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Corrosion Degree on the Mechanical Properties of Reinforcing Steel Embedded in Concrete

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ABSTRACT

The bond between steel and concrete is affected by corrosion of reinforcement, there is hardly perfect bonding in the presence of chloride in form of salt water and has shortened the service life of reinforced concrete structures. The work enumerated the bond strength of reinforcing steel and concrete of non-corroded, corroded and khaya senegalensis exudates/resin coated specimens. Corrosion accelerated process was introduced to concrete standard cubes with embedded reinforcements of uncoated and coated specimens for 150days and ascertained their effects. Results of percentile averaged failure bond load are corroded -43.622% against 77.3771% and 79.6743% percentile difference of non- corroded and coated exudates/resins members. Averaged percentile bond strength load of corroded is -36.331% against 57.0631% and 106.576% percentile difference of non-corroded and coated specimens. Averaged percentile maximum slip values of corroded is 60.548% against 153.478% and 206.125% percentile difference of control and coated specimens. Obtained results from tables 3.1-3.5 and figures 3.1-3.4 showed in clearly terms that the failure bond loads were higher in corroded specimens to non-corroded and exudates/resin coated members. Bond strength of non-corroded and coated specimens exhibited higher bonding to pull-out as compared to corroded. Exudates/resins coated specimens performance showed the effective use of researched exudates/resins as corrosion inhibitor with its recorded low failure load, high bond and maximum slip strength over corroded specimens.

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

1. INTRODUCTION

The most considered factor that shortened the service life of reinforced concrete structures that are subjected to corrosive environments is the presence of chloride in form of salt water that led to corrosion presence. It is noted that tensile force transfer to the concrete is controlled by the bond strength of the reinforcing steel bar and concrete. If the bond between steel and concrete is affected by corrosion of reinforcement, there will be no perfect bonding. A major cause of steel reinforcement corrosion is the presence of chlorides from chloride contaminated aggregates and admixtures containing chlorides which are used during construction, or from penetration of chloride ions from sea water or ingress of de-icing salt.

Otunyo & Kennedy [1] 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

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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 Control 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. [2] investigated the effect of corroded and inhibited reinforcement on the stress generated on pullout bond splitting of Control, 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.

Auyeung et al.[3] studied on the bond behavior of corroded reinforcement bars and have found that when the mass loss of the reinforcement due to corrosion reaches approximately 2%, concrete cracks along the bar. A small amount of corrosion increases both the bond strength and bond stiffness, but the slip at failure decreases considerably. However, they stated that when the mass loss exceeds 2%, bond stiffness decreases.

Charles et al. [4] 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 Control 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. [5] 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 Control 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. [6] 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.

Charles et al. [7] studied the bond strength exhibited by reinforcement embedded in concrete is controlled by corrosion effects. 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 Control, 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.

Chung et al. [8] studied the effect of corrosion on pullout 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 investigate the bond stress and length development on tension member in flexure. It was concluded that at 2% level of corrosion, increases and fails it reaches an average bond stress.

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Han-Seung Lee et al. [9] evaluated the corrosion of reinforcing steel as function of degree of bond properties between concrete and reinforcement. They evaluated pull out bond test to ascertain the bond characteristics between concrete and corroded reinforcing steel bar. Pull-out tests were conducted on specimens with and without confinement reinforcement. Experimentally, results were obtained from load versus free end slip behavior was studied and the rigidity of bond for the analysis of finite element with corroded reinforcement in reinforced concrete members.

Cairns & Plizzari [10] affirmed that the split from concrete surrounding resulted from bearing action of ribs that generates bursting forces. 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 counter balance the force generated by bond.

2. MATERIALS AND METHODS FOR EXPERINMENT

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 BS 882 [11]

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 BS EN 196-6 [12]

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 BS 3148[13]

2.1.4 Structural Steel Reinforcement

The reinforcements are gotten directly from the market in Port Harcourt. BS 4449:2005+A3[14]

2.1.5 Corrosion Inhibitors (Exudate/Resin) Khaya senegalensis

The study inhibitor (Khaya senegalensis) is of natural tree resin /exudate substance extracts.

