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Corrosion Influential Factors on Bond Mechanism of Reinforced Concrete Structures in Severe Environment

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ABSTRACT

The damaging effect from the attack by corrosion has rendered many structures unserviceable and designed life span shortened. Experimental data test conducted on 36 concrete cubes samples of 12 controlled placed in freshwater for 360 days, 12 uncoated and 12 exudates/resin coated samples all embedded with reinforcing steel and immersed in 5% sodium chloride (NaCl) aqueous solution for 360 days and evaluated their performances with examinations, monitoring, checking and testing intervals of 3 months at 90 days, 180 days, 270 days and 360 days. In comparison, the peak obtained values of the failure bond load for the controlled sample are 97.586% against corrosive -46.845% and coated 106.118%. The results of the calculation showed that the ripple samples recorded a lower failure load and decreased the accepted value from the reference range of the controlled sample, while the controlled and coated samples recorded a higher failure load with an increased percentile value with coated performance. The reduction in average and percentile values as a result of the corrosive sampling has been compared with the negative effect of corrosion attacks that have affected the modified interface between concrete and strong steel interaction. From the data obtained from the bond strength, the maximum comparable values from the controlled, corroded, and coated samples are thus; The computed results of the corroded sample shows a failure in low bond strength and decreases the values from the reference point to the controlled and coated samples, with a range of close values but with slightly additional values in the reference point coated. The results showed lower slippage failure and lower slip reported failure and reduced value towards controlled and coated samples with increased values.

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Index Terms: Corrosion, Corrosion inhibitors, Pull-out Bond Strength, Concrete and Steel Reinforcement

1.0 INTRODUCTION

The interaction and movement of both concrete and reinforcing materials on the interface are distinctive which leads to a relative displacement of the steel bar in respect to the surrounding concrete, this displacement is called slip; bond stress arises to face up to the interfacial slip ensuing in tensile pressure transfer into the concrete that finally ends up with highly-localized strains in the concrete layer near the reinforcement (interface). Variations in this property, as reported by Angst et al. [1] lead to the heterogeneity of the steel-concrete interface, which, among other things, affects the adhesion of steel-concrete. As a phenomenon influenced by many parameters, it is also a challenge to determine how the bonding of steel to concrete can be described as standards for reinforced concrete construction. This property has been studied in Rehm [2] since 1940, examining the factors that influence the relationship between reinforcing steel and concrete interactions. All these basic tests are carried out with steel rods greater than 12.0 mm in diameter. Research on steel-concrete bonds follows the development of materials such as high-strength concrete, mixed concrete and self-compacting concrete Barbosa et al. [3]. The bond existing between the reinforcement and concrete can be idealized as a shear force at the circumferential surface of reinforcement (Wang, 2009). Similarly, it is believed that there is additionally ordinary movement on the interface, which is frequently overlooked in engineering exercise Portland Cement Association (PCA).

Chung et al. [4] performed pullout tests were on concrete prisms prepared from a concrete mix with a w / c ratio of 0.58 having an average concrete 28 days compressive strength of 28.3 MPa. A depth of the concrete layer was considered, and rebar was incorporated into centers of concrete prisms, the corrosion rate was varied from 0% to 10%.

Azizinamini et al. [5] stated, that the bond as an end result from numerous parameters, consisting of the chemical adhesion between the concrete and reinforcing steel interfaces and the friction generated by the strain of the hardened concrete in opposition to the reinforcing steel bar due to the drying shrinkage of the concrete, further, friction interlock or mechanical interplay between the bar ribs and the concrete caused by the relative movements of the tensioned bar results in an accelerated resistance to slip.

Gede et al. [6] examined the strength of the bond between the concrete and the decrease in the diameter of the reinforcement due to the effect of decreasing steel reinforcement from the coastal area. Application of Artocarpus altilis reinforced with layer thicknesses, immersed in a concrete cube surrounded by sodium chloride, and an exudate/resin element for control and coating. The comparison results showed that the depleted sample values decreased and the samples coated with the exudate/resin increased during control. Overall results showed higher values of controlled tensile bond strength and coated / resin exudate over corroded samples.

Al-Sulaimani et al. [7] pull-out tests were performed on samples of concrete cubes having 150 mm sides. Three different sizes of reinforcing bars were centrally embedded in concrete specimens. An embedding length of 40 mm was selected to ensure the bond failure of concrete specimens were prepared from a concrete mix with a w ratio c / 0.55 having an average of 28 days concrete compressive strength of 30MPa. The corrosion rate was varied from 0% for the control samples to 7. 8% for other specimens. The best adhesion strength has been reported for pre-cracking, cracking, and crazing post stages of corrosion and as a function of the corrosion rate.

Mendis and French [8] stated that it is critical that reinforcement pressure is transferred to the concrete to preserve the structural integrity by adhesion, friction, and mechanical bearing transferred to the surrounding concrete.

Sofi et al. [9] reported that the best method and way of effective bonding is the use of deformed bars which have a pattern of vast deformation rolled external grip that permits better slip of steel bars and leads to a lower bond strength as compared to deformed bars which restrict the slip of a steel bar at the same time as providing higher bond strength.

Lee et al. [10] pullout tests were performed on specimens of cubic concrete 8D by side where 'D' is the diameter of the rebar. They used three different concrete mixtures having relations w / c 0.45, 0.55, and 0.65. They reported that the three ratios used for A / C was 42.1MPa, 33.0MPa, and 24.7MPa respectively in the 28-day compressive strength concrete. The individual size of the reinforcing bar is used in which embedded in the center of the concrete specimen to three different depths of concrete coating. In that study, it is assumed that at the time of concrete cracking was produced in 3% of the level of corrosion. The corrosion rate was varied from 0% for the control samples to 30% for other specimen maximum bond strengths have been reported as a function of the corrosion rate for different strengths of the concrete and proposed the bond strength as a function of the level of corrosion.

Chung et al. [11] investigated corroded reinforcing bars before and after casting the concrete. The model bond strength has been reported as a function of the percentage corrosion, where the bond strength means up to 2% of the constant etch rate.

Charles et al. [12] investigated the use of senegalese acacia exudate/resin as a paste-like material on reinforcing steel of various thicknesses, embedded in concrete cubes, immersed in sodium chloride, and accelerated for 178 days. In comparison, the value of the corroded samples decreased, but the controlled and exudate/resin coated elements increased, indicating the potential for senegalese acacia exudate/resin in armored reinforcement operations. Overall results show high values for tensile bond strength and low stress on control failure and coated over corroded samples.

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2.0 Test Program

The study examined the usefulness of exudates/resin pastes as a barrier against corrosion attacks in reinforcing steel embedded in concrete structures and exposure to high concentrations of salt in coastal marine areas. Exudate/resin was tapped from the trunk of the plant and inhibited to reinforcing steel with different thicknesses and embedded in concrete cubes and with the introduction of corrosion acceleration process of sodium chloride (NaCl) to determine the possibility of environmentally friendly use of materials commonly available to control the effects of transformations usually faced by concrete structures in the ocean. The test sample 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 made of 36 reinforced concrete cubes with dimensions of 150 mm x 150 mm x 150 mm, with an embedded 12 mm diameter centrally for pullout bond testing, and 360 days for immersion in sodium chloride after 28 days after initial cube treatment. Acidic corrosive media solutions were modified monthly and solid samples were reviewed to investigate high performance and changes.

