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Original Research Article

Friction Force Reduction of Corroded and Exudates Coated Reinforcing Steel Exposed to Severe Media

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Abstract

The performance of reinforced concrete structures, as in other composite members, depends on the bond between the steel and the concrete which ensures that load is transferred safely between the two materials. The research involved the direct application of environmentally and eco-friendly extracted exudates/resins used to control the effect of corrosion attacks by coating steel with varying thicknesses, embedded in concrete structures and immersed in sodium chloride (NaCl) solution for corrosion accelerated process. Laboratory experimental samples reflected the acid level of sea salt concentration in reinforced concrete cubes. The data for comparison of maximum obtained values are failure bond load are corroded -41.594% against 78.166% and 80.194% controlled and coated, bond strength is -34.227% against 73.201% and 69.943% and maximum slip are -42.731% against 102.034% and 113. The summarized computed and compared results of failure bond load, bond strength and maximum slip of the controlled, corroded and coated samples showed that the effect of sodium chloride as detailed in the "2.2 Experimental procedures" has adversely affected the mechanical properties of reinforcing steel of uncoated (corroded) samples which has resulted to poor performances, low load at failure state, less bond strength and slippage. The coated samples exhibited the potential of sustaining the negative effect of corrosion on reinforcing steel and by forming good contact and interlock between concrete and reinforcing steel by reducing the stress existing in the concrete surroundings. Results showed that the diameter of corroded reinforcement decreases by a maximum of -0.771% and the coated increases by 0.831%, for the cross-sectional area corroded has a maximum reduction value of -13.163% and the coated increases by 20.74%, the weight loss and increase in corroded is -22.887 % decreased (loss) and coated increased by 34.929% (gain). Regarding the mechanical properties of reinforcing steel, the effect of corrosion on reinforcing steel shows a decrease in the cross section of the rebar diameter compared to the nominal diameter before testing, weight reduction is also observed, an increase in the cross-sectional area, an increase in the diameter and minute increase in weight resulting from coating material as compared with the nominal reinforcement, which is due to differences in the thickness of the layered materials. It can be concluded that the exudate / resin studied has shown effective inhibiting properties against corrosion attack and can be used as a corrosion inhibitor

Keywords: Corrosion, Corrosion inhibitors, Pull-out Bond Strength, Concrete and Steel Reinforcement.

1.0 INTRODUCTION

The most important factor that reduced the expected or designed service life of reinforced concrete structures that are exposed to corrosive weather is the presence of chloride in the form of saltwater leading to corrosion. The tensile energy transfer to the concrete is controlled by the reinforcing steel bar and the bonding strength of the concrete. Bonding ensures that the steel bars slip little or not at all in relation to the concrete and the means used to transfer stresses to the reinforced concrete [1]. Bonding resistance consists of chemical adhesion, friction and mechanical interlocking between the rebar and the surrounding concrete. To prevent hardened concrete and structural forms from sticking, grease is often used in buildings today. If the bond between steel and concrete is affected by reinforcement corrosion, there is no definite bond. The main cause of steel reinforcement corrosion is the presence of chlorides from contaminated aggregates and mixtures of chloride used during construction or the entry of chloride ions from the seawater or the de-icing salt. The transfer of the normal stress from the reinforcing steel bar to the surrounding concrete, resulting from the development of a tangential stress component at the contact surface [2].

Research on steel-concrete composites has followed the development of materials such as high-strength concrete, concrete with admixtures and self-compacting), [3] Reinforced concrete joints are also a factor in relation to quality control of reinforced concrete structures and the operation of reinforced concrete under extreme conditions, for example in high temperature environment and corrosion [4, 5]. Although there have been several studies on steel-to-concrete connections, few have evaluated the properties of reinforcement less than 10.0 mm in diameter, including the 5.0, 6.3 and 8.0 mm diameters commonly used in reinforced concrete elements.

Provided experimental evidence that the effect of rod size on bond strength depends on the degree of retention [6]. In their tests it was found that the bond strength of samples with low retention rates and disintegration decreased with increasing rod size, but this effect was negligible for samples with high retention rates and tensile damage.

Investigated the effect of resin/exudate on corrosion prevention for reinforcement in reinforced concrete cubes [7]. The obtained results indicated that the failure bond strength, bond strength removal, and resin coating were higher by the maximum slip of reinforced cubes and higher than those obtained from controlled tests. Similar results were obtained for the maximum slip (resin-coated and control steel members) steel reinforcement had higher values of maximum slip compared to the corroded cubes. For corroded beam members, the failure bond strength, bond strength, and maximum slip of the resin-coated reinforcement were lower and higher than those obtained from controlled tests.

Investigated the effect of corroded and inhibited reinforcement on the pressure exerted on the pull-out bond separation of control, corroded and resins paste coated steel bar [8]. Overall results showed that the coating values increased as compared to corroded specimens, resulting in adhesion properties from the resins to strengthen the reinforcement and act as a protective coat against corrosion.

Studied the bond behavior of corroded reinforcement bars and found that mass loss of reinforcement due to corrosion reaches about 2%, concrete cracks are formed along the bar [9]. A little Corrosion increases both the bond strength and the bond stiffness, but the slip at failure is significantly reduced. It was stated that when the mass loss exceeds 2%, the bond strength will decrease.

Investigated the bond strength of steel bars coated with epoxy resin and embedded in underwater concrete [10]. Experimental work was carried out and it was found that the maximum terminal voltage is affected by the amount of wash loss.

Studied the effects of accelerated corrosion on the bond strength of steel bars and concrete and the results showed that samples of high strength concrete and corroded reinforcement showed a greater decrease in bond strength due to cracking of the concrete during the test [11].

Studied and evaluated the effect of corrosion on the bond between the steel and concrete interface of corrosive and resins/exudates coated members [12]. The experimental models were subjected to tensile and pull-out bond strength and the results obtained indicated that the failure load, bond strength, and maximum slip to those obtained by the control and coated members were higher than corroded members. Overall results showed good bonding characteristics and effectiveness in the use of ficus glumosa resins/exudates as protective materials.

Investigated the effect of various barrier layers on steel bars to protect them from corrosion [13]. They have used four different coatings, namely polyimide silicon epoxy with two different pigments, polyester isocyanate polyaromatic and aromatic acrylic polyol isocyanate. The conclusion is that the coating formulation based on epoxy-silicon-polyamide resin has good mechanical properties in addition to protecting steel bars from corrosive media.

