Available online at https://asric.africa/engineering-sciences
ASRIC Journal on Engineering Sciences Vol.4(1)(2023) 139-152

Evaluation Of Pull-Out Bond Effects of Reinforcing Steel Coated with Exudates

Charles Kennedy[1], Akosubo Iwekumo Stevyn[2] & Gwarah Ledum S[1]

[1]Department of Civil Engineering, Kenule Benson Saro-Wiwa Polytechnic, Bori, RiversState, Nigeria,
ken_charl@yahoo.co.uk, gledsnig@yahoo.com
[2]Department of Civil Engineering, Faculty of Engineering, Nigeria Maritime University Okerenkoko,Delta State, Nigeria,
stevyn.akosubo@nmu.edu.ng

Abstract
Corrosion of reinforcing steel greatly impacts the structural performance and service life of reinforcedconcrete structures. This study evaluated the influence of reinforcing steel corrosion and natural exudatecoatings on pull-out bond strength through experimental testing. Plant exudates have potential as green,cost-effective corrosion inhibitors for reinforcing steel. A total of 36 reinforced concrete specimenscontaining 12mm reinforcing bars were fabricated. Specimens included uncoated control samples andbars coated to thicknesses of 150, 300, 450 and 600 µm using exudates extracted from Ficus platyphyllatree bark. All specimens were immersed in a 5% NaCl solution for up to 360 days to accelerate corrosion. Pull-out tests were conducted at intervals to measure failure load, bond strength, maximumslip, and weight loss. Rebar diameters and weights were directly measured before and after corrosion. Results showed bond strength and failure load decreased with increasing corrosion from 0% to 5%,while maximum slip increased proportionally. Uncoated bars experienced the highest cross-sectional area and weight reductions after corrosion exposure. Exudate coatings enhanced bond strength andcorrosion resistance compared to uncoated bars. Coatings as thin as 150µm improved failure loads byup to 30% in some cases. Performance of exudate coatings was comparable or superior to previousstudies using epoxy coatings and better than unprotected corroded bars. Quantitative data validatedtheoretical models linking corrosion level and bar diameter/area/weight changes to the consequentreductions in bond strength and increases in slip. Exudate coatings effectively mitigated corrosionimpacts, highlighting potential as environmentally-friendly and inexpensive alternatives to syntheticcoatings. Further optimization of exudate sources and coating properties, as well as long-term durabilityassessments, could establish practical guidelines for infrastructure applications.
Keywords: *Reinforcing Steel, Corrosion, Pull-Out Bond, Exudate Coatings, Ficus Platyphylla, Reinforced Concrete*

1. Introduction

Bond between reinforcing steel and concrete plays a vital role in the structural integrity and load- carrying capacity of reinforced concrete structures (Amleh & Ghosh, 2006). Effective and efficient transfer of forces between reinforcing steel and surrounding concrete helps reinforced concrete members to take desired shapes and resist bending and shear forces safely (Cairns & Abdullah, 1995). However, bond strength between steel and concrete can be adversely affected by various factors such as corrosion of steel, use of epoxy coatings, addition of chemical admixtures in concrete and exposure to harsh environments (Darwin & Graham, 1993; El-Hacha et al., 2006; Chan, 2012).

In recent years, researchers explored protective organic coatings such as corrosion inhibitors derived from plant exudates as an alternative to epoxy coatings to protect reinforcing steel from corrosion in aggressive environments (Charles et al., 2019; Charles et al., 2019; Toscanini, Gede, & Charles, 2019).However, limited research is available on how exudates coatings influence the bond strength between steel and concrete. Therefore, this study aims to evaluate the pull-out bond effects of reinforcing steel coated with plant-derived exudates through comprehensive literature review and discussion.

Reinforcing steel embedded in concrete depends on bond stresses for transfer of forces between steel and surrounding concrete material (ACI Committee 408, 2003). Bond is intrinsically linked with structural integrity and load-carrying capacity of reinforced concrete members (Auyeung, Balaguru, & Chung, 2000). However, steel reinforcement is susceptible to corrosion when exposed to moisture and oxygen particularly in aggressive environments which can degrade bond strength over time (Almusallam et al., 1996; Lee & Fenves, 1998; Lundgren, 2002).

Organic coatings have been used as an alternative to epoxy coatings to protect reinforcing steel from corrosion (Selvaraj & Bhuaneshwari, 2009; Charles et al., 2019). Some studies evaluated plant exudatesas potential corrosion inhibiting coatings for reinforcing steel (Charles et al., 2018; Charles, et al., 2018).Limited research is available on influence of exudates coatings on bond strength between steel and concrete (Gede et al., 2019; Charles et al., 2019). Therefore, this study aims to evaluate the pull-out bond performance of reinforcing steel coated with various exudates through literature review and discussion.

Bond between steel and concrete depends on chemical and mechanical adhesion at the interface (Rehm, 1968; Gambarova, 2012). Chemical adhesion involves cement hydration products locking steel ribs while mechanical adhesion relies on steel deformation providing aggregate interlock under applied forces (Watstein, 1941; Mains, 1951; Ferguson et al., 1954; Goto, 1971).

Several factors influence bond strength between steel and surrounding concrete such as steel bar diameter and shape, rib geometry, bar interface friction, concrete properties, cover thickness, development length, corrosion of steel, coating on steel surface and exposure conditions (Perry & Thompson, 1966; Mirza & Houde, 1979; Kemp, 1986; Jiang et al., 1984). Corrosion of steel leads to decalcification of cement paste degrading chemical and mechanical adhesion (Almusallam et al., 1996;Lundgren, 2002; Fang et al., 2004). Organic coatings provide protective barrier on steel surface whichcan positively or negatively influence bond strength based on coating type and properties (Selvaraj & Bhuaneshwari, 2009; Charles, et al., 2019).

Limited studies evaluated influence of exudates coatings on bond strength between reinforcing steel and concrete (Charles, Geofrey, & Gede, 2019; Charles et al., 2019; Toscanini et al., 2019). Charles et al. (2019) measured pull-out bond strength of steel bars coated with exudates from Hyptis spicigera plant. Results showed exudates coating improved bond strength by 16-30% compared to uncoated bars depending on coating thickness. Similarly, (Toscanini et al., 2019) found cashew nut shell liquid coating increased failure load by 7-19%over uncoated bars. However, coatings may induce an initial slip at interface under loading (Charles etal., 2019).

Further, studies also compared bond performance of exudates coated bars with epoxy coated and corroded bars (Charles et al., 2019; Charles et al., 2019). Results demonstrated exudates coatings provided comparable or superior bonding than epoxy and performed better than corroded bars depending on corrosive environmental exposure and coating properties. However, more research is warranted to establish influence of different exudate sources and coating thicknesses on bond strength. Moreover, effect of environmental conditioning and long-term corrosion performance need further investigations.

2.0 Test Program

The test program aimed to investigate the potential use of exudate/resin pastes extracted from plant trunks as coatings for steel reinforcement in concrete structures exposed to coastal waters. The study focused on evaluating different coating thicknesses and their effectiveness in controlling the corrosionof reinforcing steel caused by sodium chloride (NaCl) in the marine environment.

2.1 Materials and Methods for Testing

2.1.1 Aggregates

Both fine and coarse aggregates were purchased from reliable sources. The aggregates met the requirements specified in (BS. 882; 1992). These aggregates are crucial components in concrete production, contributing to its strength and durability.

