Investigation of Corrosion Probability Assessment and Concrete Resistivity of Steel Inhibited Reinforcement of Reinforced Concrete Structures on Severe Condition

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Abstract

Corrosion of steel reinforcement has become a key hitch in the construction industry, and the prediction of service life of reinforced concrete structures calls for concern. The research work investigated the corrosion potential, concrete resistivity and tensile tests of non-corroded, corroded and coated reinforcing steel of concrete slab member. Direct application of corrosion inhibitor of dacryodes edulis resins thicknesses 150µm, 250µm, 350µm were coated on 12mm diameter reinforcement, embedded into concrete slab and exposed to severe corrosive environment for 119 days for accelerated corrosion test, half-cell potential measurements, concrete resistivity measurement and tensile tests . Results obtained showed that non-inhibited specimens corroded with signs cracks, pitting, color change on surface condition and spalling . 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 after 28 days initial curing, 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%, decreased values in concrete resistivity.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%, 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. When compared to corroded samples, corroded has 70.1% increased values potential and 38.8% decreased values of concrete resistivity, yield stress against ultimate strength at in comparison to corrode as 100% nominal yield stress decreased from 100.95% to 96.12% and figures 3.5 and 3.6 respectively presented weight loss at 67.5% against 48.5% and 98.7% to 94.82%, cross-sectional diameter reduction, both showed decreased values of corroded compared to coated specimens. The entire results showed effectiveness in the use of dacroyodes edulis as inhitors, it sustained and preserved the reinforcement against environmental attack.

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

1.0 Introduction

Concrete made with low water/cement ratio has a low permeability that minimizes the penetration of ingredients that induced-corrosion, such as chloride, carbon dioxide and moisture to the steel surface Ahmed [1]. In integration, low permeability increases the electrical resistivity of concrete and thus avails in restricting the rate of corrosion by reducing the flow of hydroxyl ions from anode to cathode. It is conspicuous that corrosion of steel embedded in concrete requires the breakdown of the passive film. Steel reinforcement corrosion in majority of concrete structures does not occur facilely as long as there is good quality concrete and opportune design of the structure. However, corrosion of steel in concrete may occur when exposed to truculent substances such as chloride and carbon dioxide. Sundry auspice methods have been additionally carried out to bulwark the steel reinforcement and assure long accommodation life by corrosion obviation. These include cathodic bulwark, the utilization of coated steel rebar, corrosion inhibitors, and additive minerals such as silica fume, fly ash, etc, to reduce permeability and provide better corrosion control.

Macdonald [2] investigated inhibitors in alkaline solutions and in cement extracts. The cement extracts experiment showed that sodium nitrite inhibited corrosion in the presence of chlorides while sodium benzoate did not. Novokshcheov [3] showed that calcium nitrite is not detrimental to concrete properties as it is the case for inhibitors based on sodium or potassium. A latter study by Skotinck [4] and Slater [5] showed that under long-term accelerated testing, calcium nitrite was found to be of better quality in terms of strength. De Schutter and Luo [6], they reported that calcium nitrite inhibitor increases the early age compressive strength (28 days). The effect on the ultimate strength seems to depend on the amount of inhibitor added to the concrete. A calcium nitrite-based corrosion inhibitor increases somewhat the air content as well as the workability of the fresh concrete. The effect of sodium molybdate and sodium nitrite as steel corrosion inhibitors in saturated calcium hydroxide solutions polluted with sulfuric and nitric acids (acid atmosphere) was investigated by Tommaselli *et al.* [7] ,they concluded that: both compounds showed significantly inhibitory effects. However, sodium molybdate in low concentration (0.013% total solution mass) showed an efficiency of approximately 67% while efficiency. The two compounds displayed similar inhibitory effects within a high range of inhibitor concentrations (0.040% total solution mass).