Investigated the fundamental details for the reduction in service life, integrity, and capacity of reinforced concrete structures in the marine environment of saline origin [14]. The results obtained on the comparison showed that the failure bond load, bond strength, and maximum slip decreased to 21.80% and 32. 00% in the corroded samples, respectively, while the coating samples were 51.90%, 74.90% and 47.14%. Overall results showed a lower percentage and greater percentage of corroded members. This justifies the effect of corrosion on the strength capacity of corroded and coated members.

Evaluated the corrosion of steel reinforcement as a function of the degree of bonding properties between concrete and reinforcement [15]. They evaluated the pull-out bond test to determine bond characteristics between the concrete and the corroded steel bar. Pull-out tests were performed on samples with and without compulsive reinforcement. Experimentally, results were obtained from load and free-end slip behavior has been studied and the strength of bonding for the analysis of finite elements with corroded reinforcement in reinforced concrete members.

Assessed the characteristics of coated and non-coated reinforcing steel embedded members in concrete members and exposed them to a harsh environment [16]. Collective results show that corrugated models with weak maximum slip during split separation testing and high failure load have lower bond strength. Non-corroded and exudates/resins coated models have high bond strength and low failure load. Exudates/resin designs show high protective properties against corrosion effects, thereby acting as inhibitors. Exudates/resins coated models exhibited high-performance resistance properties for bond strength and maximum slip with minimal failure compared to corroded models.

Investigated the adhesive strength of high-strength concrete with high-strength reinforcing steel. Concrete with a compressive strength of about 70 MPa and a steel grade of 500 MPa was used [17]. It was concluded that the extracted samples with smaller stem sizes had higher bond strength than samples with larger stem diameters. The test results also show that the initial hardness increases with the amount of concrete around the reinforcement.

Investigated the effect of inhibitors on reinforced steel coating in an accelerated experimental process of embedded steel failure bond strength over 150 days [18]. Overall results showed high values of control and exudates/adhesive coating pull-out bond strength against corroded specimens.

Investigated the use of eco-friendly corrosion inhibitors of natural source exudates/resins, coated to reinforcing steel of thicknesses 150μm, 300μm, and 450μm and embedded into reinforced concrete cubes, cured and accelerated in rapid corrosive media while pull-out bond strength parameters are investigated against non-coating [19]. In comparison, the results of the corroded models decreased while the control and cola aluminum exudates/resins increased in the steel bar coated specimens. Overall results showed that natural exudates/resins have corrosion potential inhibitive effects in steel reinforcement in concrete structures in areas where chloride is expected.

Investigated the strength of the bond between concrete and reinforcement that led to diameter reduction due to the diminishing effect of reinforcing steel from the coastal area with saltwater [20]. The application of Artocarpus altilis resin extracts on reinforcing steel with a coating thickness of 150μm, 300μm, and 450μm, and non-coated reinforcing steel was embedded into a concrete cube, immersed in sodium chloride, and accelerated corrosion process implored for 150 days. Comparative results show that the values of the corroded samples decreased and the exudates/resins coated samples increased. While in control. Overall results showed higher values of pull-out bond strength under control and coated exudates/resins against corroded specimens.

Studied the effect of olibanum exudates/resins in curbing the corrosion tendency of reinforcing steel in the coastal zones with the impact of saltwater on concrete structures [21]. Tests have shown that non-coated specimens are corroded and showed deterioration. The mean percentile bond strength load was 331.34% compared to the control difference and coated members of 45.66% and 71.84%. The mean maximum slip values are 0.083567 mm and represented 33.87% and 75.30% compared to control and coated -25.30%. The test results reviewed that the corroded models had low bond strength and high failure bond load and low maximum slip, whereas exudates/resins coated models had lower experimental models have shown that exudates/resins members have higher percentages values compared to corroded samples.

Investigated the bond strength of reinforcing steel in self-compacting concrete. They came to the conclusion that self-compacting concrete samples had a higher bond with reinforcement than normal concrete samples and that the correlation between bond strength and compressive strength of normal concrete was more consistent[22].

Investigated the impact of corrosion attack on Acacia Senegal exudates/resins paste coated and non-coated reinforcing steel embedded in concrete cubes and immersed in aggressive media for 178 days [23]. The obtained results show that non-coated members corroded and failed in the bond loading percentage value of 56.6199% and 59.15% against the controlled and exudates/resins coated members. Bond strength loads showed 83.04% and 94.92% and -45.36%, respectively, percentage values decreased against decayed and exudates/resins coated members. In comparison, the values of corrugated specimens are decreased but regulated and the exudates/resins coated members are increased, indicating the potential of acacia senegal as inhibitors.

2.1 Materials

The research involved the direct application of environmentally and eco-friendly extracted exudates/resins used to control the effect of corrosion attacks by coating steel embedded in concrete structures and immersed in sodium chloride (NaCl) solution with varying thickness. Laboratory experimental samples reflecting the acid level of sea salt concentration in reinforced concrete cubes. The embedded reinforcement steel is completely immersed in water and the samples are maintained in the pooling tank for the corrosion accelerated process. Samples were designed with 36 numbered reinforced concrete cubes measuring 150 mm × 150 mm × 150 mm, immersed in sodium chloride (Sodium Chloride) NaCl for 28 days for exhaust bond testing for all controlled, unattached, and coated specimens embedded in the 12 mm diameter reinforcement center Solution between 1 - 360 days. Samples of acid media were updated monthly and samples were monitored for high performance.

2.1.1 Aggregates

Both (fine and coarse) aggregates were purchased. Both met the requirements of [24].

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. Meets Cement Requirements [25].

2.1.2 Cement

The water samples were clean and free from contaminants. Freshwater was obtained from a pipe in the Civil Engineering Laboratory, Kenule Beeson Saro-Wiwa Polytechnic, Bori, and rivers. Water [26] met the requirements.

2.1.4 Structural Steel Reinforcement

Reinforcements are obtained directly from the market at Port Harcourt [27].

2.1.5 Corrosion Inhibitors (Resins / Exudates) Pycnanthus angolensis (African/false nutmeg)

The reddish like gum exudates was obtained from the tree bark by tapping process from the forestry reserves of Trans – Amadi in Port Harcourt, Rivers State.

2.2 Methods

Corrosion acceleration was tested on high-yielding steel (reinforcement) with a diameter of 12 mm and a length of 650 mm. Adhesives with 150µm, 300µm, 450µm, and 600µm coatings before corrosion testing. The test cubes were cast with a 150 mm x 150 mm x 150 mm metal mold and demolished after 72 hours. Samples were treated at room temperature in tanks 28 days before the initial curing period, followed by a rapid accelerated corrosion test and a test method that allowed 360 days of regular monthly monitoring. For corrosion-accelerated samples the cubes were taken every 3 months for 90 days, 180 days, 270 days, and 360 days, and failure bond loads, bond strength, maximum slip, reduction/increase of cross-sectional area, and weight loss/steel reinforcement examined.

