Bond Strength Degradation of Reinforced Concrete Structures from Corrosion-Induced Acceleration

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ABSTRACT

The research work assesses the degradation of reinforcing steel of non-coated and exudate coated samples embedded in concrete structure and exposed to harsh environment of high salinity. The experimental tests were performed on 36 concrete cubes with the first sets of 12 controlled concrete samples placed in freshwater for 360 days, and the second sets of 24 cubes subdivide into 2 with 12 non-coated samples and 12 exudate/resin coated samples as described in the test procedures with a single reinforcing embedment and immersed in 5% sodium chloride (NaCl) aqueous solution for 360 days and accessed their performance and effectiveness with a routine for three months in 90 days, 180 days, 270 days and 360 days intervals. Comparatively, the maximum computed differential values for failure bond load of controlled sample is 89.247% against values of corroded -46.253% and coated 98.1184%. Results showed that corroded samples showed declined and reduced values with failure lower failure load on the application as compared to both controlled and coated samples with incremental values and higher load failure applications. Computed obtained results indicated the lower failure bond strength in corroded samples with declined and decreased values compared to controlled and coated samples with recorded higher failure bond strength and increased values, both having a close range of values over corroded samples. Results of peak percentile maximum slip values of the controlled sample are 31.319% as against corroded with -13.529% and coated 27.127%. Comparatively, corroded samples have highly declined and decreased value judging from the reference value range failed at lower load application whereas controlled and coated samples exhibited incremental values and recorded higher failure values on load applications. In Figures 3 and 6b, it can be seen from the diameter of the reinforcement that the diameter of the non-coated reinforcement is reduced by a maximum value of (-0.595% and coated increased by 0.658%, for the cross-sectional area, corroded has maximum reduction value of -13.251% and coated increased by 15.275%, weight loss and gain are corroded -26.853% decreased (loss) and coated 46.489% increase (gain).

Key Words: Corrosion, Corrosion inhibitors, Pull-out Bond Strength, Concrete and Steel Reinforcement

1.0 Introduction

Reinforced concrete is an important component of the construction industry, in addition to the cheaper structural elements of the combination of the two materials, the alkalinity of the concrete has a natural protective effect on the steel surface, which prevents corrosion of the steel as much as possible. Environmental conditions include the entry of chlorides (e.g. from de-icing salts or seawater) and the carbonation of concrete. This protective effect may fail; however, the temporal quantification of these processes to assess the life of reinforced concrete structures is an important task in the planning stages of the new building and the repair of existing ones. Steel reinforcement corrosion in reinforced concrete is one of the major issues affecting the structures and infrastructures of the world and especially of coastal areas. De Groot et al. [1] stated that the bonding zone element contact surface between the steel bar and the concrete is formed by a material frame representing the special properties of the bond-zone Khalfallah [2]). Adequate bonding between reinforcing bars and concrete is essential for the satisfactory performance of reinforced concrete structures. In the absence of sufficient bond strength, effective beam action, as required by codes of practice, cannot be achieved, and hence, the specified design equations are no longer valid. Loss of strain compatibility at the depth of a reinforcement results in a redistribution of stresses in the reinforced concrete element, which may lead to excessive service deflections and altered load capacities (Yuxi et al. [3]). One way to evaluate the steel–concrete bond is to investigate the bond stress–slip evolution generally obtained through classical pull-out tests (RILEM [4]). Even if these tests are not totally satisfactory due to boundary conditions or stress state (Tastani and Pantazopulou [5] and replaced by other experimental setups (direct tension-pullout bond test, they remain the most convenient and simplest experiment to achieve a global estimation of the bond effect. The main characteristics of the bond stress–slip evolution and especially the maximum bond stress are found to be clearly dependent on material, geometrical or loading parameters. The positive effect of the spacing and height of ribs was investigated by Hamad [6] and Castel et al. [7]. The confinement was defined as one of the key parameters which influenced the value of the maximum bond stress. This point is of great concern especially in the case of structures which are reinforced with stirrups or submitted to a tri-axial state of stress (La Borderie and Pijaudier-Cabot [8] and Malvar [9].

Charles et al [10] studied the effect of olibanum exudate/resin in curbing the corrosion tendency of reinforcing steel in the coastal zones with the impact of saltwater on concrete structures. Tests have shown that non-coated specimens are depleted and showed deterioration. The mean percentile bond strength load was 31.33% compared to the control difference and coated members of 45.66% and 71.84%. The mean maximum slip values are 0.083 mm and represented 33.87% and 75.30% compared to control and coated -25.30%. The test results reviewed that the depleted models had low bond strength and high failure bond load and low maximum slip, whereas exudate/resin coated models had lower experimental models have shown that exudates/resin members have higher percentage values compared to corroded samples.

Chung et al. [11] investigated by examining the effects of corrosion on bond strength and duration of development. Different degrees of corrosion were used to prepare reinforced concrete samples of the same reinforcement bar and were used to evaluate the effect of the corrosion rate on the bond pressure and the development length of the members of the tension. It was concluded that the average bond pressure would increase before the rust level reached.

Mansoor and Zahang [12] studied the influence of rust reinforcement on the bond using two different concrete strengths. Their research found that the exposed bar affected the corrosion rate, bond strength was reduced by about 16% while the corrosion rate increased to 2%. In addition, the corrosion rate of the high-strength concrete steel was lower than the lowest concrete strength possible attributed to minor restorations and internal concrete installations.

Yalciner et al. [13] studied the effect of corroded reinforcement on bond strength. Their study was designed to use different concrete strengths (23 and 51 N / mm2) with three different concrete holes (15mm, 30mm, and 45mm). It was observed that the bond strength of the control specimens (unchanged) was increased by increasing the compressive strength and the depth of the concrete. In addition, they concluded that the results of a variety of high-strength concrete and steel-reinforced concrete and sub-concrete showed a high percentage of collapsed bond strength due to the fracture of the concrete during the casting test.

Charles et al. [14] investigated the fundamental reasons for the decreased service life, integrity, and efficiency of reinforced concrete structures in the marine environment of saline origin. The results obtained of failure bond load, bond strength and maximum slip decreased to 21.30%, 38.80% and 32.00%, respectively, for non-coated specimens 51.69%, 66.90%, 74.65%, coated specimens 27.08%, 55.90% and 47.14%, respectively. This justifies the effect of corrosion on the strength capacity of corroded and coated members.

Tepfers [15] stated that although a bar slip is not detected, a certain displacement occurs at this stage. This displacement is due to localized strains, which are the result of high localization stresses close to the interface. Tepfers reported that the relative displacement of the bar at this stage for the sake of it has a relative slip Shear deformation at the interface and the concrete.

Charles et al. [16] investigated the effect of decreased reinforcement on the stress produced by pull-out bond separation of corroded, corrugated and resins/exudates paste coated steel bar. Failure loads of Symphonia globulifera Linn, ficus glumosa, accordium occidental L. Bond strength decreased by 21.30%, bond strength by 64.00%, 62.40%, 66.90 by 38.88%, and maximum slip by 89.30%, respectively. The overall results showed that the values increased compared to the coating Corroded models that lead to adhesion properties from resins/exudates also increase strength and serves as a protective coat against reinforcement and corrosion.

Rasheeduzzafar et al. [17] based on their field and laboratory results, recommended for the following cover Structures operating in different climates of the Arabian Gulf: i. Salt-laden building blocks permanently exposed to corrosive weather ii. Building parts protected from the aggressive conditions of weather and exposure: 1.0 to 1.5 iii. Concrete parts exposed to seawater and pavements and other major structural members are laid against. This study examines the effect of reinforcement corrosion and inhibition on bonding and eliciting efficiency significant changes in the strength of the corroded and coated steel reinforcement and the surface conditions of the steel.

Joop and Bigaj [18] stated that the displacement of the bar is related to the slip of the concrete Crushing the concrete in front of the ribs causes carbs and vibration. The stresses surrounding the tensile forces of the restriction action are exceeded. According to the crack structure, the section of concrete cracks around the bar is in a plastic condition, while the rest of the unoccupied concrete is inelastic condition. As the cracks spread, the plastic area continues to expand radially.

