Reinforcing Steel and Concrete Bond Behavior of Corroded and Coated Members Embedded in Reinforced Concrete Structures

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ABSTRACT

The effect of load transfer between steel and concrete originates from weak bonds between steel and hardened cement, expanding its volume and creating stress in the surrounding concrete and reduces the effective cross-sectional area of reinforcing bars and weakens the bond between reinforcement and concrete. This study investigated the comparison of garcinia kola exudates/resin coated reinforcement and corroded members pull-out bond and splitting strengths of concrete cubes embedded with reinforcements and immersed in accelerated media. Results from table 3.1, summarized into 3.4 and 3.5, as shown in figures 3.1 – 3.4, corroded summed up to 14.71556kN which represented -43.1929% against 76.03443% and 80.91966% percentile difference of control and coated exudates/resin members. Bond strength load of corroded summed up to 5.64444MPa, which represented percentile value of -53.24803% against 50.31749% and 87.77559% percentile difference of control and coated and maximum slip average corroded values summed to 0.075866mm, which represented -28.949% against 40.74399% and 129.8769% percentile difference of control and coated. Corroded specimens value in comparison decreased while control and garcinia kola exudates/ resins steel bar coated specimens increased which resulted to inhibitive properties of exudates coated specimens. Indication from experimented results showed higher values of pullout bond strength in control and exudates/resin coated to corroded specimens. Results showed that resins / exudates enhances strength to reinforcement and serves as protective coat against corrosion.

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

1.0 Introduction

The products and results of corrosion occur when there is chemical reaction between metal and its environment Rust products form on the bar, expanding its volume and creating stress in the surrounding concrete causes cracking, spalling and staining of concrete, and reduces the effective cross-sectional area of reinforcing bars and weakens the bond between reinforcement and concrete, seriously affecting the durability, and the service-life of structures (Almusallam *et al*. [1], Cabrera [2], Rashid *et al*. [3]). Bond strength primarily originates from weak chemical bonds between steel and hardened cement, but this resistance is broken at a very low stress, bonding at the steel and concrete interface affects the load transfer between steel and concrete. Deformed (ribbed) reinforcing steel bars, and under increasing slip bond depend principally on the bearing, or mechanical interlock, between ribs rolled on the surface of the bar and the surrounding concrete. Bond strength is the maximum bond stress developed by friction between reinforcement and concrete, this can easily be regarded as a shear stress over the surface of the bar (Cairns and Abdullah, [4]), the interlocking mechanism along the reinforcing bar interfaces with surrounding concrete.

Charles et al. [5] studied and evaluated the effect of corrosion on bond existing between steel and concrete interface of corroded and resins / exudates coated reinforcement with ficus glumosa extracts from trees. Experimental samples were subjected to tensile and pullout bond strength and obtained results indicated failure load, bond strength and maximum slip values of coated were higher by 33.50%, 62.40%, 84.20%, non- corroded by 27.08%, 55.90% and 47.14% respectively. For corroded cube concrete members, the values were lower by 21.30%, 38.80% and 32.00% on failure load, bond strength and maximum slip to those ones obtained by non-corroded and coated members. The entire results showed good bonding characteristic and effectiveness in the use of ficus glumosa resins / exudates as protective materials against corrosion.

Charles et al. [6] investigated the primary causes of the reduction of service life, integrity and capacity of reinforced concrete structures in the marine environment of saline origin is corrosion. Results obtained on comparison showed failure bond load, bond strength and maximum slip decreased in corroded specimens to 21.30%, 38.80% and 32.00% respectively, while coated specimens 51.69%, 66.90%, 74.65%, for non-corroded specimen, 27.08%, 55.90% and 47.14%. Entire results showed lower percentages in corroded and higher in coated members. This justifies the effect of corrosion on the strength capacity of corroded and coated members.

Charles et al. [7] investigated the Corrosion of steel reinforcement in concrete is one of the principal factor that caused the splitting failures that occurred between steel and concrete, the used of epoxy, resin/exudates has been introduced to curb this trend encountered by reinforced structures built within the saline environment. Pullout bond strength test results of failure bond load, bond strength and maximum slip were 21.30%, 36.80% and 32.00% for corroded members, 36.47%, 64.00% and 49.30% for coated members respectively. The values of corroded members were lower compared to coated members. Results showed that resins / exudates enhances strength to reinforcement and serves as protective coat against corrosion.

