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Comparative Half Cell Potential and Concrete Resistivity Corrosion Probability Assessment of Embedded Coated Steel Reinforcement in Concrete Accelerated Environment

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Abstract

The study investigated corrosion probability level assessments of three different resins extracts of trees from dacryodes edulis, mangifera indica and moringa oleifera lam using half cell potential corrosion measurement, concrete resistivity measurement and tensile strength test to ascertain the surface condition of the mechanical properties of non-corroded, corroded and inhibited reinforcement coated thicknesses of 150µm, 250µm and 350µm specimens embedded in concrete, exposed to severe and corrosive environment medium for 119 days after 28 days initial cured, with required constant current for polarization potential test of -200 mV through 1200mV, with a scan rate of 1mV/s. Results recorded of potential $E_{corr,mV}$, concrete resistivity and tensile strength of moringa oleifera lam inhibited specimen indicated a 10% or uncertain probability of corrosion which indicates no corrosion presence or likelihood and concrete resistivity indicated a low probability of corrosion or no corrosion indication. When compared to corroded samples, corroded has 70.1% increased values potential $E_{corr,}{}^{mV}$ and 35.5% decreased values of concrete resistivity. Average percentile results of potential $E_{corr,}{}^{mV}$, and concrete resistivity are dacryodes edulis 29.9% and 63.6% , mangifera indica 26.57% and 61.25% and moringa oeifera lam 29.9% and 68.74% respectively. Arbitrarily and computed percentile average values of yield stress against ultimate strength, when compared to corrode as 100% nominal yield stress decreased from100.95% to 96.12% dacryodes edulis inhibited, 105.36% to 96.12% mangifera indica inhibited, and 105.75 % to 96.12% moringa oleifera lam inhibited and weight loss of

dacryodes edulis inhibited are 67.5% against 48.5% and 98.7% to 94.82%, cross-sectional diameter reduction, mangifera indica inhibited specimen 64.8% to 44.45% and 46.76% to 86.43% cross-sectional diameter reduction and moringa oleifera lam inhibited specimen 67.5% against 48.5% and 48.34% to 94.82%, cross-sectional diameter reduction, all showed decreased values of corroded compared to coated specimens.

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

1.0 Introduction

Reinforcement corrosion normally requires long exposure period of time, and usually by the first crack observed on the concrete surface. Therefore, for design of structural members and durability against corrosion as well as selection of suitable material and appropriate protective systems, it is useful to perform accelerated corrosion tests for obtaining quantitative and qualitative information on corrosion resistance in a relatively shorter period of time. There are two common methods to accelerated chloride-induced Reinforcement Corrosion: wet/dry and impressed current methods (Austin *et al.* [1). Wet/dry method requires several months before sufficient levels of chloride ions have permeated into concrete cover to cause depassivation of the passive film formed on steel due to alkaline environment. The scientific justification for accelerating corrosion using impressed current is strong, dramatically reducing the initiation period required for breakdown of the passive film from years to days and fixing the desired rate of corrosion without compromising the reality of corrosion products formed (Amleh *et al.* [2], Austin *et a*l. [1]). When an impressed current is used to drive corrosion of reinforced concrete exposed to chloride environment, steel reinforcement corrosion results from depassivation of the passive film. This means the stable products are transformed into non stable products, which diffuse away from anode to cathode area (Austin *et al*. [1], Care and Raharinaivo [3). This process agrees with some results reported that the corrosion products of iron in chlorinated environments (Sagoe and Glasser [4], Pourbaix [5]). These types of corrosion products were observed by others (Duffo *et al.* [6], Poupard *et al.* [7]) in the real reinforced concrete structures for chloride-induced reinforcement corrosion. It was reported (Austin *et al.* [1], Care and Raharinaivo, [3]) that the chloride induced corrosion using impressed current characters by uniform corrosion product (rust) forming on steel surface. An accelerated corrosion test is the impressed current technique which is an effective technique to investigate the corrosion process of steel in concrete and to assess the damage on the concrete cover. (Austin *et al.* [1], Care and Raharinaivo, [3]).

