

Corrosion Effect on Reinforcement Pull-Out Bond Strength Characteristics of Corroded and Coated Members in Concrete

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ABSTRACT

The premature and reduced services life and durability of reinforced concrete has been attributed to corrosion effect on the reduction of bond strength between steel and concrete. This experimental work examined the effective application of Acacia senegal exudates/resins paste as coating materials with thicknesses of 150µm, 300µm and 450µm on reinforcing steel, embedded in concrete cube and immersed in sodium chloride (NaCl) and accelerated for 178 days. Obtained results showed that failure bond load percentile values of corroded has -36.151% against 56.6199% and 59.1523% of non-corroded exudates/resins coated members. Bond strength load are -45.3684% against 83.04423% and 94.92628%, results showed decreased percentile values against control and exudates/resins coated members. Maximum slip average values are -32.3373% against 47.79189% and 133.4392% percentile difference of non-corroded and exudates/resins coated members. In comparison, obtained values of corroded specimens decreases while non-corroded and exudates/resins coated members increases, these indications clearly showed the potential of Acacia senegal exudates/resins in coated activities of reinforcing steel. Entire results showed higher values of pullout bond strength and low failure load in control and coated to corroded specimens.

KEY WORDS: Corrosion, Corrosion inhibitors, Pull-out Bond Strength, Concrete and Steel Reinforcement

INTRODUCTION

The durability and serviceability of concrete structures is affected by corrosion of steel reinforcement in concrete by the reduction of bond strength between steel and concrete. The influence of corroded steel reinforcement on the bond strength of reinforced concrete members has been investigated by numerous researchers.

Charles et al (2018) 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.

Al-sulaimani et al. (1990) found from studies of the effect of steel reinforcement corrosion and bond strength up to approximately 1% of corrosion level due to the increased roughness of the reinforcing bar surface at early stages with a firmly adherent layer of rust. This is in agreement with experimental results obtained from RC beam tests, which increased in bond strength when the degree of corrosion increased up to 4% due to the increase of radial pressure caused by the expansion of the corrosion products (Mangat and Elgarf, 1999b).

Almusallam et al. (1996) also demonstrated that in the pre-cracking stage the bond strength is increased, but with an increase in the corrosion level the slip at the ultimate bond strength reduces. Experimental studies showed an increase in bond strength during the initial corrosion level to about 2%. In agreement with the above results, significant literature has been published in this area by Cabrera (1996), Amleh and Mirza. (1999) & Auyeung et al. (2000). Initially, the increase in bond strength was attributed to the production of a firm layer of rust around the reinforcing steel bar which, results in increased bond strength. After the development of longitudinal corrosion cracks the bond strength reduced dramatically and the reduction in bond strength was attributed to the loss of the bearing component as a result of the ribs of the steel bars being decreased by corrosion. In addition, with a high corrosion level the tensile hoop stress in surrounding concrete exceeded the tensile strength, leading to splitting of concrete cover which decreased the bond strength and increased the slip.

Charles et al. (2018) 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. (2018) investigated the corrosion of steel reinforcement in concrete as one of the principal factor that caused the splitting failures that occurred between steel and concrete, the use of epoxy, resin/exudates has been introduced to curb this trend encountered by reinforced structures built within the saline environment. Results obtained showed presence of corrosion in uncoated members. 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 & Kennedy (2018) 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 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. (2018) 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. Results obtained showed potentiality of corrosion on uncoated concrete cube members. 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. (2018) 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 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.

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.

MATERIALS AND METHODS FOR EXPERIMENT

Aggregates

The fine aggregate and coarse aggregate were purchased. Both met the requirements of BS 882

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

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

Structural Steel Reinforcement

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

Corrosion Inhibitors (Resins / Exudates) *Acacia senegal* Exudates

The study inhibitor (*Acacia senegal* exudate) is of natural tree exudate /resin substance extracts.

Experimental Procedure and Method

Sample Preparation for Reinforcement with Coated Resin/Exudate

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 (Acacia senegal exudate), resin pastes with coating thicknesses of 150 μ m, 300 μ m and 450 μ m before corrosion test. The test cubes and beams were cast in steel mould of size 150 mm \times 150 mm \times 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.

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.

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 \times 150 mm \times 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 \times 150 mm \times 150 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.

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.

