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REINFORCING STEEL MECHANICAL PROPERTIES INFLUENCE ON BOND STRENGTH OF CORRODED AND COATED MEMBERS IN CONCRETE STRUCTURES

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ABSTRACT

The mechanism of bond is the mechanical interlocking between the concrete and any deformations of the steel bar. The bond zone element contact surface between the steel bar and concrete, along with the surrounding concrete in immediate proximity. An investigative study on the effectiveness of olibanum exudates / resin as coated materials on reinforcing steel was studied to curb the trend of corrosion of reinforcing steel in the marine coastal region with salt water influence on concrete structures. Direct application of exudates / resins on reinforcing steel with coating thicknesses of 150µm, 300µm, 450µm, inserted into concrete cubes, immersed in harsh corrosive water and accelerated for 150days. Examinations showed that non-coated specimens corroded while coated specimens showed resistive / inhibitory characteristics. Average failure load is -38.9079% against 63.6874% and 62.48896% percentile difference of control and coated exudates/resin member. Average percentile bond strength load is -31.347% against 45.66004% and 71.84448% percentile difference of control and coated. Average maximum slip values is 0.083567mm and represented -25.3054% against 33.87847% and 75.30913% percentile difference of control and coated. Test results reviewed that corroded specimens have low bond strength and higher failure bond load as well as low maximum slip while exudate/resin coated specimens possessed low failure load and high bonding strength. Experimented specimens showed exudates/resin members showed higher percentile values in comparison to corroded specimens with high bond strengths to pullout and high splitting properties to slips

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

1.0 INTRODUCTION

Corrosion of steel reinforcement embedded in concrete affects the bonding of the steel and concrete interface which in turn reduces load transfer between steel and concrete. The primary mechanism of bond is the mechanical interlocking between the concrete and any deformations (i.e. ribs) of the steel bar. De Groot et al. [1] developed the bond zone element contact surface between the steel bar and concrete, along with the surrounding concrete in immediate proximity, was modeled by a material law that represents the special properties of the bond-zone (Khalfallah [2]).

Charles et al. [3] 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.

Chung *et al.* [4] 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.

Mansoor and Zahang [5] studied the influence of corrosion of reinforcing bar on bond through the use of two different concrete strengths. Their study found that the deformed bar was affected by corrosion level, the bond strength was decreased by approximately 16% when the corrosion level increased up to 2%. Moreover, the corrosion rate of steel with high concrete strength was lower than that of the low concrete strength which may be attributed to lower porosity and impermeability of concrete.

Yalciner et al. [6] to study the effect of corroded steel reinforcement on the bond strength. Their study was designed to use different compressive strength of concrete (23 and 51 N/mm2) with three different concrete cover depths (15mm, 30mm and 45mm). It was observed that the bond strength of control specimens (un-corroded) was increased with an increase in compressive strength and concrete cover depth. Moreover, they concluded that the results for specimens with higher concrete strength and corroded steel reinforcement for specimen with low concrete cover concrete showed a higher percentage of bond strength degradation because of concrete cracking during the pull-out tests.

Charles et al. [7] 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.

Tepfers [8] stated that a certain displacement occurs in this stage, even though no bar slip is noticed. This displacement is due to the localized strains which are result of high localized stresses arising close to the interface. For that Tepfers reported that the relative displacement of a bar in this stage consists of the relative slip at the interface and the shear deformation in the concrete.

Charles et al. [9] 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 [10] 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.

Rasheeduzzafar *et al.* [11] indicated that the cover over reinforcement has the most significant effect on the extent of rebar corrosion.

Charles et al. [12] 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. 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.

Rasheeduzzafar *et al*. [13] based on their field and laboratory results, recommended the following cover for structures serving in various environments of the Arabian Gulf:

i. Building components which are permanently exposed to the salt - laden corrosive atmosphere

ii. Building components which are protected against weather and the aggressive conditions of exposure: 1.0 to 1.5 inch 28.

iii. Concrete components exposed to seawater and footings as well as other main structural members cast against the ground: 3.0 inch.