2.0 MATERIALS AND METHODS FOR EXPERINMENT

2.1 Aggregates

The fine aggregate was gotten from the river, washed sand deposit, coarse aggregate was granite a crushed rock of 12 mm size and of high quality. Both aggregates met the requirements of [8]

2.1.2 Cement

The cement used was Ordinary Portland Cement, it was used for all concrete mixes in this investigation. The cement met the requirements of [9]

2.1.3 Water

The water samples were clean and free from impurities. The fresh water used was gotten from the tap at the Civil Engineering Department Laboratory, University of Uyo, Uyo. Akwa - Ibom State. The water met the requirements of [10]

2.1.4 Structural Steel Reinforcement

The reinforcements are gotten directly from the market in Port Harcourt. [11]

2.1.5 Corrosion Inhibitors (Resins / Exudates) Dacryodes edulis, Mangifera indica and Moringa Oleifera lam

They are abundantly found in Rivers State bushes and they are sourced from plantations and bushes of Odioku communities, Ahoada West Local Government areas, Rivers State, from existed and previously formed and by tapping processes for newer ones. The study inhibitors are Dacryodes edulis, Mangifera indica and Moringa Oleifera lam are of natural tree resin /exudate substance extracts.

2.2 EXPERIMENTAL PROCEDURES

2.2.1 Experimental method

2.2.2 Sample preparation for reinforcement with coated resin/exudates

Fresh concrete mix batch were fully compacted to remove trapped air, with concrete cover of 15mm and projection of 150mm for half cell potential measurement and concrete resistivity tests. Corrosion test was conducted on high tensile reinforcing steel bar of 12mm, specimens rough surface were treated with sandpaper and wire brush, washed with acetone to remore rust and dried to enable proper adhesion of coated / inhibitive materials. Coating was done by direct application on the ribbed reinforcement rough surface with 150μm, 250μm and 350μm coated thicknesses of moringa oleifera lam paste were polished and allowed to dried for 72 hours before embedded into concrete slab. Mix ratio of 1:2:3 by weight of concrete, water cement ratio of 0.65, and manual mixing was adopted. The polarization curve was obtained as the relationship between corrosion potential and current density. The data were recorded for a fine-tuned duration of 1hr at ambient temperature. The corrosion rates were quantified predicated on current density obtained from the polarization curve and the corrosion rate quantification set-up. Slabs were demoulded after 72 hours and cured for 28 days with room temperature and corrosion acceleration ponding process with Sodium Chloride lasted for 119 days with 14 days checked intervals for readings. The samples were designed with sets of reinforced concrete slab of 150mm thick x 350mm width x 900mm long, uncoated and coated specimens of above thicknesses were embedded into the concrete, spaced at 150mm apart. The polarization test was performed utilizing scanning potential of -200 mV through 1200mV, with a scan rate of 1mV/s. The corrosion cell consisted of a saturated calomel reference electrode (SCE), counter electrode (graphite rod) and the reinforcing steel embedded in concrete specimen acted as the working electrode.

2.3 Accelerated Corrosion Test

Therefore, for design of structural members and durability against corrosion as well as selection of suitable material and appropriate protective systems, it is useful to perform accelerated corrosion tests for obtaining quantitative and qualitative information on corrosion resistance in a relatively shorter period of time. A laboratory acceleration process helps to distinguish the roles of individual factors that could affect chloride induced corrosion. (Care and Raharinaivo [12] Reinforcement corrosion normally requires long exposure period of time, and usually by the first crack observed on the concrete surface. The accelerated corrosion test allows the acceleration of corrosion to reinforcing steel embedded in concrete and can simulate corrosion growth that would occur over decades. An accelerated corrosion test is the impressed current technique which is an effective technique to investigate the corrosion process of steel in concrete and to assess the damage on the concrete cover. In order to test concrete resistivity and durability against corrosion, it was necessary to design an experiment that would accelerate the corrosion process and maximize the concrete's resistance against corrosion until failure.

2.4 Corrosion Current Measurements (Half-cell potential measurements)

This was also stated from practical experience (Figg and Marsden [13] and Langford and Broomfield [14]. If the potential measurements indicate that there is a high probability of active corrosion, concrete resistivity measurement can be subsequently used to estimate the rate of corrosion. Corrosion rates have been related to electrochemical measurements based on data first reported by Stern and Geary [15]. However, caution needs to be exercised in using data of this nature, since constant corrosion rates with time are assumed. Classifications of the severity of rebar corrosion rates are presented in Table 2.1. Half-cell potential measurements are indirect method of assessing potential bar corrosion, but there has been much recent interest in developing a means of performing perturbative electrochemical measurements on the steel itself to obtain a direct evaluation of the corrosion rate (Gowers and Millard [16]).

