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Effect of Corrosion on Bond between Steel and Concrete of Corroded and Inhibitive Reinforcement Embedded In Reinforced Concrete Structures in Accelerated Corrosive Medium

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Abstract: *This Study Evaluated The Experimental Effect Of Corrosion On Bond Existing Between Steel And Concrete Interface Of Corroded And Resins / Exudates Coated Reinforcement With Ficus Glumosa Extracts From Trees. Resins / Exudates Paste Were Directly Layered On Reinforcing Steel Of Varying Thicknesses Of Thicknesses 150µm, 250µm And 350µm, Embedded Into Standard Cube Size Of 150 Mm X 150 Mm X150 Mm. Uncoated And Coated Concrete Cube Members Of 18 Samples Were Immersed In Saline Marine Environment Of Sodium Chloride (Nacl), Accelerated For 60days For Corrosion Potential Possibility Observation. Results Obtained Indicated Corrosion Potential Presence On Uncoated Concrete Cube Members. 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.*
Key Words: *Corrosion, Corrosion Inhibitors, Pull-Out Bond Strength, Concrete And Steel Reinforcement*

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I. Introduction

The process of bonding at the steel and concrete interface affects the load transfer between steel and concrete. Bond strength primarily originates from weak chemical bonds between steel and hardened cement, but this resistance is broken at a very low stress. Once slip occurs, friction contributes to bond. In plain reinforcing steel bars, friction is the major component of strength. 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, 1996), the interlocking mechanism along the reinforcing bar interfaces with surrounding concrete.

Han-Seung Lee *et al.* (2002) 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.

Cairns and Plizzari (2003) 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.

Otunyo and Kennedy (2018) investigated the effectiveness of resin/exudates in corrosion prevention of reinforcement in reinforced concrete cubes. The reinforced concrete cubes of dimension (150mm x 150mm x 150mm) were coated with dacryodes edulis resin paste of various thicknesses: 150um, 250um, and 300um. The reinforced concrete cubes were exposed to a corrosive environment for 60days after 28 days of curing. 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.

Tepfers (2000) 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.

Joop and Bigaj (1996) 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.

Chung *et al.* (2004) 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.

II. 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 FOR EXPERINMENT

2.1.1 Aggregates

The fine aggregate was gotten from the river, washed sand deposit, coarse aggregate was granite a crushed rock of 12 mm size and of high quality. Both aggregates met the requirements of BS 882.

2.1.2 Cement

The cement used was Eagle Portland Cement, it was used for all concrete mixes in this investigation. The cement met the requirements of BS EN 196-6

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, University of Uyo, Uyo. Akwa - Ibom State. The water met the requirements of BS 3148

2.1.4 Structural Steel Reinforcement

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

2.1.5 Corrosion Inhibitors (Resins / Exudates) Ficus glumosa

The study inhibitor (ficus glumosa) is of natural tree resin /exudate substance extracts. They are abundantly found in Rivers State bushes and they are sourced from plantations and bushes of Odioku communities, Ahoada West Local Government areas, Rivers State, from existed and previously formed and by tapping processes for newer ones.

2.2 EXPERIMENTAL PROCEDURES
2.2.1 Experimental method
2.2.2 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 (ficus glumosa), resin pastes with coating thicknesses of 150µm, 250µm and 300µm 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 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 demoulded after 24hrs and cured for 28 days. The specimens were cured at room temperature in the curing tanks which then gave way for accelerated corrosion test process and testing procedure allowed for 39 days first crack noticed and a further 21 days making a total of 60 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 of beams and 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 beams specimens. Specimens were partially immersed in a 5% NaCl solution for duration of 60 days, to examine the surface and mechanical properties of rebars.

2.3 Pull-out Bond Strength Test

The pull-out bond strength tests on the concrete cubes were performed out after 54 specimens on Universal Testing Machine of capacity 50KN in accordance with BS EN 12390-2. After curing for 28days, 6 controlled cubes (non-corroded) was kept in a control condition as against corrosion as to ascertain bond difference effects, 48 cubes samples of non-coated and resins / exudates coated were partially place in ponding tank for 39 days placed to examine accelerated corrosion process. After 39 days, the accelerated corrosion subjected samples were examined to determine bond strength effects due to corrosion and corrosion inhibited samples.

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. The bond length of the bar was placed at the centre of the concrete cube with 40mm of length protruding from the top of the specimen and with the outer 75 mm of the reinforcing bar enclosed in a PVC tube to ensure that these sections remained un-bonded. Additionally, the reinforcement bar was covered with tape for a distance of 75 mm from both ends of the cube so that the corrosion could take place only within the 50 mm bonded length. The pull-out bond tests were conducted using an Instron Universal Testing Machine of 50KN capacity at a slow loading rate of 1 mm/min. 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 39 days and a further 21 days making a total of 60 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 non-corroded, 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 non-corroded steel bars were subsequently used in the bond and flexural test.