2.3 Accelerated Corrosion set-up and Testing Method

In real and natural phenomena, the manifestation 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 and less time to unravel by introducing accelerated media that represent the saltwater of the sea area. The samples were immersed in 5% NaCl solution for 360 days to test the surface and mechanical properties of the changes and effects, and to test both unlimited and exudate/resin coated specimens.

2.4 Pull-out Bond Strength Test

The tensile-bonding strength test of concrete cubes was carried out on 36 samples out of a total of 36 samples with filtered water, non-coating and coated members, and subjected to a 50kN universal testing machine according to BSEN12390-2. 36 cubes size 150 mm × 150 mm × 150 mm, embedded in the center of a single 12 mm diameter concrete cube.

2.5 Tensile Strength of Reinforcement Bars

To determine the yield and tensile strength of the bars, the 12 mm restricted, uncoated (corroded) and coated diameter steel bar reinforcement is tested under tension under a universal test machine (UTM) and subjected to direct tension until failure and failure loads are recorded.

3.1 Experimental Results and Discussions

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 Pycnanthus angolensis (African/false nutmeg) 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.

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

Sample Numbers	CPA	CPA1	CPA2	CPA3	CPA4	CPA5	CPA6	CPA7	CPA8	CPA9	CPA10	CPA11
	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)	29.430	29.359	29.424	28.501	29.317	29.561	28.502	29.358	29.423	29.234	29.342	28.456
Bond strength (MPa)	15.692	16.585	15.082	16.013	16.385	17.309	17.402	16.732	16.766	17.472	16.784	17.330
Max. slip (mm)	0.149	0.151	0.141	0.146	0.145	0.144	0.157	0.161	0.169	0.167	0.171	0.169
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)	11.998	11.990	11.999	11.998	11.989	12.008	11.999	11.988	11.998	11.995	11.989	11.999
Rebar Diameter- at 28 Days Norminal(mm)	11.998	11.990	11.999	11.998	11.989	12.008	11.999	11.988	11.998	11.995	11.989	11.999
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)	0.577	0.577	0.575	0.577	0.577	0.578	0.578	0.577	0.579	0.576	0.576	0.584
Rebar Weights- at 28 Days NorminFS(Kg)	0.577	0.577	0.575	0.577	0.577	0.578	0.578	0.577	0.579	0.576	0.576	0.584
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

Sampling and Durations	Samples 1 (90 days)			Samples 2 (180 Days)			Samples 3 (270 Days)			Samples 4 (360 Days)		
Failure Bond Loads (kN)	17.520	16.832	17.122	16.565	15.813	16.680	16.259	16.567	16.265	17.500	16.379	17.113
Bond strength (MPa)	10.242	10.253	10.017	10.239	10.006	9.978	9.777	10.465	9.440	9.929	9.776	10.080
Max. slip (mm)	0.081	0.084	0.085	0.094	0.084	0.088	0.087	0.077	0.083	0.084	0.084	0.084
Norminal 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)	11.998	11.990	11.999	11.998	11.989	12.008	11.999	11.988	11.998	11.995	11.989	11.999
Rebar Diameter- After Corrosion(mm)	11.955	11.948	11.947	11.958	11.939	11.964	11.956	11.945	11.953	11.952	11.939	11.957
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.043	0.042	0.052	0.041	0.050	0.044	0.043	0.043	0.045	0.043	0.050	0.042
Rebar Weights- Before Test(Kg)	0.577	0.577	0.575	0.577	0.577	0.578	0.578	0.577	0.579	0.576	0.576	0.584
Rebar Weights- After Corrosion(Kg)	0.524	0.523	0.524	0.522	0.524	0.518	0.523	0.523	0.526	0.521	0.525	0.531
Weight Loss /Gain of Steel (Kg)	0.053	0.054	0.051	0.055	0.053	0.060	0.054	0.054	0.053	0.054	0.051	0.053

Table-3.3: Results of Pull-out Bond Strength Test (τu) (MPa) of Pycnanthus angolensis (African/false nutmeg) 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)	29.431	29.359	29.341	28.455	29.317	29.018	29.542	29.358	29.560	29.235	29.017	29.541
Bond strength (MPa)	15.369	16.261	14.759	15.689	16.062	16.985	17.079	16.409	16.443	17.149	16.460	17.007
Max. slip (mm)	0.159	0.160	0.151	0.156	0.155	0.154	0.167	0.171	0.179	0.176	0.181	0.179
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)	11.998	11.989	11.999	11.998	11.995	12.008	11.999	11.988	11.989	11.999	11.990	11.998
Rebar Diameter- After Corrosion(mm)	12.051	12.041	12.051	12.051	12.048	12.061	12.051	12.040	12.041	12.052	12.042	12.050
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052
Rebar Weights- Before Test(Kg)	0.576	0.584	0.575	0.577	0.579	0.577	0.578	0.577	0.578	0.576	0.577	0.577
Rebar Weights- After Corrosion(Kg)	0.643	0.651	0.643	0.646	0.657	0.656	0.647	0.645	0.656	0.646	0.646	0.646
Weight Loss /Gain of Steel (Kg)	0.068	0.068	0.069	0.069	0.078	0.079	0.069	0.069	0.078	0.070	0.069	0.069

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

	Control, Corroded and Resin Steel bar Coated											
Sample	Non-Corroded Specimens Average VFSues				Corroded Specimens Average VFSues				Coated Specimens Average VFSues of 150µm, 300µm, 450µm, 6000µm)			
Failure load (KN)	29.404	29.126	29.094	29.010	17.158	16.352	16.364	16.998	29.377	28.930	29.487	29.264
Bond strength (MPa)	15.786	16.569	16.967	17.195	10.171	10.074	9.894	9.928	15.463	16.246	16.644	16.872
Max. slip (mm)	0.147	0.145	0.162	0.169	0.083	0.089	0.082	0.084	0.157	0.155	0.172	0.179
Norminal 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)	11.995	11.998	11.995	11.994	11.995	11.998	11.995	11.994	11.995	12.001	11.992	11.996
Rebar Diameter- After Corrosion(mm)	11.995	11.998	11.995	11.994	11.950	11.954	11.951	11.949	12.048	12.053	12.044	12.048
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.000	0.000	0.000	0.000	0.046	0.045	0.043	0.045	0.052	0.052	0.052	0.052
Rebar Weights- Before Test(Kg)	0.576	0.577	0.578	0.578	0.576	0.577	0.578	0.578	0.578	0.577	0.577	0.577
Rebar Weights- After Corrosion(Kg)	0.576	0.577	0.578	0.578	0.523	0.521	0.524	0.526	0.646	0.653	0.649	0.646
Weight Loss /Gain of Steel (Kg)	0.000	0.000	0.000	0.000	0.053	0.056	0.054	0.053	0.068	0.075	0.072	0.070