Table 2.1: Dependence between potential and corrosion probability

Potential E_{corr}	Probability of corrosion
Ecorr < −350mV	Greater than 90% probability that reinforcing steel corrosion is occurring in that area at the time of measurement
−350mV ≤ Ec$_{orr}$ ≤ −200mV	Corrosion activity of the reinforcing steel in that area is uncertain
E_{corr} > −200mV	90% probability that no reinforcing steel corrosion is occurring in that area at the time of measurement (10% risk of corrosion

2.5 Concrete Resistivity Measurement Test

Henceforth, these measurements will be referred to as the measurements in «dry» conditions. Different readings were taken at different locations at the surface of the concrete. Before applying water on the slabs, the concrete electrical resistivity was measured in the dry condition at the specified locations. The mean values of the readings were recorded as the final readings of the resistivity in the study. These locations were chosen at the side of the slabs, since concrete electrical resistivity measurements could be taken when water was on the top surface of the slab. The electrical resistivity becomes constant once the concrete has reached saturation. After applying water on the surface of the slabs, the concrete resistivity was measured daily at the reference locations, looking for the saturation condition. In the study, the Wenner four probes method was used, it was done by placing the four probes in contact with the concrete directly above the reinforcing steel bar. Once one slab would reach the saturated condition, the water could be drained from that slab, while the other slabs remained ponded. Time limitation was the main challenge to perform all the experimental measurements, as the concrete saturation condition changes with time. The saturation level of the slabs was monitored through concrete electrical resistivity measurements, which are directly related to the moisture content of concrete.

Since each of the slabs had a different w/c, the time needed to saturate each of the slabs was not the same

Table 2.2: Dependence between concrete resistivity and corrosion probability

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 Reinforcing Bars

To ascertain the yield and tensile strength of tension bars, bar specimens of 12 mm diameter of non-corroded, corroded and coated were tested in tension in a Universal Testing Machine and were subjected to direct tension until failure; the yield, maximum and failure loads being recorded. To ensure consistency, the remaining cut pieces from the standard length of corroded and non-corroded steel bars were subsequently used for mechanical properties of steel.

3.0 Experimental results and discussion

The results of the half-cell potential measurements in table 3.1 were plotted against concrete resistivity of table 3.2 for easy interpretation. It is evident that potential E_{corr} if low (< -350mV) in an area measuring indicates a 95% probability of corrosion. In the other measuring points, potential E_{corr} is high ($-350\text{mV} \leq E_{\mathrm{corr}} \leq -200\text{mV}$), which indicates a 10% or uncertain probability of corrosion

Results of the concrete resistivity measurements are shown in Table 3.2. It used as indication of likelihood of significant corrosion ($\rho < 5$, $5 < \rho < 10$, $10 < \rho < 20$, $\rho > 20$) for Very high, High, Low to moderate and Low, for Probability of corrosion. Resistivity survey data gives an indication of whether the concrete condition is favorable for the easy movements of ions leading to more corrosion. Concrete resistivity is commonly measured by four-electrode method.

3.1 Non-corroded Concrete Slab Members

Results obtained from table 3.1 of half-cell potential measurements for and concrete resistivity for 7days to 119 days respectively indicated a 10% of uncertain probability of corrosion which indicates no corrosion presence or likelihood and concrete resistivity which indicated a low probability of corrosion or no corrosion indication.

Table 3.1, 3.2 and 3.3 are the results summary and of average values derived from randomly slab samples from A-I of control, corroded and coated specimens of 150µm, 250µm, 350µm summarized to A, B and C from ABC, DEF and GHI. Figures 3.1 and 3.2 are the plots representations of Concrete Resistivity ρ, kΩcm versus Potential $E_{corr,}{}^{mV}$ Relationship which showed average of 27.2% Potential $E_{corr,}{}^{mV}$ and 87.8% Concrete Resistivity. Figures 3.3 and 3.4 are the plots of yield stress versus Ultimate strength, results showed that non-corroded specimens have 100.3% and 104 .50%, while figures 3.5 and 3.6 are the plots of weight loss versus cross-section diameter reduction at 67.1% and 98.2% respectively

3.2 Corroded Concrete Slab Members

Tables 3.1, 3.2 and 3.3 are the results recorded of potential $E_{corr,mV}$, and concrete resistivity for non- inhibited concrete specimens on the mapping areas for the accelerated periods of 7days to 119 days which indicated 95% probability of corrosion and indicating a high or moderate probability of corrosion. Average results on comparison showed an increase of 70.1% against 27.2% non-corroded of Potential $E_{corr,}{}^{mV}$ and 87.8% to 38.8% a decrease values in Concrete Resistivity. Figures 3.1 and 3.2 are the plots representations of Concrete Resistivity ρ, kΩcm versus Potential $E_{corr,}{}^{mV}$ Relationship. Figures 3.3 and 3.4 are the plots of yield stress against ultimate strength at summary and average state of corroded slab with nominal values of 100% and decreased in ultimate strength from 100.68% to 96.12%, while figures 3.5 and 3.6 presented the weight loss versus cross-section diameter reduction decreased due to attack from sodium chloride from 67.1% to 48.5% and 98.2% to 94.82% respectively.

