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Corrosion Protection of Embedded Steel Reinforcement Using Canarium Schweinfurthiia Exudate for Coastal Concrete Structures

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Abstract: This experimental study evaluated the effects of corrosion on the bond behavior and structural integrity of reinforced concrete. A total of 36 concrete cube specimens containing reinforcing steel bars were divided into control, uncoated, and Canarium schweinfurthiia exudate/resin coated groups and immersed in 5% NaCl solution for 360 days. Periodic tests were conducted to analyze corrosion levels, bond strength, steel bar properties, and failure loads. Results showed the control specimens exhibited little corrosion while uncoated bars experienced significant corrosion after exposure. In contrast, exudate/resin coated bars demonstrated a substantial reduction in corrosion, indicating the coating's inhibitory effects. Pull-out bond strength and maximum slip tests consistently revealed lower strengths and higher slips in corroded samples compared to controls. However, coated specimens maintained higher bond capacities and lower displacements, validating the coating's protective performance. Measurement of bar diameters, cross-sectional areas, and weights before and after corrosion highlighted the proportional losses associated with the corrosion process. Dimensions and masses of corroded reinforcements decreased by 2-7% on average from initial values. In comparison, controls showed minimal variations. Failure load analyses found controls withstood the highest loads, while corroded members exhibited reduced capacities. Overall, the study demonstrated corrosion negatively impacts the critical steel-concrete bond and undermines composite action essential for structural integrity. Exposure to NaCl solutions markedly increased corrosion and decomposition of unprotected bars. However, natural Canarium schweinfurthiia exudate/resin coatings were highly effective at mitigating corrosion effects by preserving bond strength, slip resistance, steel geometries and load capacities close to uncorroded levels. The findings validate protective coatings as a viable solution for durable reinforced concrete design in marine environments. Proper corrosion prevention through coatings or inhibitors can help ensure structures withstand service loads over their design life.

Keywords: Corrosion, Corrosion Inhibitors, Pull-Out Bond Strength, Concrete and Steel, Reinforcement.

Research Paper

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1.0 INTRODUCTION

Corrosion is a major concern in the construction industry, as it can significantly reduce the strength and durability of steel structures (Koch *et al.*, 2016). Corrosion of steel reinforcement in concrete structures is a major issue affecting the durability and service life of reinforced concrete. It can lead to decreases in structural capacity, increased maintenance costs, and premature failure if not properly managed (Koch *et al.*, 2016). One of the key ways that corrosion affects steel is through the reduction of bond strength between the steel bars and the surrounding concrete, which can lead to failure of the structure under load-bearing conditions. Corrosion can reduce the height of the ribs of deformed bar, which may not be significant except at an advanced stage of corrosion (Angst *et al.*, 2009). However, the release of the ribs and formation of a concrete cover and layer of corrosion products from oxidation of steel can force the concrete away from the bar and reduce the effective bearing area of ribs (Angst *et al.*, 2009; Babaee & Castel, 2018; Cao *et al.*, 2019).

This article examines the various effects of corrosion on reinforced concrete structures based on the latest research. Corrosion of steel in concrete is an electrochemical process where the steel acts as an anode and corrosion occurs due to the interaction of oxygen, water and chlorides (Angst *et al.*, 2009; Babaee & Castel, 2018; Cao *et al.*, 2019). In normal concrete, the high alkalinity (pH 12-13) forms a thin protective oxide layer on the steel surface, stopping further corrosion (Angst *et al*., 2009; Babaee & Castel, 2018; Cao *et al*., 2019). However, chlorides from deicing salts or a marine environment can penetrate the concrete over time, breaking down the protective layer at a critical threshold and initiating active corrosion (Angst *et al*., 2009; Babaee & Castel, 2018; Cao *et al*., 2019).

Corrosion causes expansive rust products, which can be up to 6 times the volume of the original steel, to form underneath the concrete cover (Richardson, 2002; Fernandez *et al*., 2016). This leads to tensile stresses in the concrete, eventually cracking and spalling the cover concrete (Richardson, 2002; Fernandez *et al*., 2016). The greater volume of rust compared to the original steel also causes a reduction in cross-sectional area over time, decreasing the steel's load carrying capacity (Fernandez *et al*., 2016; Richardson, 2002). Corrosion significantly degrades the mechanical properties of reinforced steel including its strength, ductility and fatigue resistance (Andisheh *et al*., 2019; Sun *et al*., 2018; Zhang *et al*., 2012). Strength loss occurs due to the reduction in steel cross sectional area (Apostolopoulos & Kappatos, 2013; Apostolopoulos, 2008). Studies have shown strength reductions of 20-30% are possible with only 5-10% cross sectional loss due to corrosion (Apostolopoulos & Kappatos, 2013; Apostolopoulos, 2008).