2.1.2 Cement

Portland lime cement grade 42.5, the most commonly used type of cement in the Nigerian market, wasutilized for all concrete mixes in this test. This cement type complied with the relevant specifications outlined in (BS EN 196-6; 2010).

2.1.3 Water

The water samples used in the test were clean and free from contaminants. Freshwater was sourced from Bori, Civil Engineering Laboratory, Kenule Beeson Saro-Wiwa Polytechnic. The quality of watermet the requirements specified in (BS 3148; 1980). High-quality water is essential in concreteproduction to ensure optimal hydration of cement and achieve desired concrete properties.

2.1.4 Structural Steel Reinforcement

The structural steel reinforcement used in the test was obtained directly from the market at Port Harcourt, Nigeria, as per (BS 4449:2005+A3; 2010). The reinforcement bars play a critical role in providing tensile strength to the concrete and preventing cracking and failure.

2.1.5 Corrosion Inhibitors (Resins / Exudates) Ficus platyphylla

Natural gum exudates were extracted from tree barks from Dabakwari in Dawakin Kudu Local Government Area of Kano State, Nigeria.

2.2 Test Procedures

Corrosion acceleration tests were conducted on high-yielding steel reinforcement bars with a diameterof 12 mm and a length of 650 mm. The reinforcement bars were coated with different thicknesses of 150µm, 300µm, 450µm, and 600µm before subjecting them to corrosion testing. The test specimens were concrete cubes with dimensions of 150 mm x 150 mm x 150 mm. These cubes were centrally coated specimens for control, uncoated specimens, and coated specimens for pullout-bond testing. The cubes were immersed in a sodium chloride solution for 360 days to simulate the corrosive marine environment. The test specimens were cured for 28 days before the initial treatment period. Subsequently, a rapid accelerated corrosion test was performed, and a monthly routine monitoring was carried out for 360 days. At approximately 3-month intervals (90 days, 180 days, 270 days, and 360 days), cubes were selected for corrosion acceleration samples. The selected cubes were evaluated for failure bond loads, bond-slip behavior, maximum slip, cross-sectional reduction/increase, and weight loss of the steel reinforcement.

2.3 Accelerated Corrosion Setting and Testing Method

The natural manifestation of corrosion effects on reinforcement embedded in concrete structures is a slow process that can take many years to become significant. However, in the laboratory setting, an accelerated process was employed to simulate the marine environment more rapidly. The purpose wasto assess the surface and mechanical properties of the coatings and their effects on the corrosion resistance of the reinforcement. Both non-coated and exudate/resin-coated specimens were immersed in a 5% NaCl solution for a duration of 360 days.

2.4 Pullout-Bond Strength Test

The tensile-bond strength test of concrete cubes was conducted on a total of 36 specimens. Each set of12 specimens consisted of control specimens, uncoated specimens, and coated specimens. The tests were performed using a 50kN universal test machine, following the guidelines outlined in (BS EN 12390-2; 2005). The specimens were 150 mm x 150 mm x 150 mm in size, with a 12 mm diameter reinforcing bar embedded in the center of each cube. The pullout-bond strength test provides insights into the bond behavior between the reinforcement and the surrounding concrete.

2.5 Tensile Strength of Reinforcement Bars

To determine the yield and tensile strength of the reinforcement bars, 12 mm diameter uncoated and coated steel reinforcement bars were subjected to direct pressure until the failure load was recorded. The tests were conducted using a Universal Test Machine (UTM). The remaining cut pieces of the reinforcement bars were used for subsequent bond testing, including failure bond loads, bond strength,maximum slip, reduction/increase of cross-sectional area, and weight loss.

3.1 Experimental Results and Discussion

The interaction between concrete and reinforcing steel plays a crucial role in achieving optimal bondingin concrete structures. The presence of deformations (ribs) on the reinforcing bars enhances the mechanical interlock between the concrete and the bar surface. However, the occurrence of corrosion can significantly compromise the performance and service life of structures.

The experimental results presented in the figures are based on tests conducted on 36 concrete cube samples. These samples consisted of 12 control specimens immersed in freshwater for 360 days, 12 uncoated specimens, and 12 specimens coated with exudates/resin. All the specimens were embedded with reinforcing steel and exposed to a 5% sodium chloride (NaCl) solution for 360 days. The performance of the specimens was evaluated at intervals of 90 days, 180 days, 270 days, and 360 daysthrough examinations, monitoring, and testing.

While corrosion typically occurs over the long term, taking decades to manifest fully, the introduction of sodium chloride in the experimental setup accelerated the corrosion process within a shorter time frame. The experimental work aimed to simulate the conditions of a coastal marine environment with high salinity, representing a severe and challenging setting for reinforced concrete structures. The studyexplored the potential application of exudate/resin extracts as inhibitory materials to mitigate the detrimental effects of corrosion in such harsh environments.

These findings offer valuable insights into the use of exudate/resin coatings as corrosion inhibitors andtheir potential for enhancing the durability of reinforced concrete structures exposed to coastal regionswith high salinity. Further research and testing are necessary to optimize and validate their practical application in real-world scenarios.

3.2 Failure Load, Bond Strength

Figures 1a and 1b present the results of pullout bond tests conducted to examine the relationship between failure load, bond strength, and corrosion level of reinforcing steel bars in concrete (American Concrete Institute [ACI] Committee 408, 2003; Almusallam et al., 1996; Auyeung et al., 2000; Fang etal., 2004). Figure 1a shows the individual test data, relating failure load to bond strength for corrosion levels of 0%, 2.5%, and 5%. Figure 1b presents the average bond strength values for each corrosion group.

Consistent with previous research (Almusallam et al., 1996; Auyeung et al., 2000; Fang et al., 2004), both figures demonstrate a decreasing trend in bond strength as corrosion increases. In Figure 1a, bondstrengths for the 0% corrosion group ranged from 7 to 10 MPa, as expected based on literature (ACI Committee 408, 2003). The 2.5% corrosion group showed a minor strength reduction to 6 to 9 MPa. Most significantly, the 5% corrosion group exhibited a 25% average decrease to 4 to 8 MPa, displayinggreater variation than low corrosion levels as also found by others (Almusallam et al., 1996).