3.3 Dacryodes edulis, Mangifera indica and Moringa Oleifera lam Steel Bar Coated Concrete Cube Members

Tables 3.1, 3.2 and 3.3 are the results recorded of potential $E_{corr,mV}$, concrete resistivity and tensile strength of Dacryodes edulis, Mangifera indica and Moringa Oleifera lam inhibited specimen, the results indicated a 10% or uncertain probability of corrosion which indicates no corrosion presence or likelihood and concrete resistivity indicated a low probability of corrosion or no corrosion indication. Average percentile results of potential $E_{corr,mV}$, and concrete resistivity are dacryodes edulis 29.9% and 63.6% , mangifera indica 26.57% and 61.25% and moringa oleifera lam 29.9% and 68.74% respectively. When compared to corroded samples, corroded has 70.1% increased values potential $E_{corr,mV}$ and 35.5% decreased values of concrete resistivity . Figures 3.1 and 3.2 are the plots representations of Concrete Resistivity ρ, kΩcm versus Potential $E_{corr,}{}^{mV}$ Relationship. Figures 3.3 and 3.5 are the plots for arbitrarily and computed percentile average values of yield stress against ultimate strength, when compared to corrode as 100% nominal yield stress decreased from100.95% to 96.12% dacryodes edulis inhibited, 105.36% to 96.12% mangifera indica inhibited, and 105.75 % to 96.12% moringa oleifera lam inhibited and figures 3.5 and 3.6 respectively presented weight loss of dacryodes edulis inhibited at weight loss at 67.5% against 48.5% and 98.7% to 94.82%, cross-sectional diameter reduction, mangifera indica inhibited specimen 64.8% to 44.45% and 46.76% to 86.43% cross-sectional diameter reduction and moringa oleifera lam inhibited specimen 67.5% against 48.5% and 48.34% to 94.82%, cross-sectional diameter reduction, both showed decreased values of corroded compared to coated specimens.

Table 3.1 : Potential $E_{corr,}$ after 28 days curing and 119 days acceleration Ponding

s/no	Inhibitor (resin/exudates) and controlled sample	**Potential $E_{corr,mV}$**								
		Time Intervals after 28 days curing								
		A	B	C	D	E	F	G	H	I

		(7days)	(21days)	(35days)	(49days)	(63days)	(77days)	(91days)	(105 days)	(119 days)
1	Control Concrete slab	-102	-102.2	-100.3	-101.2	-101.7	-100.8	-100.3	-101.4	-100.4
2	Non-inhibitor	-268.5	-294.7	-328.6	-367.7	-377.5	-384.5	-418.4	-425.6	-429.7
		150µm,			250µm,			`350µm,		
3	Dacryodes edulis	-108.6	-107.6	-115.8	-108.3	-115.5	-110.5	-118.2	-113.5	-118.6
3	Moringa Oleifera lam	-119	-129.5	-124.6	-127.6	-123.6	-127.5	-124.4	-115.5	-111.7
3	Mangifera indica	-129.5	-135.5	-128.6	-121.5	-124.8	-115.6	-125.6	-132.6	-138.7
Average values Potential $E_{corr,mV}$										
		ABC = A			`DEF = B			GH1 = C		
1A	Control Concrete slab	-101.5			-102.2			-100.7		
2A	Non-inhibitor	-297.3			-393.5			-424.6		
		150µm,			250µm,			`350µm,		
3A	Dacryodes edulis	-110.7			-111.4			`-116.8		
3A	Moringa Oleifera lam	-124.4			-126.2			`-117.2		
3A	Mangifera indica	-131.2			-201.6			`-132.3		