Abosra et al. [19] evaluate the corrosion effect of embedded steel in different compressed concrete. They observed that bond strength is affected by corrosion levels and found that the bond strength decreased when the exposure time increased to 7 days. Many researchers are continuing to investigate the effect of corrosion on bond strength by using different methods

Toscanini et al. [20] appraised the presence of chloride and carbonation contamination in marine zones of the Niger Delta, Nigeria, are the main reasons for the lack of bonding between steel reinforcement and concrete, leading to premature deterioration in reinforced concrete structures in rough weather. Steel bars of 150μm, 300μm, and 450μm thickness were embedded in coated and concrete cubes, treated in fast corrosive medium, and investigated pull-out bond strength parameters against non-coated. Relatively, the results of corroded specimens decreased when control and cola accuminata exudates/resins were increased in steel bar coating samples. The overall results showed that natural exudates/resins should be explored as inhibitors for the corrosion effects of steel reinforcement in concrete construction in the following places.

Charles et al. [21] studied the strengthening of bond strength of steel and reinforced concrete structures using corroded and khaya senegalensis for exudates/resins coated samples. The results of the failure bond loads showed a difference of -43.62% and 77.37% and 79.67% for corrosive and coated exudates/resin members, respectively. Reduced mean percentage bond strength load varies from 57.06% to 36.33% and 106.57% in corroded and coated samples. The results obtained showed that bonding loads were higher for corroded than for exudates/adhesive coated members of the corrosive sample. The binding strength of the corroded and coated specimens showed a higher affinity for strain compared to corroded members.

Charles et al. [22] investigated the effect of exudates/resins in the curb of corrosion attack on the bond strength between steel and concrete. Non-coated and exudates/resins coated samples of varying thickness were embedded in concrete and pooled for 178 days corrosion acceleration process. Comparable results showed that the values of the corrosive samples are reduced, but the non-corrosive and exudates/resins coated members are increased, which indicates the ability of acacia senegal exudates/resins in reinforcing steel coating. Overall results showed high values of pull-out bond strength and low failure load in the control and were coated over the corroded samples.

Charles et al. [23] investigated the effect of Acacia Senegal exudates/resins paste coated and non-coated steel embedded in a concrete cube and accelerated in sodium chloride (NaCl) solution for 178 days. In comparison, the values of the corroded samples are reduced, but they are constrained and the exudates/resins coated members increase, indicating the potential of

Acacia Senegal. The overall results of the steel-exudates / resins showed high values of the pull-out bond strength and control and low failure load in the coated specimens.

Terence et al. [24] examined the effect of corrosion inhibitors on coated reinforcing steel under accelerated process examination of failure bond strength of embedded steel for 150days. Comparatively, the results of the corroded samples are reduced and the exudates coated samples r control samples increased. The overall results showed higher values of pull-out bond strength in the control and exudates/resin coated members as against corroded samples.

Gede et al. [25] studied the factors that led to a reduction in the bonding between reinforcing steel and concrete within the saline environment of the Niger Delta region. An examination of non-coated and exudates/resin extracts from artocarpus altilis with a coating thickness of 150µm, 300µm, and 450µm were immersed in a concrete cube, pooled for 150 days in corrosive media to ascertain their effects. Comparative results showed that the values of the non-coated (corroded) specimens decreased and the exudates/resin coating samples increased. Overall results showed high values of controlled pull-out bond strength and coated exudates/resin over corroded specimen.

2.0 Test program

The research examined the utility of exudates/resin paste as inhibitive material against corrosion attacks on reinforcing steel embedded in concrete structures and exposed to the coastal marine region with high concentrations of salt. Extracted exudate/resin from the trunk of the plant was coated with reinforcing steel with varying thicknesses and embedded into the concrete cubes and with the introduction of corrosion acceleration process of sodium chloride (NaCl) into the environment as to determine the feasibility of using environmentally friendly and widely available materials to control the effects of modification change, usually encountered by concrete structures at sea. The test specimen represents the level of hard acidic, indicating the level of concentration of sea salt in the marine atmosphere in reinforced concrete structures. The embedded reinforcement steel is completely submerged and the samples for the corrosion acceleration process are maintained in the pooling tank. These samples were designed with 36 reinforced concrete cubes of dimensions 150 mm × 150 mm x 150 mm, centered 12 mm in diameter for pullout bond testing, and immersed in sodium chloride for 360 days after initial cube treatment for 28 days. Acidic corrosive media solutions were modified monthly and solid samples were reviewed for examination on high performance and changes.

2.1 Materials and Methods for Testing

2.1.1 Aggregate

Aggregates (fine and coarse) were purchased. Both met the requirements of BS882 [26]

2.1.2 Cement

Portland Lime Cement Grade 42.5 is the most common type of cement in the Nigerian market. It was used for all concrete mixes in this test. It meets the requirements of cement (BS EN 196-6[27])

2.1.3 Water

The water samples were clean and free of impurities. The freshwater was obtained from the Civil Engineering Laboratory, Beeson Kenule Saro-Wiwa Polytechnic, Bori, Rivers State. Water met (BS3148 [28]) requirements

2.1.4 Structural Steel Reinforcement

Reinforcements are obtained directly from the market at Port Harcourt, (BS4449: 2005 + A3 [29])

2.1.5 Corrosion Inhibitors (Resins / Exudates) Lannea coromandelica

The light - dark brown exudates are obtained from wounded tree trunk. Exudates are liquid nature but changes to solid states with time. They are obtained from Aba Adetipe in Ife North Local Government Area of Osun sate, Nigeria.

2.2 Test procedures

Corrosion acceleration was tested on high-yielding steel (reinforcement) with a diameter of 12 mm and a length of 650 mm. Glue with coatings 150µm, 300µm, 450µm and 600µm before corrosion testing. The test cubes were coated with a 150 mm x 150 mm x 150 mm metal mold and removed after 72 hours. The samples were treated at room temperature in the tank for 28 days before the initial treatment period, followed by rapid acceleration corrosion testing and a 360-day monthly routine monitoring by trial rule. Cubes for corrosion-acceleration samples were taken at approximately 90-month, 180-day, 270-day, and 360-day intervals of approximately 3 months, and failure bond loads, bond strength, maximum slip, cross/section area decrease/increase, and weight loss/steel reinforcement is sought.

2.3 Accelerated Corrosion Setting and Testing Method

In real and natural phenomena, the expression of corrosion effects on reinforcement embedded in concrete members is very slow and can take many years to achieve; but the laboratory-accelerated process will take less time to accelerate the marine media. Immersion for 360 days in 5% NaCl solution, to test the surface and mechanical properties of the reinforcing steel and effects on both non-coating and exudate/resin coated samples.

4.4 Pull-out Bond Strength Test

The stress-binding strength test of the concrete cube was performed on a total of 36 samples with control, uncoated, and coated members in each of the 12 samples, and 50 kN according to BSEN12390 [30]. The universal test was subject to the machine. 2. A Total number of 36 cubes measuring 150 mm × 150 mm × 150 mm were designed and 12 mm diameter of reinforcing steel embedded in the center of a concrete cube.

2.5 Tensile Strength of Reinforcement Bars

To determine the yield and tensile strength of the bar, 12 mm diameter controlled, uncoated, and coated steel reinforcement was tested under pressure on the Universal Test Machine (UTM) and subjected to direct pressure until the failure load was recorded. To ensure stability, the remaining cut pieces are used in subsequent bond testing and failure bond loads, bond strength, maximum slip, decrease/increase in cross-sectional area, and weight loss/steel reinforcement.