2.1 Materials and Methods for Testing

2.1.1 Aggregates

Aggregates (fine and coarse) were purchased. Both meet the requirements of BS882 [13]

2.1.2 Cement

Portland Lime Cement Grade 42.5 is the most common type of cement on the Nigerian market. It was used for all concrete mixes in this test. It meets the requirements of cement (BS EN 196-6) [14]

2.1.3 Water

The water samples were clean and free of impurities. Freshwater was obtained from Civil Engineering Laboratory, Kenule Beeson Saro-Wiwa Polytechnic. Water met (BS 3148) [15] requirements.

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2.1.4 Structural steel reinforcement

Reinforcements are obtained directly from the market at Port Harcourt, (BS4449: 2005 + A3) [16]

2.1.5 Corrosion Inhibitors (Resins / Exudates) Anogeissus (Combretaceae)

Gum exudation / resins were extracted from the wounded stem of tree. Samples were obtained from Arku in Dambam Local Government of Bauchi State, 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 and with coating thicknesses of 150µm, 300µm, 450µm and 600µm before corrosion testing. The test cubes were cast in 150 mm x 150 mm x 150 mm metal mold and removed after 72 hours. Samples were treated at room temperature in the tank for 28 days before the initial treatment period, followed by rapid acceleration corrosion testing for 360-days and monthly routine monitoring. Cubes for corrosion-acceleration samples were taken at approximately 90-days, 180-days, 270-days, and 360-days intervals of approximately 3 months, and failure bond loads, bond strength, maximum slip, decrease/increase in cross-sectional area, and weight loss/steel reinforcement.

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 may take many years to achieve; but the laboratory-accelerated process will take less time to accelerate the marine media. Immersion in 5% NaCl solution for 360 days to test the effects on the surface and mechanical properties of reinforcing steel and on both non-coating and exudate/resin coated samples.

2.4 Pull-out Bond Strength Test

The pullout-bond strength of the concrete cube was tested on a total of 36 cubes measuring 150 mm × 150 mm × 150 mm with 12 mm diameter of steel embedded in the center of the concrete cube, samples with control, uncoated, and coated members, each of the 12 samples were subjected to in a 50kN pressure according to BSEN12390.2 [17], using Universal Testing Machine.

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 Discussion

The interaction between concrete and reinforcing steel is expected to be cordially perfect to enable the exhibition of maximum bonding in the surroundings concrete structures. The increase in deformed (rib) reinforcing bars and slip bonds mainly depends on the bearings or mechanical interlocks between the concrete around the ribs on the surface of the bar. The damaging effect from the attack by corrosion has rendered many structures unserviceable and designed life span shortened.

Experimental data presented in tables 3.2.3.2 and 3.3, summarized into tables 3.4 and 3.5 are test conducted on 36 concrete cubes samples of 12 controlled placed in freshwater for 360 days, 12 uncoated and 12 exudates/resin coated samples all embedded with reinforcing steel and immersed in 5% sodium chloride (NaCl) aqueous solution for 360 days and evaluated their performances with examinations, monitoring, checking and testing intervals of 3 months at 90 days, 180 days, 270 days and 360 days. Indeed, the manifestation of corrosion is a long-term process which takes decades for full functionality, but the artificially introduction of sodium chloride triggers the manifestation and occurrence of corrosion with lesser time. The experimental work represented the ideal coastal marine region of high salinity and the potential application for of anogeissus (Combretaceae) exudate / resin extract as inhibitory material in curbing the scourge and menace of corrosion effect on reinforced concrete structure exposed or built within such severe and harsh region.

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

Sample Numbers	ACC	ACC1	ACC2	ACC3	ACC4	ACC5	ACC6	ACC7	ACC8	ACC9	ACC10	ACC11
	Time Interval after 28 days curing											
Sampling and Durations	**Samples 1 (28 days)**			**Samples 2 (28 Days)**			**Samples 3 (28 Days)**			**Samples 4 (28 Days)**		
Failure Bond Loads (kN)	30.223	28.133	28.697	29.294	30.109	29.810	30.333	30.150	30.215	32.026	31.151	31.352
Bond strength (MPa)	11.436	12.329	10.826	11.757	12.129	13.053	13.146	12.476	12.510	13.216	12.528	13.074
Max. slip (mm)	0.145	0.146	0.137	0.141	0.140	0.139	0.152	0.156	0.164	0.162	0.167	0.165
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)	11.992	12.001	12.000	11.991	11.998	11.990	12.001	11.991	12.001	11.991	12.000	12.002
Rebar Diameter- at 28 Days Nominal(mm)	11.992	12.001	12.000	11.991	11.998	11.990	12.001	11.991	12.001	11.991	12.000	12.002
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)	0.578	0.581	0.580	0.581	0.581	0.580	0.581	0.580	0.581	0.581	0.579	0.581
Rebar Weights- at 28 Days Nominal (Kg)	0.578	0.581	0.580	0.581	0.581	0.580	0.581	0.580	0.581	0.581	0.579	0.581
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

	Corroded Concrete Cube Specimens											
Sampling 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)	11.982	12.003	11.984	11.993	11.992	12.004	11.993	11.982	11.993	11.993	11.982	11.993
Rebar Diameter- After Corrosion(mm)	11.933	11.954	11.935	11.944	11.943	11.955	11.944	11.933	11.944	11.944	11.933	11.944
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)	0.582	0.583	0.583	0.583	0.583	0.583	0.589	0.582	0.589	0.582	0.581	0.582
Rebar Weights- After Corrosion (Kg)	0.540	0.538	0.540	0.540	0.540	0.541	0.540	0.540	0.541	0.539	0.547	0.539
Weight Loss /Gain of Steel (Kg)	0.042	0.045	0.042	0.042	0.043	0.042	0.049	0.042	0.048	0.043	0.034	0.043

Table 3.3: Results of Pull-out Bond Strength Test (τu) (MPa) of Anogeissus (Combretaceae) Exudate / Resin (steel bar coated specimen)

Sampling 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)	31.035	28.945	29.509	30.106	30.921	30.622	31.145	30.963	31.027	32.838	31.963	32.164
Bond strength (MPa)	12.901	13.793	12.291	13.221	13.594	14.517	14.611	13.941	13.975	14.681	13.992	14.539
Max. slip (mm)	0.134	0.135	0.126	0.130	0.129	0.128	0.141	0.145	0.153	0.151	0.156	0.154
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)	11.962	11.963	11.953	11.953	11.973	11.963	11.963	11.960	11.964	11.954	11.960	11.964
Rebar Diameter- After Corrosion(mm)	12.016	12.017	12.007	12.007	12.027	12.017	12.017	12.014	12.018	12.008	12.014	12.018
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
Rebar Weights- Before Test (Kg)	0.580	0.589	0.582	0.582	0.582	0.583	0.583	0.582	0.583	0.582	0.581	0.580
Rebar Weights- After Corrosion (Kg)	0.643	0.643	0.641	0.643	0.643	0.642	0.644	0.643	0.643	0.644	0.642	0.650
Weight Loss /Gain of Steel (Kg)	0.061	0.062	0.057	0.061	0.060	0.061	0.060	0.060	0.060	0.061	0.060	0.069