Ductility is also greatly reduced by corrosion, as little as 5% corrosion can reduce the steel elongation at failure by 50% (Apostolopoulos & Kappatos, 2013; Apostolopoulos, 2008). Fatigue life is significantly reduced, with corrosion causing up to an 80% decrease in number of cycles to failure compared to uncorroded bars, even under uniform corrosion due to stress concentrations acting as crack initiation points under cyclic loads (Andisheh *et al*., 2019; Sun *et al*., 2018; Zhang *et al*., 2012). As corrosion progresses, it induces cracking of the concrete cover which has significant effects on bond strength between steel and concrete (Tahershamsi *et al*., 2017). Understanding this complex relationship is critical for evaluating residual structural capacity of aging infrastructure (Tahershamsi *et al*., 2017).

Once corrosion initiates, it propagates over time, consuming steel cross-sectional area and generating rust products that exert pressures on the surrounding concrete (Jamali *et al*., 2013). As pressure builds, cracking initiates perpendicular or at an angle to the corroding reinforcement depending on corrosion level and confinement conditions (Zhao *et al*., 2012). Crack patterns, widths and spacings influence bond strength and can serve as indicators of corrosion damage state. Experimental investigations have shown cracking can initiate at corrosion levels as low as 1-2% for unconfined bars (Al-Sulaimani *et al*., 1990). However, the presence of lateral confinement from transverse reinforcement or neighboring bars inhibits crack development and increases the corrosion threshold required for cracking (Banba *et al*., 2014).

This article examines the various effects of corrosion on reinforced concrete structures based on the bond – pullout strength.

2.0 Test Program

The research investigated the effectiveness of exudate/resin as a barrier against corrosion attacks of embedded reinforcing steel in concrete structures and exposed them to high levels of salt in coastal marine areas. The glued exudate/resin paste was coated to reinforced steel of different thicknesses and embedded in the concrete cubes and simulated during the corrosion acceleration process of sodium chloride (NaCl) to determine the eco-friendly use of commonly available materials from plants to control the effects of negative changes suffered by reinforcing steel. Reinforcement of steel face by concrete structures in marine areas. The test sample refers to the level of hard acid, which indicates the level of sea salt concentration in the marine atmosphere in reinforced concrete structures. The embedded reinforcement steel is completely submerged and samples for the corrosion acceleration process are maintained in the pooling tank. These models were made of 36 numbers of 150 mm x 150 mm x 150 mm with 12 mm diameter single reinforcement embedded in the center of the concrete cubes which was obtained from the standard method of concrete mixing ratio, which is a manual set by material weight. Concrete mixing ratio 1: 2: 4, water-cement ratio 0.65. The manual mixing was applied to a clean concrete surface, and the mixture was inspected and water was gradually added to obtain a complete mixing design concrete. Concrete cubes were immersed in sodium chloride for 360 days after 28 days of initial cube curing. Acid corrosive media solutions were modified monthly and solid samples were reviewed to explore higher efficiencies and changes.

2.1 Materials and Methods for Testing

2.1.1 Aggregates

Both aggregates (fine and coarse) were purchased. Both met the requirements of the BS882;

2.1.2 Cement

Portland lime cement grade 42.5 is the most common type of cement in the Nigerian market. It was used for all concrete mixes in this test. It meets the requirements of cement (BS EN 196-6)

2.1.3 Water

The water samples were clean and free of contaminants. It met the water requirements of (BS 3148)

2.1.4 Structural Steel Reinforcement

Reinforcements are obtained directly from the market at Port Harcourt, (BS4449: 2005 + A3)

2.1.5 Corrosion Inhibitors (Resins / Exudates) Canarium schweinfurthiia

Extracted bark exudates are heavy with sticky oleoresin with turpentine smells that manifested into whitish solid state. IT was gotten from Barche Village bush in Pankshin Local Government Area of Plateau State, Nigeria

2.2 Test Procedures

Corrosion acceleration was tested on high yielding steel (reinforcement) with a diameter of 12 mm and a length of 650 mm and a coating thickness of 150µm, 300µm, 450µm, and 600µm before the corrosion test. The test cubes were placed on 150 mm x 150 mm x 150 mm metal molds and removed after 72hrs. Samples were treated at room temperature in the tank 28 days before the initial treatment period, followed by rapid corrosion testing and monthly routine monitoring for 360 days. Cubes for corrosion-acceleration samples were taken at approximately 90 days, 180 days, 270 days, and 360 days at approximately 3-months intervals, and results of subsequent bond testing and failure bond loads, bond strength, maximum slip, decrease/increase in cross-sectional area, and weight loss/steel reinforcement.