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 (Khaya senegalensis), 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. Fresh concrete mix for each batch was fully compacted by tamping rods, to remove trapped air, which can reduce the strength of the concrete and 12 mm

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reinforcements of coated and non-coated were spaced at 150 mm with concrete cover of 25 mm had been embedded inside the slab and projection of 100 mm for half cell potential measurement. Specimens were demolded after 24hrs and cured for 28 days. 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. RESULTS AND DISCUSSIONS

Tables 1, 2 and 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 Khaya senegalensis 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 1 and 2 are the plots of entire failure bond load versus bond strength and bond strength versus maximum slip, while figures 3 and 4 are the plots of average failure bond load versus maximum slip obtained from tables 1, 2 and 3.

3.1 Control Concrete Cube Members

Randomly sampled specimens of table 1 were fused into tables 4 and 5, with graphical representations shown in figures 1 – 4. Failure bond load averaged values are 26.04kN, 27.13kN and 26.36kN, fused to 26.51kN and represented 77.3771% percentile value. Averaged bond strength values are 8.30MPa, 8.83MPa and 8.665MPa, fused to 8.5983MPa and percentile value of 57.0631%. Averaged maximum slip values are 0.18166mm, 0.1905mm, and 0.187mm fused into 0.18628mm and represented 153.478% percentile values.

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3.2 Corroded Concrete Cube Members

Randomly sampled specimens of table 3.1 were fused into tables 4 and 5, as shown in figures 1 – 4, averaged failure bond load are 14.9433kN, 14.9766kN and 14.916kN, fused into 14.9455kN, and represented -43.622% against 77.3771% and 79.6743% percentile difference of control and coated exudate/resin members. Averaged bond strength load 5.41333MPa, 5.59333MPa, 5.4166MPa fused into 5.47444MPa and represented percentile value of -36.331% against 57.0631% and 106.576% percentile difference of control and coated. Averaged maximum slip values are 0.06985mm, 0.07713mm, 0.0734mm, fused into 0.07346mm, represented 60.548% against 153.478% and 206.125% percentile difference of control and coated. Obtained results from tables 3.1-3.5 and figures 3.1-3.4 showed in clearly terms that the failure bond loads were higher in corroded specimens to non-corroded and exudates/resin coated members. Bond strength of non-corroded and coated specimens exhibited higher bonding to pull-out as compared to corroded.

3.3Khaya senegalensis Exudates/ Resins Steel bar Coated Specimens (Concrete Cube Members)

Randomly sampled specimens of table 3.1 were fused into tables 3.4 and 3.5, as shown in figures 3.1 – 3.4, failure bond load averaged values are 25.9433kN, 27.2566kN, 27.36kN fused into 26.8533kN and represented 79.6743% over -43.622% corroded percentile differences, averaged bond strength values are 10.93MPa, 11.07MPa, 11.9266MPa fused into 11.3088MPa and represented 106.576% over -36.331% and averaged maximum slip values are 0.2039mm, 0.21223mm, 0.25856mm fused into 0.2249mm and represented 206.125% over -60.548% corroded percentile differences. Exudates/resins coated specimens performance showed the effective use of researched exudate/resin as corrosion inhibitor with its recorded low failure load, high bond and maximum slip strength over corroded specimens.