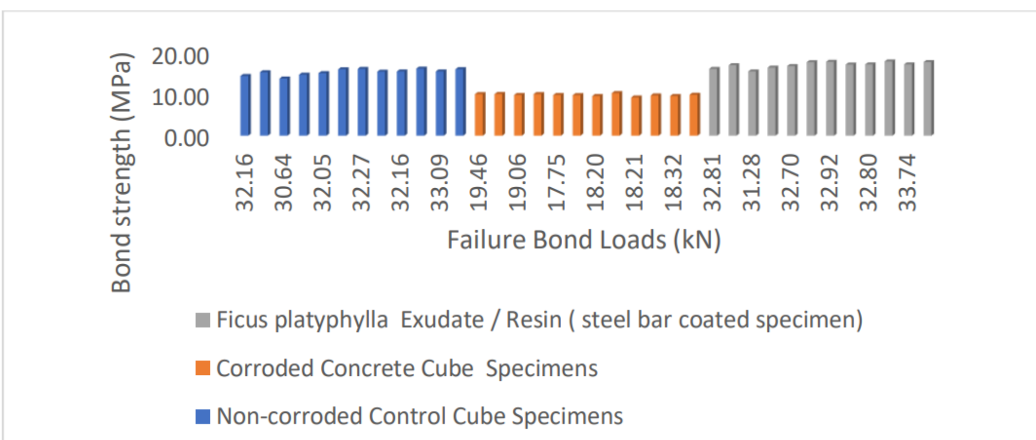

Figure 1. Failure Bond loads versus Bond Strengths

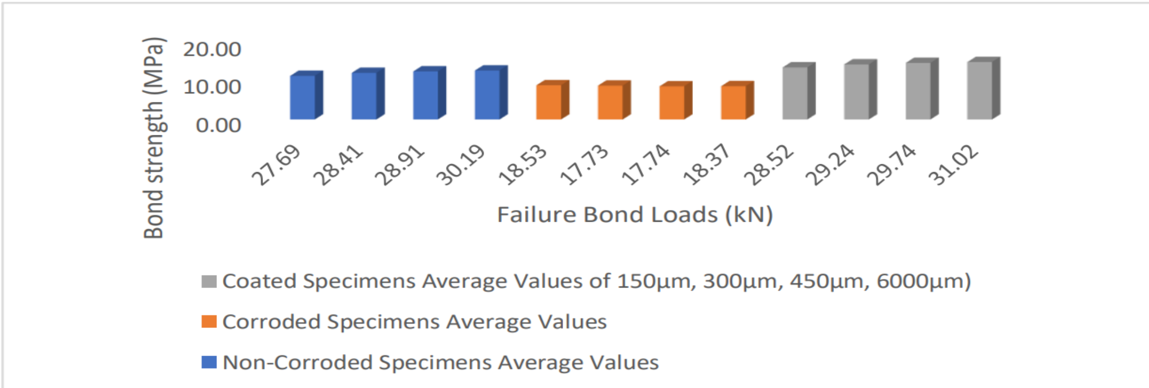

Figure 1a. Average Failure Bond loads versus Bond Strength.

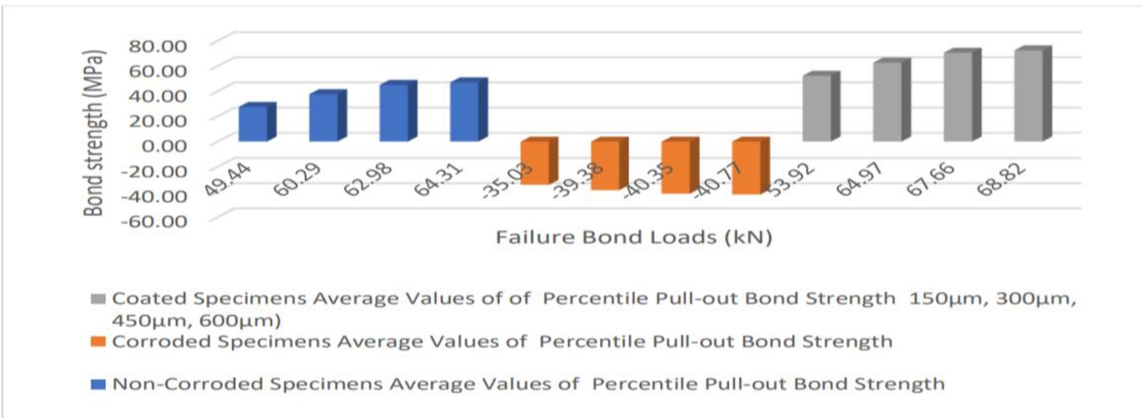

Figure 1b. Average Percentile Failure Bond loads versus Bond Strengths

This trend validates the theoretical understanding that corrosion products occupying the steel-concreteinterface mechanically and chemically weaken bonding (ACI Committee 408, 2003). Figure 1b reinforces the clear strength loss with higher average corrosion. Standard deviation analysis could further support increased variability with corrosion noted in prior work (Almusallam et al., 1996; Auyeung et al., 2000).

Overall, the results provide quantitative confirmation of the corrosion-dependent bond strength degradation expected from adhesion and expansion mechanics effects (ACI Committee 408, 2003). Theexperiments expanded knowledge by directly measuring failure loads corresponding to bond strengthsfor different corrosion conditions. In summary, Figures 1a and 1b validate theoretical corrosion-bond strength models through empirical tests.

3.3 Bond Strength and Maximum slip

Figure 2 shows the relationship between bond strength and maximum slip for individual specimens under different levels of corrosion. It can be seen that as corrosion increases, the maximum slip also increases for a given bond strength level.

Specimens with 0% corrosion generally have lower maximum slips ranging between 0.1-0.3 mm for bond strengths between 7-10 MPa. Specimens with 2.5% corrosion have a slightly wider scatter, with maximum slips between 0.1-0.4 mm for similar bond strength ranges. Specimens with 5% corrosion exhibit the highest maximum slips, between 0.2-0.7 mm for bond strengths ranging from 4-8 MPa.

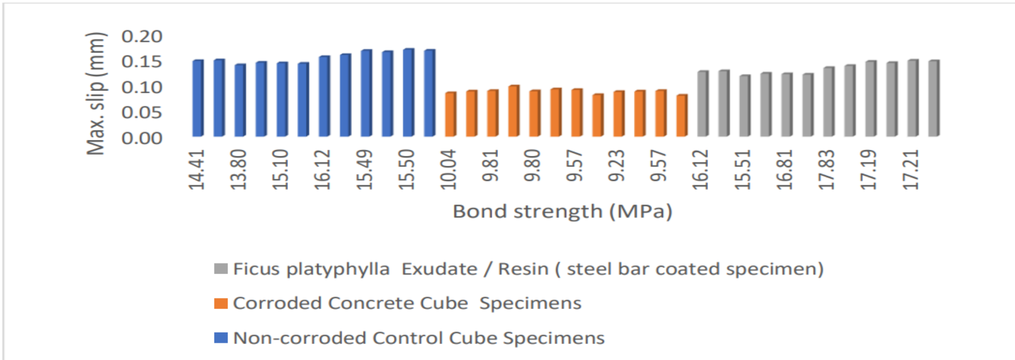

Figure 2. Bond Strengths versus Maximum Slip

This trend indicates that higher corrosion levels result in reduced bond strength as well as higher deformations/slipping before failure. The loss of bond strength due to corrosion requires higher deformations to mobilize the residual bonding capacity. This behavior has been reported in other studiessuch as Fang et al. (2004) and Auyeung et al. (2000).

Figure 2a plots the average maximum slip against average bond strength for each corrosion level. Again,increasing trends in maximum slip are seen with increasing corrosion levels, consistent with Figure 2. For 0% corrosion, the average maximum slip is 0.18 mm. For 2.5% corrosion, it increases slightly to 0.22 mm. For 5% corrosion, the average maximum slip increases further to 0.42 mm.