3.1 Experimental Results and Discussion

The relationship between concrete and the length of reinforcement development is very important for the bonding effect in reinforced concrete structures (Al-Zaid and Al-Negheimish, [31]; Ahmed et al., [32]). It is known that the use of deformed bars can greatly increase the steel-concrete bonding capacity. The three main components that determine the bond strength between adjacent ribs of reinforcement are shear stress due to adhesion to the surface of the bar, bearing stress to the ribs (mechanical interlock), and friction between the reinforcing ribs and the surrounding concrete. The interaction between the concrete and the reinforcing steel is expected to be perfectly warm to enable the exhibition of high bonding in the surrounding concrete structures. The harmful effects of corrosion attacks have caused many structures to be repaired and repaired for life. The experimental data presented in Tables 3.2, 3.2, and 3.3, summarized in tables 3.4 and 3.5 s were experimental tests performed on 36 concrete cubes with first sets of 12 controlled concrete samples placed in freshwater for 360 days, and second sets of 24 cubes subdivide into 2 with 12 non-coated samples and 12 exudate/resin coated samples as described in test procedures with a single reinforcing embedment and immersed in 5% sodium chloride (NaCl) aqueous solution for 360 days and accessed their performance and effectiveness with a routine for three months in 90 days, 180 days, 270 days and 360 days intervals. Indeed, the manifestation of corrosion is a long-term process that takes decades to fully work, but the introduction of sodium chloride causes the appearance of corrosion in a short period of time. The experimental work represents a suitable high-salt marine environment and the potential use of lannea coromandelica exudate/resin extract as a barrier to prevent corrosion and corrosion impact from the reinforced concrete structure exposed or built within this high salinity region.

Table 3.1: Results of Pull-out Bond Strength Test (τu) (MPa) of Non-corroded Control Cube Specimen

Sample Numbers	LCC	LCC1	LCC2	LCC3	LCC4	LCC5	LCC6	LCC7	LCC8	LCC9	LCC10	LCC11
	Time Interval after 28 days curing											
Samplin g and Durations	**Samples 1 (28 days)**			**Samples 2 (28 Days)**			**Samples 3 (28 Days)**			**Samples 4 (28 Days)**		
Failure Bond Loads (kN)	28.417	26.327	26.891	27.488	28.303	28.004	28.527	28.344	28.409	30.220	29.345	29.546
Bond strength (MPa)	9.399	10.292	8.789	9.720	10.092	11.016	11.109	10.439	10.473	11.179	10.491	11.037
Max. slip (mm)	0.106	0.109	0.110	0.119	0.109	0.113	0.112	0.102	0.108	0.109	0.110	0.101
Nominal Rebar Diameter	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000
Measured Rebar Diameter Before Test(mm)	12.027	12.037	12.027	12.026	12.027	12.037	12.026	12.037	12.037	12.037	12.036	12.027
Rebar Diameter- at 28 Days Nominal(mm)	12.027	12.037	12.027	12.026	12.027	12.037	12.026	12.037	12.037	12.037	12.036	12.027
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Rebar Weights- Before Test(Kg)	0.575	0.575	0.573	0.575	0.575	0.575	0.576	0.575	0.575	0.576	0.574	0.582
Rebar Weights- at 28 Days Nominal(Kg)	0.575	0.575	0.573	0.575	0.575	0.575	0.576	0.575	0.575	0.576	0.574	0.582
Weight Loss /Gain of Steel (Kg)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 3.2: Results of Pull-out Bond Strength Test (τu) (MPa) of Corroded Concrete Cube Specimens

Samplin g and Durations	**Samples 1 (90 days)**			**Samples 2 (180 Days)**			**Samples 3 (270 Days)**			**Samples 4 (360 Days)**		
Failure Bond Loads (kN)	16.218	15.530	15.820	15.263	14.511	15.378	14.957	15.265	14.963	16.198	15.077	15.811
Bond strength (MPa)	7.867	7.878	7.642	7.864	7.631	7.603	7.402	8.090	7.065	7.554	7.401	7.714
Max. slip (mm)	0.080	0.084	0.085	0.093	0.084	0.088	0.087	0.077	0.083	0.084	0.085	0.075
Nominal Rebar Diameter	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000
Measured Rebar Diameter Before Test(mm)	12.029	12.025	12.019	12.018	12.029	12.019	12.019	12.025	12.018	12.029	12.019	12.019
Rebar Diameter- After Corrosion(mm)	11.980	11.976	11.970	11.969	11.980	11.970	11.970	11.976	11.969	11.980	11.970	11.970
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049
Rebar Weights- Before Test(Kg)	0.579	0.575	0.574	0.583	0.579	0.577	0.577	0.576	0.579	0.576	0.575	0.577
Rebar Weights- After Corrosion(Kg)	0.534	0.532	0.535	0.536	0.535	0.535	0.534	0.541	0.533	0.533	0.536	0.534
Weight Loss /Gain of Steel (Kg)	0.045	0.043	0.040	0.047	0.044	0.042	0.043	0.035	0.046	0.043	0.039	0.043

Table 3.3: Results of Pull-out Bond Strength Test (τu) (MPa) of Lannea Coromandelica Exudate / Resin (Steel Bar Coated Specimen)

Samplin g and Durations	**Samples 1 (90 days)**			**Samples 2 (180 Days)**			**Samples 3 (270 Days)**			**Samples 4 (360 Days)**		
Sample	**150µm (Exudate/Resin) coated**			**300µm (Exudate/Resin) coated**			**450µm (Exudate/Resin) coated**			**600µm (Exudate/Resin) coated**		
Failure Bond Loads (kN)	30.706	28.617	29.181	29.777	30.592	30.293	30.817	30.634	30.699	32.510	31.634	31.836
Bond strength (MPa)	12.521	13.413	11.911	12.841	13.214	14.137	14.231	13.561	13.595	14.301	13.612	14.159
Max. slip (mm)	0.095	0.098	0.099	0.108	0.099	0.102	0.101	0.091	0.097	0.098	0.099	0.090
Nominal Rebar Diameter	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000
Measured Rebar Diameter Before Test(mm)	11.988	11.999	11.999	11.988	11.988	11.988	11.999	11.998	11.988	11.999	11.998	11.995
Rebar Diameter- After Corrosion(mm)	12.045	12.055	12.055	12.045	12.045	12.045	12.055	12.054	12.045	12.055	12.054	12.028
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.057	0.057	0.057	0.057	0.057	0.057	0.057	0.057	0.057	0.057	0.057	0.033
Rebar Weights- Before Test(Kg)	0.576	0.577	0.575	0.577	0.577	0.577	0.577	0.576	0.575	0.584	0.575	0.575
Rebar Weights- After Corrosion(Kg)	0.637	0.637	0.635	0.637	0.638	0.637	0.638	0.637	0.636	0.644	0.636	0.636

Weight Loss /Gain of Steel (Kg)	0.061	0.062	0.059	0.061	0.062	0.060	0.060	0.060	0.060	0.060	0.060	0.060

Table 3.4: Results of Average Pull-out Bond Strength Test (τu) (MPa) of Control, Corroded and Exudate/ Resin Coated Steel Bar

Sample	Non-Corroded Specimens Average Values				Corroded Specimens Average Values				Coated Specimens Average Values of 150µm, 300µm, 450µm, 6000µm)			
Failure load (KN)	27.212	27.931	28.427	29.704	15.856	15.050	15.062	15.696	29.501	29.192	29.850	30.221
Bond strength (MPa)	9.493	10.276	10.674	10.902	7.796	7.699	7.519	7.556	12.615	12.722	12.655	13.398
Max. slip (mm)	0.108	0.114	0.107	0.107	0.083	0.088	0.082	0.081	0.098	0.102	0.102	0.103
Nominal Rebar Diameter	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000
Measured Rebar Diameter Before Test(mm)	12.030	12.030	12.033	12.033	12.024	12.022	12.021	12.022	11.995	11.995	11.992	11.988
Rebar Diamete r- After Corrosion(mm)	12.030	12.030	12.033	12.033	11.975	11.973	11.972	11.973	12.052	12.052	12.048	12.045
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.000	0.000	0.000	0.000	0.049	0.049	0.049	0.049	0.057	0.057	0.057	0.057
Rebar Weights- Before Test(Kg)	0.574	0.575	0.575	0.577	0.576	0.580	0.577	0.576	0.576	0.576	0.576	0.577
Rebar Weights- After Corrosion(Kg)	0.574	0.575	0.575	0.577	0.534	0.535	0.536	0.535	0.636	0.637	0.637	0.637
Weight Loss /Gain of Steel (Kg)	0.000	0.000	0.000	0.000	0.043	0.044	0.041	0.042	0.061	0.061	0.061	0.061