This study investigate the effect of reinforcement corrosion and inhibitor on bond and pull out capacity of degraded and inhibited steel reinforcement and monitor significant changes on the surface conditions of steel reinforcing bars embedded in concrete.

Joop and Bigaj [14] stated that the displacement of the bar in respect to the concrete (slip) consists of bending of the corbels and movement due to crushing of the concrete in front of the ribs. Cracks start to appear once the circumferential stresses exceed the tensile forces of the confining action. According to the crack formation, the concrete cracked section surrounding the bar tends to be in a plastic state while the rest section of the un-cracked concrete remains in an elastic situation. The plastic region continues to extend radially as cracks are spreading.

Abosrra et al. [15] to evaluate the effect of corrosion of embedded steel in concrete of different compressive strengths (20, 30 and 46 N/mm2). They observed that the bond strength was affected by the corrosion levels. They also found that when the exposure time increased up to 7 days the bond strength was reduced due to the formation of longitudinal cracks because of corrosion.

Many researchers have continued to investigate the effect of corrosion on bond strength by using various analytical and numerical models (Berra et al.[16] and Lundgren [17], [18]).

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 and 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 EXPERINMENT

2.1.1 Aggregates

The fine aggregate and coarse aggregate were purchased. Both met the requirements of [19]

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 [20].

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 [21].

2.1.4 Structural Steel Reinforcement

The reinforcements are gotten directly from the market in Port Harcourt [22].

2.1.5 Corrosion Inhibitors (Exudates/Resins) Olibanum

The study inhibitor (Olibanum) 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 Exudates/Resins

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 (Milicia excels 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 Olibanum 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

Preliminary sampled cubes from table 3.1 were summarized into tables 3.4 and 3.5, with graphs presentations in figures 3.1 – 3.4. Failure bond load average obtained values are 28.35kN, 29.22667kN and 28.92667kN with summation of 28.83444kN and represented 63.6874% percentile value. Average bond strength values are 8.67MPa, 9.09MPa and 9.09MPa, with summation of 8.95MPa and percentile value of 45.66004%. Average maximum slip values are 0.10676mm, 0.115767mm, and 0.1131mm with summation of 0.111878mm and represented 33.87847% percentile values.

3.2 Corroded Concrete Cube Members

Specimens randomly sampled from table 3.1, into 3.4 and 3.5, as shown in figures 3.1 – 3.4, average failure bond load are 17.61333kN, 17.64667kN and 17.58667kN, with summation of 17.61556kN and represented -38.9079% against 63.6874% and 62.48896% percentile difference of control and coated exudates/resin member. Average bond strength load 6.083333MPa, 6.263333MPa, 6.086667MPa with summation of 6.144444MPa and represented percentile value of -31.347% against 45.66004% and 71.84448% percentile difference of control and coated. Average maximum slip values are 0.0799mm, 0.087233mm, 0.083567mm, with summation of 0.083567mm and represented -25.3054% against 33.87847% and 75.30913% percentile difference of control and coated. Test results reviewed that corroded specimens have low bond strength and higher failure bond load as well as low maximum slip while exudate/resin coated specimens possessed low failure load and high bonding strength.

3.3 Olibanum Exudates/ Resins Steel Bar Coated Specimens (Concrete Cube Members)

Specimens randomly sampled from table 3.1, into 3.4 and 3.5, as shown in figures 3.1 – 3.4, failure bond load average values are 27.71333kN, 29.02667kN, 29.13kN with summation of 28.62333kN, represented 62.48896% over -38.9079% corroded percentile differences, average bond strength values are 10.18MPa, 10.32MPa, 11.17667MPa with summation of 10.55889MPa, represented 71.84448% over -31.347% and average maximum slip values are 0.1255mm, 0.133833mm, 0.180167mm with summation of 0.1465mm represented 75.30913% over -25.3054% corroded percentile differences. Experimented specimens showed exudates/resin members showed higher percentile values in comparison to corroded specimens with high bond strengths to pullout and high splitting properties to slips.