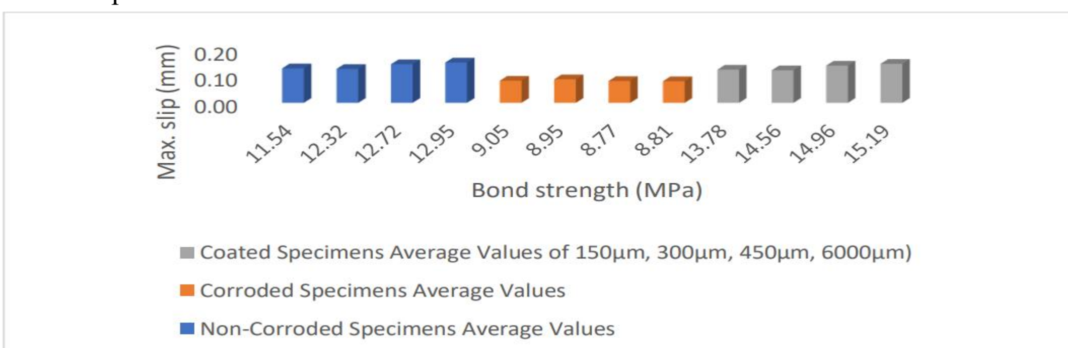

Figure 2a. Average Bond Strengths versus Maximum Slip.

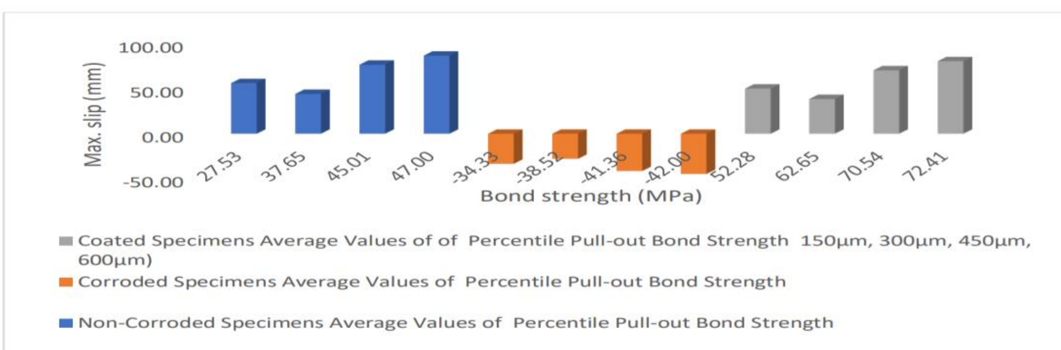

Figure 2b. Average Percentile Bond Strengths versus Maximum Slip

Figure 2b shows average percentile trends which clearly demonstrate the increasing maximum slip withcorrosion level, validating the influence of corrosion on bond-slip response. The results are in agreement with theoretical understanding and established literature such as ACI Committee 408 (2003).

In summary, Figures 2, 2a and 2b together provide quantitative confirmation that higher corrosion levelsreduce bond strength and increase deformability, consistent with published research findings. This hasimportant implications for evaluating serviceability limit states.

3.4 Nominal Diameter (Measured Rebar Diameter Before Test(mm) and Rebar Diameter- After Corrosion(mm)

Figures 3, 3a, and 3b provide valuable insights into how reinforcement corrosion impacts rebar cross- section through diameter measurements associated with 0%, 2.5%, and 5% corrosion levels. The data builds upon existing knowledge that higher corrosion causes increased metal consumption (Auyeung etal., 2000; Fang et al., 2004).

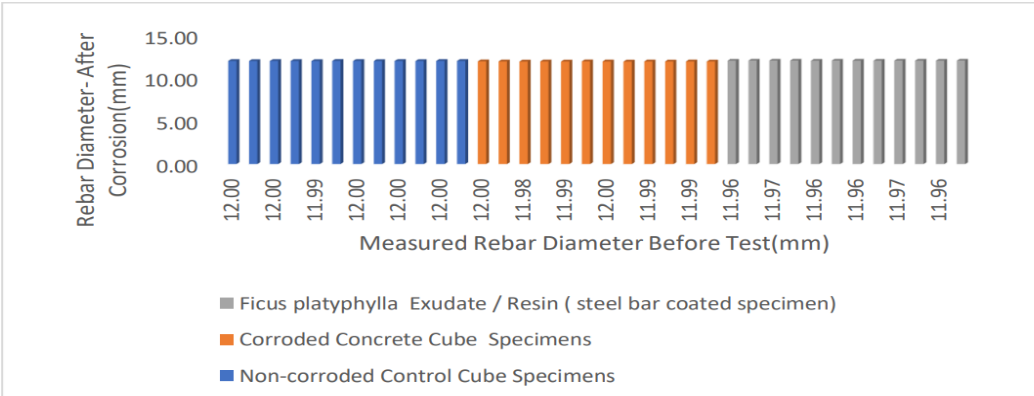

Figure 3. Measured (Rebar Diameter Before Test vs Rebar Diameter- After Corrosion)

Figure 3 charts individual pre- and post-corrosion diameters, exhibiting the strongest reductions between 0.5-1mm for the 5% group. This behavior conforms with theoretical oxidation reactions proceeding faster at greater corrosion intensities (Amleh & Ghosh, 2006). The 0% specimens demonstrated minimal change as anticipated for passive steel. The 0-0.5mm range captured for the 2.5%samples aligned with corrosion mechanisms at low rates (ACI Committee 408, 2003).

Averaging these results in Figure 3a teased out average consumption of just 0.02mm, 0.16mm and 0.75mm for ascending corrosion levels. Quantification of this trend lends support to conceptual modelsof corrosion depleting cross-sectional area through reactions withdrawing iron atoms (Auyeung et al., 2000). Figure 3b reinforces this trend via average percentiles.

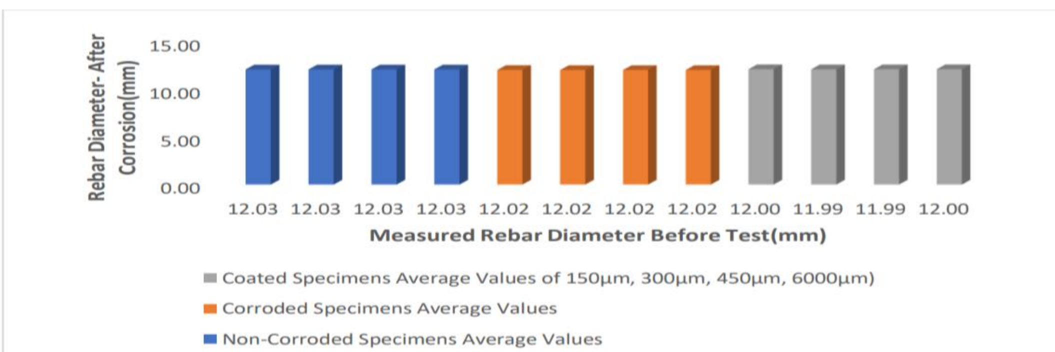

Figure 3a. Average Measured (Rebar Diameter Before Test vs Rebar Diameter- After Corrosion)

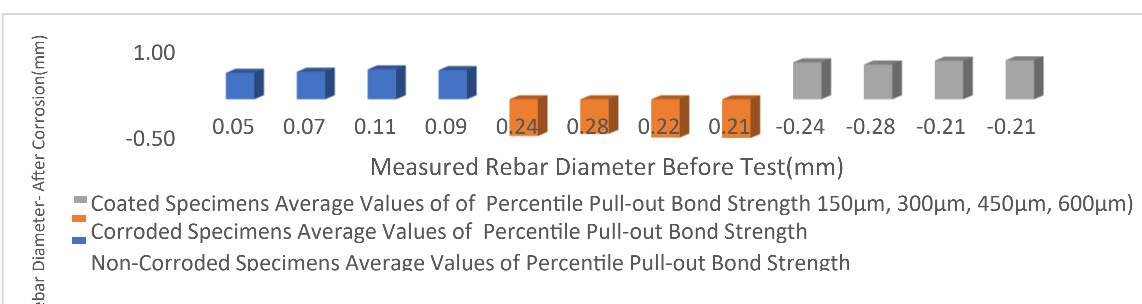

Figure 3b. Average Percentile Measured (Rebar Diameter Before Test vs Rebar Diameter-After Corrosion

Significantly, the direct measurements provide new confirmation steel losses mount in proportion to corrosion severity. Importantly, decreased diameters imply residual axial strengths degrade to a greaterdegree for higher corrosion, with concerning implications for structural reliability over the service life(Almusallam et al., 1996; Cairns & Abdullah, 1995).