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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)	29.018	29.737	30.233	31.510	15.856	15.050	15.062	15.696	29.830	30.550	31.045	32.322
Bond strength (MPa)	11.530	12.313	12.711	12.939	7.796	7.699	7.519	7.556	12.995	13.778	14.176	14.404
Max. slip (mm)	0.142	0.140	0.158	0.164	0.083	0.088	0.082	0.081	0.131	0.129	0.147	0.153
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	11.998	11.993	11.998	11.998	11.990	11.996	11.989	11.990	11.960	11.963	11.962	11.959

Test(mm)												
Rebar Diameter- After Corrosion(mm)	11.998	11.993	11.998	11.998	11.941	11.947	11.940	11.941	12.013	12.017	12.016	12.013
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.000	0.000	0.000	0.000	0.049	0.049	0.049	0.049	0.054	0.054	0.054	0.054
Rebar Weights- Before Test (Kg)	0.580	0.581	0.581	0.581	0.583	0.583	0.587	0.582	0.584	0.582	0.583	0.581
Rebar Weights- After Corrosion (Kg)	0.580	0.581	0.581	0.581	0.539	0.540	0.540	0.542	0.642	0.643	0.643	0.645
Weight Loss /Gain of Steel (Kg)	0.000	0.000	0.000	0.000	0.043	0.043	0.047	0.040	0.060	0.061	0.060	0.064

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)	83.007	97.586	97.25	95.56	- 46.845	- 50.735	- 51.484	- 51.439	88.129	102.983	106.118	105.928
Bond strength (MPa)	47.908	59.919	69.049	71.242	- 40.011	- 44.117	- 46.958	- 47.542	66.698	78.944	88.530	90.627
Max. slip (mm)	72.068	59.070	92.665	102.589	- 37.062	- 31.839	- 44.240	- 47.132	58.888	46.712	79.340	89.149
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)	0.069	-0.026	0.071	0.068	0.251	0.278	0.224	0.255	-0.250	-0.278	-0.224	-0.254
Rebar Diameter- After Corrosion(mm)	0.680	0.684	0.682	0.680	-0.677	-0.679	-0.634	-0.664	0.861	0.883	0.858	0.857
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.000	0.000	0.000	0.000	-8.905	-8.905	-8.905	-8.905	9.776	9.776	9.776	9.776
Rebar Weights- Before Test (Kg)	0.256	0.260	0.253	0.266	0.256	0.261	0.221	0.243	0.206	0.269	0.216	0.243
Rebar Weights- After Corrosion (Kg)	7.567	7.479	7.516	7.202	- 15.999	- 15.961	- 15.988	- 16.021	19.047	18.993	19.030	19.077
Weight Loss /Gain of Steel (Kg)	0.000	0.000	0.000	0.000	- 28.073	- 30.099	- 22.848	- 36.892	39.030	43.059	29.614	58.458

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3.2 Failure load, Bond Strength, and Maximum slip

The main characteristic of the bond stress - the development of slippage, and in particular the maximum bond stress, clearly depends on the material, geometry, or load parameters. Torre-Casanova et al., [18] showed that the failures in splitting and pullout depend on the concrete shell and low concrete cover and tensile failure in other cases. Several factors also negatively affect the bond strength, such as epoxy coating. This effect is due to the reduction of the adhesion and friction components on the smooth epoxy surface (Joseph, and Camille, [19]). Compared to uncoated bars, it was found that the reduction in adhesive strength varies between 15% and 50% depending on various factors such as coating thickness, bar size and position, deformation pattern, concrete properties, and casting conditions (De Anda et al., [20]; Choi et al., 2003[21]). To solve and curb these limiting factors affecting the bond characteristics between concrete and reinforcing steel, the introduction of exudate/resin was implored to improve these limiting factors and as well eliminate corrosion scourge and the attack on reinforced concrete structures built and exposed to corrosive media within the coastal areas of high salinity level.

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

The minimum and maximum computed average and percentile derived results of failure bond load are controlled 29.018kN and 31.51kN (83.007% and 97.586%), corroded 15.05kN, and 15.856kN (-51.484% and -46.845%), coated 29.83kN and 32.322kN (88.129% and 106.118%).

The bond strength values for controlled are 11.53MPa and 12.939MPa (47.908% and 71.242%), corroded 7.519MPa and 7.796MPa (-47.542% and -40.011%), Coated are 12.995MPa and 14.404MPa (66.698% and 90.627%). Results of maximum slip are controlled are 0.14mm and 0.164mm (59.07 % and 102.589%), corroded are 0.081mm and 0.088mm (-47.132% and -31.839%), coated are 0.129mm and 0.153mm (46.712% and 89.149%).

In comparison, the peak obtained values of failure bond load for the controlled sample is 97.586% against the corroded -46.845% and coated 106.118%. Enumerative results showed that corroded samples recorded lower failure load and decreased value acknowledged from the reference range of the controlled sample, on the other hand, controlled and coated samples recorded higher failure load with coated exhibiting increased percentile value. Reduction in average and percentile values resulted from the corroded sample is likened to the negative effect from corrosion attacks that have affected the modified interface between concrete and reinforcing steel interaction.

From the data obtained of bond strength, the maximum comparative values from controlled, corroded, and coated samples are thus; 71.242%, -40.011%, and 90.627% respectively. Results computed showed corroded sample exhibited lower bond strength failure and decreased values from reference point towards controlled and coated samples, with the closest value ranges but with slight incremental values recorded in coated from the reference point. Enumeration showed the effect of corrosion attacks on the corroded sample with a modified interface, low rib, and high swollen surface showing fibre peel- off. These noticed factors reduced the bond relationship between concrete and reinforcing.

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Results of maximum slip obtained have peak values in comparison as controlled 102.589% against corroded and corroded values of -31.839% and 89.149% respectively. Results showed corroded recorded lower slippage failure and decrease value towards controlled and coated samples with higher slippage failure and increased values. (Mendis and French, [8]; Chung et al., [11]; Lee et al., [10]; Al-Sulaimani et al.[7]; Azizinamini et al.[5])

The effect of corrosion on corroded sample drastically caused lower slippage with deformed rebar turning into smooth rebar resulting from rib pealed-off.

Conclusively, the exudative material showed a high potential of inhibitory characteristics as well the effectiveness in use as anti-corrosive material in reinforcing steel protection against corrosion.