III. Experimental Results and Discussion

Tables 3.1, 3.2 and 3.3 shows the experimental results of pull-out bond strength test of 27 specimens of 9 samples of 3 group, non-corroded, uncoated (now corroded) and resins / exudates paste coated with (ficus glumosa) trees extract. Samples A – I, showed the entire results of the failure bond load, pull-out bond strength and maximum slip. Tables 3.2, 3.4 and 3.5 showed the results of the derive average values of non-corroded, corroded and resins/ exudates coated paste samples A,B and C obtained from tables 3.1, 3.2 and 3.3.

Figures 3.1 and 3.3 are the plot of failure bond load versus bond strength and figures 3.2 and 3.4 are the plots of bond strength versus maximum slips. The plots of 3.1 – 3.4 explained the behavior of the steel reinforcement effect due to corrosion potential.

3.1 Non-corroded Concrete Cube Members

Tables 3.1 and 3.4 and figures 3.1 – 3.4 shows failure bond load, bond strength and maximum slip of 27.08%, 55.90% and 47.14% respectively.

3.2 Corroded Concrete Cube Members

Tables 3.2 and 3.5, figures 3.1 – 3.4 shows the results of pullout load bond, bond strength and maximum slip of 21.30%, 36.80%, 32.00%. When compared to results of non-corroded, corroded members have lower values.

3.3 Ficus glumosa Steel Bar Coated Concrete Cube Members

Tables 3.3, 3.6, form the entire and average derive values of the results, figure 3.1 – 3.6 represented the plotted values of failure bond load versus bond strength and bond strength versus maximum slip. Observations from experimental work showed the results of coated when compared to corroded has tremendous increasing values of failure bond load, bond strength and maximum slip of 33.60%, 62.40%, 88.2% against 21.30%, 36.80%, 32.00% of corroded respectively. This shows decreased in values in corroded members.

Results of Pull-out Bond Strength Test (τu) (MPa) Non-corroded Control,

Corroded and Resin Steel bar Coated

1	**Table 3.1 : Results of Pull-out Bond Strength Test (τu) (MPa)**									
S/N0		A	B	C	D	E	F	G	H	I
Concrete Cube	**Non-corroded Control Cube**									
CCk1-1	Failure Bond Loads (kN)	22.83	21.97	21.47	23.68	22.18	23.04	23.18	21.98	22.84
CCk1-2	Bond strength (MPa)	7.35	7.22	7.09	7.75	7.21	7.96	7.75	7.81	7.36
CCk1-3	Max. slip (mm)	0.114	0.099	0.089	0.119	0.102	0.108	0.109	0.094	0.118
CCk1-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12
2	**Table 3.2 : Results of Pull-out Bond Strength Test (τu) (MPa**									
	Corroded									
CCk 2-1	Failure Bond load (KN)	17.34	18.09	17.86	18.32	17.57	17.50	18.09	17.57	17.55
CCk 2-2	Bond strength (MPa)	4.25	4.90	4.75	5.27	4.71	4.46	4.87	4.56	4.48
CCk 2-3	Max. slip (mm)	0.054	0.080	0.073	0.085	0.072	0.072	0.078	0.070	0.070
CCk 2-5	Bar diameter (mm)	12	12	12	12	12	12	12	12	12
	Table 3.3 : Results of Pull-out Bond Strength Test (τu) (MPa									
	Coated specimens									
		(150μm) coated (A, B, C)			**(250μm) coated(D,E, F)**			**(350μm) coated (G,H,I)**		
3	**Ficus glumosa(steel bar coated specimen)**									
CCk 3-1	Failure load (KN)	21.23	22.06	21.35	23.55	23.47	22.85	25.39	27.52	25.60
CCk 3-2	Bond strength (MPa)	6.32	7.08	6.32	7.85	7.88	7.18	8.09	8.36	8.13
CCk 3-3	Max. slip (mm)	0.101	0.125	0.101	0.132	0.132	0.128	0.139	0.153	0.133
CCk 3-4	Bar diameter (mm)	12	12	12	12	12	12	12	12	12

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

Control, Corroded and Resin Steel bar Coated				
S/N0		A	B	C
Concrete Cube	**Table 3.4: Results of Average Pull-out Bond Strength Test (τu) (MPa)**			
1A	**Non-corroded Control Cube**			
CCk1A-1	Failure Bond Loads (kN)	22.09	22.46	22.66