Otunyo and Kennedy [8] investigated the effectiveness of resin/exudates in corrosion prevention of reinforcement in reinforced concrete cubes. Results obtained indicated that the failure bond strength, pull out bond strength and maximum slip of the resin coated reinforced cubes were higher by (19%), (84%) and (112%). respectively than those obtained from the controlled tests. Similar results were obtained for the maximum slip (the resin coated and non-corroded steel members) had higher values of maximum slip compared to the cubes that had corroded steel reinforcements. For the corroded beam members, the failure bond strength, pull out bond strength and maximum slip of the resin coated reinforcements were lower by (22%), (32%) and (32%). respectively than those obtained from the controlled tests.

Charles *et al* [9] investigated the effect of corroded and inhibited reinforcement on the stress generated on pullout bond splitting of non-corroded, corroded and resins / exudates paste coated steel bar of 150µm, 250µm and 350µm thicknesses from three trees extract of symphonia globulifera linn, ficus glumosa, acardium occidentale l. In comparison, failure loads of symphonia globulifera linn, Ficus glumosa, Acardium occidentale l are 36.47%, 32.50% and 29.59% against 21.30% corroded, bond strength are 64.00%, 62.40%, 66.90 against 38.88% and maximum slip are 89.30%, 84.20%, 74.65% against 32.00% corroded. Entire results showed values increased in coated compared to corroded specimens resulted to adhesion properties from the resins / exudates also enhances strength to reinforcement and serves as protective coat against corrosion.

Charles *et al*. [10] studied the bond strength exhibited by reinforcement embedded in concrete is controlled by corrosion effects. Results showed that uncoated specimens corrosion potential with signs associated with cracks, spalling and pitting. Pullout bond strength results of failure load, bond strength and maximum slip for dacryodes edulis are 75.25%, 85.30%, 97.80%, moringa oleifera lam; 64.90%, 66.39%, 85.57%, magnifera indica; 36.49%, 66.30% and 85.57%, for non-corroded, 27.08%, 5590% and 47.14% while corroded are 21.30%, 36.80% and 32.00%. The entire results showed lower values in corroded specimens as compared to coated specimens; coated members showed higher bonding characteristics variance from dacryodes edulis (highest), moringa oleifera lam (higher) and magnifera indica (high) and coated serves as resistance and protective membrane towards corrosion effects.

Han-Seung Lee *et al.* [11]) evaluated the degree of corrosion of reinforcement as the function of bond properties between concrete and reinforcement. Pull out test were conducted and evaluated to ascertain the effects of reinforcement corrosion on the bond behavior between corroded reinforcement and concrete. Rebars were corroded with the accelerated corrosion method inside the pull-out test specimen to the desired level. Pull-out tests were conducted on specimens with and without confinement reinforcement. The load versus free end slip behavior was studied.

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Cairns and Plizzari [12] affirmed that the split from concrete surrounding resulted from bearing action of ribs that generates bursting forces, the resultant compressive force exerted by the ribs on the concrete is inclined at an angle to the bar axis. A ring tension in the concrete cover around the bar is created by the radial component of the exerted force. As soon as tensile capacity of the ring is exceeded during the development of the bond action, a splitting failure occurs by fracturing the concrete cover surrounding the reinforcement. If the concrete confinement was enough to counterbalance the force generated by bond.

Chung *et al.* [13] investigated experimentally the corrosion effects on bond strength and development length. Different level of corrosion were used to corrode the reinforcement, concrete slab specimens with one steel reinforcing bar were used to evaluate the effect of corrosion level on bond stress and development length of flexural tension members. It was concluded that the average bond stress increases before corrosion level reached 2% and then starts to decrease after 2% corrosion level.

2.0 Experimental program

The present study involves direct application of resins / exudates of trees extract known as inorganic inhibitor, coated on the reinforcing steel surface were studied in this test program. The main objective of this study was to determine the effectiveness of locally available surface-applied corrosion inhibitors under severe corrosive environments and with chloride contamination. The test setup simulates a harsh marine environment of saline concentration in the concrete in the submerged portion of the test specimens, corrosion activity of the steel cannot be sustained in fully immersed samples. The samples were designed with sets of reinforced concrete cubes of 150 mm × 150 mm × 150 mm with a single ribbed bar of 12 mm diameter embedded in the centre of the concrete cube specimens for pull out test and was investigated. To simulate the ideal corrosive environment, concrete samples were immersed in solutions (NaCl) and the depth of the solution was maintained.