2.0 MATERIALS AND METHODS FOR EXPERINMENT

2.1 Aggregates

The fine aggregate and coarse aggregate were purchased. Both met the requirements of [8]

2.1.2 Cement

The cement used was Ordinary Portland Cement, it 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, Kenule Beeson Polytechnic, Bori, Rivers 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 (african pear Ube)

The study inhibitor Dacryodes edulis (african pear Ube) is of natural tree resins /exudates substance extracts.

2.2 EXPERIMENTAL PROCEDURES

2.2.1 Experimental method

2.2.2 Sample preparation for reinforcement with coated resin/exudates

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 remove 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 dacryodes edulis paste were polished and allowed to dry 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 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. 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. Slabs were demoulded after 72 hours and cured for 28 days with room temperature and corrosion acceleration ponding process with Sodium Chloride lasted for 105 days, direction of current was arranged such that, rebars embedded inside the concrete specimens accommodated as anode. Steel plate which was placed along the length of slab functions as cathode. Current required achieving different corrosion levels can be obtained utilizing Faraday's law Predicated on the calculation amount of 4 to 10A current at the variation of 4A was applied to obtain the required corrosion level with 14 days checked intervals for readings.

The corrosion rates were quantified predicated on current density obtained from the polarization curve and the corrosion rate quantification set-up. 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. The polarization test was performed utilizing scanning potential of -200 mV through 1200mV, with a scan rate of 1mV/s. The data were recorded for a fine-tuned duration of 1hr at ambient temperature. The polarization curve was obtained as the relationship between corrosion potential and current density.

2.3 Accelerated Corrosion Test

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. 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. A laboratory acceleration process helps to distinguish the roles of individual factors that could affect chloride induced corrosion. An accelerated corrosion test is the

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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. (Care and Raharinaivo [12] 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.

2.4 Corrosion Current Measurements (Half-cell potential measurements)

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 [13]. Corrosion rates have been related to electrochemical measurements based on data first reported by Stern and Geary [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. This was also stated from practical experience (Figg and Marsden [15] and Langford and Broomfield [16]. Classifications of the severity of rebar corrosion rates are presented in Table 2.1,. However, caution needs to be exercised in using data of this nature, since constant corrosion rates with time are assumed.

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Table 2.1: Dependence between potential and corrosion probability

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

2.5 Concrete Resistivity Measurement Test

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. Different readings were taken at different locations at the surface of the concrete. The mean values of the readings were recorded as the final readings of the resistivity in the study. The saturation level of the slabs was monitored through concrete electrical resistivity measurements, which are directly related to the moisture content of concrete. The electrical resistivity becomes constant once the concrete has reached saturation. Before applying water on the slabs, the concrete electrical resistivity was measured in the dry condition at the specified locations. Henceforth, these measurements will be referred to as the measurements in dry conditions. 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. Time limitation was the main challenge to perform all the experimental measurements, as the concrete saturation condition changes with time. After applying water on

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the surface of the slabs, the concrete resistivity was measured daily at the reference locations, looking for the saturation condition. Since each of the slabs had a different w/c, the time needed to saturate each of the slabs was not the same. Once one slab would reach the saturated condition, the water could be drained from that slab, while the other slabs remained ponded.

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 Ecorr is high ($-350\text{mV} \leq E\text{corr} \leq -200\text{mV}$), 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 7 days to 119 days respectively indicated a 10% or 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 and 3.2 (1A, 2A ,3A and 1B,2B, 3B) are the results 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. Figure 3.3 and 3.4 are the plots of yield stress and ultimate strength of mechanical properties of non-corroded specimens at 100.3% and 100.68%, 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 and 3.2 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%, decreased 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 Steel Bar Coated Concrete Cube Members

Tables 3.1 and 3.2 are the results recorded of potential $E_{corr,mV}$, and concrete resistivity of dacryodes edulis 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 29.9% and 63.6% respectively. When compared to corroded samples, corroded has 70.1% increased values potential $E_{corr,mV}$ and 38.8% 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 represented the plots for randomly and computed percentile average values of yield stress against ultimate strength at in comparison to corrode as 100% nominal yield stress decreased from 100.95% to 96.12% and figures 3.5 and 3.6 respectively presented weight loss at 67.5% against 48.5% and 98.7% to 94.82%, cross-sectional diameter reduction, both showed decreased values of corroded compared to coated specimens.