CCk1A-2	Bond strength (MPa)	7.22	7.40	7.64
CCk1A-3	Max. slip (mm)	0.100	0.104	0.107
CCk1A-4	Bar diameter (mm)	12	12	12
	Results of Average Pull-out Bond Strength Test (τu) (MPa)			
2A	**Corroded**			
CCk 2A-1	Failure Bond load (KN)	17.76	17.77	17.74
CCk 2A-2	Bond strength (MPa)	4.63	4.71	4.64
CCk 2A-3	Max. slip (mm)	0.069	0.0.72	0.073
CCk 2A-5	Bar diameter (mm)	12	12	12
	Results of Average Pull-out Bond Strength Test (τu) (MPa) (Coated specimens)			
		150µm) coated (A, B, C)	**(250µm) coated(D,E, F)**	**(350µm) coated(G,H, I)**
3A				
CCk 3A-1	Failure load (KN)	21.54	23.29	26.17
CCk 3A-2	Bond strength (MPa)	6.57	7.65	8.19
CCk 3A-3	Max. slip (mm)	0.109	0.131	0.147
CCk 3A-4	Bar diameter (mm)	12	12	12

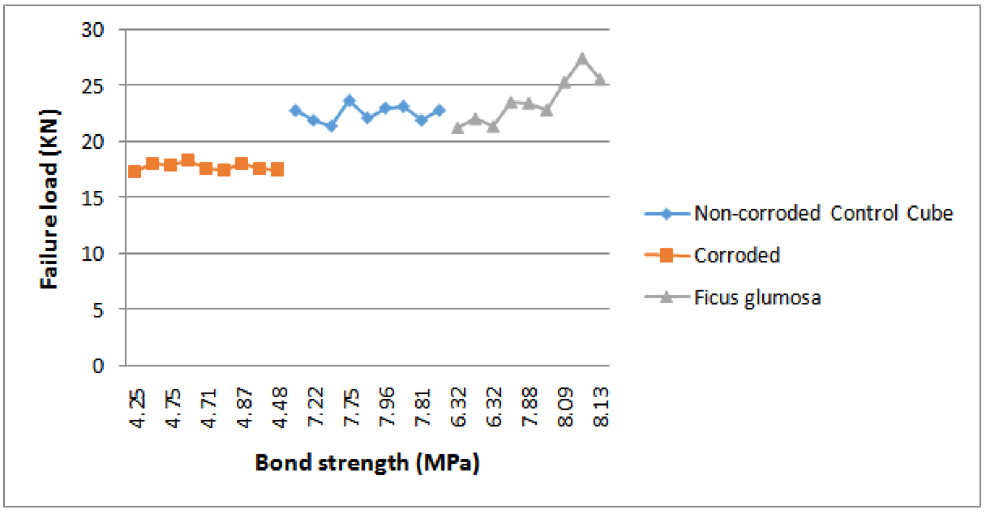

Figure 3.1: Summary Results of Pull-out Bond Strength Test (τu) (MPa) (Failure loads versus Bond Strengths)

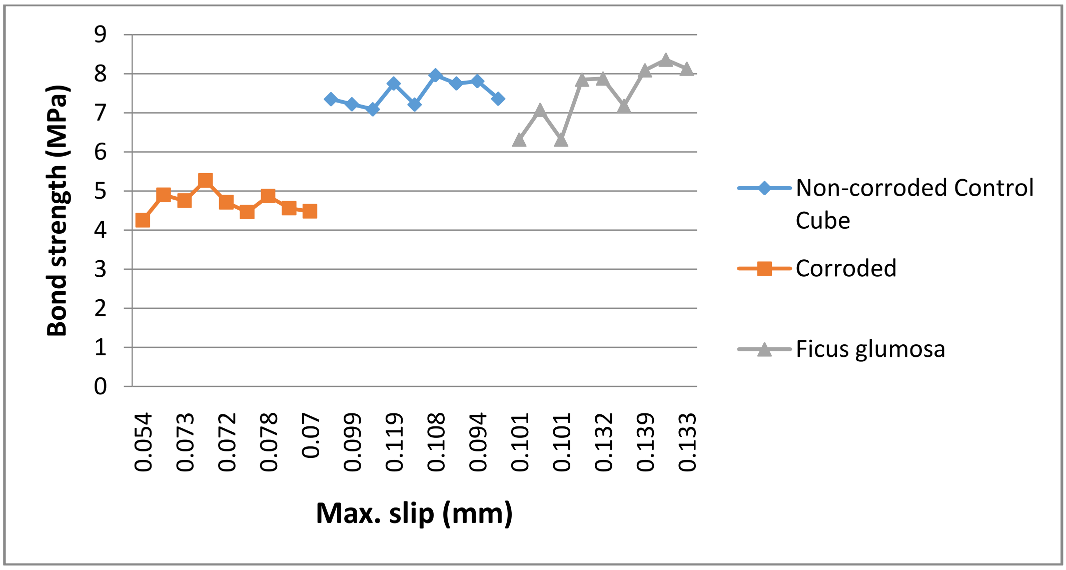

Figure 3.2: Summary Results of Pull-out Bond Strength Test (τu) (MPa) (Bond Strength versus Maximum Slip)