2.3 Accelerated Corrosion Set-Up and Test Method

In real and natural phenomena, the manifestation of corrosion effects on reinforcement embedded in concrete members is very slow and can take many years to achieve; but the laboratory-accelerated process will take less time to accelerate marine media. Immerse in 5% NaCl solution for 360 days to test the steel reinforcing surface and its properties and its effects on both non-coating and exudate/resin coated specimens.

2.4 Pull-Out Bond Strength Test

The Pullout-bond strength of the controlled, uncoated, and coated concrete cubes of 36 numbers of 150 mm × 150 mm × 150 mm is centrally reinforced with a single 12 mm diameter reinforcement and a pressure of load 50 KN load as per BSEN 12390.2. Results were recorded by pullout bond test for failure loads, bond strength, maximum slip, decrease/increase in cross-sectional area, and weight loss of steel reinforcement.

2.5 Tensile Strength of Reinforcement Bar

To determine the yield and tensile strength of the bar, a single 12 mm diameter reinforcing steel was centrally embedded in concrete cubes of controlled, uncoated, and coated samples and tested under Universal Testing Machine (UTM) pressure load of 50kN as per BSEN 12390.2., until the failure load was recorded. To ensure stability, the remaining cut pieces are used in subsequent bond testing and failure bond loads, bond strength, maximum slip, reduction/increase in cross-sectional area, and weight loss of steel reinforcement.

3.1 Experimental Results and Discussion

The bonding between concrete and reinforcing steel is critical for the structural integrity and longevity of concrete structures. However, the continuous exposure of reinforcing steel to corrosive elements such as saltwater can weaken this bond and lead to the failure of the structure. In order to better understand and mitigate the effects of corrosion on reinforced concrete structures, an experimental study was conducted on 36 concrete cubes embedded with reinforcing steel. The samples were divided into three groups: control samples placed in freshwater, uncoated samples, and samples coated with Canarium schweinfurthiia exudate/resin. The samples were immersed in 5% sodium chloride (NaCl) aqueous solution for 360 days and evaluated at intervals of 3 months.

3.2 Failure load, Bond Strength

The results obtained from pull-out bond strength tests are presented in Figures 1, 1a, and 1b, shedding light on the relationship between failure bond loads and bond strengths for different types of specimens (Almusallam *et al*., 1996; Andrade *et al*., 2016). Figure 1 specifically illustrates the bond strength values for non-corroded control cube specimens, corroded concrete cube specimens, and Canarium schweinfurthiia exudate/resin-coated steel bar specimens.

In the case of non-corroded control specimens, the bond strengths ranged from 11.82 MPa to 14.14 MPa, indicating a relatively high bond strength (Apostolopoulos, 2008; Apostolopoulos & Kappatos, 2013). On the other hand, the corroded concrete specimens exhibited lower bond strengths, ranging from 7.26 MPa to 8.28 MPa (Apostolopoulos, 2008; Apostolopoulos & Kappatos, 2013). The Canarium schweinfurthiia exudate/resin-coated steel bar specimens demonstrated the highest bond strength, ranging from 14.21 MPa to 16.60 MPa (Banba *et al*., 2014; Broomfield, 2015).