Table 3.2 : Results of Concrete Resistivity ρ, kΩcm Time Intervals after 28 days curing curing and 119 days acceleration ponding

s/no	Inhibitor (resin/exudates) and controlled	Concrete Resistivity ρ, kΩcm

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	sample	Time Intervals after 28 days curing								
		A (7days)	B (21days)	C (35days)	D (49days)	E (63days)	F (77days)	G (91days)	H (105 days)	I (115 days)
1	Control Concrete slab	15.35	15.52	15.42	15.65	15.48	14.43	15.45	15.45	15.48
2	Non-inhibitor	6.77	6.91	7.74	8.05	8.22	8.38	9.12	9.55	9.59
		150µm,			250µm,			`350µm,		
3	Dacryodes edulis	13.14	13.19	13.28	13.33	13.48	13.42	13.54	13.69	13.71
3	Moringa Oleifera lam	13.18	13.21	13.33	13.59	14.18	14.23	14.32	14.38	13.33
3	Mangifera indica	13.88	14.02	14.36	14.47	14.5	14.67	14.84	14.92	14.65

Average values Concrete Resistivity ρ, kΩcm

		ABC = A	`DEF = B	GH1 = C
1B	Control Concrete slab	15.43	15.19	15.46
2B	Non-inhibitor	7.14	8.21	9.42
3B		150µm,	250µm,	`350µm,
	Dacryodes edulis	13.2	13.4	13.64
	Moringa Oleifera lam	13.2	13.4	13.64
	Mangifera indica	14.1	14.5	14.8

Table 3.3 : Mechanical properties of Non-Corroded, Corroded and Coated Beam

s/no	Inhibitor (resin/exudates) and controlled sample	**Yield Stress (N/mm^2)**								
		Time Intervals after 28 days curing								
		A (7days)	B (21days)	C (35days)	D (49days)	E (63days)	F (77days)	G (91days)	H (105 days)	I (119 days)
1	Control Concrete slab	410.4	410.1	410.3	410.0	410.3	410.7	410.0	410.5	410.4
2	Non-inhibitor	4.10.2	410.0	410.0	410.4	410.0	410.3	410.0	410.3	410.2
		150µm,			**250µm,**			**`350µm,**		
3	Dacryodes edulis	4.10.0	410.0	410.9	410.8	410.6	410.9	410.7	410.8	410.9
3	Moringa Oleifera lam	410.0	410.0	410.9	410.8	410.6	410.9	410.7	410.8	410.9
3	Mangifera indica	410.6	410.2	410.7	410.7	410.7	410.4	410.2	410.2	410.4
		Average values Yield Stress (N/mm^2)								
		ABC = A			`DEF = B			GH1 = C		
1C	Control Concrete slab	410.27			410.33			410.3		
2C	Non-inhibitor	410.01			410.23			410.17		
		150µm,			250µm,			`350µm,		
3C	Dacryodes edulis	410.45			410.77			419.8		

3C	Moringa Oleifera lam	410.45			410.77			410.8		
3C	Mangifera indica	410.45			410.60			410.27		
		Ultimate strength (N/mm^{2})								
1	Control Concrete slab	564.7	565.6	562.4	562.6	566.8	562.2	565.2	562.7	562.4
2	Non-inhibitor	584.7	585.8	586.8	582.8	586.8	582.8	585.4	582.6	588.4
		150µm,			**250µm,**			**`350µm,**		
3	Dacryodes edulis	587.7	582.8	582.9	589.8	587.1	583.8	582.1	583.8	584.4
3	Moringa Oleifera lam	567.7	562.8	562.9	569.8	567.1	563.8	562.1	563.8	564.4
3	Mangifera indica	560.9	566.4	568.4	568.7	569.5	568.7	568.5	568.9	569.5
	Average value of Ultimate strength (N/mm^{2})									
		ABC = A			`DEF = B			GH1 = C		
1D	Control Concrete slab	564.23			563.87			563.43		
2D	Non-inhibitor	585.77			584.13			585.47		
		150µm,			250µm,			`350µm,		
3D	Dacryodes edulis	584.47			586.9			583.43		
3D	Moringa Oleifera lam	564.47			566.9			563.43		
3D	Mangifera indica	565.23			568.3			567.97		
		Weight Loss of Steel Loss (in grams)								
1	Control Concrete slab	7.25	7.37	7.25	7.26	7.35	7.28	7.28	7.28	7.35