Table 3.5: Results of Average Percentile Pull-out Bond Strength Test (τu) (MPa) of Control, Corroded and Exudate/ Resin Coated Steel Bar)

	Non-corroded Control Cube				**Corroded Cube Specimens**				**Exudate / Resin steel bar coated specimens**			
Failure load (KN)	71.617	85.586	88.734	89.247	-46.23	-48.44	-49.54	-48.06	86.058	93.960	98.184	92.544
Bond strength (MPa)	21.778	33.462	41.958	44.283	-38.20	-39.47	-40.58	-43.60	61.822	65.231	68.312	77.307
Max. slip (mm)	30.676	28.798	31.013	31.319	-15.16	-13.52	-19.78	-21.33	17.874	15.646	24.664	27.127
Nominal Rebar Diameter	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Measured Rebar Diameter Before Test(mm)	0.247	0.266	0.257	0.243	0.243	0.223	0.241	0.284	0.243	0.223	0.240	0.283
Rebar Diamete r- After Corrosion(mm)	0.457	0.475	0.516	0.504	-0.634	-0.654	-0.637	-0.595	0.638	0.658	0.641	0.599
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.000	0.000	0.000	0.000	-13.25	-13.25	-13.25	-13.25	15.275	15.275	15.275	15.275
Rebar Weights- Before Test(Kg)	0.365	0.368	0.381	0.374	0.035	0.342	0.374	0.387	0.335	0.338	0.373	0.387
Rebar Weights- After Corrosion(Kg)	7.591	7.396	7.295	7.951	-16.15	-15.88	-15.83	-16.13	19.269	18.883	18.769	19.233

Weight Loss /Gain of Steel (Kg)	0.000	0.000	0.000	0.000	-29.89	-26.85	-31.73	-31.19	42.488	36.712	46.489	45.346

3.2 Failure load, Bond Strength, and Maximum slip

Adequate alignment between the reinforcing bars and the concrete is essential for the efficient operation of the reinforced concrete structures. In the absence of sufficient bond strength, the active reinforced concrete structures, as required by the design codes and standard will not be achieved, therefore, the design parameter is no longer valid. Loss of coherence in the depth of the rigidity leads to redistribution of pressure on the reinforced concrete material, which can lead to excessive deviation of services and changes in load capacity (Zhao et al., [33]). The negative effects encountered by reinforcing steel embedded in concrete exposed to corrosive media can be reduced or curb down with the introduction of anti-corrosion materials of exudates/resins extract obtained from extruded tree trunks and coated to the steel bar and investigative their behavioral characteristics.

The results of failure bond loads, bond strength, and maximum slip were carried out on 36 concrete cubes, as shown in tables 3.1, 3.2, and 3.3, average in 3.4 and percentile summarized in 3.5, graphically plotted in figures 1 - 6b. The results obtained refer to 12 controlled, 12 corroded and 12 coated samples tested to failure using Instron Universal Testing Machines at 50 kN as described in the test procedure.

The minimum and maximum calculated average and percentile values obtained from the failure bond load of controlled samples are controlled 27.212 kN and 29.704 kN representing percentile values of 71.617% and 89.247%, the corroded samples are 15.05 kN and 15.856 kN with percentile values of -49.542% and -46.253% and coated with 29.192 kN and 30.221 kN with percentile values of 86.058% and 98.1184%).

The bond strength values of controlled samples are 9.493 MPa and 10.902 MPa with percentile values 21.778% and 44.283%), the corroded are 7.519 MPa and 7.796 MPa representing percentile values of -43.601% and -38.204%), coated values are 12.615 MPa and 13.398 MPa having percentile of 61.822% and 77.307%). The maximum slip results obtained of controlled samples are 0.107 mm and 0.114 mm and percentile values of 28.798% and 31.319%), corroded samples values are 0.081 mm and 0.088 mm with percentile values of -21.339% and -13.529%), while coated sample values are 0.098 mm and 0.103 mm with percentile values of 15.646% and 27.127%.

Comparatively, the maximum computed differential values for failure bond load of controlled sample is 89.247% against values of corroded -46.253% and coated 98.1184%. Results showed that corroded samples showed declined and reduced values with failure lower failure load on the application as compared to both controlled and coated samples with incremental values and higher load failure applications. The effect of corrosion might have led to the decline in percentile values resulting from surface modification and effect of the reinforcing steel fibre.

The maximum percentile values of bond strength comparison are controlled 44.283% against corroded -38.204% and coated 77.307%. Computed obtained results indicated the lower failure bond strength in corroded samples with declined and decreased values compared to controlled and coated samples with recorded higher failure bond strength and increased values, both having a close range of values over corroded samples.

Results of peak percentile maximum slip values of the controlled sample are 31.319% as against corroded with -13.529% and coated 27.127%. Comparatively, corroded samples have highly declined and decreased value judging from the reference value range failed at lower load application whereas controlled and coated samples exhibited incremental values and recorded higher failure values on load applications as validated in the works of (Charles et al., [10]; Charles et al., [14]; Gede et al., [25]; Terence et al.,[24])

The lower failure loads recorded in corroded samples are attributed to corrosion attack on the reinforcing steel with high surface modifications and lower bonding interaction between concrete and reinforcing steel.