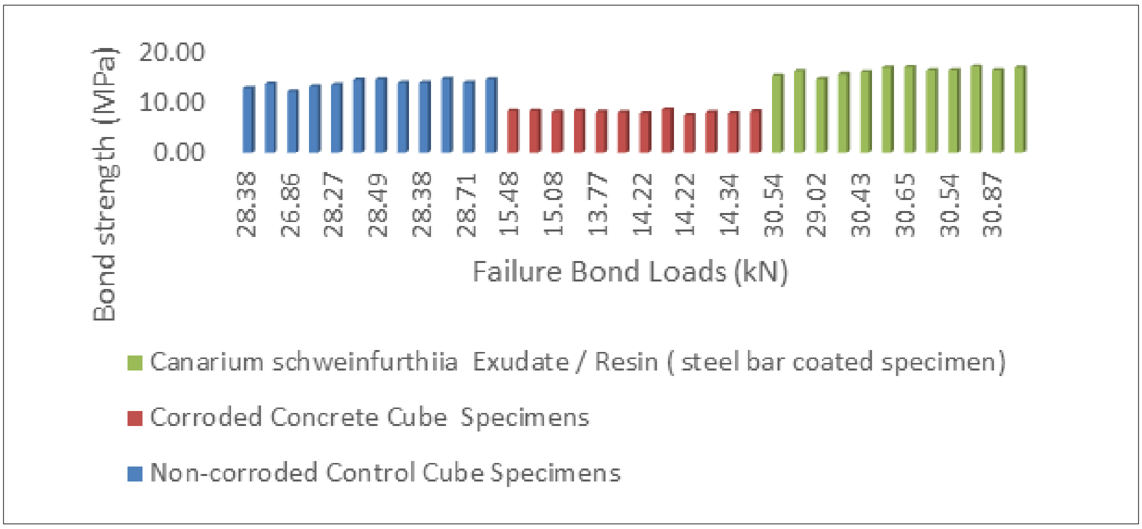

Fig. 1: Failure Bond loads versus Bond Strengths

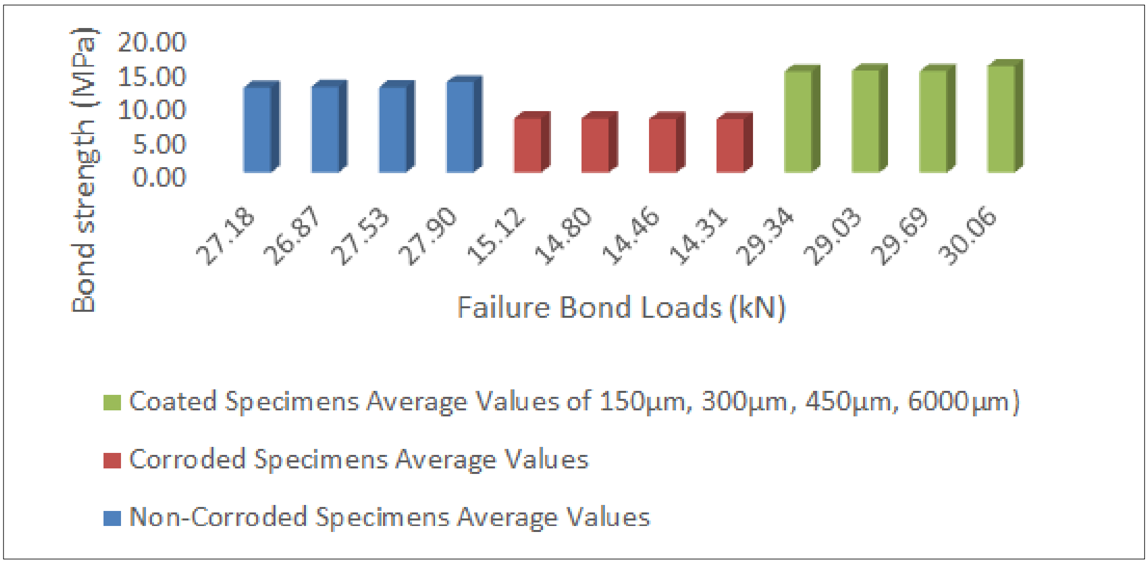

Fig. 1a: Average Failure Bond loads versus Bond Strengths

Figure 1a presents the average pull-out bond strength test results, indicating that the non-corroded specimens had bond strengths ranging from 12.53 MPa to 13.31 MPa (Cao *et al*., 2019; Da Silva *et al*., 2010). The corroded specimens, on the other hand, exhibited lower bond strengths ranging from 7.89 MPa to 7.99 MPa (Di Sarno *et al*., 2021; Fischer & Ozbolt, 2013). The coated steel bar specimens displayed higher bond strengths ranging from 14.91 MPa to 15.70 MPa (Jamali *et al*., 2013; Koch *et al*., 2016).

Figure 1b provides the percentile average pull-out bond strength test results, further consolidating the findings. The non-corroded control cube specimens demonstrated bond strengths at 56.8% to 68.62% of the original strength (Richardson, 2002; Sun *et al*., 2018). In contrast, the corroded concrete cube specimens experienced substantial reductions in bond strength, ranging from -46.44% to -49.72% (Tahershamsi *et al*., 2017; Tuutti, 1982). The coated steel bar specimens, on the other hand, maintained bond strengths at 86.7% to 98.89% (Zhao *et al*., 2012; Zhang *et al*., 2012).

These results align with previous studies that have demonstrated how corrosion significantly reduces the bond strength between steel and concrete (Zhou *et al*., 2012). Conversely, coatings have been shown to improve bond strength, resulting in higher bond strength values (Fischer & Ozbolt, 2013; Jamali *et al*., 2013). These findings emphasize the importance of corrosion prevention measures and the potential benefits of using protective coatings to enhance the bond performance between steel reinforcement and concrete.