2.1 Materials and Methods for Experiment

2.1.1 Aggregates

The fine aggregate and coarse aggregate were purchased. Both met the requirements of [14]

2.1.2 Cement

Portland limestone cement grade 42.5 is the most and commonly type of cement in Nigerian Market. It was used for all concrete mixes in this investigation. The cement met the requirements of [15]

2.1.3 Water

The water samples were clean and free from impurities. The fresh water used was gotten from the tap at the Civil Engineering Department Laboratory, Kenule Beeson Polytechnic, Bori, and Rivers State. The water met the requirements of [16]

2.1.4 Structural Steel Reinforcement

The reinforcements are gotten directly from the market in Port Harcourt, [17

2.1.5 Corrosion Inhibitors (Resins / Exudates) Garcinia kola

The study inhibitor (Garcinia kola) is of natural tree resin /exudates substance extracts. It was sourced from farm plantation, in Ahoada - West Local Government of Rivers State, Nigeria

2.2 EXPERIMENTAL PROCEDURES

2.2.1 Experimental method

2.2.2 Sample Preparation for Reinforcement with Coated Resins / Exudates

Corrosion tests were performed on high yield steel (reinforcement) of 12 mm diameter with 550 mm lengths for cubes, Specimen surfaces roughness was treated with sandpaper / wire brush and specimens were cleaned with distilled water, washed by acetone and dried properly, then polished and coated with (Garcinia kola exudates), resin pastes with coating thicknesses of 150µm, 300µm and 450µm before corrosion test. The test cubes and beams were cast in steel mould of size 150 mm × 150 mm × 150 mm. The specimens were cured at room temperature in the curing tanks for accelerated corrosion test process and testing procedure allowed for 120 days first crack noticed and a further 30 days making a total of 150 days for further observations on corrosion acceleration process.

2.3 Accelerated corrosion set-up and testing procedure

In real and natural conditions the development of reinforcement corrosion is very slow and can take years to be achieved; as a result of this phenomenon, laboratory studies necessitate an acceleration of corrosion process to achieve a short test period. After curing the cubes specimens for 28 days, specimens were lifted and shifted to the corrosion tank to induce desired corrosion levels. Electrochemical corrosion technique was used to accelerate the corrosion of steel bars embedded in cubes specimens. Specimens were partially immersed in a 5% NaCl solution for duration of 150 days, to examine the surface and mechanical properties of rebar.

2.3 Pull-out Bond Strength Test

The pull-out bond strength tests on the concrete cubes were performed 9 specimens each of non-corroded, corroded and exudates/resins coated specimens, totaling 27 specimens on Universal Testing Machine of capacity 50KN in accordance with BS EN 12390-2. The dimensions of the pull-out specimens were 27 cubes 150 mm × 150 mm × 150 mm with a single ribbed bar of 12mm diameter embedded in the centre of the concrete cube. After 150 days, the accelerated corrosion subjected samples were examined to determine bond strength effects due to corrosion and corrosion inhibited samples. Specimens of 150 mm x150 mm x150 mm concrete cube specimens were also prepared from the same concrete mix used for the cubes, cured in water for 28 days, and accelerated with 5% NaCl solution for same 150 days making a total of 178 days was consequently tested to determine bond strength.

2.4 Tensile Strength of Reinforcing Bars

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

3.0 Experimental results and discussion

Tables 3.1, 3.2 and 3.3 are the detailed results of pullout bond strength test of failure bond load, bond strength and maximum slip obtained from 27 samples of control, corroded and garcinia kola exudates/ resins steel bar coated specimens paste on reinforcement embedded in concrete cubes member. Table 3.4 and 3.5 showed the results of average and summary pull-out bond strength values of failure load, bond strength and maximum slip of control, corroded and resins/exudates coated specimens. Figures 3.1 and 3.2 are the plots of entire failure bond load versus bond strength and bond strength versus maximum slip, while figures 3.3 and 3.4 are the plots of average failure bond load versus maximum slip obtained from tables 3.1, 3.2 and 3.3

3.1 Control Concrete Cube Members

Obtained results from table 3.1, are summarized to average percentile values and percentile differences of pull-out bond strength results in tables 3.4 and 3.5 as represented graphically in figures 3.1 – 3.4, obtained average values of failure load are 25.42kN, 26.29667kN, 25.99667kN, summed to 25.90444kN and represented 76.03443% percentile value. Bond strength average values are 8.37MPa, 8.79MPa and 8.79MPa, summed to 8.65MPa and percentile value of 53.24803%. Maximum slip average values are 0.102767mm, 0.111767mm, and 0.1091mm summed to 0.107878mm, represented 30.65536% percentile values.