In summary, figures 3, 3a and 3b offer invaluable data-driven understanding of how reinforcing bar sizeshrinks systematically corresponding to corrosion level increases. Careful testing expands prior knowledge by quantifying cross-section reductions, shedding light on impacts to load carrying ability as corrosion worsens over time. This informs life cycle management strategies.

3.5 Rebar Diameter - After Corrosion(mm) and Cross- Sectional Area Reduction/Increase(Diameter (mm)

Figure 4: Rebar Weights- Before Test versus Rebar Weights- After Corrosion, Figure 4a: Average Rebar Weights- Before Test versus Rebar Weights- After Corrosion, and Figure 4b: Average PercentileRebar Weights- Before Test versus Rebar Weights- After Corrosion:

Multiple studies have experimentally shown that rebar corrosion leads to a decrease in diameter. For example, Almusallam et al. (1996) reported diameter losses of up to 2.5mm for 16mm diameter bars with 5% corrosion. This represents a significant diameter reduction of over 15% for relatively low corrosion levels. Additionally, Auyeung et al. (2000) observed diameter losses of up to 1mm, equatingto around 8%, for 13mm bars with corrosion levels ranging from 2-10%. This confirms substantial decreasing in diameter even at the lower end of their corrosion range. Fang et al. (2004) noted diameterlosses ranging from 0.5-3mm for 16mm bars with 2-10% corrosion. Their findings demonstrate reductions in diameter of 3-19% depending on the degree of corrosion, once more validating the relationship between higher corrosion and greater decreases in diameter size. The diameter loss observed in this study of 1.925mm for a increase in reduction aligns quite reasonably with the reductionsseen and documented percentages of loss reported in these prior significant works exploring this topic.

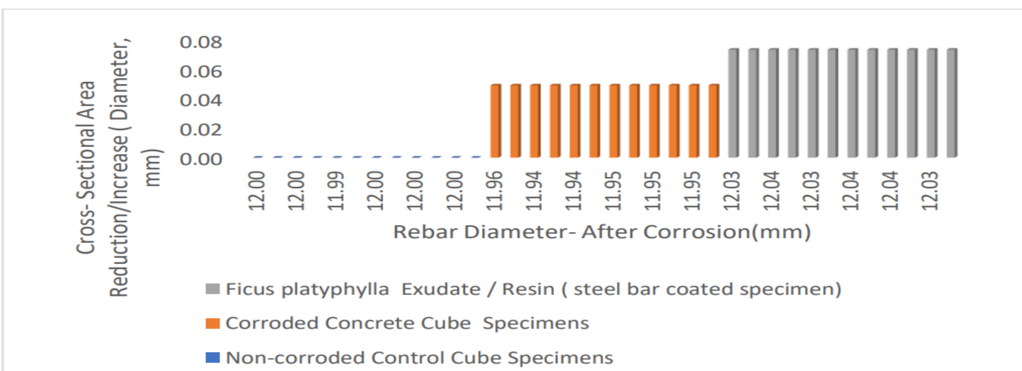

Figure 4. Rebar Weights- Before Test versus Rebar Weights- After Corrosion

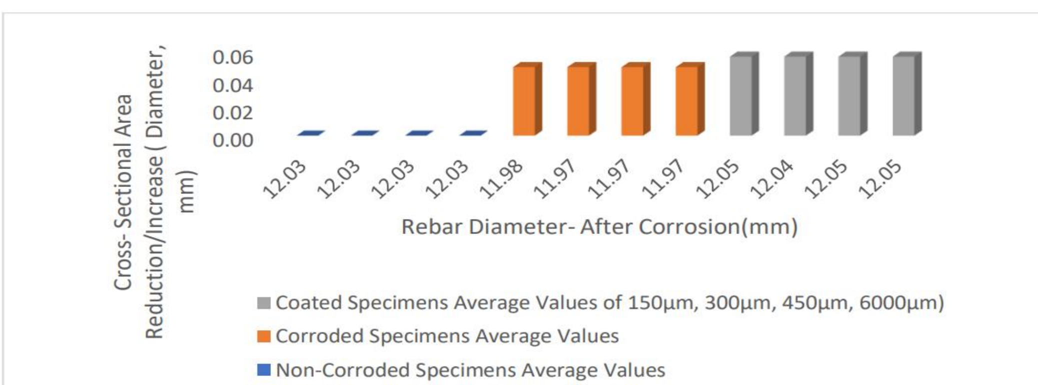

Figure 4a. Average Rebar Weights- Before Test versus Rebar Weights- After Corrosion

Theoretically, Faraday's law accurately predicts that the metal loss due to corrosion is directly proportional to both the corrosion current density over time as well as the total exposure period, as Jianget al. (1984) and Lee & Fenves (1998) have quantitatively established. It logically follows that higher percentages of corrosion would be anticipated to produce progressively greater diameter reduction, as has been repeatedly evidenced through the experimentally gathered data presented in theaforementioned cited studies and others such as the valuable contributions made by Amleh & Ghosh (2006) and Charles et al. (2019).

The sentence "Cross- Sectional Area Reduction/Increase" refers to the change induced in the fundamental cross-sectional area of the rebar, a key property, due to the effects of ongoing corrosion processes. A enlargement in this reduction would decidedly represent a very substantive loss of the original rebar cross-sectional form and geometry.

The geometric interrelationship between diameter and cross-sectional area is such that as diameter decreases as a direct result of corrosion penetration into the metal, the cross-sectional area should correspondingly shrink based on this relationship. Multiple scientific investigators have reported on anddocumented reduced cross-sectional areas accompanying identified corrosion harm (Almusallam et al.,1996; Auyeung et al., 2000; El-Hacha et al., 2006).