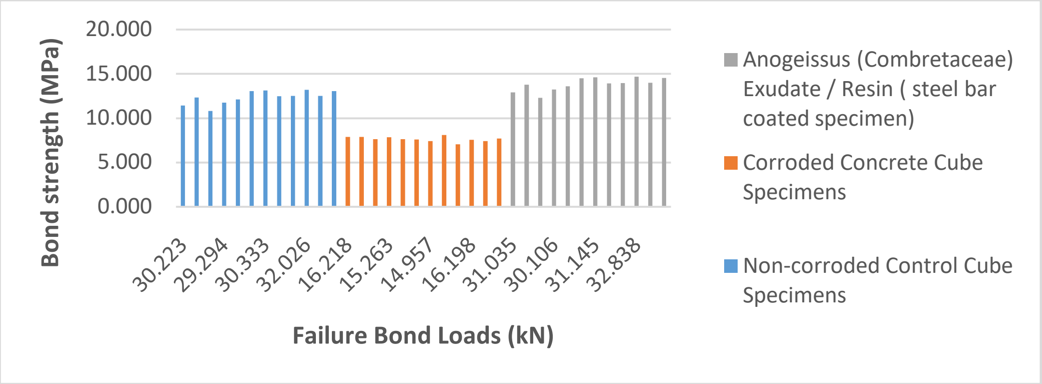

Figure 1. Failure Bond loads versus Bond Strengths

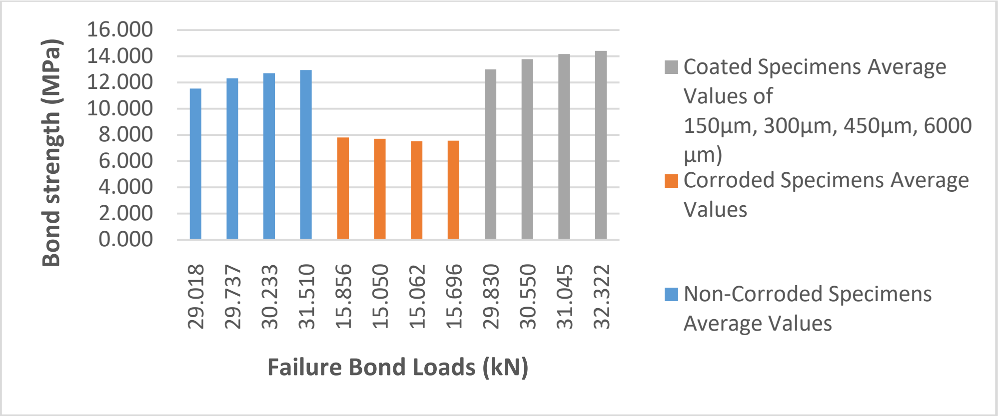

Figure 1a. Average Failure Bond loads versus Bond Strengths

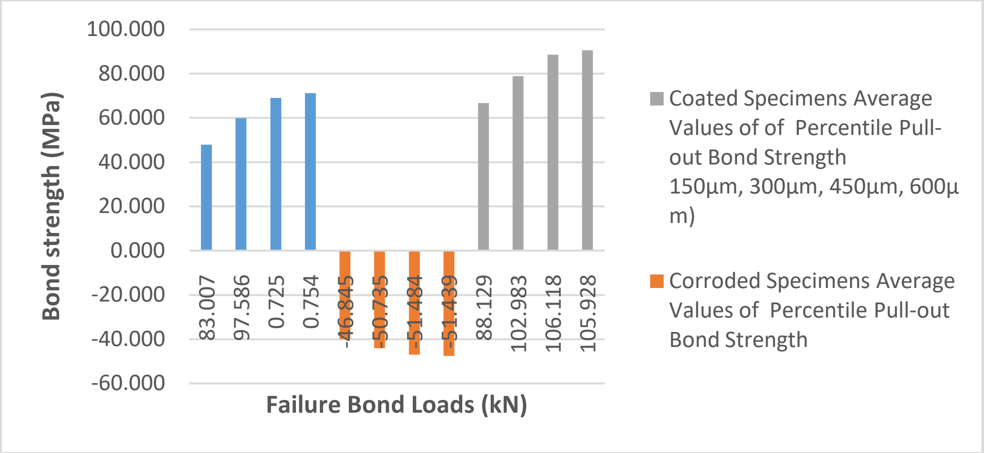

Figure 1b. Average Percentile Failure Bond loads versus Bond Strengths

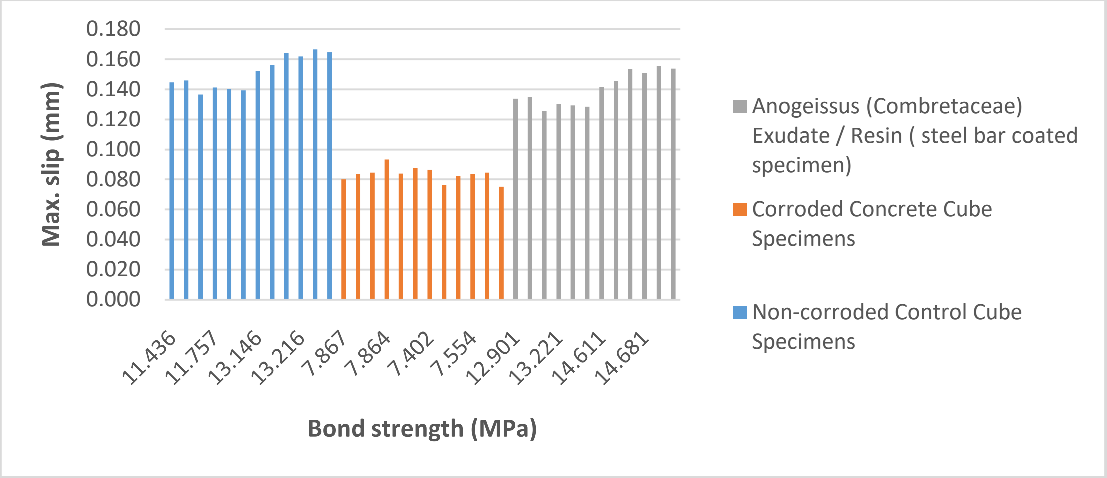

Figure 2. Bond Strengths versus Maximum Slip

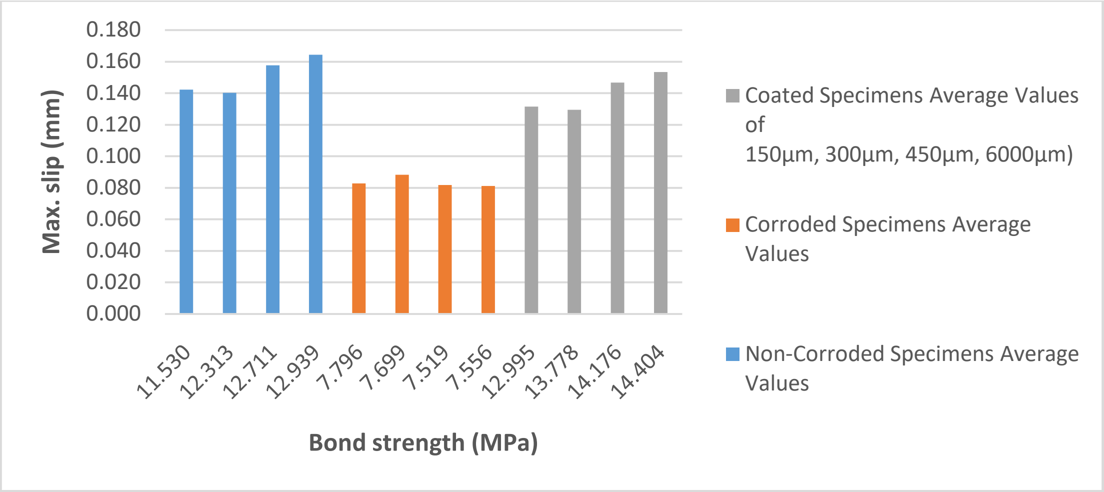

Figure 2a. Average Bond Strengths versus Maximum Slip

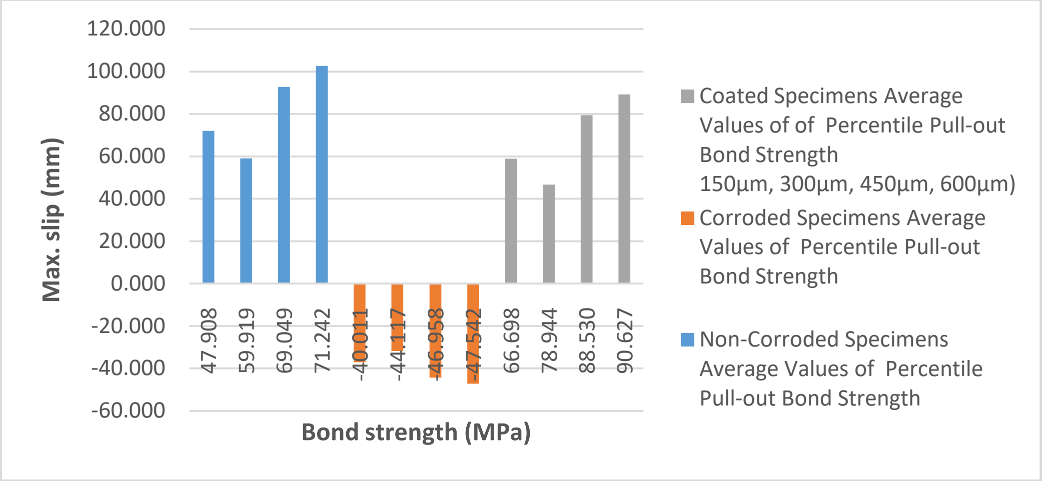

Figure 2b. Average Percentile Bond Strengths versus Maximum Slip

3.3 Mechanical Properties of Reinforcing Bars

Steel reinforcement corrosion in reinforced concrete structures is the most important issue affecting structures and infrastructures worldwide and especially in coastal marine areas with saline water. This causes concrete cracking and spalling, reducing the effective cross-sectional area of the steel reinforcement and weakening the bond between the steel and the concrete. This severely affects the durability and service life of reinforced concrete structures.

The bond strength is mainly derived from the weak chemical bond between steel and hardened cement, but this strength is destroyed under minute pressure. Once slippage occurs, friction will help bond. In smooth steel bars, friction is an important part of strength whereas reinforcing steel bars with ribs under increased sliding connections mainly depend on the bearing or mechanical interlocking between the ribs and the surrounding concrete on the surface. This research introduced the application of exudates/resin to increase the slippage problem encountered by smooth reinforcing steel and the potential of the exudate/resin curb eliminate the trend of corrosion damages to reinforced concrete structures built in saline areas.

Data presented in table 3.1, 3.2, and 3.3 and collapsed into table 3.4 and finally summarized into 3.5 of averages and percentile values. This work examined the mechanical properties of reinforcing steel embedded in both freshwater and artificial saltwater as described in the test program for controlled, non-coated, and coated samples for 360 days with routine checks for 90 days, 180 days, 270 days, and 360 days and examined surface modifications arising from corrosion attacks.