3.2 Corroded Concrete Cube Members

Results from table 3.1, summarized into 3.4 and 3.5, as shown in figures 3.1 – 3.4, failure bond load are 14.71333kN, 14.74667kN and 14.68667kN, summed to 14.71556kN represented -43.1929% against 76.03443% 80.91966% percentile difference of control and coated exudates/resin member. Bond strength load are 5.583333MPa, 5.763333MPa, 5.586667MPa summed to

5.64444MPa, represented percentile value of -53.24803% against 50.31749% and 87.77559% percentile difference control and coated and maximum slip average values are 0.16173mm, 0.0795333mm, 0.07586mm, summed to 0.075866mm, represented -28.949% against 40.74399% and 129.8769% percentile difference of control and coated. Corroded specimens values in comparison decreased while control and garcinia kola exudates/ resins steel bar coated specimens increased which resulted to inhibitive properties exudates coated specimens.

3.3 Garcinia Kola Exudates/ Resins Steel Bar Coated Specimens Steel Bar Coated Concrete Cube Members

Results from table 3.3 into 3.4 and 3.5, as shown in figures 3.1 – 3.4, obtained failure bond load average values are 25.71333kN, 27.02667kN, 27.13kN summed to 26.6233kN, represented 76.03443% against -43.1929% corroded percentile differences, bond strength average values are 10.22MPa, 10.36MPa, 11.21667MPa summed to 10.59889MPa, represented 53.24803% against -33.474% and maximum slip values are 0.0789mm, 0.086233mm, 0.082567mm summed to 0.1365mm represented 65.32095% against -23.4628% corroded percentile differences. Indication from experimented results showed higher values of pullout bond strength in control and exudates/resin coated to corroded specimens.

Table 3.1: Results of Pull-out Bond Strength Test (τu) (MPa)

S/no		Non-corroded Control Cube Specimens								
Concrete Cube	**Sample**	ACB1	BCB1	BCB1	DCB1	ECB1	FCB1	GCB1	HCB1	ICB1
BBSA1-1	Failure Bond Loads (kN)	26.16	25.3	24.8	27.01	25.51	26.37	26.51	25.31	26.17
BBSA1-2	Bond strength (MPa)	8.5	8.37	8.24	8.9	8.36	9.11	8.9	8.96	8.51
BBSA1-3	Max. slip (mm)	0.1161	0.1011	0.0911	0.1211	0.1041	0.1101	0.1111	0.0961	0.1201
BBSA1-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12

Table 3.2: Results of Pull-out Bond Strength Test (τu) (MPa)

S/no		Corroded Cube Specimens								
Concrete Cube	**Sample**	ACB2	BCB2	BCB2	DCB2	ECB2	FCB2	GCB2	HCB2	ICB2
BBSA 2-1	Failure Bond load (KN)	14.29	15.04	14.81	15.27	14.52	14.45	15.04	14.52	14.5
BBSA 2-2	Bond strength (MPa)	5.2	5.85	5.7	6.22	5.66	5.41	5.82	5.51	5.43
BBSA 2-3	Max. slip (mm)	0.0639	0.0899	0.0829	0.0949	0.0819	0.0819	0.0879	0.0799	0.0799
BBSA2-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12

Table 3.3: Results of Pull-out Bond Strength Test (τu) (MPa)

		Garcinia kola Exudate (steel bar coated specimen)								
S/no		(150μm) coated			(300μm) coated			(450μm) coated		
Concrete Cube	**Sample**	ACB3	BCB3	BCB3	DCB3	ECB3	FCB3	GCB3	HCB3	ICB3
BBSA3-1	Failure load (KN)	25.8	25.35	25.99	26.58	27.4	27.1	27.31	27.48	26.6
BBSA3-2	Bond strength (MPa)	10.59	10.79	9.28	9.79	10.59	10.7	11.69	10.99	10.97
BBSA3-3	Max. slip (mm)	0.1255	0.1155	0.1055	0.1225	0.1155	0.1335	0.1615	0.1755	0.1735
BBSA3-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12

Table 3.4: Results of Average Pull-out Bond Strength Test (τu) (MPa)