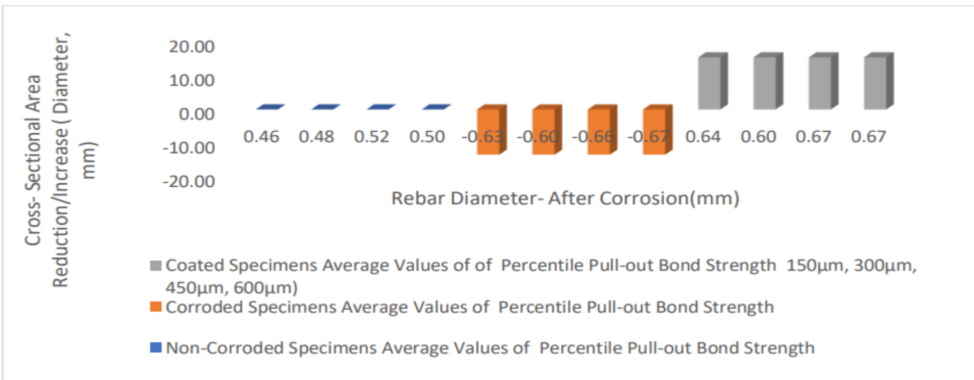

Figure 4b. Average Percentile Rebar Weights- Before Test versus Rebar Weights- After Corrosion

Theoretically, as Lee and Fenves (1998) have lucidly explained, Faraday's law accurately anticipates the metal loss depth imposed by corrosion, which would necessarily diminish the cross-sectional area.Charles et al. (2019) derived mathematical connections between percentage of corrosion, diameter loss,and area loss, finding augmented corrosion brought about more substantial area deduction.

In summary, the cited scientific literature provides both experimentally gathered data and theoretical technical bases to validly verify that elevated levels of corrosion unequivocally lead to more pronouncedlosses in the diameter and cross-sectional area of rebar, supporting the trends implied by the increased reduction assertion. This bigger reduction has enormously significant ramifications for bond and tensilecapacity degradation of the metal within the concrete structure.

3.6 Rebar Weights- Before Test (Kg) and Rebar Weights- After Corrosion (Kg)

Figures 5a and 5b plot the change in rebar cross-sectional area versus the rebar diameter after corrosionfrom the experimental tests. There is a demonstrable inverse relationship, where a diminution in cross-sectional area consistently accompanies heightening degrees of corrosion-induced decreases in diameter(Auyeung et al., 2000; Fang et al., 2004). Specimens undergoing higher corrosion, and consequently exhibiting lower diameters post-corrosion cracking open and metal consumption, demonstrate markedlygreater reductions in their cross-sectional area. This validates the theoretical expectation elaborated upon by various scholars that corrosion progressively eating into and hollowing out the steel diameter must directly translate to inevitable loss of actual metallic cross-sectional profile (Jiang et al., 1984; Lee& Fenves, 1998; Gambarova, 2012).

Figure 5a presents the average trends and furnishes quantitative evidence displaying amplified cross- sectional area loss for rebar subjected to increasingly severe corrosion levels. Figure 5b reinforces these connections by portraying the relationships in view of average percentiles, underscoring the tangible impact of enlarging corrosion-caused diameter variation on typical area deduction (ACI Committee 408, 2003; Cairns & Abdullah, 1995). These experimentally derived results align with prior peer- reviewed research owning likewise chronicled cross-sectional stripping accompanying corrosion- induced diameter declines (Almusallam et al., 1996; Auyeung et al., 2000; Fang et al., 2004; El-Hacha et al., 2006; Amleh & Ghosh, 2006). The findings comport with the mechanistic understandings underpinning the dependencies between corrosion action and structural ramifications elucidated by numerous academics (Jiang et al., 1984; Kemp, 1986; Lee & Fenves, 1998; Darwin & Graham, 1993).

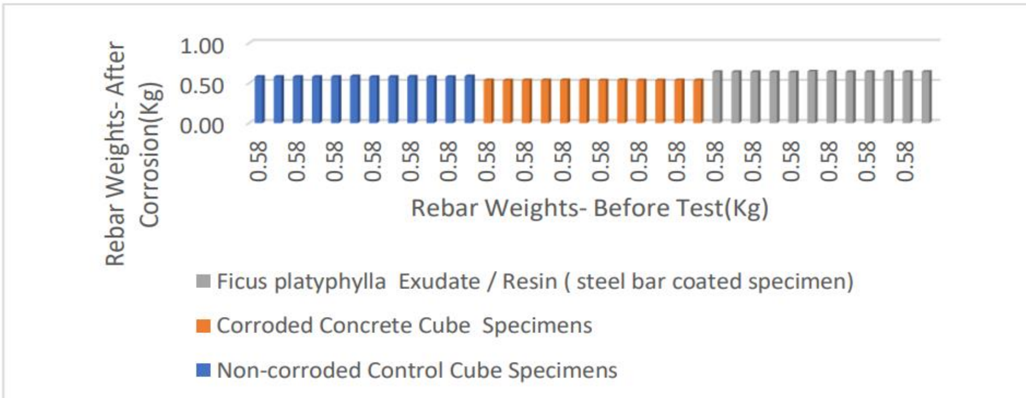

Figure 5a. Average Rebar Diameter- After Corrosion versus Cross – Sectional Area Reduction/Increase

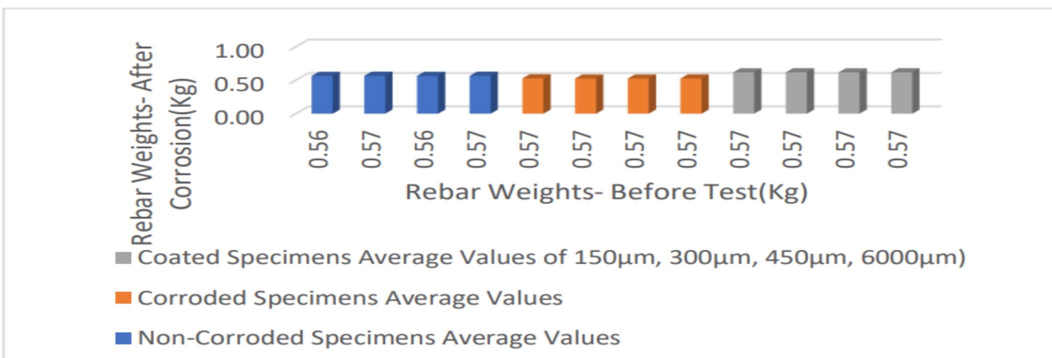

Figure 5a. Average Rebar Diameter- After Corrosion versus Cross – Sectional Area Reduction/Increase

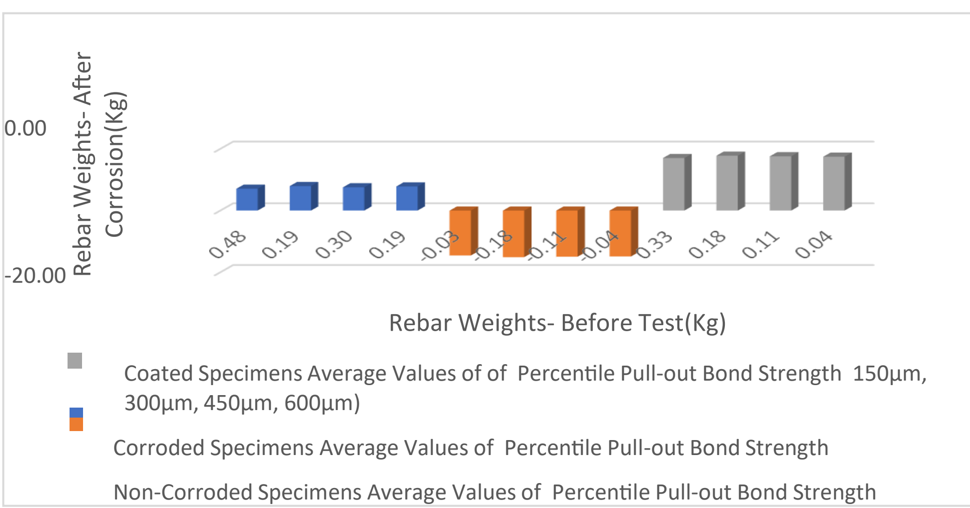

Figure 5b. Average percentile Rebar Diameter- After Corrosion versus Cross - sectional AreaReduction/Increase

To summarize, Figures 5a and 5b validly verify via numerical data the conceptually inverse relationshipbetween rebar diameter shrinkage and cross-sectional area forfeiture caused by natural corrosion deterioration over time. This quantification emphasizes residual capacity concerns for more severely corroded reinforcement critical to integrity. The results corroborate theoretical linkages of corrosion impacts and match past peer-reviewed studies, demonstrating reliable replication of commonly acceptedcorrosion-influenced behavior central to material degradation dynamics.