EXPERIMENTAL RESULTS AND DISCUSSION

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 acacia senegal exudates/ resins steel bar coated specimens paste on reinforcement embedded in concrete cubes member. Table 4 and 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. Fig. 1 and 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

Control Concrete Cube Members

Results obtained from table 1 and summarized in tables 4 and 5 indicated average pullout out bond strength of failure bond load of 26.04kN, 26.92KN and 26.62kN, summarized to

26.52kN with percentile values increased of 156.62% and percentile difference of 56.6199% against corroded decreased value of 36.151%, bond strength average values of 9.10MPa, 9.52MPa, and 9.52MPa into 194.9263% and percentile difference of 83.04423% against 45.3684% corroded and maximum slip as 0.108578mm, 0.073467mm and 0.1715mm with into percentile values of 147.7919% and percentile difference of 47.79189% against decreased values of 32.3373% respectively.

Corroded Concrete Cube Members

From table 2, the obtained average failure load values are 16.93kN, 16.97kN, 16.91kN, summarized into 16.9356kN representing 36.151% against 56.6199% and 59.1523% of non-corroded and exudates/resins coated members. This showed percentile decreased of corroded members. Bond strength load are 5.06MPa, 5.24MPa, 5.07MPa, summarized into 45.3684% against 83.04423% and 94.92628%, result showed decreased percentile values against control and exudates/resins coated members and maximum slip average values are 0.1034667mm, 0.1124667mm, summarized into 0.10857mm, indicating 32.3373% against 47.79189% and 133.4392% percentile difference from non-corroded and exudates/resins coated members. In comparison, obtained values of corroded specimens decreases while non-corroded and exudates/resins coated members increases, these indications clearly showed the potential of exudates/resins in coated activities of reinforcing steel.

Acacia senegal exudates Steel Bar Coated Concrete Cube Members

Results obtained from table 3, summarized into average and percentile values into tables 4, 5 and figures 1 – 4 showed the descriptive behavior of values of exudates/resins coated members. Average failure load values are 26.04kN, 27.36kN, 27.46kN, summarized into 26.9336kN representing 59.1523% % failure bond load, bond strength are 9.61MPa, 9.75MPa, 10.6MPa summarized to 9.98Mpa, representing 94.92628% and maximum slip as values are 0.1505mm, 0.1588mm and 0.2051667mm representing 133.4392%. Entire results showed higher values of pullout bond strength in control and coated to corroded specimens.

Table 1: Results of Pull-out Bond Strength Test (τ_u) (MPa)

S/no		Control Cube Specimens								
Concrete Cube	Sample	2VAC	2VBC	2VCC	2VDC	2VEC	2VFC	2VGC	2VHC	2VIC
CCC1-1	Failure Bond Loads (kN)	26.78	25.92	25.42	27.63	26.13	26.99	27.13	25.93	26.79
CCC1-2	Bond strength (MPa)	9.23	9.1	8.97	9.63	9.09	9.84	9.63	9.69	9.24
CCC1-3	Max. slip (mm)	0.1168	0.1018	0.0918	0.1218	0.1048	0.1108	0.1118	0.0968	0.1208
CCC1-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12

Table 2: Results of Pull-out Bond Strength Test (τ_u) (MPa)

S/no		Corroded Cube Specimens								
Concrete Cube	Sample	2VAC2	2VBC2	2VBC2	2VDC2	2VEC2	2VFC2	2VGC2	2VHC2	2VIC2
CCC 2-1	Failure Bond load (KN)	16.51	17.26	17.03	17.49	16.74	16.67	17.26	16.74	16.72
CCC 2-2	Bond strength (MPa)	4.68	5.33	5.18	5.7	5.14	4.89	5.3	4.99	4.91
CCC 2-3	Max. slip (mm)	0.0548	0.0808	0.0738	0.0858	0.0728	0.0728	0.0788	0.0708	0.0708
CCC2-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12

Table 3: Results of Pull-out Bond Strength Test (τ) (MPa)

		Acacia senegal exudates (steel bar coated specimen)								
S/no		(150 μ m) coated			(300 μ m) coated			(450 μ m) coated		
Concrete Cube	Sample	3VAC3	3VBC3	3VBC3	3VDC3	3VEC3	3VFC3	3VGC3	3VHC3	3VIC3
CCC3-1	Failure load (KN)	26.13	25.68	26.32	26.91	27.73	27.43	27.64	27.81	26.93
CCC3-2	Bond strength (MPa)	9.98	10.18	8.67	9.18	9.98	10.09	11.08	10.38	10.36
CCC3-3	Max. slip (mm)	0.1605	0.1505	0.1405	0.1575	0.1505	0.1685	0.1965	0.2105	0.2085
CCC3-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12

Table 4: Results of Average Pull-out Bond Strength Test (τ) (MPa)