The controlled sample result is 100% values because they are pooled in a tank of freshwater of compliance to (BS 3148 [15]) requirements.

The results are summarized into minimum and maximum values obtained from tables 3. 4 and 3.5, and graphically represented from figures 3-6b.

Nominal diameter steel bars of all samples are 100%, and the minimum and maximum diameters of the steel bars measured before the tests are within the range of 11.993mm and 11.998mm (0.681% and 0.684%). The diameter of the rebar uncoated samples (corroded) after the corrosion test is 11.94mm and 11.947mm (-0.634% and -0.679%), after coated are 12.013mm and 12.017mm (0.657% and 0.683%). The results of cross-sectional area for uncoated (corroded) are 0.049mm and 0.049mm (-8.905% and -8.905%), for coated are 0.054mm and 0.057mm (9.776% and 9.886%).

The result for rebar weight before test for all samples are 0.583Kg and 0.586Kg (0.253% and 0.266%), weight after corrosion test for corroded are for 0.539Kg and 0.542Kg (-16.021% and -15.961%), coated are 0.642Kg and 0.645Kg (18.993% and 19.077%), and weight loss /gain of steel are corroded 0.04Kg and 0.047Kg (-36.892% and -22.848%) and coated values are 0.06Kg and 0.064Kg (29.614% and 58.458%). From the results obtained and presented in the figures, the effect of corrosion on uncoated and coated reinforcing steel are enumerated, in figures 3 and 6b on the diameter of rebar, it can be seen that the diameter of uncoated decreased by the maximum value of (-0.634% and coated increased by 0.683%, for the cross-sectional area, corroded has maximum reduction value -8.905% and coated increased by 9.886%, weight loss and gain are corroded -22.848% decreased (loss) and coated 58.458% increase (gain). Indication, as analyzed from the experimental work, showed the effect of corrosion on uncoated concrete cubes caused diameter and cross-sectional area reduction and weight decrease while coated concrete cubes have a diameter and cross-sectional area increases and weight gain resulting from the varying thickness coated to reinforcing steel as validated by (Charles et al. [12]; Gede et al. [6];Mendis and French, [8])

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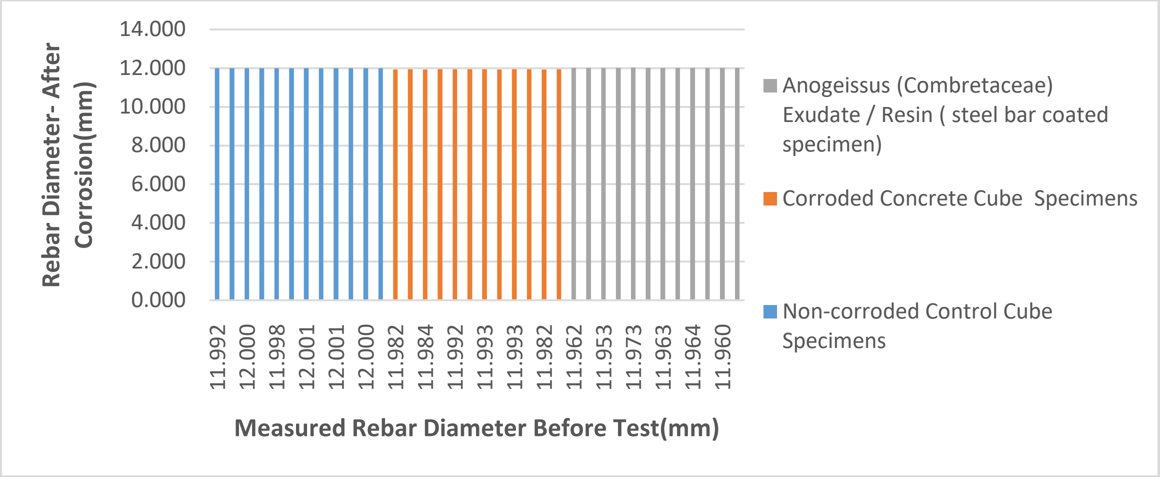

Figure 3. Measured (Rebar Diameter before Test vs Rebar Diameter- after Corrosion)