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)	71.374	78.116	77.797	70.674	-41.594	-43.477	-44.504	-41.917	71.216	76.917	80.194	72.167
Bond strength (MPa)	55.218	64.467	71.488	73.201	-34.227	-37.987	-40.554	-41.157	52.038	61.257	68.220	69.943
Max. slip (mm)	77.202	63.921	97.732	102.034	-46.978	-42.731	-52.212	-53.127	88.601	74.616	109.256	113.340
Norminal 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)	0.000	0.000	0.000	0.000	0.001	0.017	0.026	0.009	0.001	0.017	0.026	0.009
Rebar Diameter- After Corrosion(mm)	0.381	0.375	0.364	0.376	-0.813	-0.824	-0.771	-0.818	0.820	0.831	0.777	0.824
Cross- Sectional Area Reduction/Increase (Diameter, mm)	0.000	0.000	0.000	0.000	-13.163	-14.637	-17.177	-14.384	15.158	17.147	20.740	16.800
Rebar Weights- Before Test(Kg)	0.031	0.025	0.028	0.029	0.248	0.025	0.025	0.294	0.250	0.025	0.280	0.294
Rebar Weights- After Corrosion(Kg)	10.037	10.698	10.238	10.003	-18.987	-20.103	-19.281	-18.641	23.437	25.161	23.886	22.912
Weight Loss /Gain of Steel (Kg)	0.000	0.000	0.000	0.000	-22.887	-25.887	-25.469	-24.403	29.680	34.929	34.172	32.280

3.2 Failure load, Bond Strength, and Maximum slip

The basis of reinforced concrete is mainly based on the connection mechanism between steel bars and concrete. The properties of the steel-concrete interface are affected by a large number of parameters related to steel and concrete and their interactions. These various aspects are discussed in detail in [28]). This property has been explored since the 1940s, such as Rehm [29], who investigated the factors affecting the relationship between steel bars and concrete. Other suitable studies are those conducted by [30] and Jiang *et al*. [31]. All these basic investigations were carried out using reinforcing steel with a diameter greater than 12.0 mm. Corrosion of reinforcing steel has been a crucial factor affecting the designed lifespan of structures built within the coastal areas with a high concentration of salt and related substances. Data presented in tables 3.1 - 3.3 and summarized in 3.4 - 3.5, plotted graphically in figures 1-2b are the laboratory results of experimental work conducted on 36 concrete cubes made up of 3 subs, controlled, corroded, and coated samples. The failure bond load, bond strength, and maximum slip subjected to pressure loads of failure as documented in the tables and presented figures using 50KN Instron Universal Testing Machine using the prescribed standard procedures for the pullout bond test. The obtained minimum and maximum calculated average and percentiles from the results of the failure bond load are controlled 29.01kN and 29.404 kN (70.674% and 78.166%), corroded 16.352 kN and 17.158 kN (-44.504% and -41.594%) and coated 28.93 kN and 29.487 kN (71.216% and 80.194%). The results indicated a decreased value in the corroded as against the controlled and coated with the coated having closed average and percentile values to the standard controlled samples. This is an indication that corroded samples failed at low load application that resulted from corrosion effect on the mechanical properties of the reinforcing steel.

The bond strength values for control are 15.786 MPa and 17.195 MPa (55.218% and 73.201%), corroded 9.894 MPa and 10.171 MPa (-41.157% and -34.227%), coated 15.463 MPa and 16.872 MPa (52.038% and 69.943%) respectively.

The maximum slip results were controlled 0.145 mm and 0.169 mm (63.921% and 102.034%), corroded 0.082 mm and 0.089 mm (-53.127% and -42.731%), and coated 0.155 mm and 0.179 mm (74.616% and 113. 34%) respectively. The results of bond strength and maximum slip showed decreased average and percentile values as compared to the set standard from controlled samples. The coated samples have increased values over the controlled resulting from the bonding characteristics exhibited by the exudates /resin material which resulted in higher load in bond strength and slippage.

The data for comparison of maximum obtained values are failure bond load are corroded -41.594% against 78.166% and 80.194% controlled and coated, bond strength is -34.227% against 73.201% and 69.943% and maximum slip are -42.731% against 102.034% and 113.34% respectively of controlled and coated. The summarized computed and compared results of failure bond load, bond strength and maximum slip of the controlled, corroded and coated samples showed that the effect of sodium chloride as detailed in the "2.2 Experimental procedures" has adversely affected the mechanical properties of reinforcing steel of uncoated (corroded) samples which has resulted to poor performances, low load at failure state, less bond strength and slippage [8-10]. The coated samples exhibited the potential of sustaining the negative effect of corrosion on reinforcing steel and by forming good contact and interlock between concrete and reinforcing steel by reducing the stress existing in the concrete surroundings housing the steel.