Table 1. Results of Pull-out Bond Strength Test (τu) (MPa)

S/no		**Control Cube Specimens**								
Concrete Cube	**Sample**	YAC	YBC	YCC	YDC	YEC	YFC	YGC	YHC	YIC
LCP1-1	Failure Bond Loads (kN)	26.78	25.92	25.42	27.63	26.13	26.99	27.13	25.93	26.79
LCP1-2	Bond strength (MPa)	8.43	8.3	8.17	8.83	8.29	9.04	8.83	8.89	8.44
LCP1-3	Max. slip (mm)	0.195	0.18	0.17	0.2	0.183	0.189	0.19	0.175	0.199
LCP1-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12

Table 2. Results of Pull-out Bond Strength Test (τu) (MPa)

S/no		**Corroded Cube Specimens**								
Concrete Cube	**Sample**	YAC2	YBC2	YBC2	YDC2	YEC2	YFC2	YGC2	YHC2	YIC2
LCP 2-1	Failure Bond load (KN)	14.52	15.27	15.04	15.5	14.75	14.68	15.27	14.75	14.73
LCP 2-2	Bond strength (MPa)	5.03	5.68	5.53	6.05	5.49	5.24	5.65	5.34	5.26
LCP 2-3	Max. slip (mm)	0.0548	0.0808	0.0738	0.0858	0.0728	0.0728	0.0788	0.0708	0.0708
LCP2-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12

Table 3. Results of Pull-out Bond Strength Test (τu) (MPa)

		Khaya senegalensis exudates (steel bar coated specimen)								
S/no		**(150µm) coated**			**(300µm) coated**			**(450µm) coated**		
Concrete Cube	**Sample**	YAC3	YBC3	YBC3	YDC3	YEC3	YFC3	YGC3	YHC3	YIC3
LCP3-1	Failure load (KN)	26.03	25.58	26.22	26.81	27.63	27.33	27.54	27.71	26.83
LCP3-2	Bond strength (MPa)	11.3	11.5	9.99	10.5	11.3	11.41	12.4	11.7	11.68
LCP3-3	Max. slip (mm)	0.2139	0.2039	0.1939	0.2109	0.2039	0.2219	0.2499	0.2639	0.2619
LCP3-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12

Table 4. Results of Average Pull-out Bond Strength Test (τu) (MPa)

S/no		**Control Cube**			**Corroded Cube Specimens**			**Exudate steel bar coated specimens**		
Concrete Cube	**Sample**	**Control Specimens Average Values**			**Corroded Specimens Average Values**			**Coated Specimens Average Values of 150µm, 300µm, 450µm)**		
LCP4-1	Failure load (KN)	26.04	27.13	26.36	14.9433	14.9766	14.916	25.9433	27.2566	27.36
LCP4-2	Bond strength (MPa)	8.3	8.83	8.665	5.41333	5.59333	5.4166	10.93	11.07	11.9266
LCP4-3	Max. slip (mm)	0.18166	0.1905	0.187	0.0698	0.07713	0.0734	0.2039	0.21223	0.25856
LCP4-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12

Table 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**		
LCP5-1	Failure load (KN)	26.51	14.9455	26.8533	177.377	56.37704	179.6743	77.3771	-43.622	79.6743
LCP5-2	Bond strength (MPa)	8.5983	5.47444	11.3088	157.063	63.66867	206.5760	57.0631	-36.331	106.576
LCP5-3	Max. slip (mm)	0.1862	0.07346	0.2249	253.478	39.45107	306.1252	153.478	-60.548	206.125
LCP5-4	Bar diameter (mm)	12	12	12	100	100	100	0	0	0