S/no		Control, Corroded and Resin Steel bar Coated								
Concrete Cube	**Sample**	Non-Corroded Specimens Average Values			Corroded Specimens Average Values			Coated Specimens Average Values of 150μm, 300μm, 450μm)		
BBSA4-1	Failure load (KN)	25.42	26.29667	25.99667	14.71333	14.74667	14.68667	25.71333	27.02667	27.13
BBSA4-2	Bond strength (MPa)	8.37	8.79	8.79	5.583333	5.763333	5.586667	10.22	10.36	11.21667
BBSA4-3	Max. slip (mm)	0.102767	0.111767	0.1091	0.0789	0.086233	0.082567	0.1155	0.123833	0.170167
BBSA4-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12

Table 3.5: Results of Average Pull-out Bond Strength Test (τu) (MPa)

		Summary Specimens Average Values of Control, Corroded and Exudate Steel bar Coated			Summary of Percentile Values of Control, Corroded and Exudate Steel bar Coated			Percentile Difference of Control, Corroded and Exudate Steel bar Coated		
BBSA5-1	Failure load (KN)	25.90444	14.71556	26.62333	176.0344	56.80707	180.9197	76.03443	-43.1929	80.91966
BBSA5-2	Bond strength (MPa)	8.65	5.644444	10.59889	153.248	65.25369	187.7756	53.24803	-34.7463	87.77559
BBSA5-3	Max. slip (mm)	0.107878	0.082567	0.1365	130.6554	76.53723	165.321	30.65536	-23.4628	65.32095
BBSA5-4	Bar diameter (mm)	12	12	12	100	100	100	0	0	0

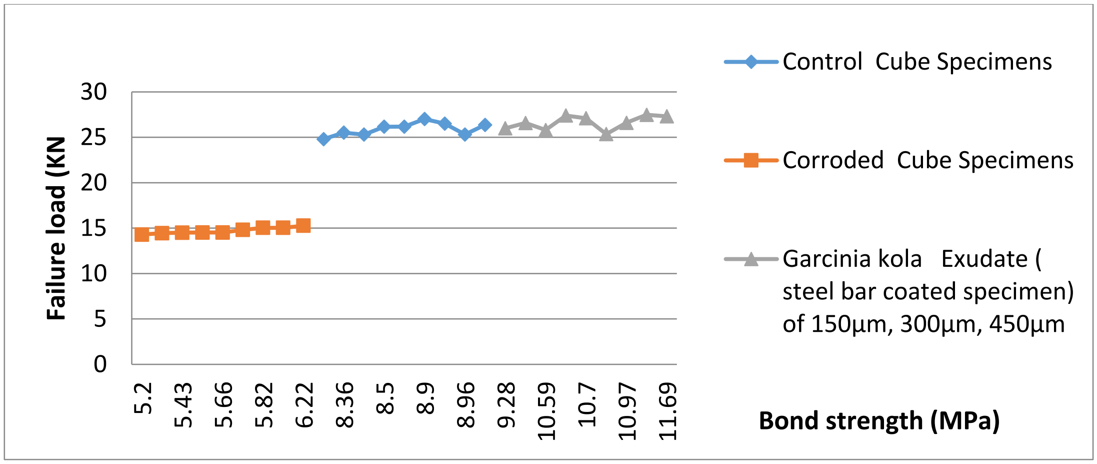

Figure 3.1: Summary Results of Pull-out Bond Strength Test (τu) (MPa) (Failure loads versus Bond Strengths)

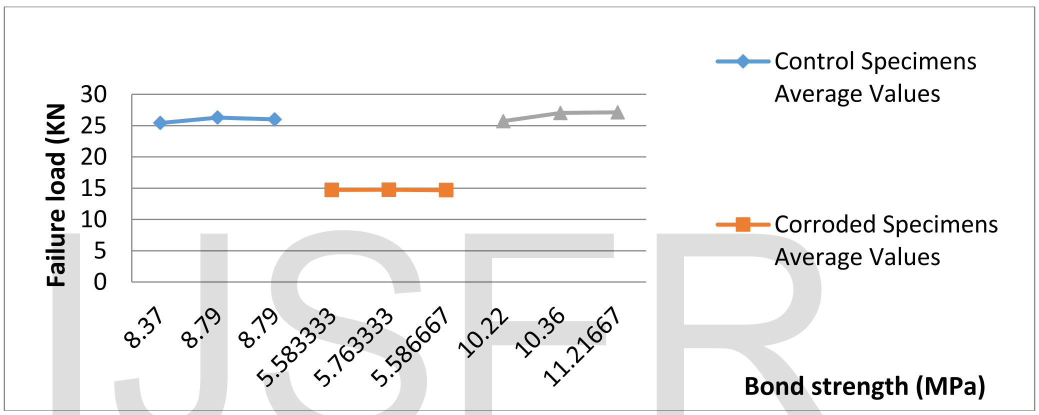

Figure 3.2: Average Results of Pull-out Bond Strength Test (τu) (MPa) (Failure loads versus Bond Strengths)