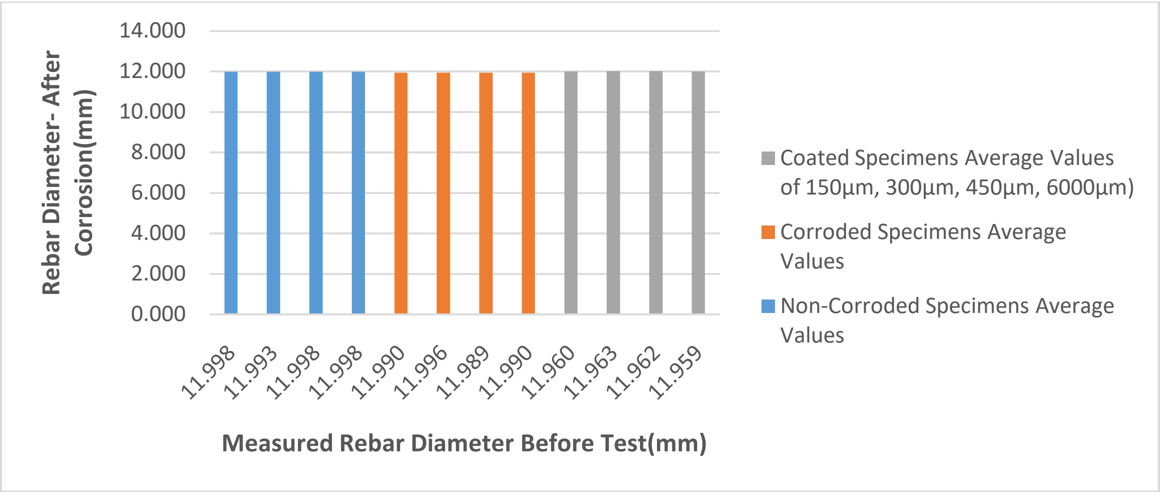

Figure 3a. Average Measured (Rebar Diameter before Test vs Rebar Diameter- after Corrosion

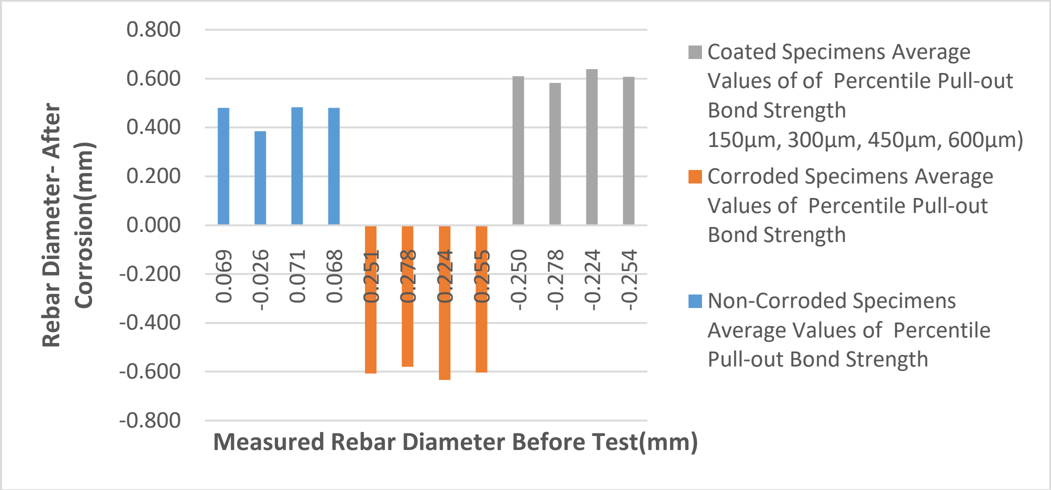

Figure 3b. Average Percentile Measured (Rebar Diameter before Test vs Rebar Diameter- after Corrosion

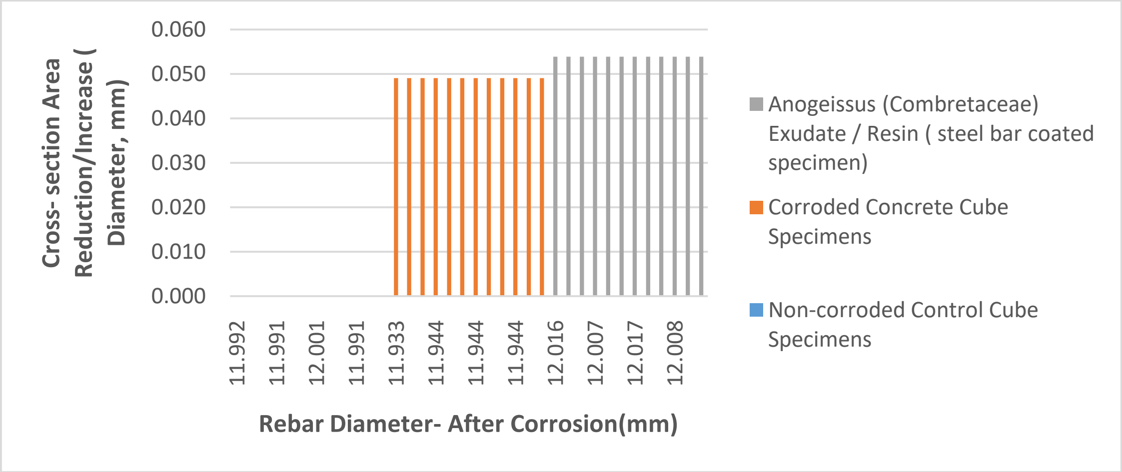

Figure 4. Rebar Diameter- After Corrosion versus Cross - Sectional Area Reduction/Increase

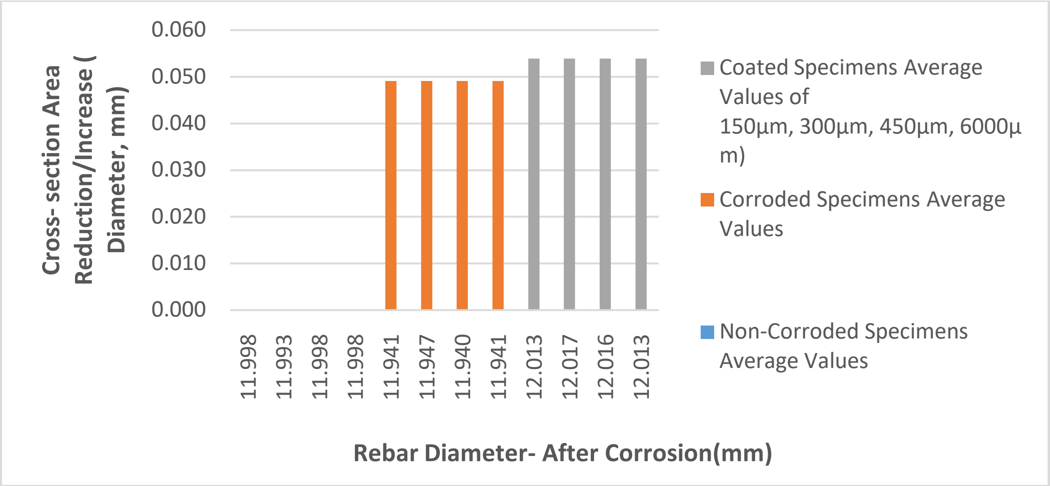

Figure 4a. Average Rebar Diameter- after Corrosion versus Cross – Sectional Area Reduction/Increase