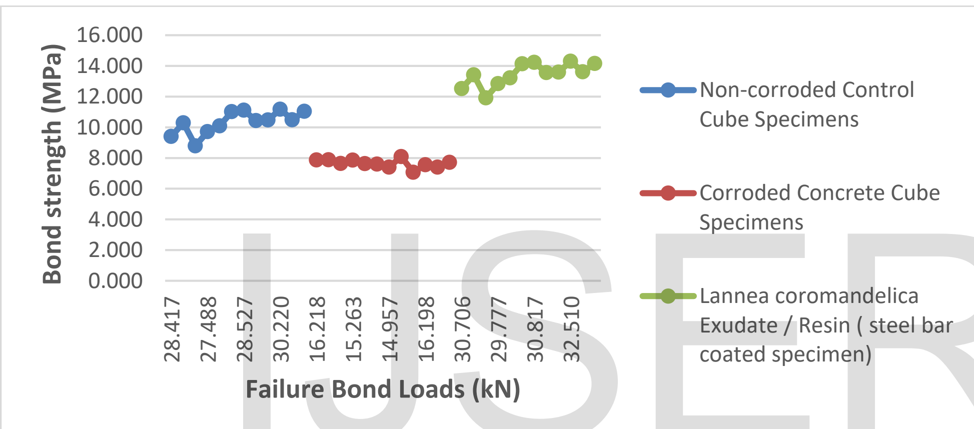

Figure 1. Failure Bond loads versus Bond Strengths

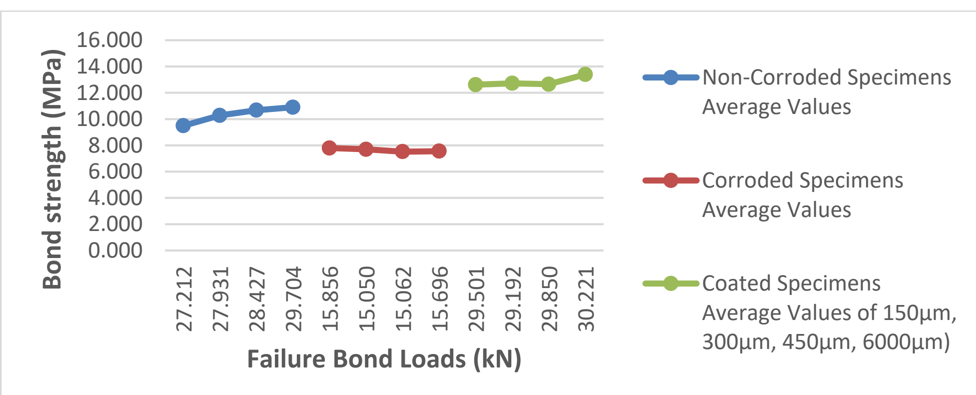

Figure 1a. Average Failure Bond loads versus Bond Strengths

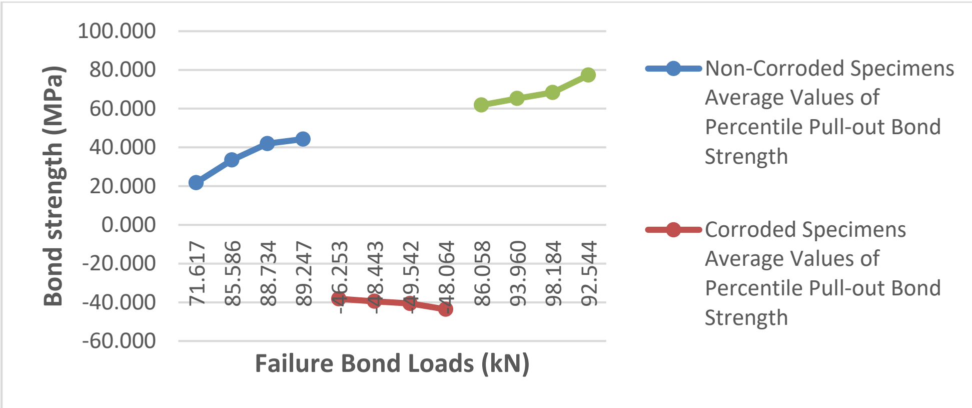

Figure 1b. Average Percentile Failure Bond loads versus Bond Strengths

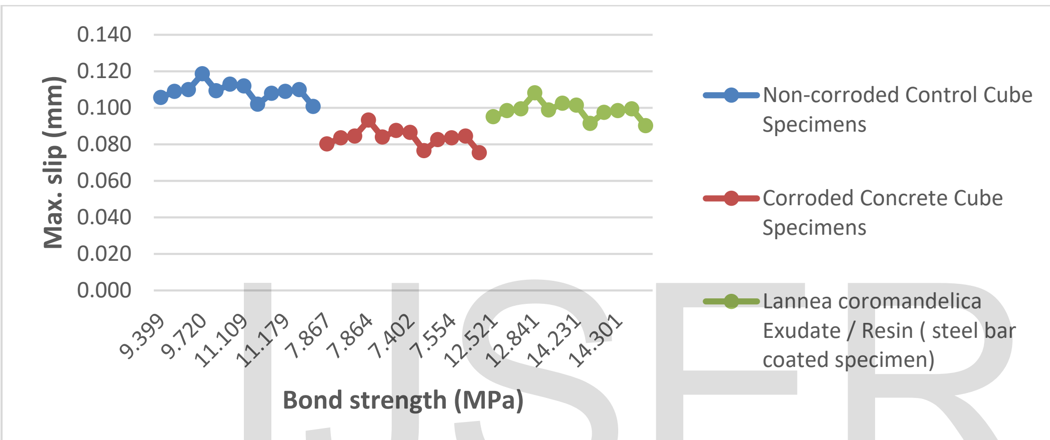

Figure 2. Bond Strengths versus Maximum Slip

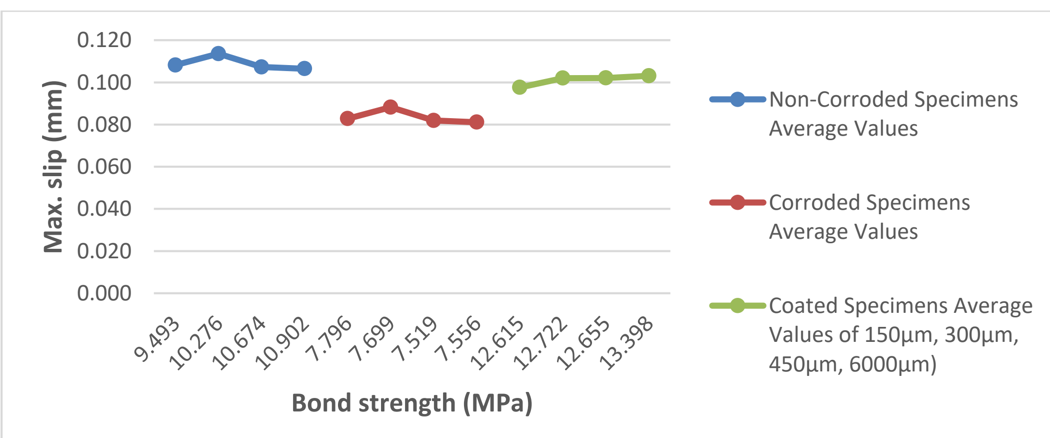

Figure 2a. Average Bond Strengths versus Maximum Slip

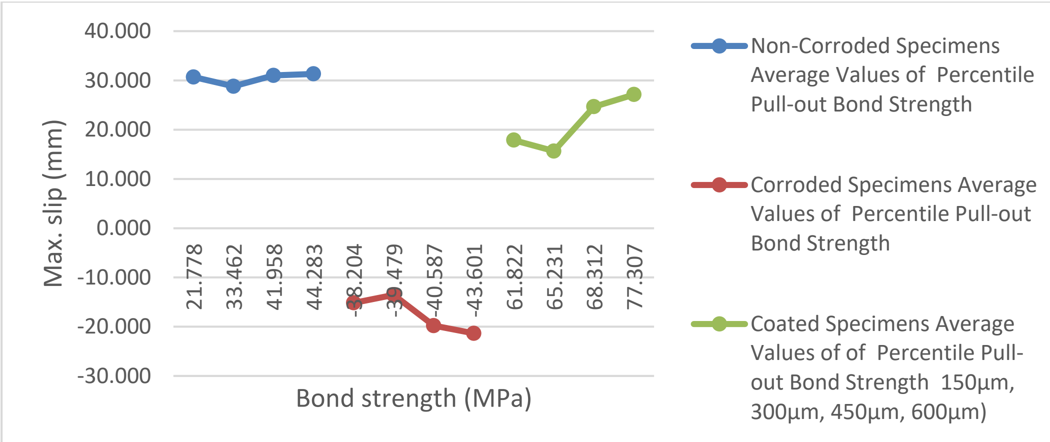

Figure 2b. Average Percentile Bond Strengths versus Maximum Slip

3.3 Mechanical Properties of Reinforcing Bars

Corrosion of reinforced steel causes a reduction in the cross-sectional area of the steel bar and the accumulation of corrosion products, which in turn reduces the ductility and strength of the steel. Corrosion products occupy a volume 2 to 6 times greater than original reinforcing steel (Liu and Weyers, 1998). The initial corrosion products around the surface of the steel bar cause longitudinal cracking, hatching, and delamination of the concrete shell. The loss of the concrete layer, in turn, causes the loss of enclosed space by reducing the strength of the joints in the intermediate zone between the steel and the concrete. The soft layer obtained from the corrosion products accumulated on the surface of the rods succeeded in reducing the friction component of the bond strength. In this way, the rib damage from the deformed beam reduces the blocking force between the ribs and the surrounding concrete structure. This affects the basic mechanism of adhesion between deformed rods and concrete, thereby significantly reducing adhesion. The adhesive strength is mainly due to the weak chemical bond between the steel and hardened concrete, but this strength is destroyed at low pressure. Immediately after slipping, friction aids in binding with a fine steel bar, friction is an important part of strength. This study introduces the use of lannea coromandelica exudates/resins to increase the slip problem in plain and low rib reinforcing steel bonding with concrete and also to curb the scourge effects of corrosion attack to reinforcing steel in the high salinity coastal region.

The data presented in Tables 3.1, 3.2, and 3.3 and collapsed in Table 3.4 and summarized in 3.5 and plotted in figures 1-6, accounted for the behavioral mechanical properties of the controlled, uncoated (corroded) and coated concrete e cube samples exposed to freshwaters for the controlled and in 5% sodium chloride aqueous solution for non-coated and coated samples for 360 days period and routinely monitored and tested to failure using Instron Universal Testing Machine and ascertained surface modifications at 90 days, 180 days, 270 days and 360 days.