		Control, Corroded and Resin Steel bar Coated								
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 150 μ m, 300 μ m, 450 μ m)		
CCC4-1	Failure load (KN)	26.04	26.9166	26.6166	16.9333	16.9666	16.9066	26.0433	27.3566	27.46
CCC4-2	Bond strength (MPa)	9.1	9.52	9.52	5.06333	5.24333	5.06666	9.61	9.75	10.6066
CCC4-3	Max. slip (mm)	0.10346	0.11246	0.1098	0.0698	0.07713	0.07346	0.1505	0.15883	0.20516
CCC4-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12

Table 5: Summary Results of Average Pull-out Bond Strength Test (τ) (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		
CCC5-1	Failure load (KN)	26.52444	16.93556	26.95333	156.6199	63.84886	159.1523	56.61987	-36.1511	59.15234
CCC5-2	Bond strength (MPa)	9.38	5.124444	9.988889	183.0442	54.6316	194.9263	83.04423	-45.3684	94.92628
CCC5-3	Max. slip (mm)	0.108578	0.073467	0.1715	147.7919	67.66271	233.4392	47.79189	-32.3373	133.4392
CCC5-4	Bar diameter (mm)	12	12	12	100	100	100	0	0	0

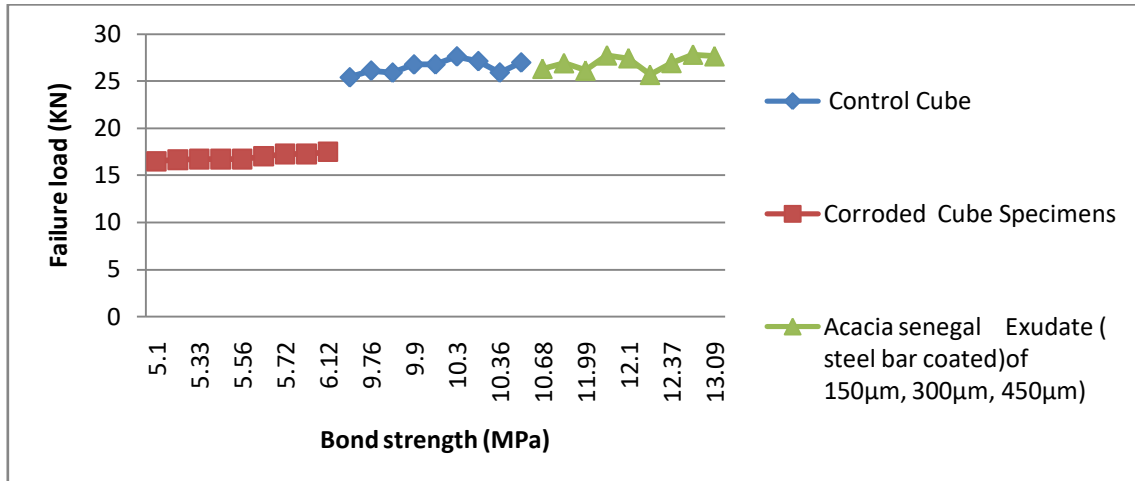


Fig. 1 Summary Results of Pull-out Bond Strength Test (τ) (MPa)
(Failure loads versus Bond Strengths)

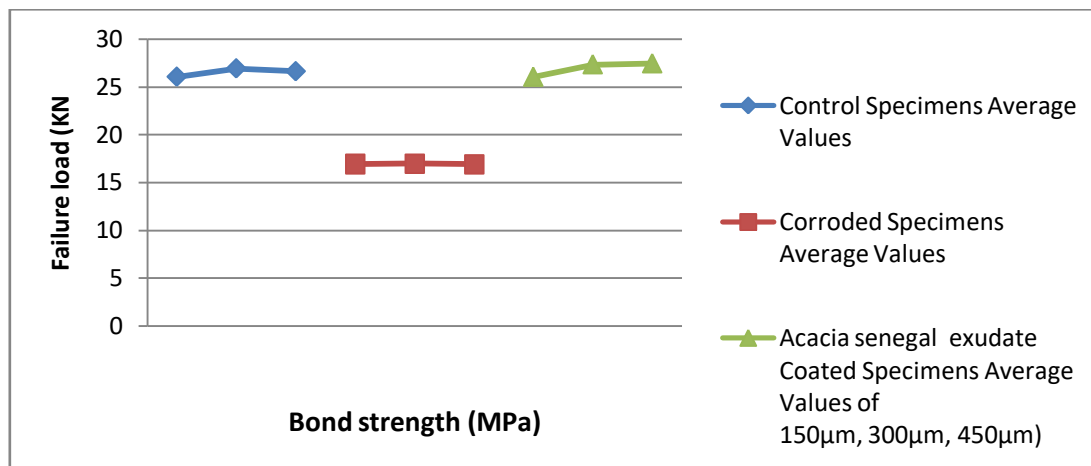


Fig. 2 Average Results of Pull-out Bond Strength Test (τ) (MPa)
(Failure loads versus Bond Strengths)