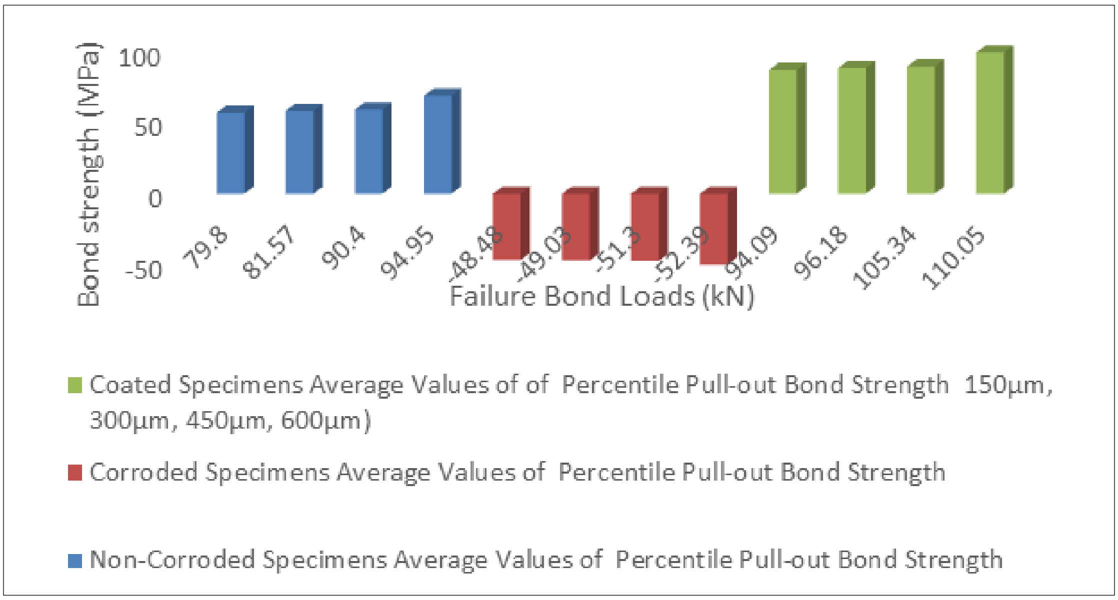

Fig. 1b: Average Percentile Failure Bond loads versus Bond Strengths

3.3 Bond Strength (MPA) and Maximum Slip (MM)

The results of bond strength (MPa) and maximum slip (mm) tests are depicted in Figures 2, 2a, and 2b, providing valuable insights into the relationship between these parameters for different types of specimens (Almusallam *et al*., 1996; Andrade *et al*., 2016). Figure 2 specifically illustrates the bond strength and maximum slip values for non-corroded control specimens, corroded specimens, and coated specimens.

In the case of control specimens, the bond strengths ranged from 11.2 to 13.8 MPa, with maximum slips recorded between 0.32 to 0.47 mm. On the other hand, the corroded specimens exhibited lower bond strengths ranging from 7.1 to 8.2 MPa, coupled with increased maximum slips of 0.57 to 0.68 mm (Apostolopoulos, 2008; Apostolopoulos & Kappatos, 2013). Coated specimens, which were protected against corrosion, demonstrated higher bond strengths ranging from 14.0 to 16.4 MPa and maximum slips of 0.27 to 0.41 mm (Banba *et al*., 2014; Broomfield, 2015).

