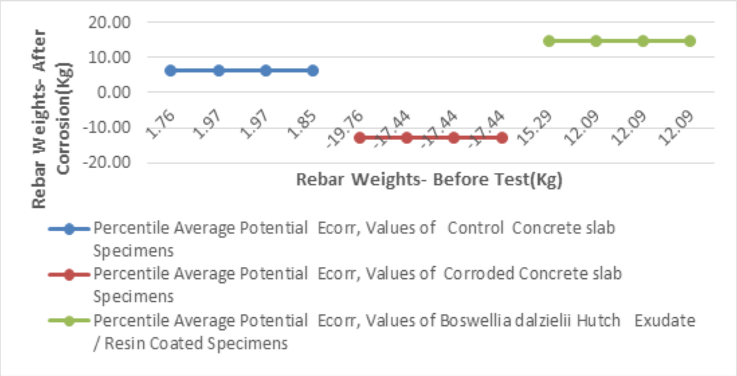

Figure 3.6B: Average Percentile Rebar Diameter - After Corrosion(mm) versus Cross- section Area Reduction/Increase (Diameter, mm)

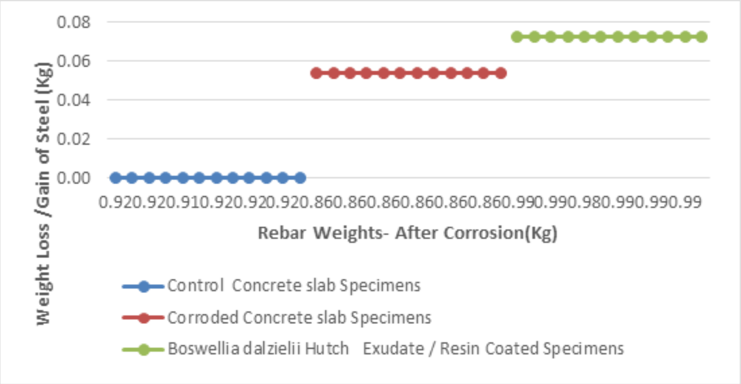

Figure 3.7: Rebar Weights- After Corrosion(Kg) versus Weight Loss /Gain of Steel (Kg)

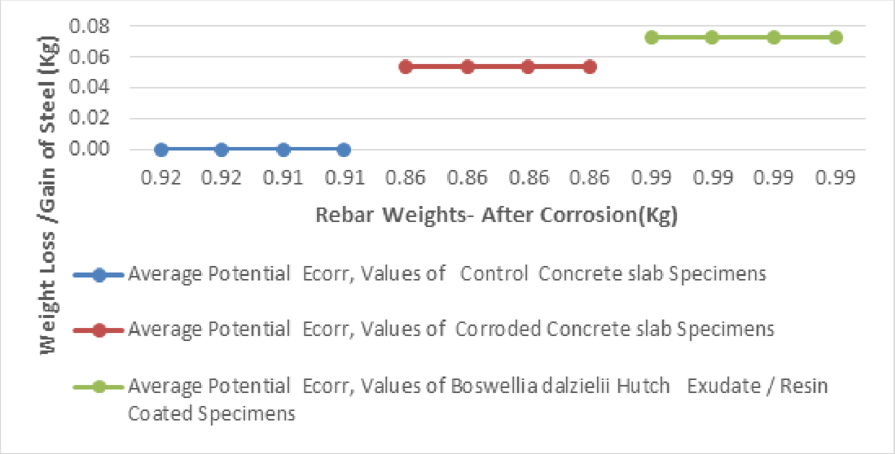

Figure 3.7A: Average Rebar Weights- After Corrosion(Kg) versus Weight Loss /Gain of Steel (Kg)

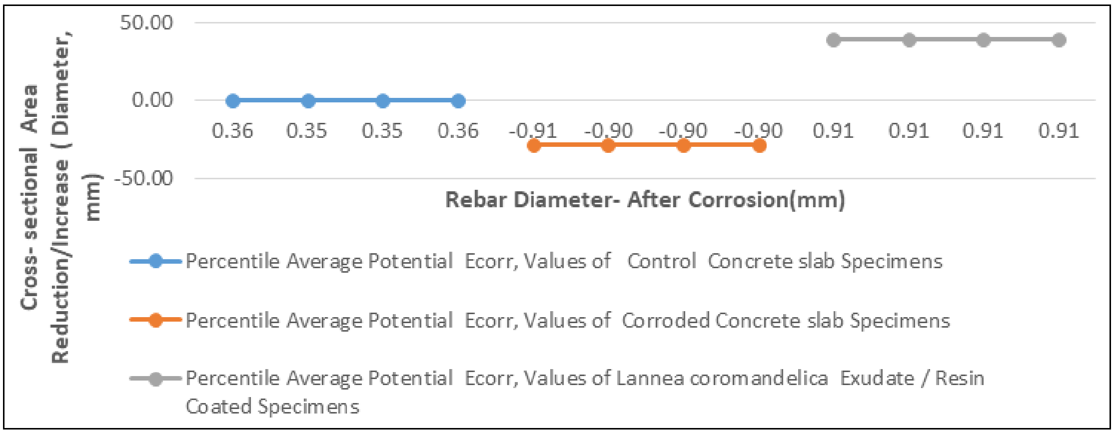

Figure 3.7B: Average Percentile Rebar Weights- After Corrosion(Kg) versus Weight Loss /Gain of Steel (Kg)

4.0 CONCLUSION

Experimental results showed the following conclusions:

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

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