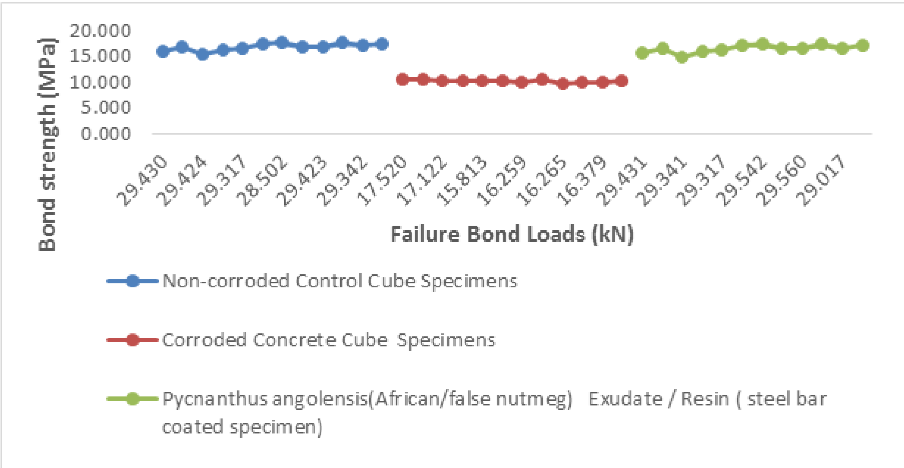

Fig-1: Failure Bond loads versus Bond Strengths

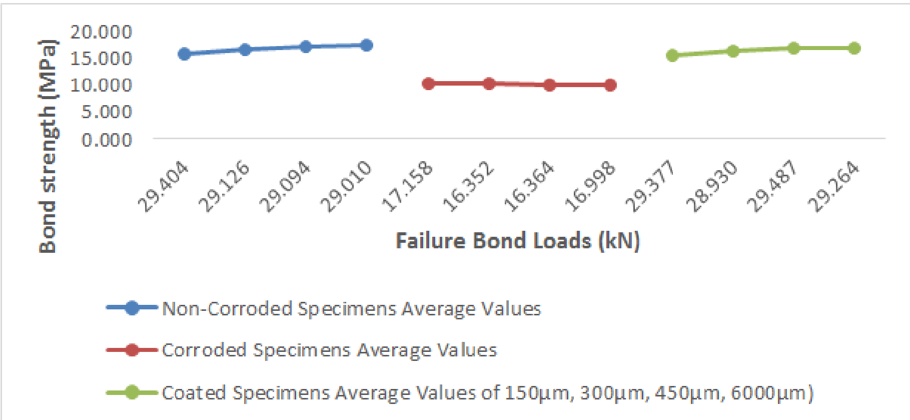

Fig-1a: Average Failure Bond loads versus Bond Strengths

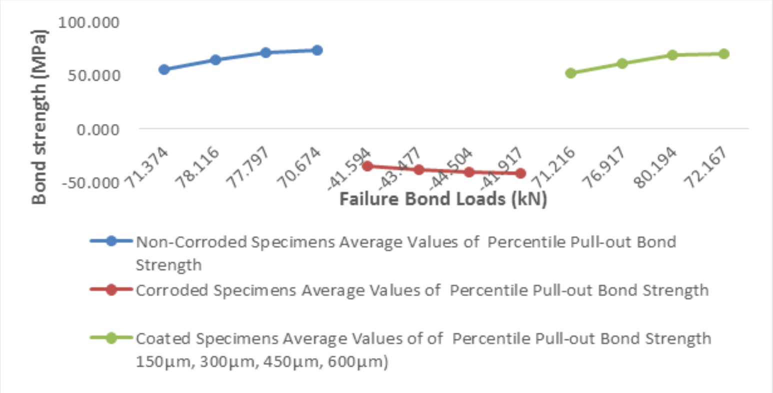

Fig-1b: Average Percentile Failure Bond loads versus Bond Strengths

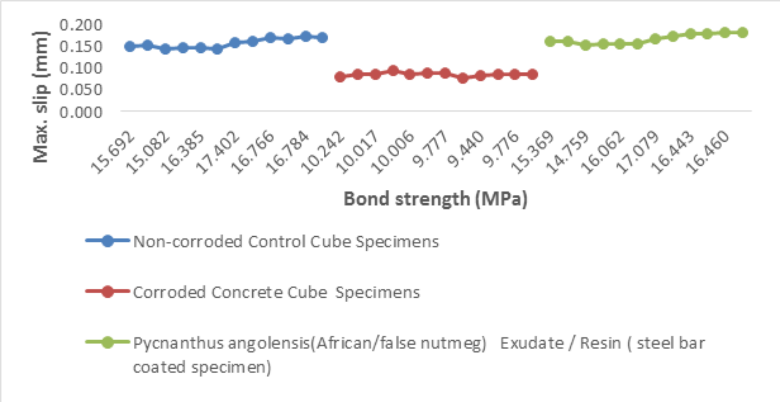

Fig-2: Bond Strengths versus Maximum Slip

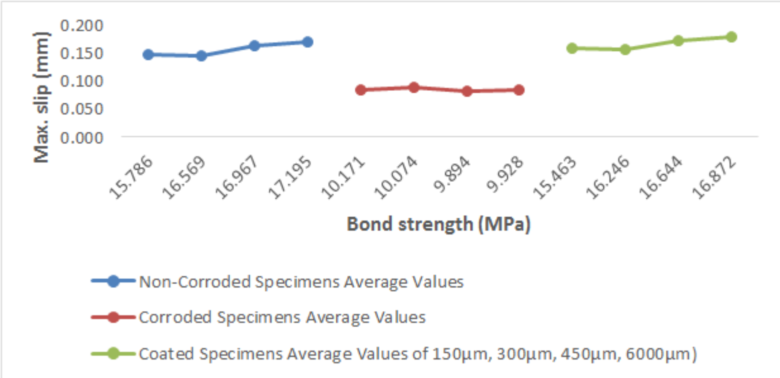

Fig-2a: Average Bond Strengths versus Maximum Slip

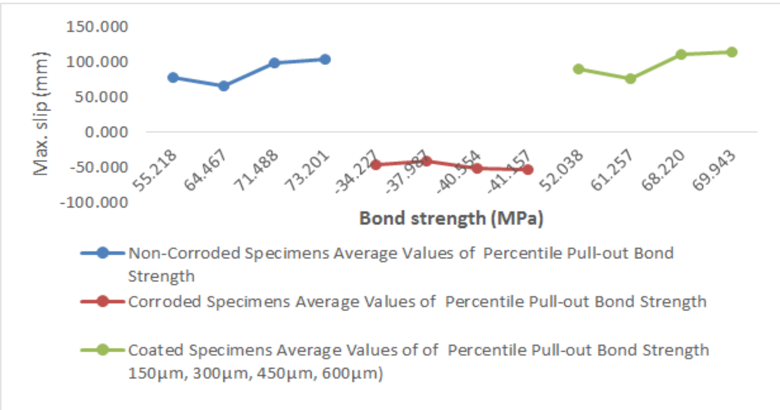

Fig-2b: Average Percentile Bond Strengths versus Maximum Slip

3.3 Mechanical Properties of Reinforcing Bars (Cross-Sectional Reduction and Weight loss / Gain)

Mechanical interlocking: This sliding joint becomes more important as the relative displacement in the composite mechanism increases. The force of transmission mechanism mainly relies on mechanical interlocking between steel reinforcement and concrete. For smooth rods, the mechanisms of chemical adhesion and friction are the most important. In the case of deformed bars, the mechanical locking of steel bars in concrete is the main mechanism that determines the behavior of the bond strength during shear [32-34]. This study investigated the performances of reinforcing steel the use of exudates / resins to improve bond strength and slip problems in plain reinforcing steel.