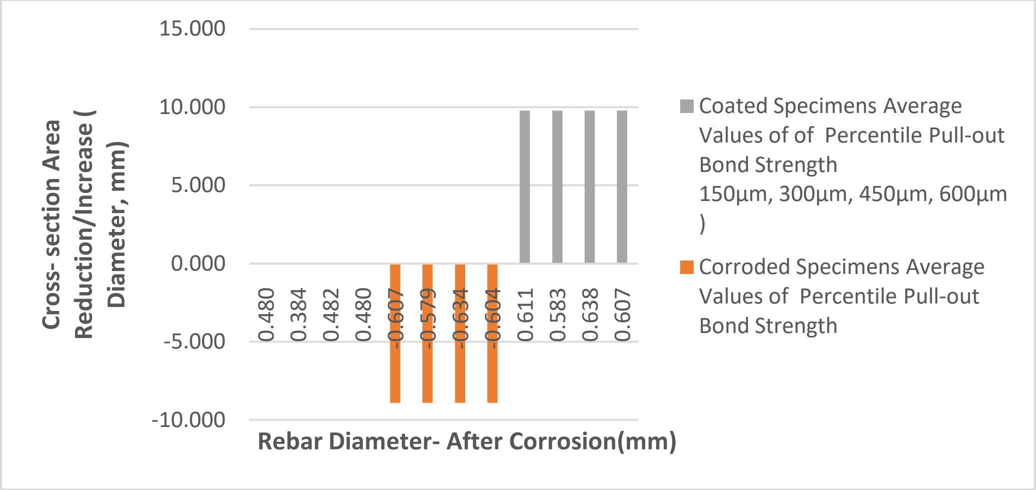

Figure 4b. Average percentile Rebar Diameter- after Corrosion versus Cross - sectional Area Reduction/Increase

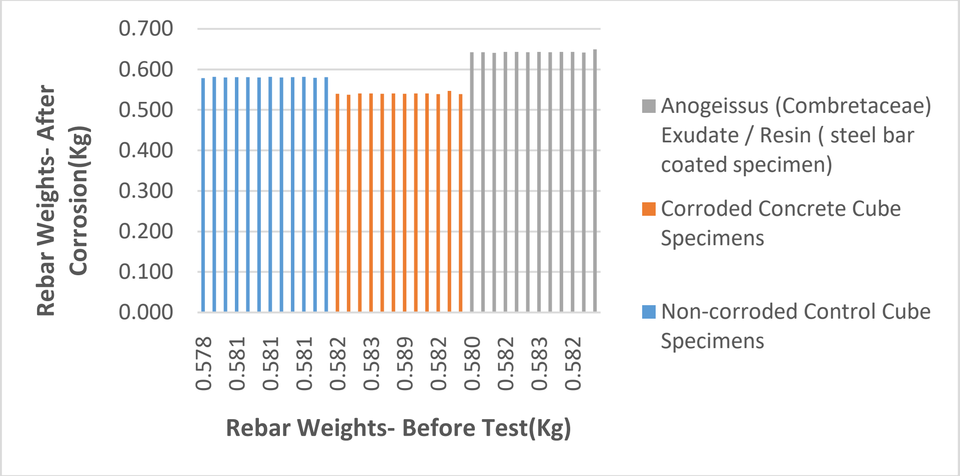

Figure 5. Rebar Weights- before Test versus Rebar Weights- after Corrosion

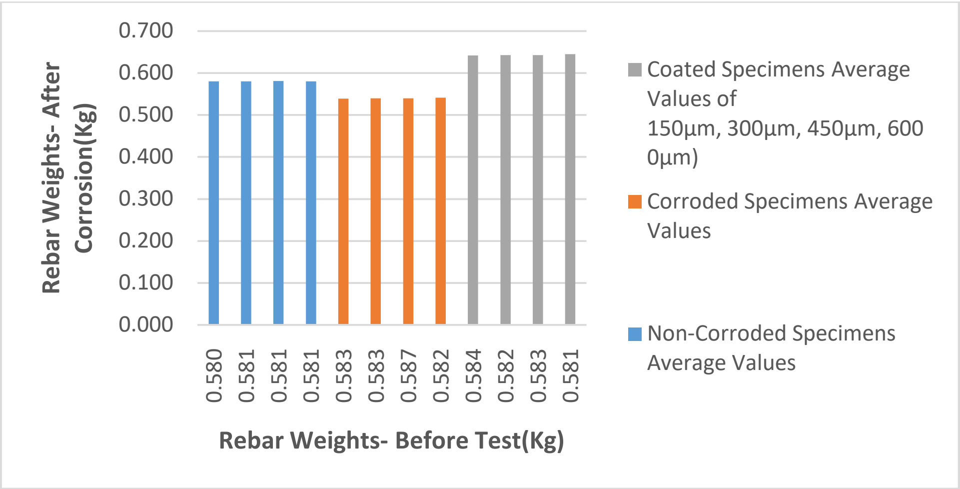

Figure 5a. Average Rebar Weights- before Test versus Rebar Weights- after Corrosion

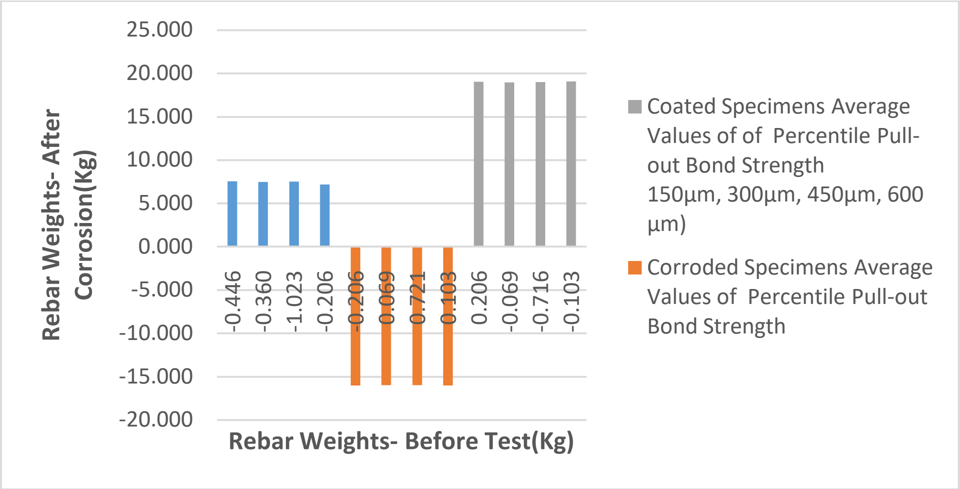

Figure 5b. Average Percentile Rebar Weights- before Test versus Rebar Weights- after Corrosion