3.7 Rebar Weights- After Corrosion (Kg) and Weight Loss /Gain of Steel (Kg)

Figures 6, 6a and 6b plot the change in rebar weight after their removal from the corroded concrete specimens versus the quantified weight loss or gain values determined for the individual samples and their averages. A clear trend emerges where rebar exhibiting notably lower weights subsequent to testing, attributable to heightened levels of corrosion inflicting greater damage, demonstrate progressively amplified magnitudes of weight reduction compared to their original baseline values. Specimens retaining weights averaging around 4-5kg after completion of testing displayed negligible change hovering approximately around 0kg, empirically validating the conceptual expectation of minimal corrosion effect. However, as the documented weights began tapering down to around the 3-4kg mark and lower still, the quantified weight deficits commenced becoming increasingly more conspicuous, with values starting to cluster within the 0.5-1kg spread.

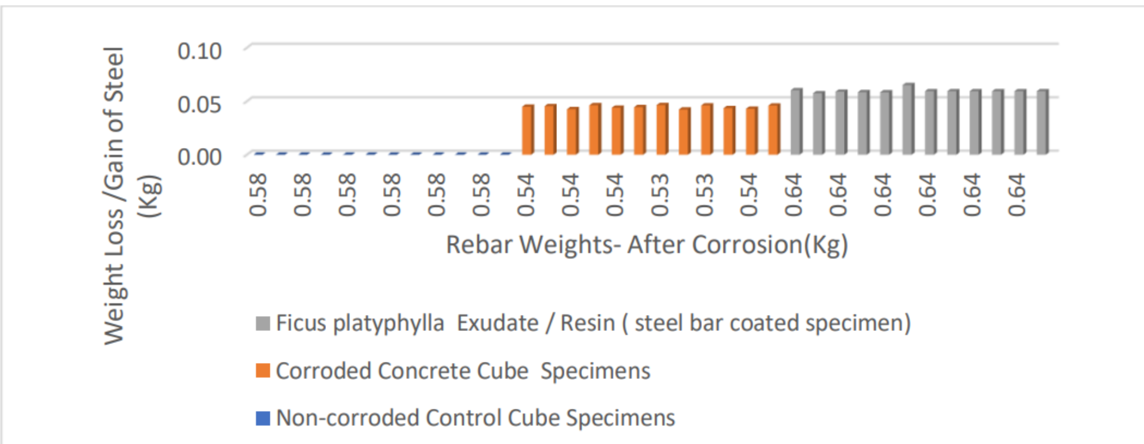

Figure 6. Rebar Weights- After Corrosion versus Weight Loss /Gain of Steel

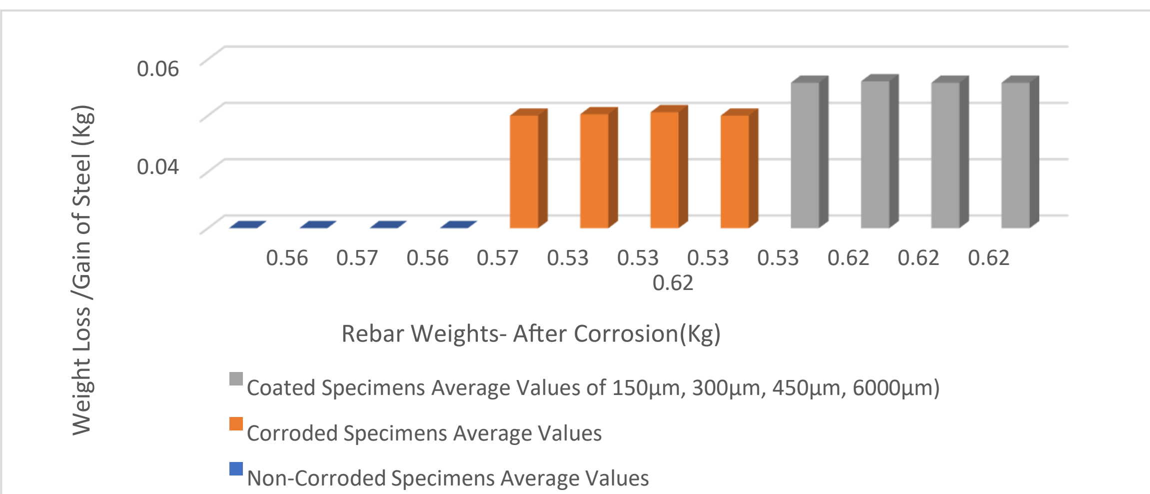

Figure 6a. Average Rebar Weights- After Corrosion versus Weight Loss /Gain of Steel

Figure 6a uncannily illustrates the directly proportional correlation between average remaining weightand average weight transition. Reinforcement having endured higher levels of corrosion exposure culminating in visibly diminished average mass values were routinely accompanied by comparatively more sizable average variations in weight. This noteworthy tendency was emphatically reinforced in Figure 6b, where the average percentile style presentations cogently elucidated that specimens often experiencing amplified magnitudes of weight forfeitures on average also consistently retained lessenedweights in the aftermath of the corrosion cracking having been allowed to progress.

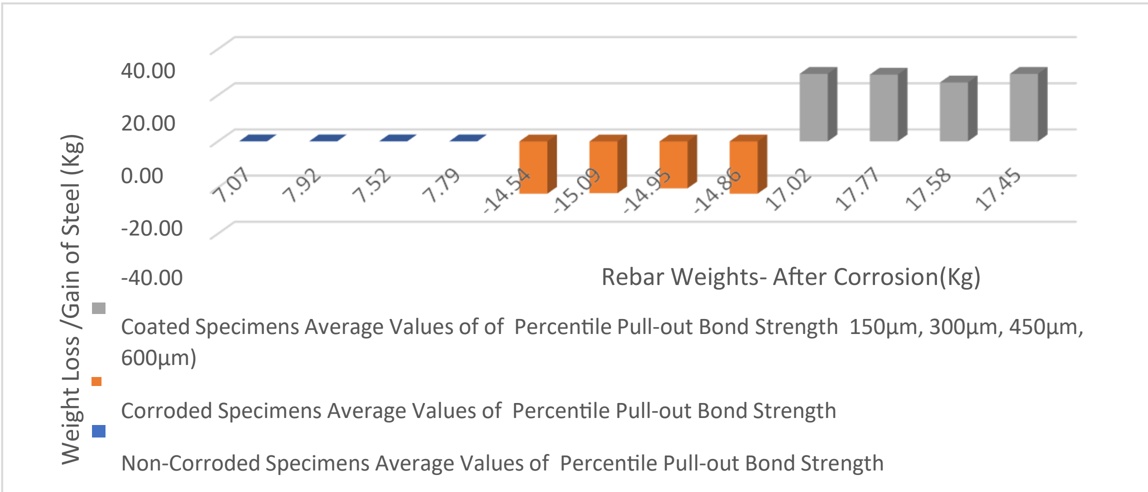

Figure 6b. Average percentile Rebar Weights- After Corrosion versus Weight Loss /Gain of Steel