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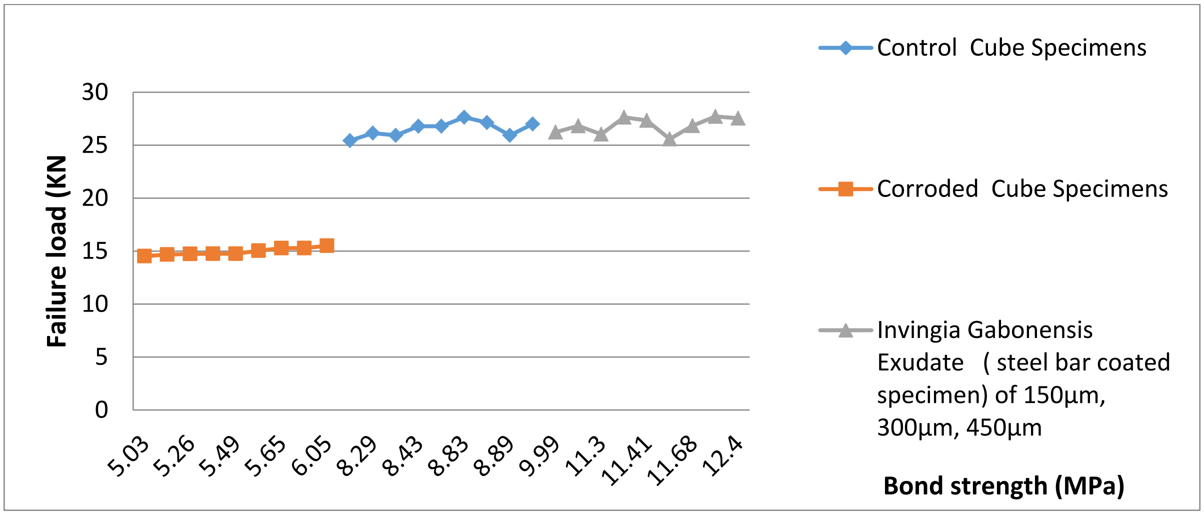

Fig. 5 Summary Results of Pull-out Bond Strength Test (τu) (MPa)
(Failure loads versus Bond Strengths

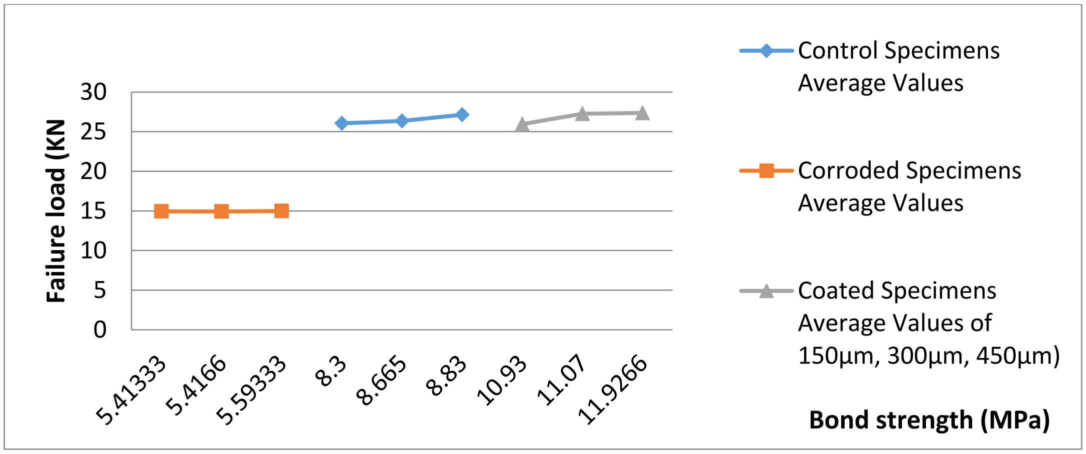

Fig. 2 Average Results of Pull-out Bond Strength Test (τu) (MPa)
(Failure loads versus Bond Strengths)