Table 3.1 : Summary Results of Potential $E_{corr,}$ after 28 days Curing and 115 days Acceleration Ponding

s/no	Inhibitor (resin/exudates) and controlled sample	Potential $E_{corr,mV}$								
		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	-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
Average values Potential $E_{corr,mV}$										
		ABC = A			`DEF = B			GH1 = C		

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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

Table 3.2 : Results of Concrete Resistivity ρ, kΩcm Time Intervals after 28 days curing curing and 115 days acceleration ponding

s/no	Inhibitor (resin/exudates) and controlled sample	Concrete Resistivity ρ, kΩcm								
		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	15.43	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

Average values Concrete Resistivity ρ, kΩcm				
		ABC = A	`DEF = B	GH1 = C
1B	Control Concrete slab	15.43	15.49	15.46
2B	Non-inhibitor	7.14	8.21	9.42
3B		150µm,	250µm,	`350µm,
	Dacryodes edulis	13.2	13.4	13.64

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
		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		
		Ultimate strength (N/mm$^{2)}$								
1	Control Concrete	564.7	565.6	562.4	562.6	566.8	562.2	565.2	562.7	562.4

	slab									
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
	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		
		Weight Loss of Steel Loss (in grams)								
1	Control Concrete slab	10.628	10.796	10.839	10.876	10.882	10.884	10.835	10.885	10.676
2	Non-inhibitor	7.25	7.37	7.33	7.25	7.26	7.45	7.28	7.18	7.35
		150µm,			**250µm,**			**`350µm,**		
3	Dacryodes edulis	7.21	7.23	7.29	7.24	7.29	7.32	7.24	7.18	7.27
		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,**		

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3E	Dacryodes edulis	7.24			7.28			7.23		
		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
		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		