The nominal diameter of steel rods for all samples was 100% and the minimum and maximum steel bar diameters measured before the test were in the range of 12.03 mm and 12.033 mm with percentile values of 0.243% and 0.266%, after the corrosion test, obtained values are 11.972 mm and 11.975 mm, representing percentile values of -0.654% and -0.595%), after coating, computed diameter is 12.045 mm and 12.052 mm representing percentile values of 0.599% and 0.658%. The results of the cross-sectional area for uncoated (corroded) are 0.049 mm and 0.049 mm with percentile values of -13.251% and -13.251%, for the coated samples are 0.057 mm and 0.057 mm with percentile values of 15.275% and 15.275%.

The results of the weight of reinforcement before testing for all samples are 0.574 kg and 0.577 kg denoting percentile values 0.365% and 0.381%, the weight after the corrosion test is 0.534 kg and 0.536 kg denoting percentile values of -16.156% and -15.803%, the coated samples are 0.636 kg and 0.637 kg with percentile values of 18.769% and 19.269% and weight loss /gain of steel are corroded 0.041 Kg and 0.044Kg with percentile values of -31.736% and -26.853% and coated values are 0.061Kg and 0.061Kg with percentile values of 36.712% and 46.489%.

From the results obtained and shown in the figure, the effects of corrosion on uncoated and coated reinforcing steel are noted; In Figures 3 and 6b, it can be seen from the diameter of the reinforcement that the diameter of the non-coated reinforcement is reduced by a maximum value of (-0.595% and coated increased by 0.658%, for the cross-sectional area, corroded has maximum reduction value of -13.251% and coated increased by 15.275%, weight loss and gain are corroded -26.853% decreased (loss) and coated 46.489% increase (gain). Observed signs showed that the effect of corrosion on concrete cubes without coating causes a decrease in cross-sectional area and rebar diameter as well as unit weight reduction. The cross-sectional diameter and cross-sectional area as well as the increase in weight by varying the thickness coated with reinforcing steel were noticed from coated samples as validated in the works of (Charles et al., [10]; Charles et al., [14]; Gede et al., [25]; Terence et al.,[24]). Exudate/resin proved to be an inhibitory material in curbing the damaging effects caused by corrosion attack on reinforced concrete structures built and exposed to coastal marine environment with severe weather.

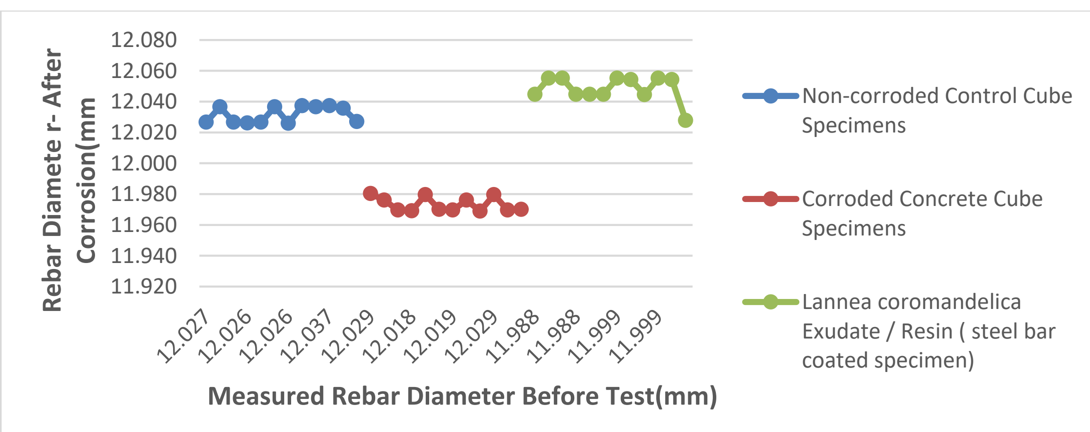

Figure 3. Measured (Rebar Diameter before Test vs Rebar Diameter- after Corrosion)

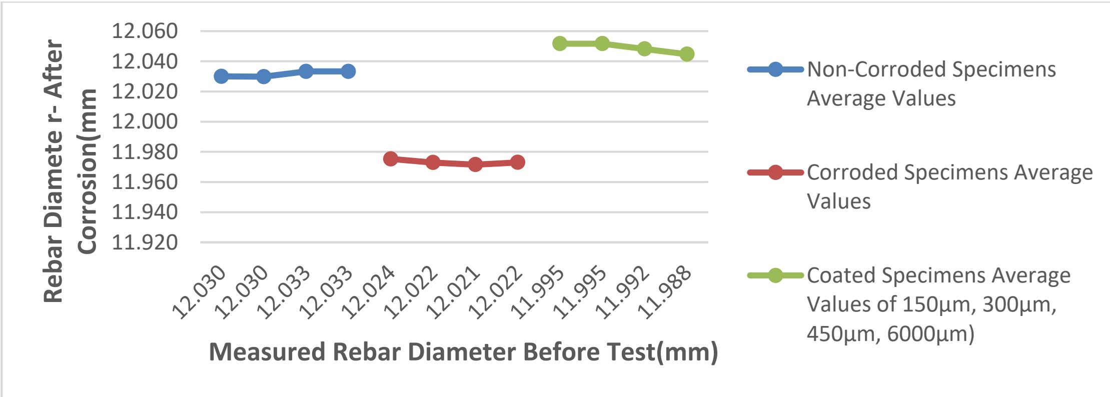

Figure 3a. Average Measured (Rebar Diameter before Test vs Rebar Diameter- after Corrosion

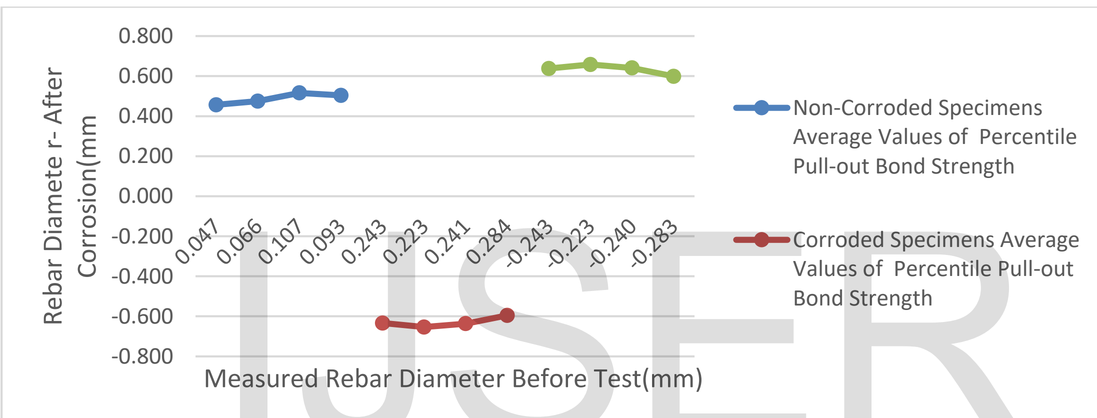

Figure 3b. Average Percentile Measured (Rebar Diameter before Test vs Rebar Diameter- after Corrosion