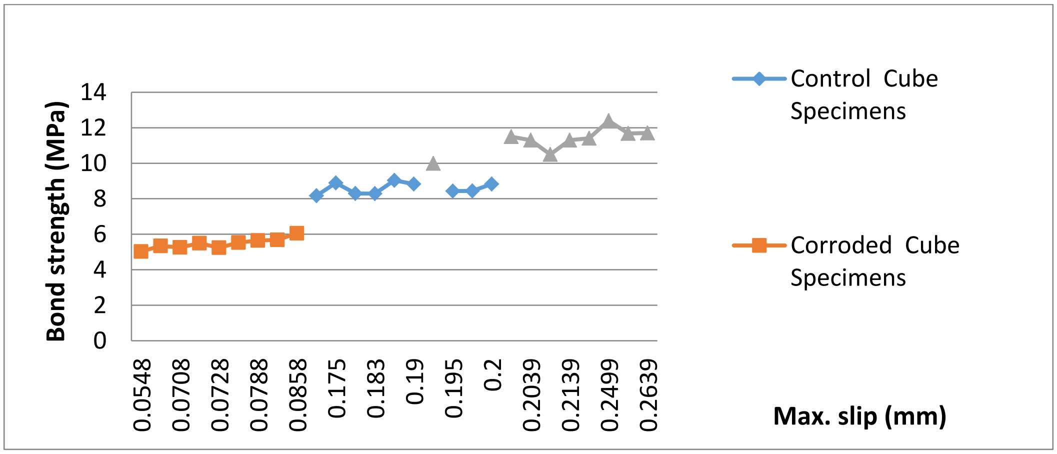

Fig. 3 Summary Results of Pull-out Bond Strength Test (τu) (MPa)

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(Bond Strength versus Maximum Slip)

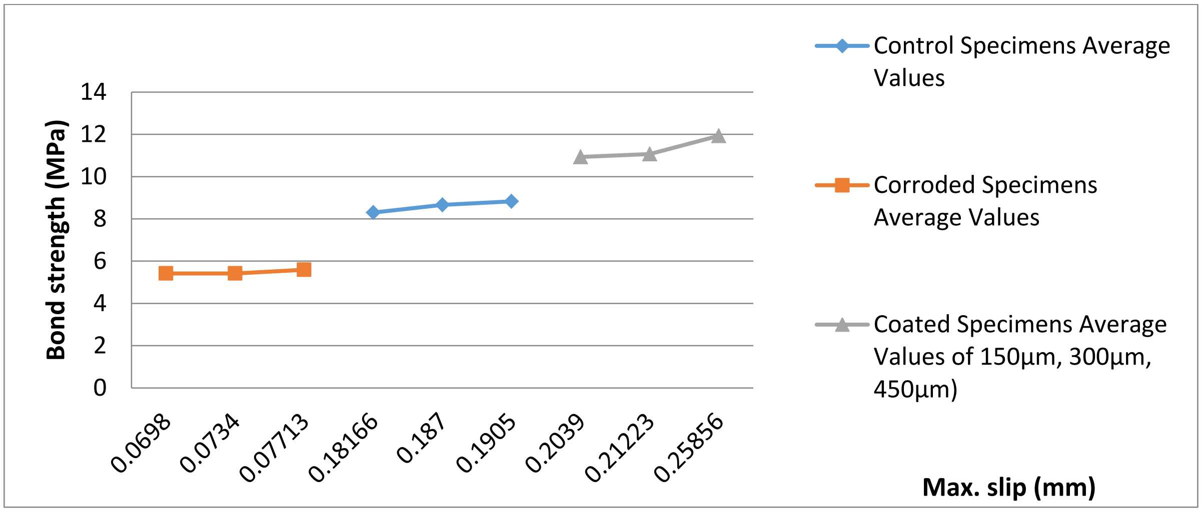

Fig. 4 Average Results of Pull-out Bond Strength Test (τu) (MPa)
(Bond Strength versus Maximum Slip)

4. CONCLUSIONS

Experimental results showed the following conclusions:

i. Obtained results from tables 1-5 and figures 1-4 showed in clearly terms that the failure bond loads were higher in corroded specimens to non-corroded and exudates/resin coated members.

ii. Bond strength of non-corroded and coated specimens exhibited higher bonding to pull-out as compared to corroded.

iii. Exudates/resins coated specimens performance showed the effective use of researched exudates/resin as corrosion inhibitor with its recorded low failure load, high bond and maximum slip strength over corroded specimens

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

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