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

S/no		Non-corroded Control Cube Specimens								
Concrete Cube	**Sample**	ACX1	BCX1	BCX1	DCX1	ECX1	FCX1	GCX1	HCX1	ICX1
WBVA1-1	Failure Bond Loads (kN)	29.09	28.23	27.73	29.94	28.44	29.3	29.44	28.24	29.1
WBVA1-2	Bond strength (MPa)	8.8	8.67	8.54	9.2	8.66	9.41	9.2	9.26	8.81
WBVA1-3	Max. slip (mm)	0.1201	0.1051	0.0951	0.1251	0.1081	0.1141	0.1151	0.1001	0.1241
WBVA1-4	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**	ACX2	BCX2	BCX2	DCX2	ECX2	FCX2	GCX2	HCX2	ICX2
WBVA 2-1	Failure Bond load (KN)	17.19	17.94	17.71	18.17	17.42	17.35	17.94	17.42	17.4
WBVA 2-2	Bond strength (MPa)	5.7	6.35	6.2	6.72	6.16	5.91	6.32	6.01	5.93
WBVA 2-3	Max. slip (mm)	0.0649	0.0909	0.0839	0.0959	0.0829	0.0829	0.0889	0.0809	0.0809
WBVA2-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12

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

		Olibanum Exudate (steel bar coated specimen)								
S/no		(150µm) coated			(300µm) coated			(450µm) coated		
Concrete Cube	**Sample**	ACX3	BCX3	BCX3	DCX3	ECX3	FCX3	GCX3	HCX3	ICX3
WBVA3-1	Failure load (KN)	27.8	27.35	27.99	28.58	29.4	29.1	29.31	29.48	28.6
WBVA3-2	Bond strength (MPa)	10.55	10.75	9.24	9.75	10.55	10.66	11.65	10.95	10.93
WBVA3-3	Max. slip (mm)	0.1355	0.1255	0.1155	0.1325	0.1255	0.1435	0.1715	0.1855	0.1835
WBVA3-4	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)

		Control, Corroded and Resin Steel bar Coated								
S/no		Non-corroded Control Cube			Corroded Cube Specimens			Exudate steel bar coated specimens		
Concrete Cube	Sample	Non-Corroded Specimens Average Values			Corroded Specimens Average Values			Coated Specimens Average Values of 150µm, 300µm, 450µm)		
WBVA4-1	Failure load (KN)	28.35	29.22667	28.92667	17.61333	17.64667	17.58667	27.71333	29.02667	29.13
WBVA4-2	Bond strength (MPa)	8.67	9.09	9.09	6.083333	6.263333	6.086667	10.18	10.32	11.17667
WBVA4-3	Max. slip (mm)	0.106767	0.115767	0.1131	0.0799	0.087233	0.083567	0.1255	0.133833	0.180167
WBVA4-4	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)

		Non-corroded Control Cube			Corroded Cube Specimens			Exudate steel bar coated specimens		
		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		
WBVA5-1	Failure load (KN)	28.83444	17.61556	28.62333	163.6874	61.09206	162.489	63.6874	-38.9079	62.48896
WBVA5-2	Bond strength (MPa)	8.95	6.144444	10.55889	145.66	68.65301	171.8445	45.66004	-31.347	71.84448
WBVA5-3	Max. slip (mm)	0.111878	0.083567	0.1465	133.8785	74.69461	175.3091	33.87847	-25.3054	75.30913
WBVA5-4	Bar diameter (mm)	12	12	12	100	100	100	0	0	0