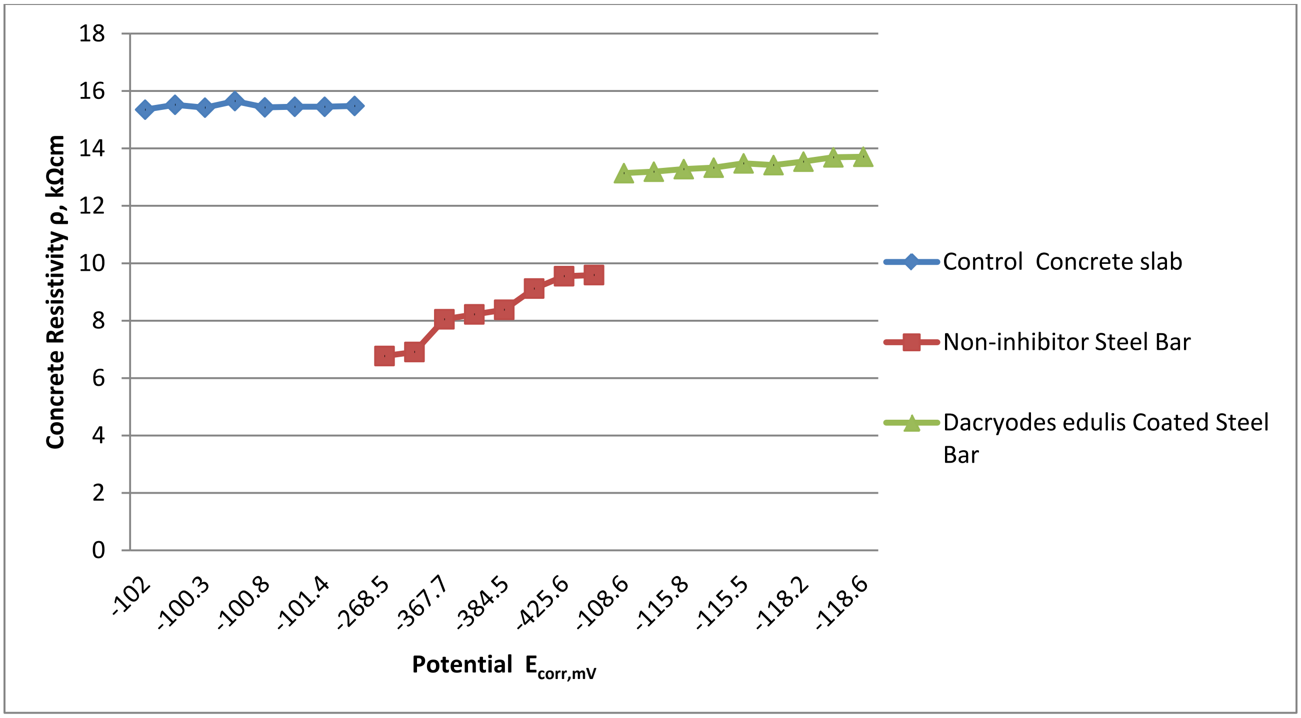

Figure 3.1: Concrete Resistivity versus Potential Relationship

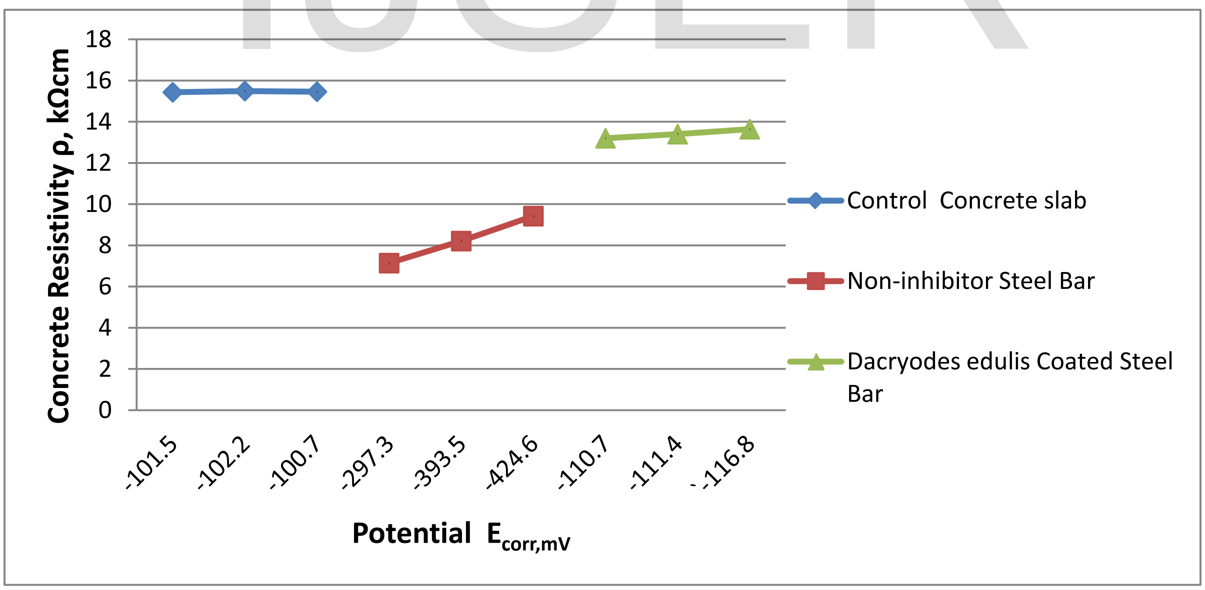

Figure 3.2: Average Concrete Resistivity versus Potential Relationship