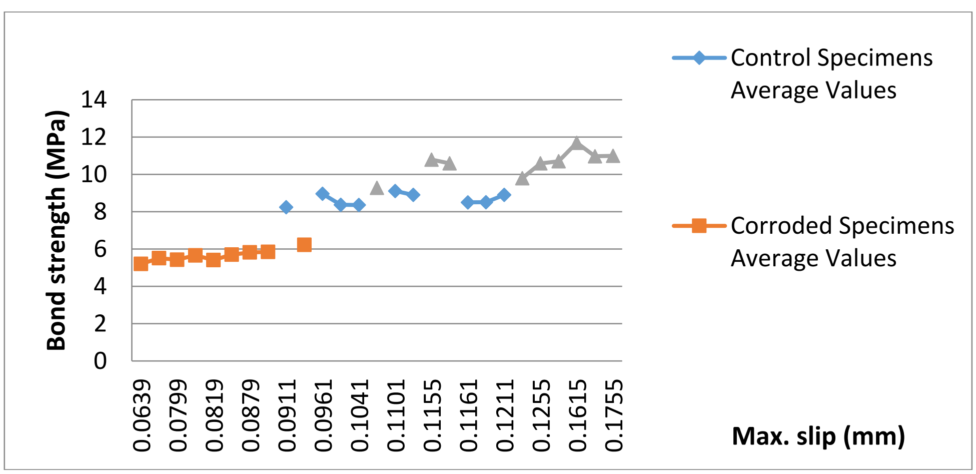

Figure 3.3: Summary Results of Pull-out Bond Strength Test (τu) (MPa) (Bond Strength versus Maximum Slip)

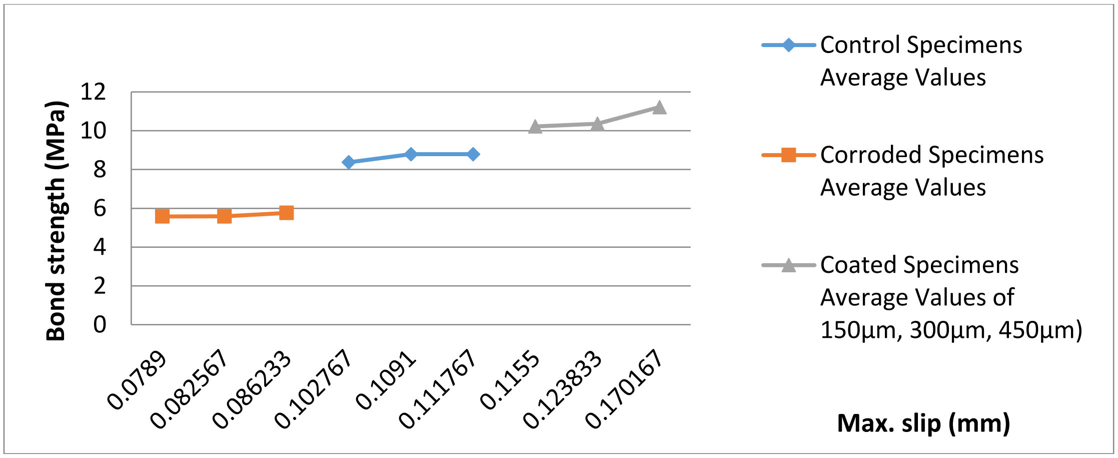

Figure 3.4: Average Results of Pull-out Bond Strength Test (τu) (MPa) (Bond Strength versus Maximum Slip)

4.0 Conclusion

Experimental results showed the following conclusions:

i. Garcinia kola exudates/ resins coated specimens showed high protective membrane towards corrosion which led to higher pullout bond values

ii. Corroded specimens showed lower pullout bond percentile values to control and coated specimens

iii. Low strength capacities of corroded specimens were recorded with higher failure bond load.

iv. Summarized results showed higher values of pullout bond strength in control and exudates/ resins coated to corroded specimens

v. Higher bond stresses were experienced in exudates /resin coated reinforcements over controlled specimens.

vi. Garcinia kola exudates/ resins showed potential of corrosion inhibitive characteristic

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