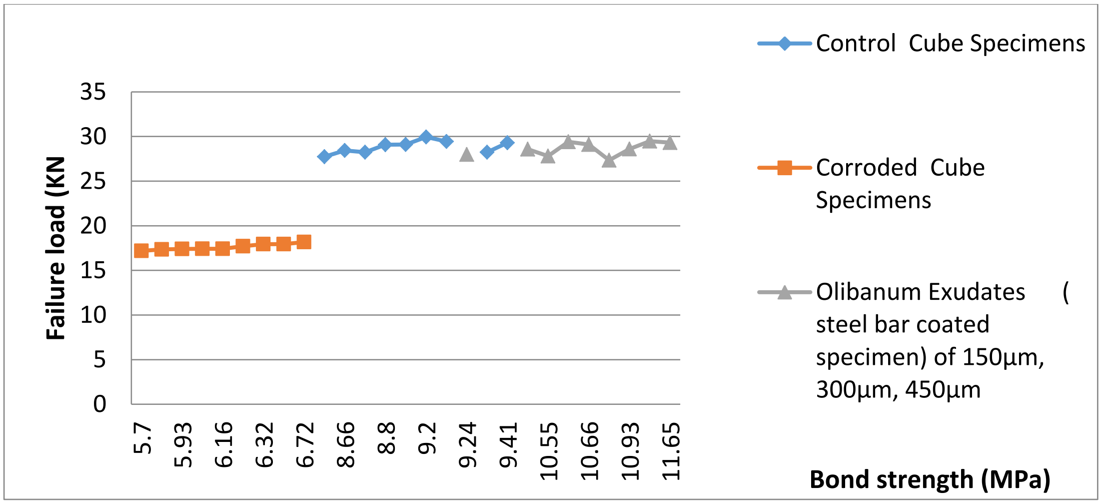

Figure 3.1: Summary Results of Pull-out Bond Strength Test (τu) (MPa)
(Failure loads versus Bond Strengths

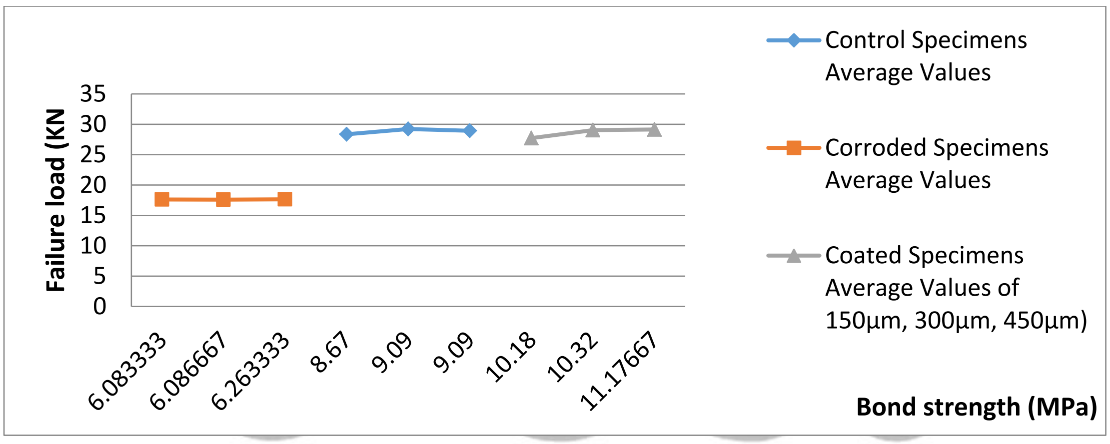

Figure 3.2: Average Results of Pull-out Bond Strength Test (τu) (MPa)
(Failure loads versus Bond Strengths)