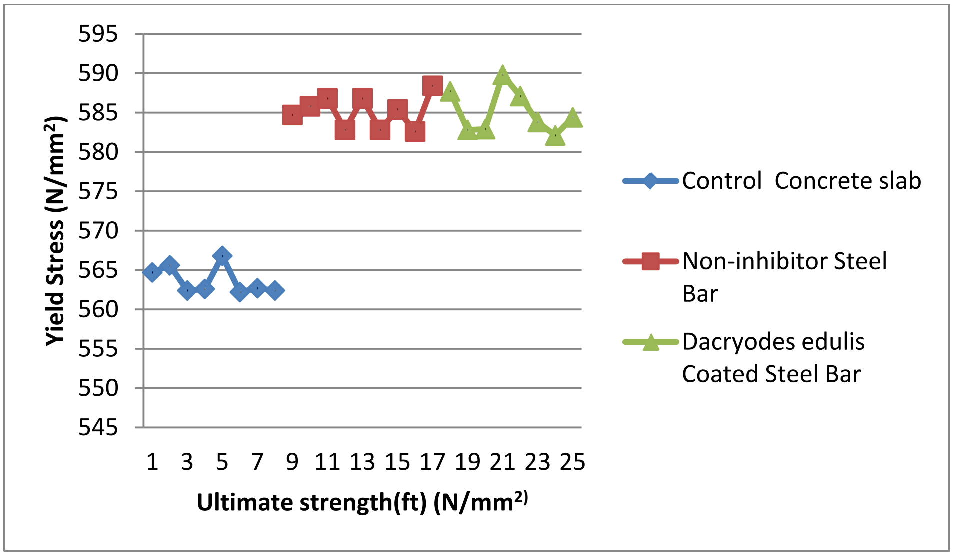

Figure 3.3: Yield Stress versus Ultimate strength.

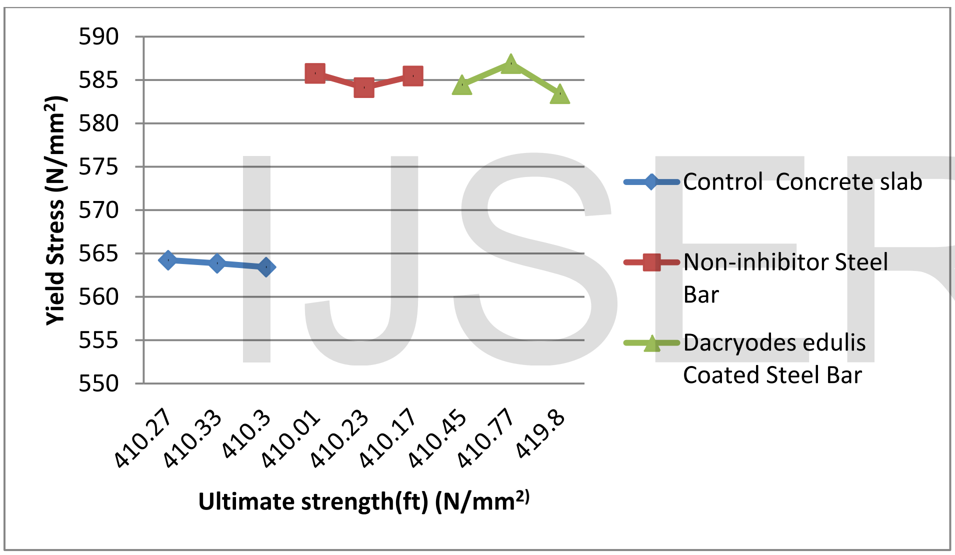

Figure 3.4: Average Yield Stress versus Ultimate strength.