The data shown in tables 3.1, 3.2 and 3.3 and summarized in table 3.4 - 3.5, accounted for the behavioral mechanical properties of reinforcing steel exhibited by controlled, uncoated (corroded) and coated concrete cubes, subject to failure conditions using the Instron Universal Testing Machine with designed load of 50KN after an induced accelerated corrosion test processes for 360 days and periodic performance tests of samples at 3 month intervals are as shown in the tables and plotted in Figures 1-6b.

The results are summarized in the minimum and maximum values obtained from Tables 3.4 and 3.5., of the nominal diameter of the steel bars of all samples was 100%, and the minimum and maximum diameters of steel bars measured before the test was 11.994 mm and 11.998 mm, respectively. The diameter of the uncoated (corroded) reinforcement sample after the corrosion test was 11.949 mm and 11.954 mm (-0.824% and -0.771%) after coating were 12.044mm and 12.053mm (0.777% and 0.831%). The results of the cross-sectional area for uncoated (corroded) are 0.043mm and 0.046 mm (-17.177% and -13.163%) for coating 0.052mm and 0.055mm (15.158% and 20.74%).

The rebar weight pre-test result for all samples was 0.576 Kg and 0.578 kg (0.025% and 0.031%), the weights after the corrosion test were 0.521 kg and 0.526 kg (-20.103% and -18.641%), coating 0.646 kg and 0.653 kg (22.912% and 25.161%).) and the weight loss / weight gain of corroded steel is 0.053 kg and 0.056 kg (-25.887% and -22.887%), and the coating values are 0.068 kg and 0.075 kg (29.68% and 34.929%). The results obtained and presented in a list of drawings of the effects of corrosion on uncoated and coated reinforcing steel. Figures 3 and 6b on the diameter of the reinforcement show that the diameter of the reinforcement without layers decreases by a maximum of -0.771% and the coating increases by 0.831%, for the cross-sectional area of corrosion has a maximum reduction value of - 13.163% and the coating increases 20.74%, the weight loss and increase in corrosion is - 22.887 % decreased (loss) and layers increased by 34.929% (gain). Indications analyzed from experimental work showed the effect of corrosion on uncoated (corroded) concrete cubes causes a decrease in the cross-sectional area as well as a decrease in unit weight, while the cube-coated concrete has diameter and cross-sectional area and increased with minute incremental unit weight due to differences in the thickness of the reinforcing steel layers [16, 20, 21].

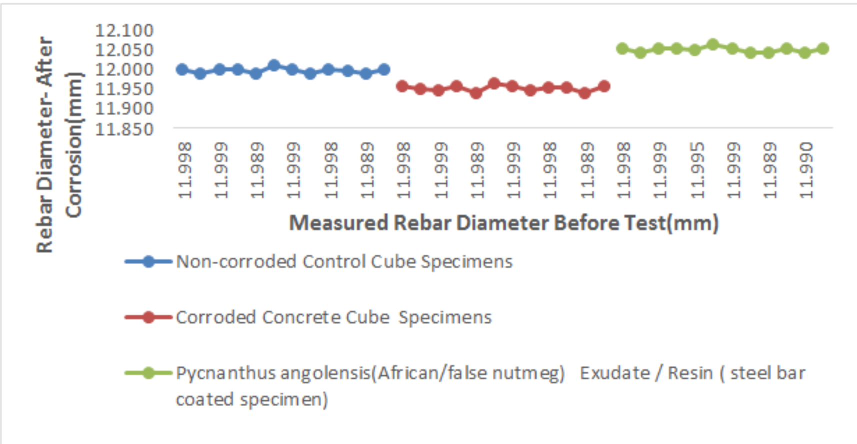

Fig-3: Measured (Rebar Diameter before Test vs Rebar Diameter- after Corrosion)

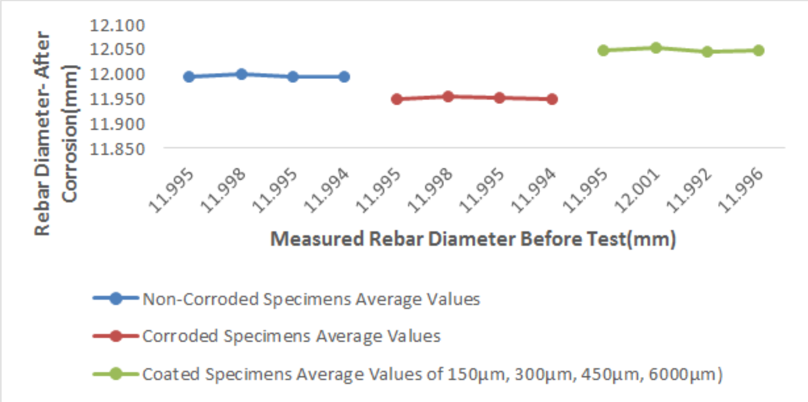

Fig-3a: Average Measured (Rebar Diameter before Test vs Rebar Diameter- after Corrosion)

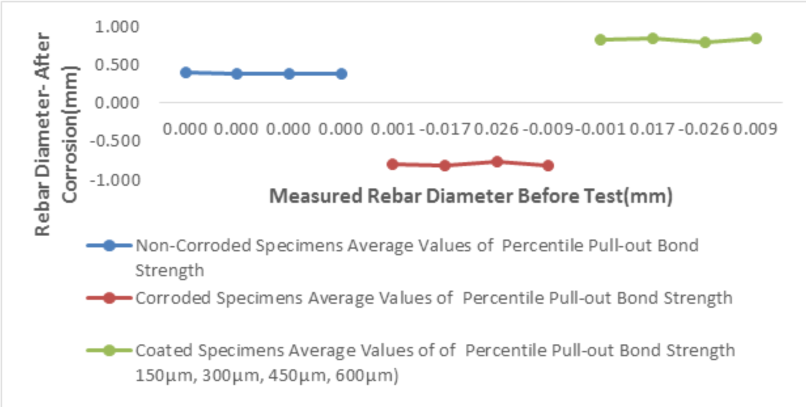

Fig-3b: Average Percentile Measured (Rebar Diameter before Test vs Rebar Diameter- after Corrosion)