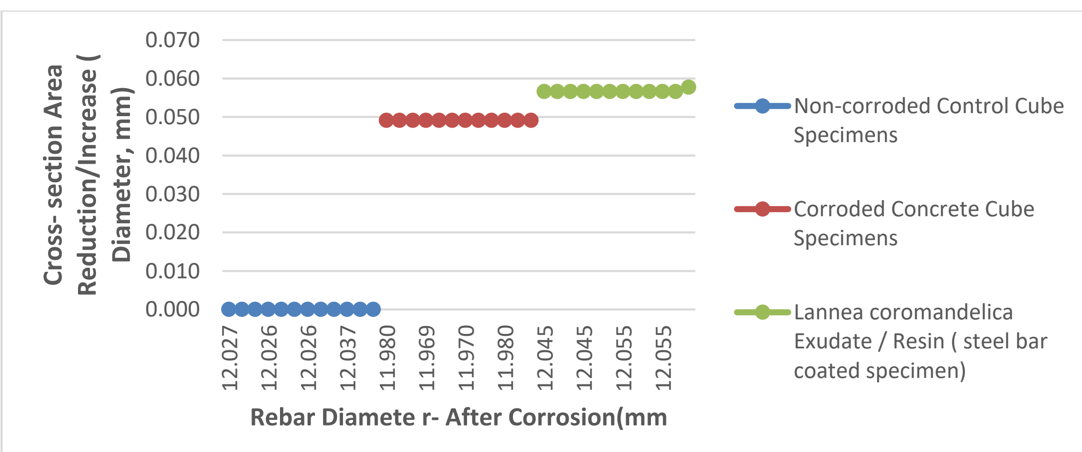

Figure 4. Rebar Diameter- After Corrosion versus Cross - Sectional Area Reduction/Increase

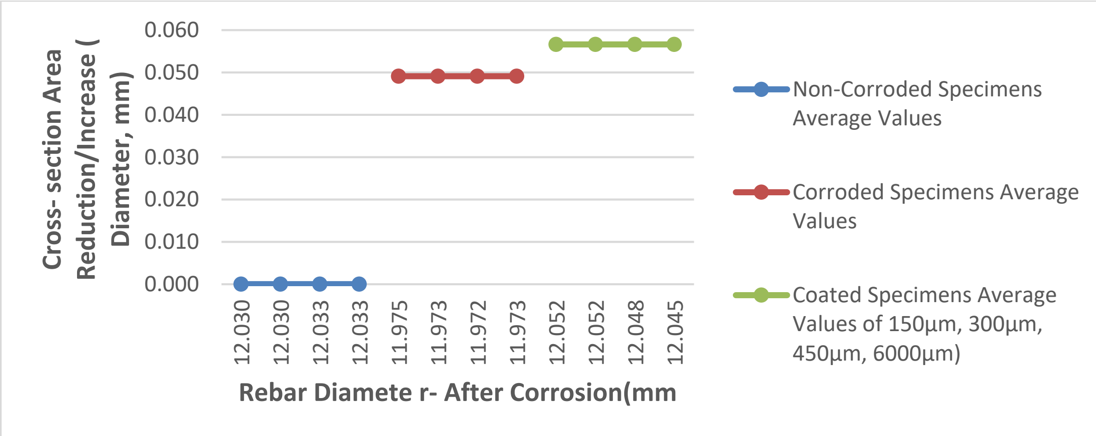

Figure 4a. Average Rebar Diameter- after Corrosion versus Cross – Sectional Area Reduction/Increase

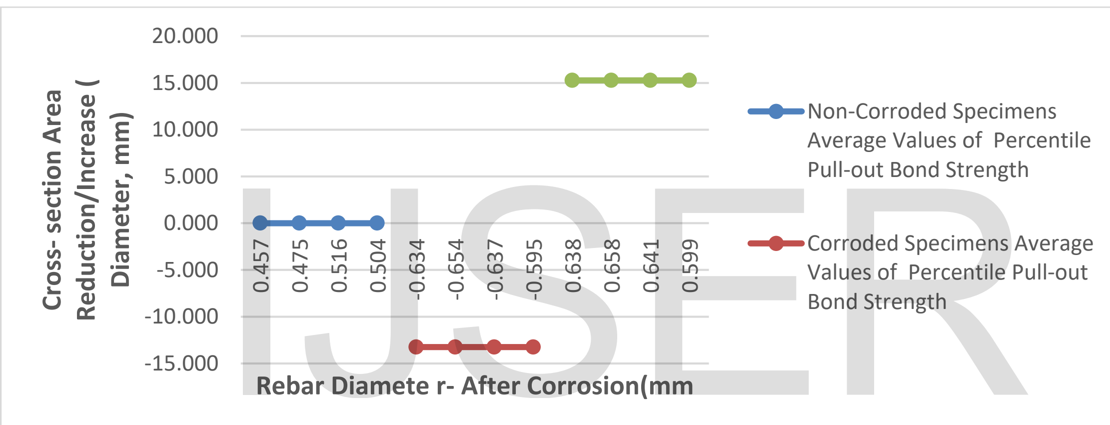

Figure 4b. Average percentile Rebar Diameter- after Corrosion versus Cross - sectional Area Reduction/Increase

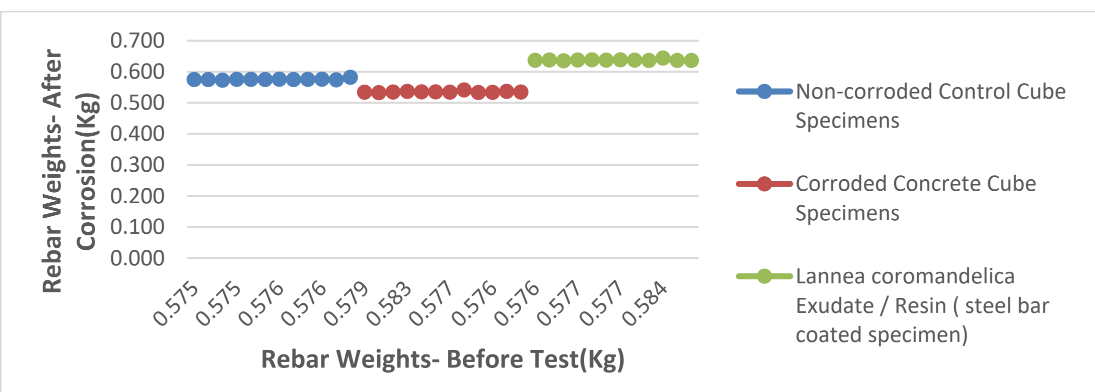

Figure 5. Rebar Weights- before Test versus Rebar Weights- after Corrosion

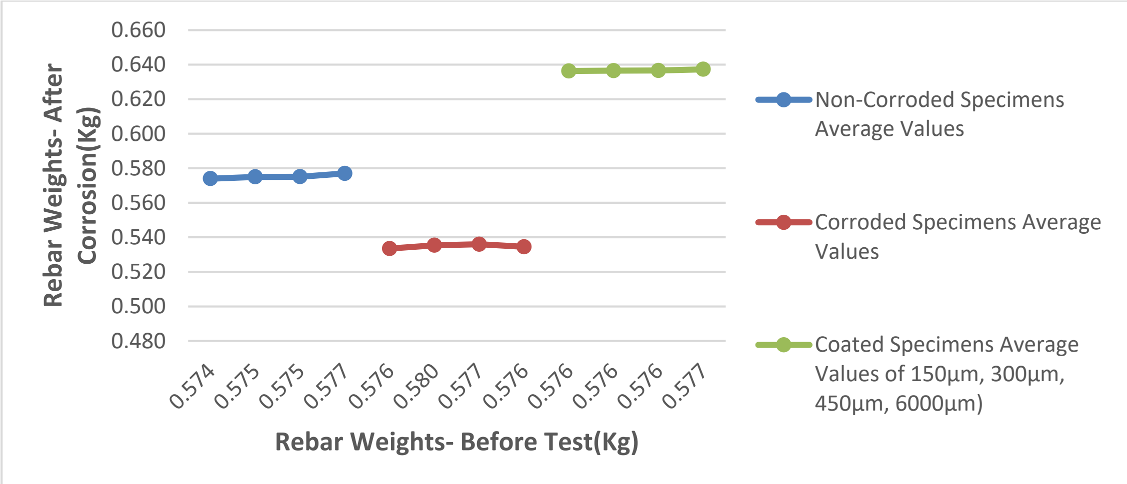

Figure 5a. Average Rebar Weights- before Test versus Rebar Weights- after Corrosion