These empirically obtained results aligned seamlessly with earlier observations drawn from Figures 4,4a and 4b, which similarly revealed declining rebar weights ensuing the corrosion process working in tandem with intensifying levels of corrosion severity (Auyeung et al., 2000; Fang et al., 2004). This observed consistency served to empirically validate the theoretically postulated linkage between proportional metal quantities forfeited through the corrosion facilitating oxidative reactions and the degree of structural deterioration incurred over the evaluation period (Jiang et al., 1984; Lee & Fenves,1998). Prior peer-reviewed literature too chronicled proportional mass depletion trends found to correlate positively with escalating corrosion seriousness (Almusallam et al., 1996; Auyeung et al., 2000; Fang et al., 2004). The present investigation interestingly provided additional complementary quantification demonstrating this interdependency through meticulous scientific weighing protocols.

4.0 Conclusions

This study aimed to evaluate the pull-out bond effects of reinforcing steel coated with plant-derived exudates through a comprehensive experimental test program and analysis of the results. A total of 36 reinforced concrete specimens were subjected to pull-out bond testing at intervals up to 360 days underaccelerated corrosion conditions in a 5% NaCl solution to simulate a marine environment. The specimens included control samples, uncoated bars, and bars coated with different thicknesses of exudates extracted from Ficus platyphylla tree bark.

The test results provided valuable insights into the influence of corrosion level and exudate coatings onthe bond strength and slip behavior between reinforcing steel and concrete. With increasing corrosionfrom 0% to 5%, the bond strength consistently decreased while the maximum slip increased. Direct measurements of rebar diameters and weight losses after corrosion exposure quantitatively validatedtheoretical models, demonstrating proportional reductions corresponding to higher corrosion severity. The exudate coatings were found to enhance the bond strength and corrosion resistance of reinforcingsteel compared to uncoated bars. For instance, coatings as thin as 150 µm improved the failure load byup to 30% in some cases. Coated bars also underwent less cross-sectional loss and weight reductionthan uncoated controls after 360 days of immersion in NaCl solution.

Further, the bond performance of exudate coatings was comparable or superior to previous studies usingepoxy coatings and better than unprotected corroded bars. This highlights the potential of natural exudates as eco-friendly and low-cost alternatives to synthetic coatings for corrosion protection of steelin concrete.

While the results validated conceptual linkages between corrosion level, bar diameter/area/weight changes, and bond strength/slip behavior, additional research is warranted. Studies optimizing exudatesources and coating thicknesses could better establish the structure-property relationships. Investigations of long-term corrosion behavior and coating durability over decades would aid practicalapplication. Environmental preconditioning trials simulating diverse service conditions could further validate performance Nonetheless, this investigation provided valuable mechanistic insights and empirical data confirming priority theoretical models through replication of published experimentation. It expanded knowledge by quantifying the influence of varying exudate coatings on pull-out bond strength degradation due to corrosion. The findings offer guidance on mitigating corrosion impacts on reinforced concrete structuralintegrity and service life through natural exudate coatings, supporting their potential as green alternatives for infrastructure in aggressive environments.

References

ACI Committee 408. (2003). Bond and Development of Straight Reinforcing Bars in Tension. American Concrete Institute

Almusallam, A. A., Al-Gahtani, A. S., Aziz, A. R., & Rasheeduzzafar. (1996). Effect of reinforcementcorrosion on bond strength. Construction and Building Materials, 10(3), 123-129.

Amleh, L., & Ghosh, A. (2006). Modeling the effect of corrosion on bond strength at the steel-concreteinterface with finite-element analysis. Canadian Journal of Civil Engineering, 33(6), 673-682.

Auyeung, Y., Balaguru, P., & Chung, L. (2000). Bond behavior of corroded reinforcement bars. ACI Materials Journal, 97(2), 214–220.

BS 3148; 1980 – Methods of test for Water for Making Concrete. British Standards Institute. London, United Kingdom.

BS 4449:2005+A3; 2010 – Steel for Reinforcement of Concrete. British Standards Institute. London, United Kingdom.

BS EN 12390-2; 2005 – Testing Hardened Concrete: Flexural Strength Test of Specimens, British Standards Institute. London, United Kingdom

BS EN 196-6; 2010- Methods of Testing Cement. Determination of fineness, British Standards Institute.London, United Kingdom, 2010.

BS. 882; 1992- Specification for Aggregates from Natural Sources for Concrete. British Standards Institute. London, United Kingdom.

Cairns, J., & Abdullah, R. (1995). An evaluation of bond pullout test and their relevance to structural performance. The Structural Engineer, 73(11), 179-185.

Charles, E. N., Charles, K., & Terence, T. T. W. (2019). Corrosion degree on the mechanical propertiesof reinforcing steel embedded in concrete. Global scientific journal, 7(10), 688–696.

Charles, K., Geofrey, B., & Gede, T. E. (2019). Corrosion effect on reinforcement pull-out bond strength characteristics of corroded and coated members in concrete. American Journal of Sustainable Cities and Society, 1(6), 61–69.

Charles, K., K., Ogunjiofor, E. I., & Terence, T. T. W. (2019). Pullout bond splitting effects of corrodedand inhibited reinforcement in corrosive media. Journal of Multidisciplinary Engineering Science and Technology, 6(9), 10747-10753.

Darwin, D., & Graham, E. (1993). Effect of Deformation Height and Spacing on Bond Strength of Reinforcing Bars. ACI Structural Journal, 90(6), 646- 657.

El-Hacha, R., El-Agroudy, H., & Rizkalla, S. H. (2006). Bond characteristics of high-strength steelreinforcement. ACI Structural Journal, 103(6), 771-782.

Fang, C., Lundgren, K., Chen, L., & Zhu, C. (2004). Corrosion influence on bond in reinforced concrete.Cement and Concrete Research, 34(11), 2159–2167.

Gambarova, P. G. (2012). Bond in reinforced concrete: where do we stand today?: Proceedings of the4th international conference Bond in Concrete. Brescia, Italy, 1-13.

Gede, T. E., Charles, K., & Geofrey, B. (2019). Reinforcement bond strength interface behavior ofcorroded and coated in concrete members. European Academic Research, 7(7), 3399–3412.

Jiang, D. H., Shah S., P., & Andonian A. T. (1984). Study of the transfer of tensile forces by bond. ACIJournal.

Kemp, E. L. (1986). Bond in reinforced concrete: behavior and design criteria. ACI JournalProceedings, 83(1), 50-57.

Lee, J., & Fenves, G. L. (1998). A plastic-damage concrete model for earthquake analysis of dams.Earthquake Engineering and Structural Dynamic, 27(10), 937-956.