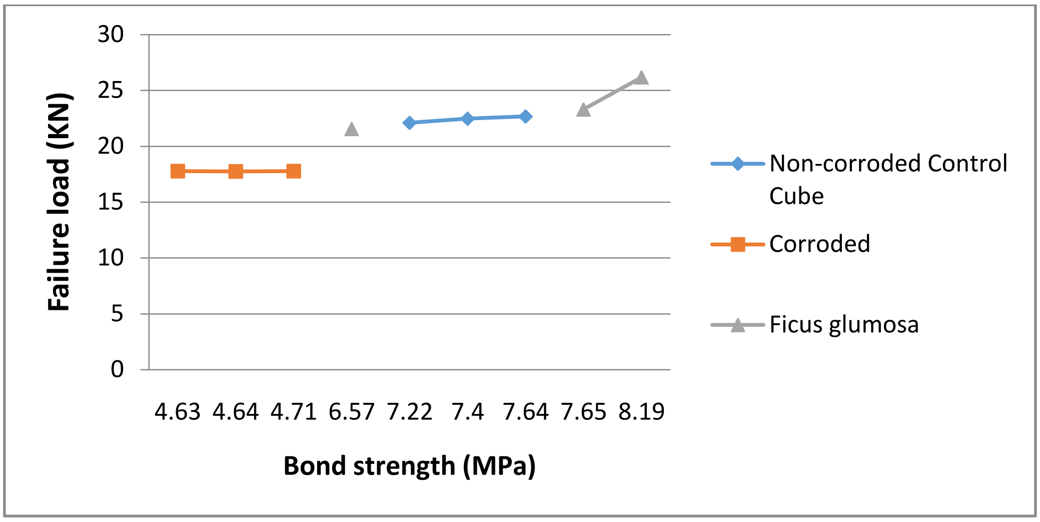

Figure 3.3: Average Results of Pull-out Bond Strength Test (τu) (MPa) (Failure loads versus Bond Strengths)

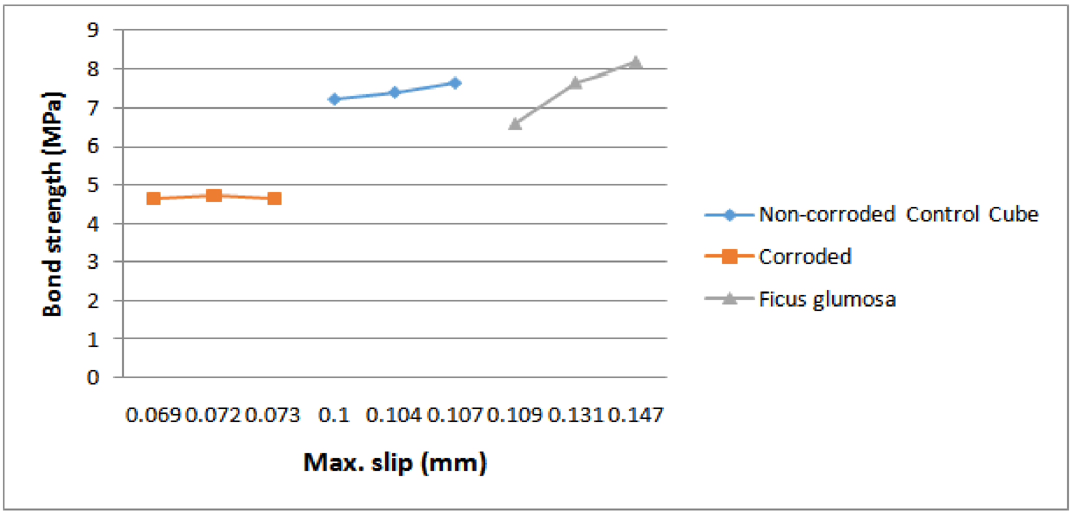

Figure 3.4: Average Results of Pull-out Bond Strength Test (τu) (MPa) (Bond Strength versus Maximum Slip)

IV. Conclusion

From the experimental investigations, the following conclusions were drawn:

i. The entire results showed good bonding characteristic and effectiveness in the use of ficus glumosa resins / exudates as protective materials against corrosion.

ii. Corrosion potential was observed in uncoated concrete cube members

iii. Bond stresses experienced in inhibitor coated reinforcements are higher compared to the controlled specimens.

iv. Non-corroded and resin/exudates coated values were all higher than that of corroded specimens which indicated good bonding potentials.

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