2	Non-inhibitor	10.628	10.796	10.839	10.876	10.882	10.884	10.835	10.885	10.676
		150µm,			**250µm,**			**`350µm,**		
3	Dacryodes edulis	7.21	7.23	7.29	7.24	7.29	7.32	7.24	7.18	7.27
3	Moringa Oleifera lam	7.21	7.23	7.29	7.24	7.29	7.32	7.24	7.18	7.27
3	Mangifera indica	7.29	7.29	7.25	7.30	7.26	7.26	7.31	7.29	7.28
		Average values of Weight Loss of Steel Loss (in grams)								
		ABC = A			`DEF = B			GH1 = C		
1E	Control Concrete slab	7.32			7.33			7.27		
2E	Non-inhibitor	10.754			10.681			10.799		
		150µm,			**250µm,**			**`350µm,**		
3E	Dacryodes edulis	7.24			7.28			7.23		
3E	Moringa Oleifera lam	7.24			7.28			7.23		
3E	Mangifera indica	7.27			7.27			7.29		
		Cross- section Area Reduction (Diameter, mm)								
1	Control Concrete slab	12	12	12	12	12	12	12	12	12
2	Non-inhibitor	11.53	11.53	11.54	11.61	11.64	11.71	11.75	11.76	11.79
		150µm,			**250µm,**			**`350µm,**		
3	Dacryodes edulis	12	12	12	12	12	12	12	12	12
3	Moringa Oleifera lam	12	12	12	12	12	12	12	12	12

3	Mangifera indica	12	12	12	12	12	12	12	12	12
		Average Values of Cross- section Area Reduction (Diameter, mm)								
		ABC = A			`DEF = B			GH1 = C		
1F	Control Concrete slab	12			12			12		
2F	Non-inhibitor	11.587			11.563			11.662		
		150µm,			**250µm,**			**`350µm,**		
3F	Dacryodes edulis	12			12			12		
3F	Moringa Oleifera lam	12			12			12		
3F	Mangifera indica	12			12			12		

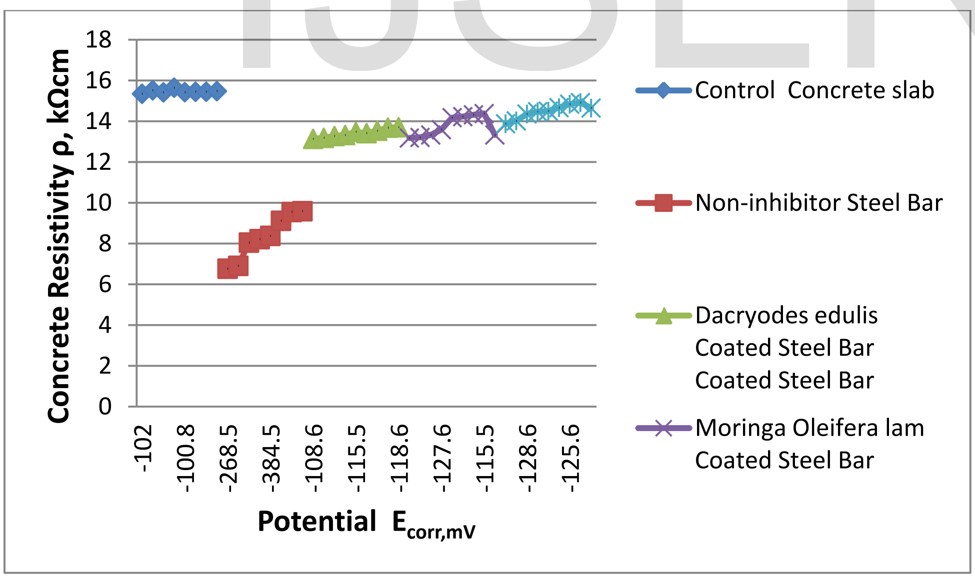

Figure 3.1: Concrete Resistivity versus Potential Relationship Concrete Resistivity ρ, kΩcm versus Potential $E_{corr,}$^{mV} Relationship