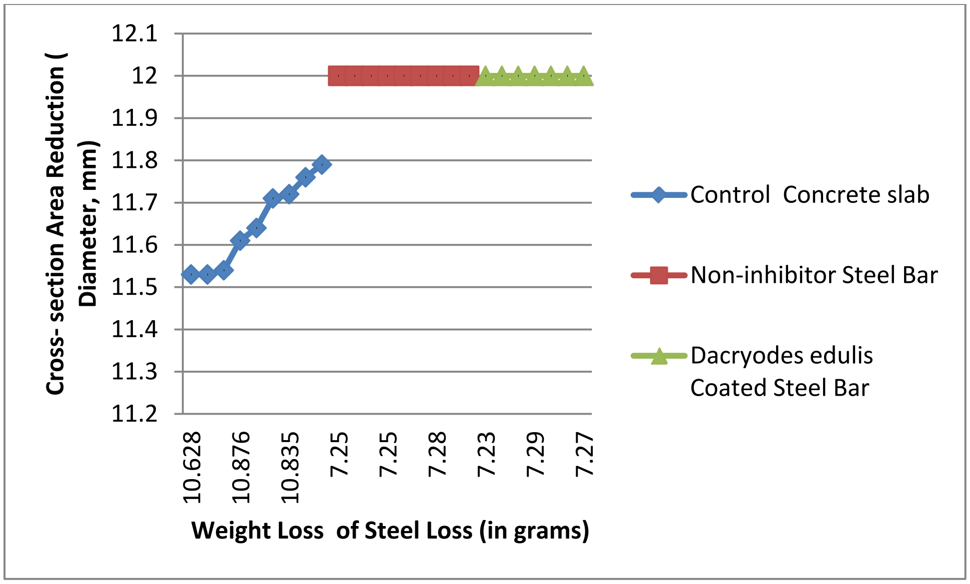

Figure 3.5: Weight Loss of Steel Loss versus Cross- section Area Reduction

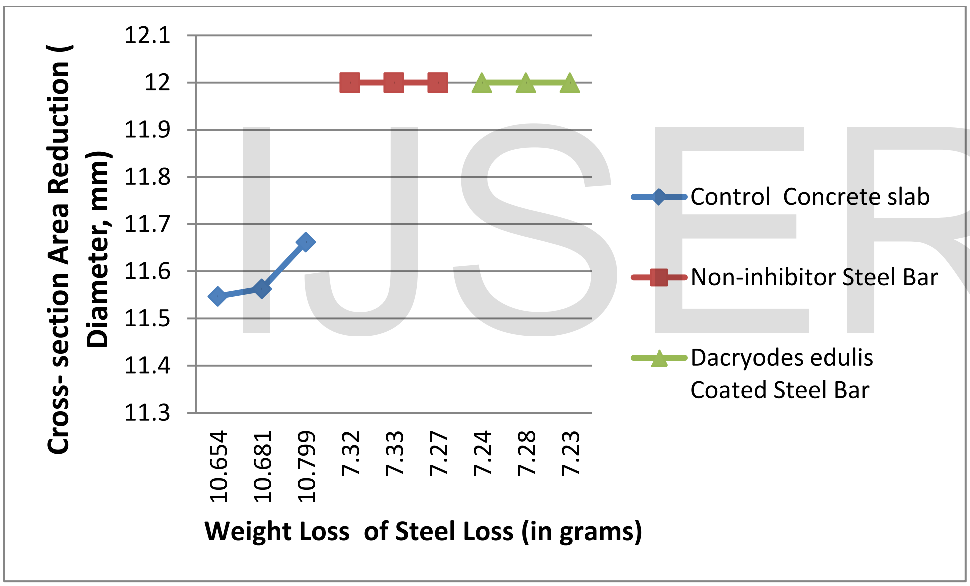

Figure 3.6: Average Weight Loss of Steel Loss versus Cross- section Area Reduction

4.0 Conclusion

Experimental results showed the following conclusions:

i. Assessment of the probability of corrosion in concrete slabs based on electrochemical test methods of the half-cell potential and the concrete resistivity methods and nondestructive was effective.

ii. Results justified the effect of corrosion on the strength capacity of corroded and coated members.

iii. Resins/ Exudates (inhibitors) did not add strength to investigated members but serves as protective coat.

iv. Surfaces changes was observed in uncoated member due to corrosion attack

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