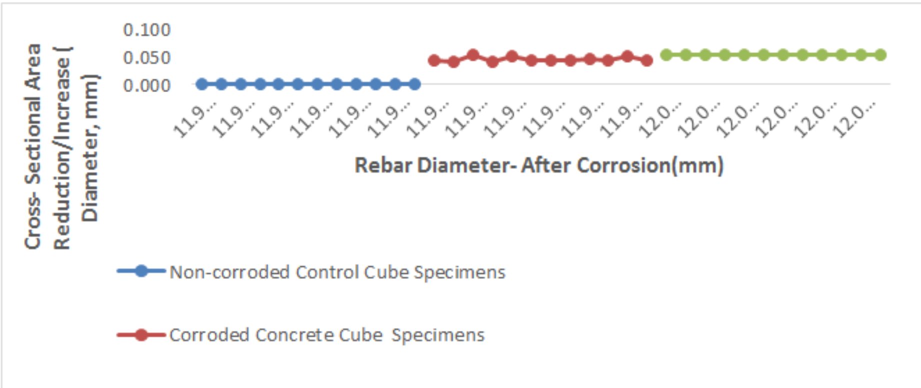

Fig-4: Rebar Diameter- After Corrosion versus Cross - Sectional Area Reduction/Increase

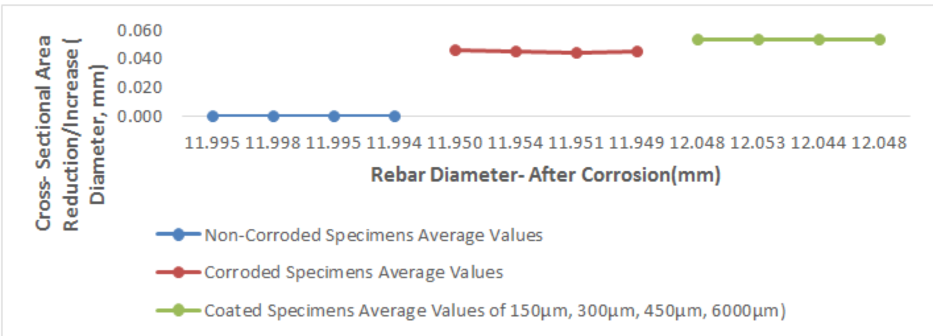

Fig-4a: Average Rebar Diameter- after Corrosion versus Cross – Sectional Area Reduction/Increase

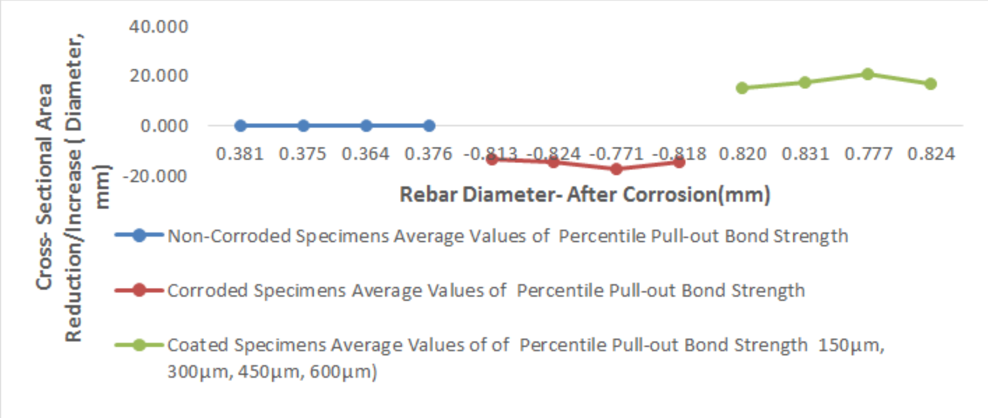

Fig-4b: Average percentile Rebar Diameter- after Corrosion versus Cross –Sectional Area Reduction/Increase

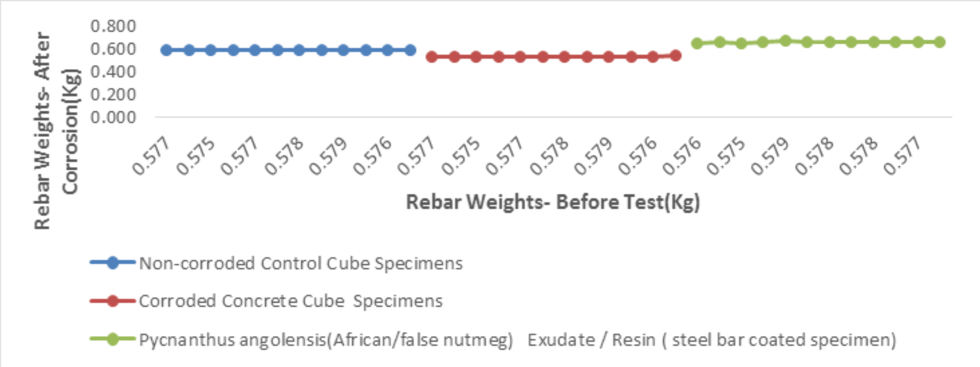

Fig-5: Rebar Weights- before Test versus Rebar Weights- after Corrosion

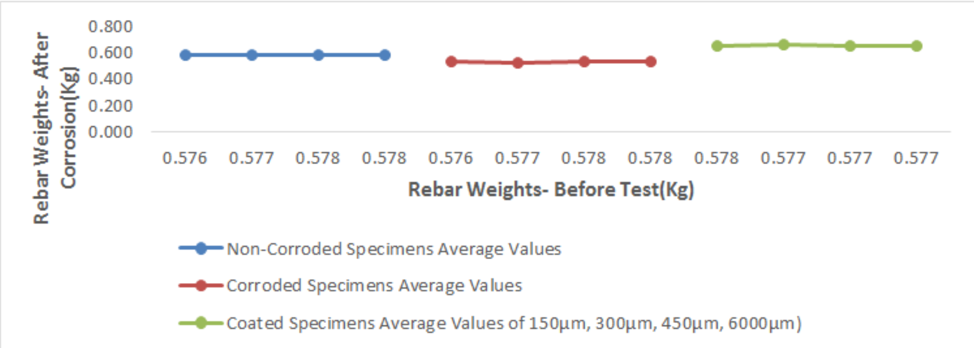

Fig-5a: Average Rebar Weights- before Test versus Rebar Weights- after Corrosion

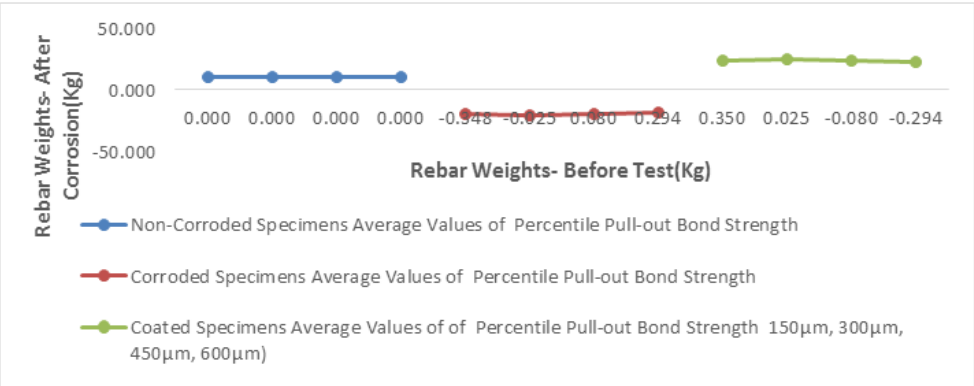

Fig-5b: Average Percentile Rebar Weights- before Test versus Rebar Weights- after Corrosion