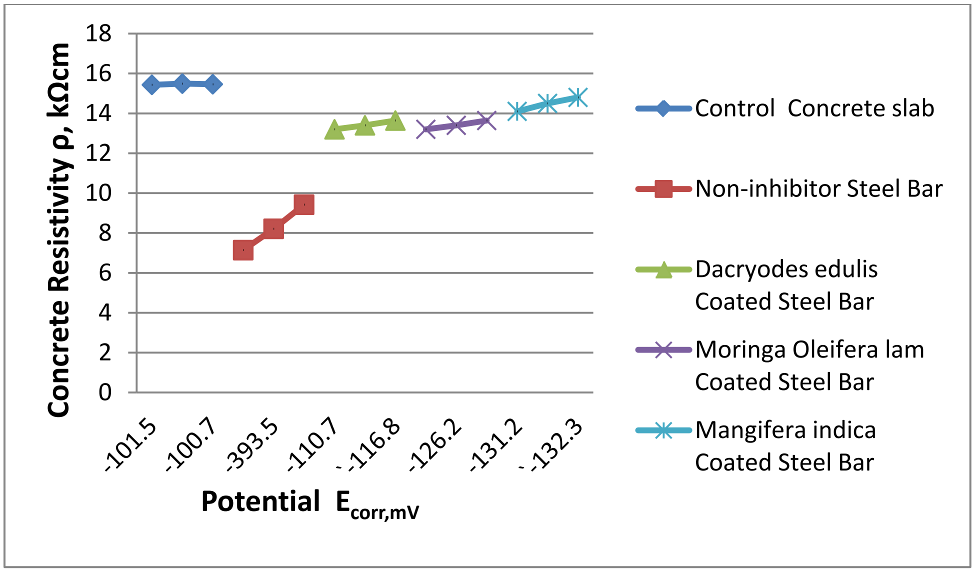

Figure 3.2: Average Concrete Resistivity versus Potential Relationship

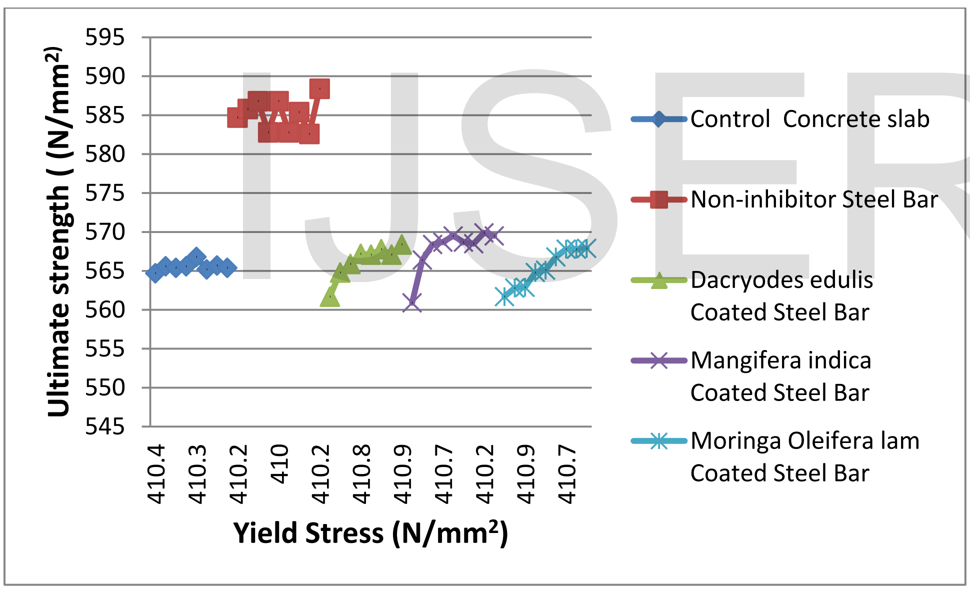

Figure 3.3: Yield Stress versus Ultimate strength

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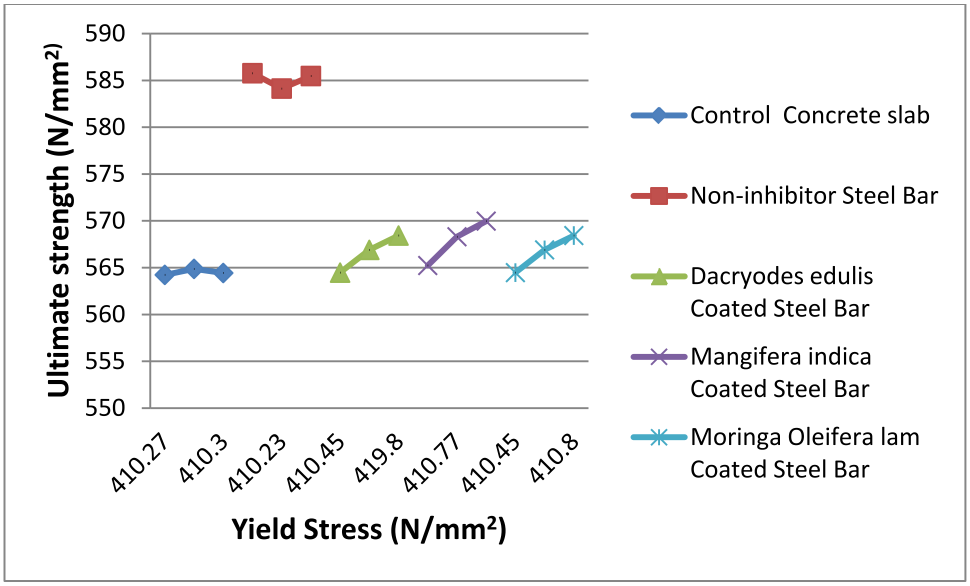

Figure 3.4: Average Yield Stress versus Ultimate strength.