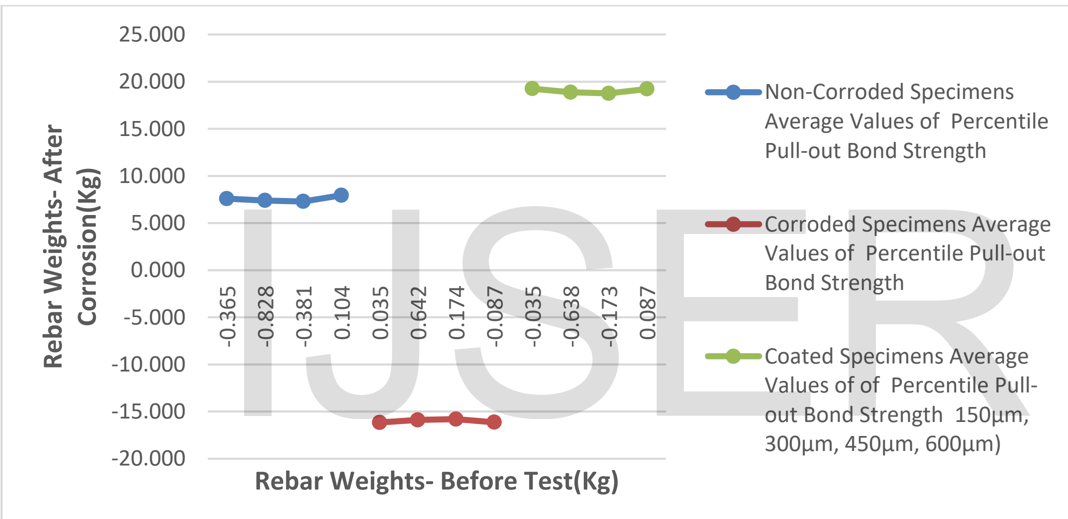

Figure 5b. Average Percentile Rebar Weights- before Test versus Rebar Weights- after Corrosion

Figure 6. Rebar Weights- after Corrosion versus Weight Loss /Gain of Steel

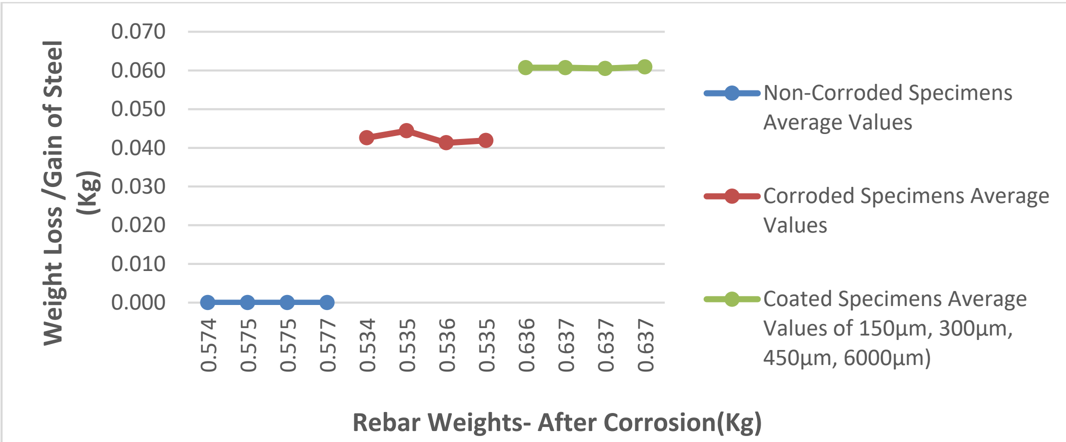

Figure 6a. Average Rebar Weights- after Corrosion versus Weight Loss /Gain of Steel

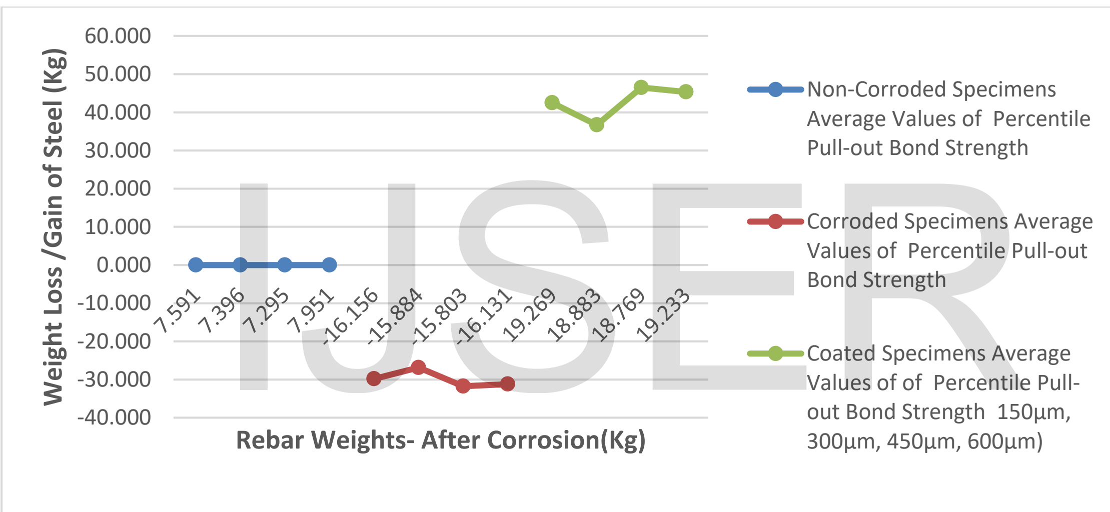

Figure 6b. Average percentile Rebar Weights- after Corrosion versus Weight Loss /Gain of Steel

3.3 Comparison of Control, Corroded, and Coated Concrete Cube Members

By comparison, from the data in Tables 3.1, 3.2, and 3.3 and in figures 3, 4,5, and 6 of the 12 controlled samples immersed in freshwater tank for 360 days, and the second sets; 12 uncoated and 12 coated immersed in 5% sodium chloride (NaCl) aqueous solutions for 360-day as described in 3.1 - 3.3 and summarized in tables 3.4 - 3.5 with figures 3a, 3b, 4a, 4b, 5a, 5b, 6a and 6b with medium and percentile failure bond loads, bond strength and maximum slip, cross-sectional reduction/increase, the diameter of rebar before /after corrosion, weight loss/gain. In relative terms, the corroded samples had significantly reduced values, measured against a range of reference values that failed at the lower load, while the controlled and coated samples showed additional values and recorded higher failure values during load applications.

The lower failure loads recorded in corroded samples are attributed to corrosion attack on the reinforcing steel with high surface modifications and lower bonding interaction between concrete and reinforcing steel.

Computed obtained results indicated the lower failure bond strength in corroded samples with declined and decreased values compared to controlled and coated samples with recorded higher failure bond strength and increased values, both having a close range of values over corroded samples. Results showed that corroded samples showed declined and reduced values with failure lower failure load on the application as compared to both controlled and coated samples with incremental values and higher load failure applications. The effect of corrosion might have led to the decline in percentile values resulting from surface modification and effect of the reinforcing steel fibre.

Observed signs showed that the effect of corrosion on concrete cubes without coating causes a decrease in cross-sectional area and rebar diameter as well as unit weight reduction. The cross-sectional diameter and cross-sectional area as well as the increase in weight by varying the thickness coated with reinforcing steel were noticed from coated samples. Exudate/resin proved to be an inhibitory material in curbing the damaging effects caused by corrosion attack on reinforced concrete structures built and exposed to coastal marine environment with severe weather.

4.0 Conclusion

In the experiment, the results obtained are drawn as:

i. The exudate/resin has an inhibitory effect on corrosion as its waterproofing resisted to corrosion penetration and attacks.
ii. The interaction between concrete and steel in the coated component is greater than that in the corroded samples
iii. The properties of the bonds in the coated and controlled components are greater than those in the corroded
iv. The lowest failure bond load, bond strength, and maximum slip were recorded in corroded member
v. The coating and control sample registered higher values of bond load and bond strength.
vi. Weight loss and reduction in cross section are mainly recorded in corroded coatings and controlled samples

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