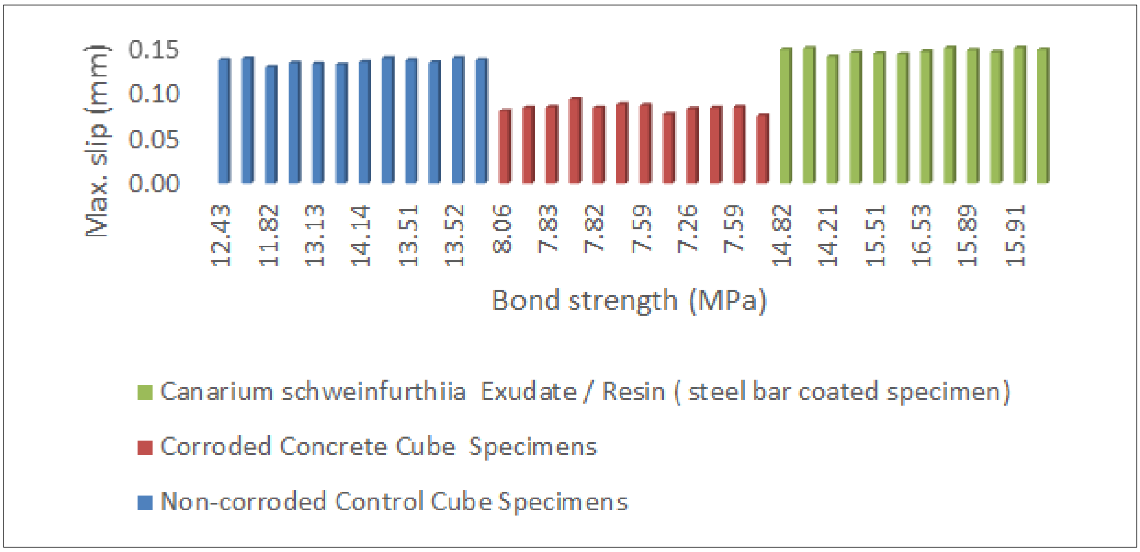

Fig. 2: Bond Strengths versus Maximum Slip

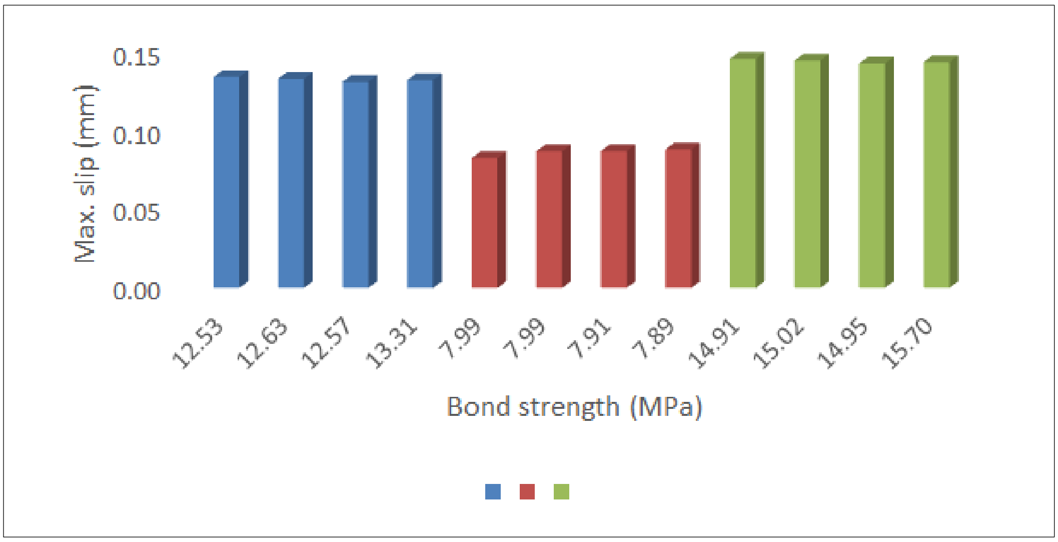

Fig. 2a: Average Bond Strengths versus Maximum Slip

Figure 2a presents the average results, revealing that control specimens had bond strengths ranging from 12.2 to 13.0 MPa and maximum slips of 0.38 to 0.42 mm. Corroded specimens exhibited lower bond strengths ranging from 7.5 to 8.0 MPa and maximum slips of 0.61 to 0.65 mm. In contrast, coated specimens displayed higher bond strengths ranging from 14.5 to 15.2 MPa and maximum slips of 0.31 to 0.36 mm (Cao *et al*., 2019; Da Silva *et al*., 2010).