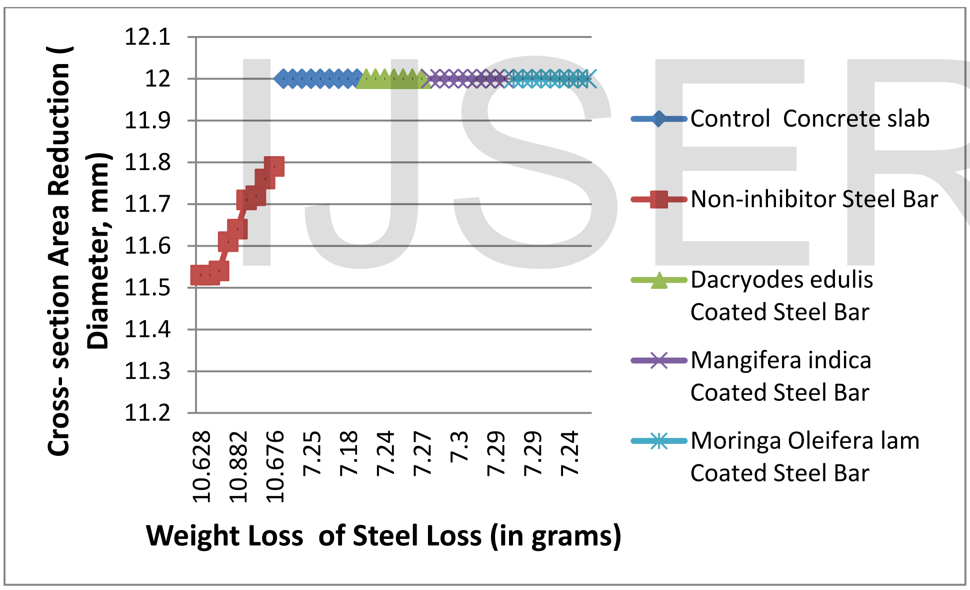

Figure 3.5: Weight Loss of Steel Loss versus Cross- section Area Reduction

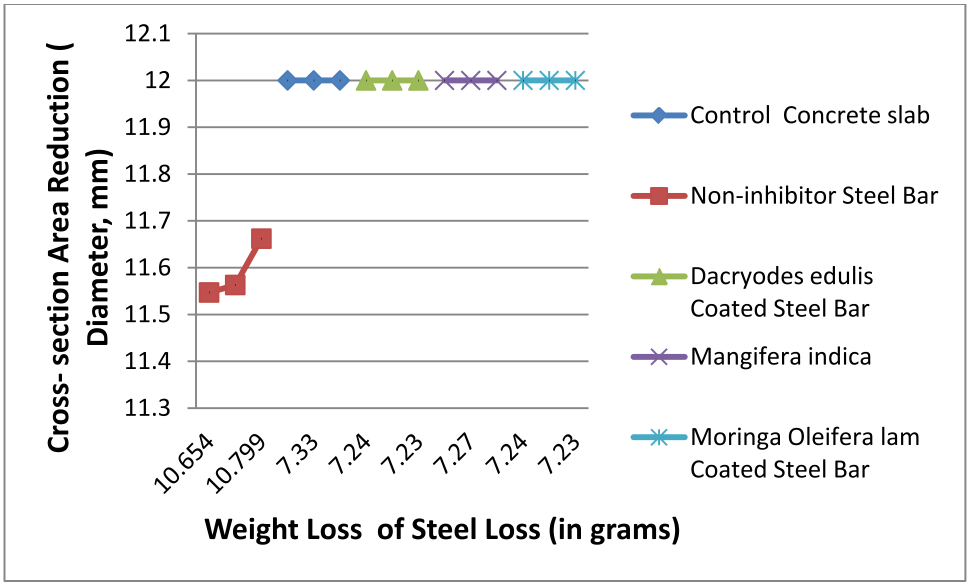

Figure 3.6: Average Weight Loss of Steel Loss versus Cross- section Area Reduction

4.0 Conclusion

Experimental results showed the following conclusions:

i. Corrosive environmental condition resulted to corrosion potential on corroded reinforcing steel.

ii. Effectiveness in the use of corrosion inhibitors sustained the strength capacity of coated members.

iii. All resins coated specimens showed high level of protection compared to corroded

iv. Half cell potential and concrete resistivity test produces best non-destructive method

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