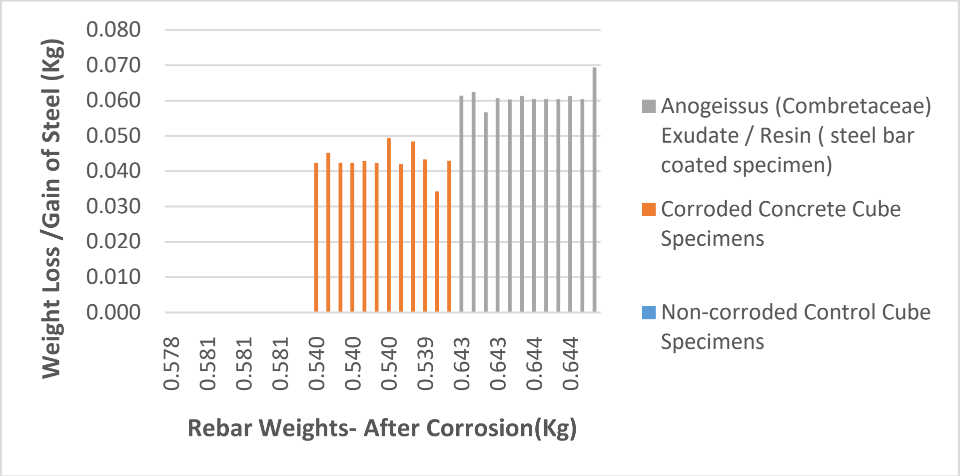

Figure 6. Rebar Weights- after Corrosion versus Weight Loss /Gain of Steel

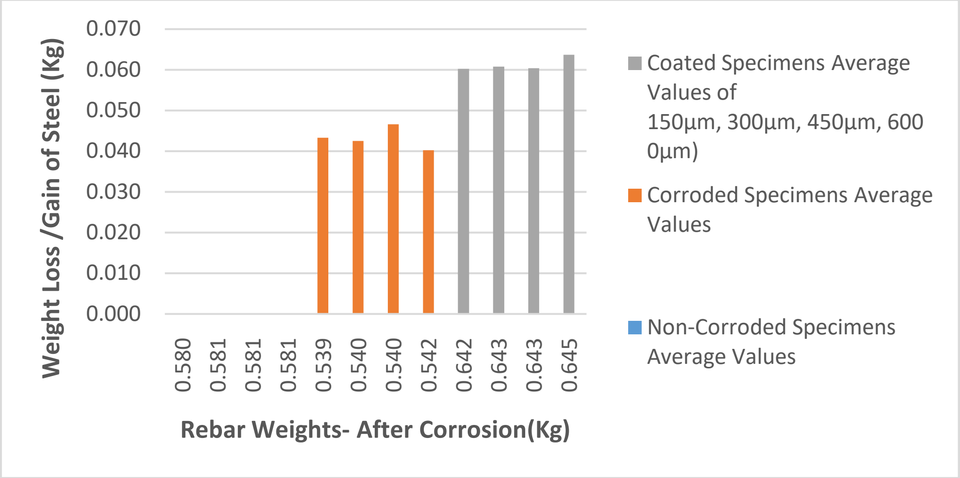

Figure 6a. Average Rebar Weights- after Corrosion versus Weight Loss /Gain of Steel

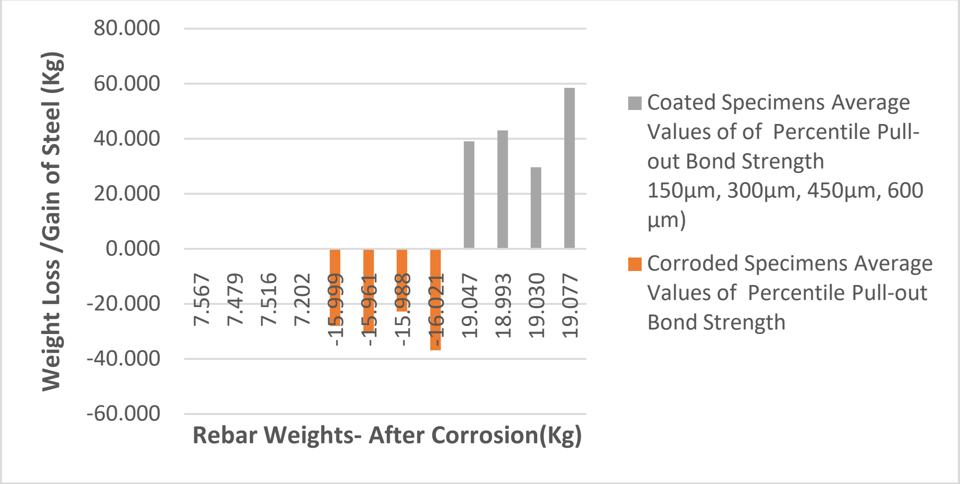

Figure 6b. Average percentile Rebar Weights- after Corrosion versus Weight Loss /Gain of Steel

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

Steel reinforcement erosion in reinforced concrete is the most important issue affecting structures and infrastructure worldwide and especially in coastal areas. This causes the concrete to cracks and spall, reducing the effective cross-sectional area of the steel reinforcement and weakening the bond between the steel and the concrete.

Comparatively, from the data in tables 3.1, 3.2, and 3.3 and in figures 3, 4,5, and 6 for 12 controlled samples pooled in a freshwater tank for 360 days, 12 uncoated and 12 coated pooled in 5% sodium chloride (NaCl) aqueous solutions for 360 days ad described in 3.1 – 3.3 and summarized into tables 3.4 – 3.5 and figures 3a,3b,4a,4b,5a,5b, 6a and 6b for average and percentile values for failure bond loads, bond strength and maximum slip, cross-sectional reduction/increase, the diameter of rebar before /after corrosion, weight loss/gain..

In comparison, the top obtained values of the failure bond load for the controlled sample are 97.586% against corrosive -46.845% and coated 106.118%. The results of the calculation showed that the ripple samples recorded a lower failure load and decreased the accepted value from the reference range of the controlled sample, while the controlled and coated samples recorded a higher failure load with an increased percentile value with coated performance. The reduction in average and percentile values as a result of the corrosive sampling has been compared with the negative effect of corrosion attacks that have affected the modified interface between concrete and strong steel interaction.

From the data obtained from the bond strength, the maximum comparable values from the controlled, corroded, and coated samples are thus; 71.242%, -40.011%, and 90.627%, respectively. The calculation of the results shows that the rusty sample shows a failure in low bond strength and decreases the values from the reference point to the controlled and coated samples, with a range of close values but with slightly additional values in the reference point coated. The effect of corrosion was observed on a rusty sample showing a fiber peel with a modified interface, lower ribs, and a higher swollen surface. These reported factors reduced the bond relationship between concrete and reinforcement.

The results of the maximum slip obtained have the highest values compared to the corrosive and corrosive values of -31.839% and 89.149%, respectively, compared to 102.589% controlled. The results showed lower slippage failure and lower slip reported failure and reduced value towards controlled and coated samples with increased values. The effect of corrosion on rusty specimen results in the closure of the rib peel due to less easily slipping with a sharp deformed rubber.

Certainly, the exudative material demonstrated a potentially high probability, as well as the efficacy of the barrier characteristics used as an anti-corrosive material to strengthen steel protection against corrosion.

The indication, as analyzed in the experimental work, shows the effect of corrosion on non-concrete cubes due to reduction in diameter and cross-sectional area and weight loss while the diameter and cross-sectional area of coated concrete cubes increase and weight increases as a result of different thicknesses of steel.

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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