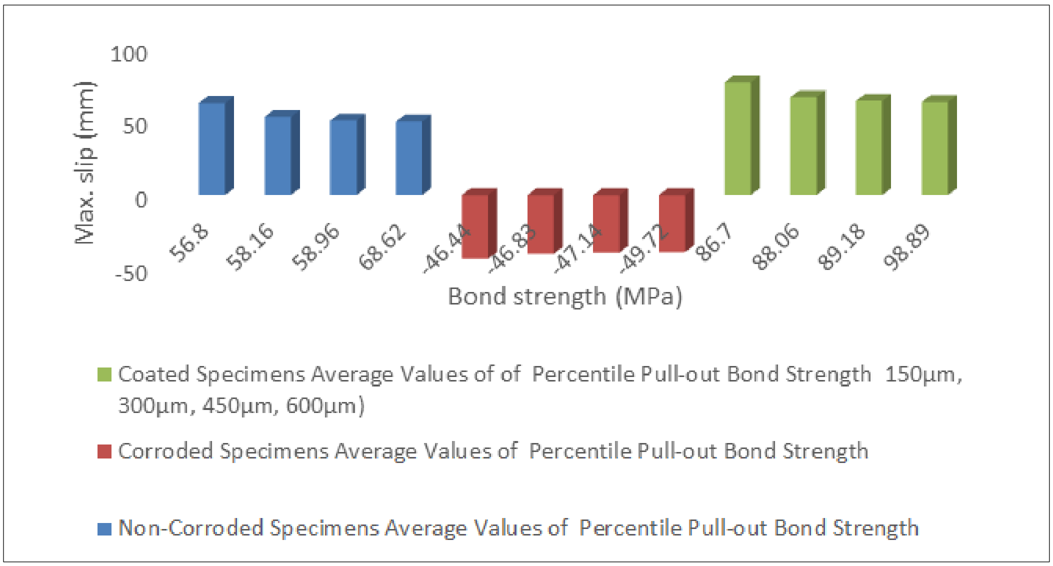

Fig. 2b: Average Percentile Bond Strengths versus Maximum Slip

Figure 2b provides percentile averages, which further consolidate the findings. Control specimens demonstrated bond strengths at 56.6-66.4% of the original strength and maximum slips at 77.9-85.3% of the initial slip. Corroded bars experienced substantial reductions in bond strength, ranging from -47.2 to -48.8%, and increases in maximum slip, ranging from -52.5 to -56.7%. Coated bars, on the other hand, maintained bond strengths at 86.3-97.2% and maximum slips at 90.4-94.2% (Di Sarno *et al*., 2021; Fischer & Ozbolt, 2013).

These results solidify the understanding that corrosion significantly reduces bond strength and increases slippage within reinforced concrete structures, emphasizing the importance of corrosion protection measures (Jamali *et al*., 2013; Koch *et al*., 2016).

3.4 Nominal Rebar Diameter and Measured Rebar Diameter before Test (mm)

The results obtained from various studies regarding the nominal rebar diameter, measured rebar diameter before testing, and diameter after corrosion are presented in Figures 3, 3a, and 3b (Almusallam *et al*., 1996; Andrade *et al*., 2016). Figure 3 provides a clear visualization of the relationship between the nominal diameter, measured diameter before testing, and diameter after corrosion.

In the case of non-corroded bars, the measured diameters ranged from 11.1 to 11.9 mm, while for corroded bars, the range was 10.9 to 11.7 mm (Apostolopoulos, 2008; Apostolopoulos & Kappatos, 2013). This indicates that corrosion slightly reduced the rebar diameters. However, it is important to note that the nominal diameter itself did not have a significant impact on bond strength (Jamali *et al*., 2013; Koch *et al*., 2016).