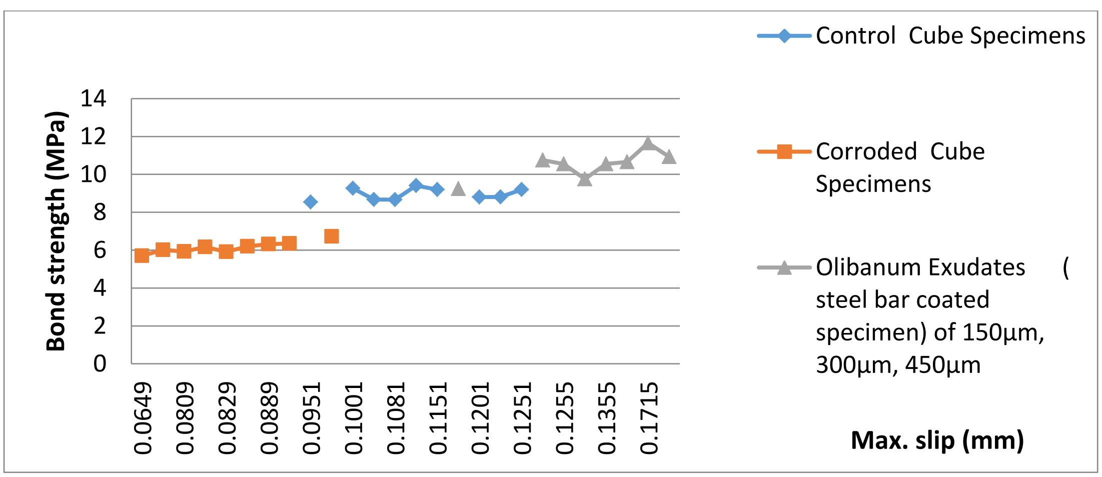

Figure 3.3: Summary Results of Pull-out Bond Strength Test (τu) (MPa)
(Bond Strength versus Maximum Slip)

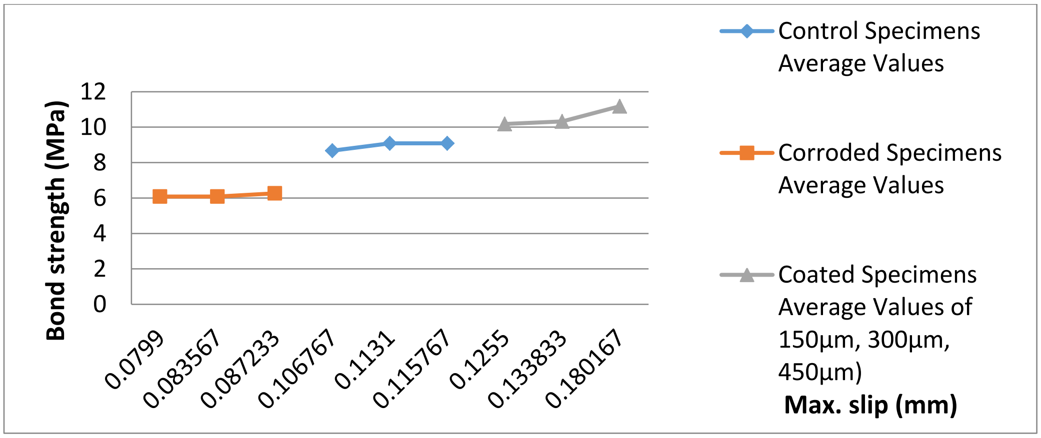

Figure 3.4: Average Results of Pull-out Bond Strength Test (τu) (MPa) (Bond Strength versus Maximum Slip)

4.0 CONCLUSION

Experimental results showed the following conclusions:

i. Experimented specimens showed exudates/resin members showed higher percentile values in comparison to corroded specimens with high bond strengths to pullout and high splitting properties to slips.

ii. Test results reviewed that corroded specimens have low bond strength and higher failure bond load as well as low maximum slip

iii. Exudates/resins coated specimens possessed low failure load and high bonding strength.

iv. Exudates/resins specimens showed high protective characteristics against corrosion effects thus serves as inhibitors.

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