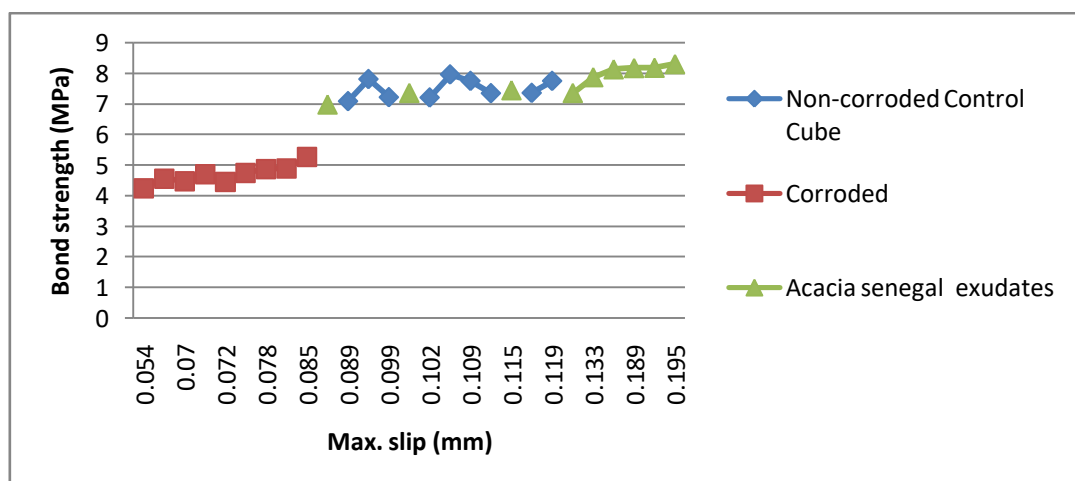
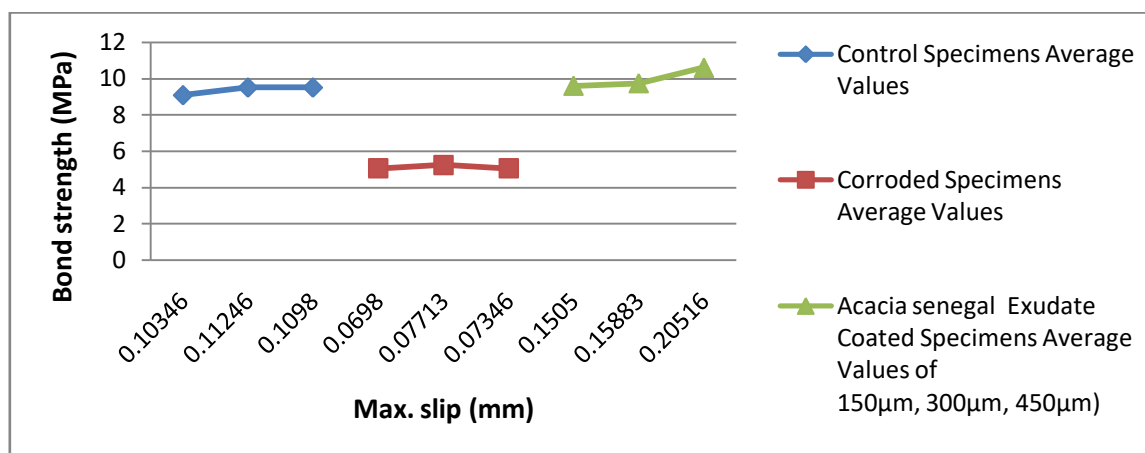


Fig. 3 Summary Results of Pull-out Bond Strength Test (τ) (MPa)
(Bond Strength versus Maximum Slip)



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

CONCLUSION

Experimental results showed the following conclusions:

- Lower percentile values were recorded in corroded while control and acacia senegal exudates/ resins coated specimens have higher values, especially in coated members.
- Results vindicated the negative and positive effects of corrosion on the strength capacity of corroded and coated members.
- Summarized results showed higher values of pullout bond strength in control and exudates/ resins coated to corroded specimens
- Bond test results showed, bond stresses experienced in inhibited coated reinforcements are higher compared to the controlled specimens.

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