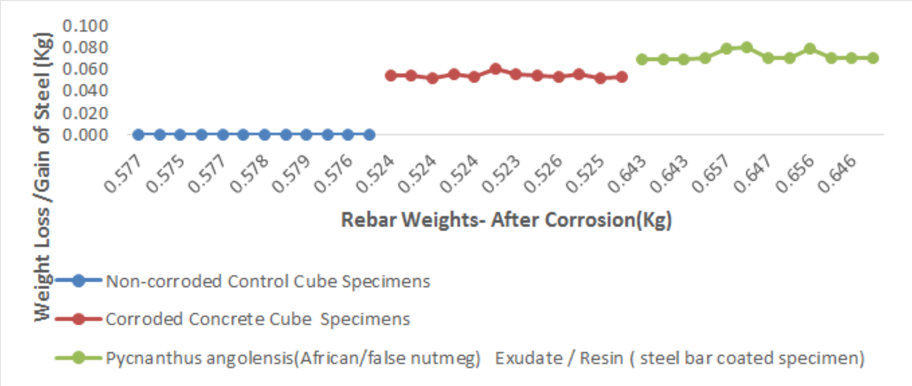

Fig-6: Rebar Weights- after Corrosion versus Weight Loss /Gain of Steel

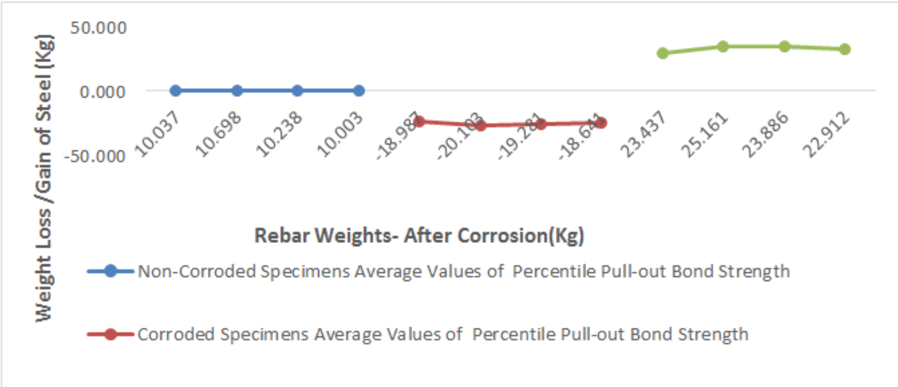

Fig-6a: Average Rebar Weights- after Corrosion versus Weight Loss /Gain of Steel

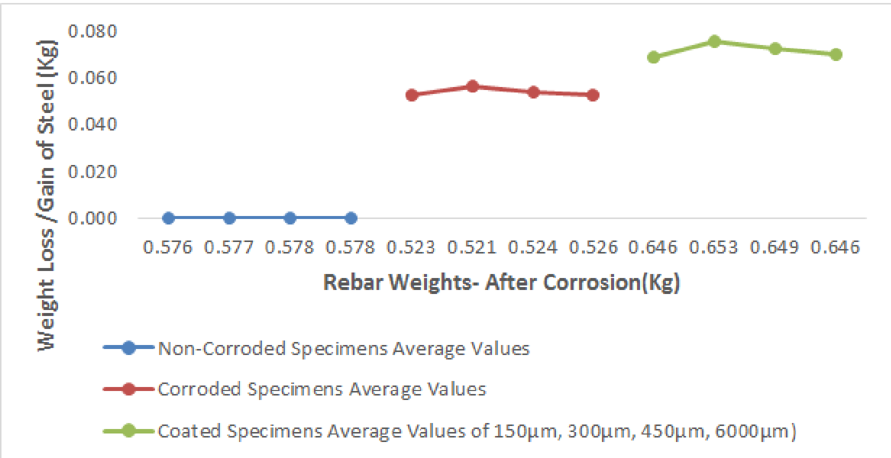

Fig-6b: Average percentile Rebar Weights- after Corrosion versus Weight Loss /Gain of Steel

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

The data in tables 3.1, 3.2 and 3.3 and figures 3,4,5 and 6 are the results of 36 sampled concrete cubes subdivided into 12 controlled cured in a fresh water tank for 360 days, 12 uncoated and 12 coated samples induced 5% aqueous sodium chloride (NaCl) solution and accelerated for 360 days and detailed and described in 3.1 - 3.3 and summarized in Tables 3.4 - 3.5 and plotted graphically in figures 3a, 3b, 4a, 4b, 5a, 5b, 6a and 6b for average values and percentile values of failure loads, bond strength and maximum slip. Other investigated parameters are reduction / increase of the cross-sectional area, diameter of reinforcement before / after corrosion, weight loss / weight gain. The results obtained by comparison showeded that the failure loads from controlled and coated samples maintained closed range of values with coated dorminanance, whereas the corroded elements produced lower loads, the same factors for bond strength and maximum slip. Regarding the mechanical properties of reinforcing steel, the effect of corrosion on reinforcing steel shows a decrease in the cross section of the rebar diameter compared to the nominal diameter before testing, weight reduction is also observed, an increase in the cross-sectional area, an increase in the diameter and minute increase in weight resulting from coating material as compared with the nominal reinforcement, which is due to differences in the thickness of the layered materials. It can be concluded that the exudate / resin studied has shown effective inhibiting properties against corrosion attack and can be used as a corrosion inhibitor.

4.0 CONCLUSIONS

In the experiment, the results obtained were summarized as follows:

i. The studied exudate / resin has a corrosion-inhibiting effect, as the seal is resistant to corrosion and attack.
ii. The interaction between concrete and steel in the coated component is greater than that of the corroded sample
iii. The bonding properties in coated and controlled components are greater than in those that are corroded.
iv. The slightest damage to the connection, connection breakage and maximum slippage are listed in the corroded elements.
v. The coverage and control patterns show higher bond load values and bond strength.
vi. Weight loss and area reduction were recorded mainly in the corroded layers and in controlled samples

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