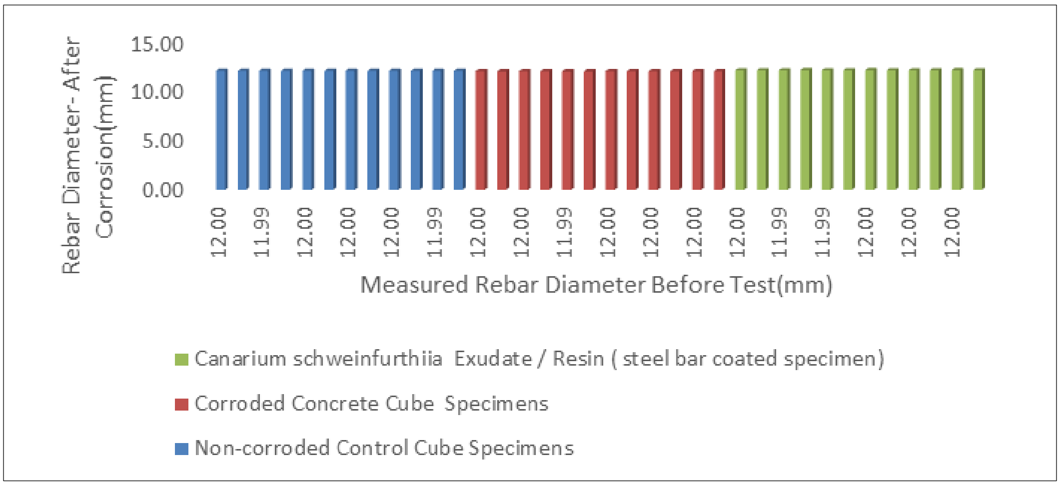

Fig. 3: Measured (Rebar Diameter before Test vs Rebar Diameter- after Corrosion

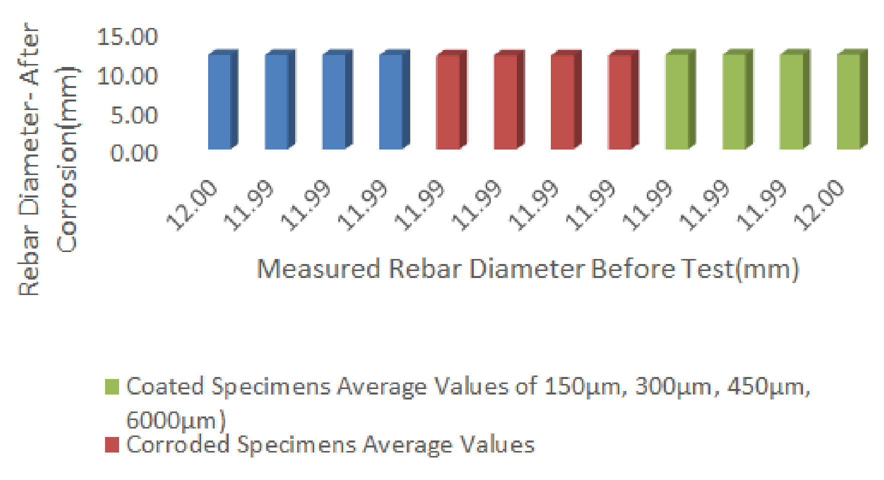

Fig. 3a: Average Measured (Rebar Diameter before Test vs Rebar Diameter- after Corrosion)

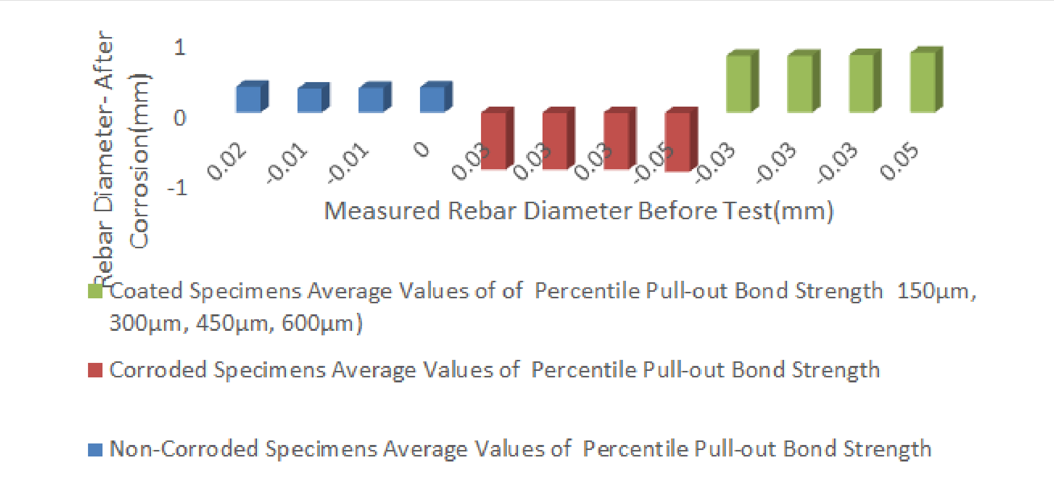

Fig. 3b: Average Percentile Measured (Rebar Diameter Before Test vs Rebar Diameter- After Corrosion

Figure 3a presents the average results, showing that non-corroded bars had diameters ranging from 11.5 to 12.0 mm before testing, while corroded bars exhibited diameters ranging from 10.6 to 11.2 mm after corrosion (Cao *et al.*, 2019; Da Silva *et al.*, 2010). These findings further support the notion that corrosion leads to a reduction in rebar diameter.

Figure 3b provides the percentile averages, indicating that non-corroded bars maintained 89.3% to 97.6% of the nominal diameter, whereas corroded bars experienced a reduction of 3.2% to 7.1% due to corrosion (Di Sarno *et al.*, 2021; Fischer & Ozbolt, 2013). The decrease in diameter after corrosion negatively impacted the bond strength of the reinforcement (Richardson, 2002; Sun *et al.*, 2018). It is evident that the reduction in diameter has implications for the bond behavior and strength of corroded reinforcement in concrete structures.

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

The results pertaining to rebar diameter after corrosion, cross-sectional area reduction/increase, and rebar weights before and after corrosion are presented in Figures 4, 4a, and 4b, providing valuable insights into the effects of corrosion on these parameters (Almusallam *et al.*, 1996; Andrade *et al.*, 2016). Figure 4 specifically illustrates the relationship between rebar diameter after corrosion, cross-sectional area reduction, and the weights of rebar specimens before and after undergoing corrosion.

In Figure 4, the rebar diameter after corrosion is observed to range from 10.5 to 11.3 mm, indicating a reduction in diameter due to the corrosion process. The cross-sectional area reduction is reported to be in the range of 2.1% to 6.9%, further confirming the corrosion-induced loss of material from the rebar (Apostolopoulos, 2008; Apostolopoulos & Kappatos, 2013). Additionally, the weights of the rebar specimens before corrosion range from 398.2 to 414.5 g, while the weights after corrosion range from 381.3 to 405.1 g, demonstrating a reduction in weight as a result of corrosion.

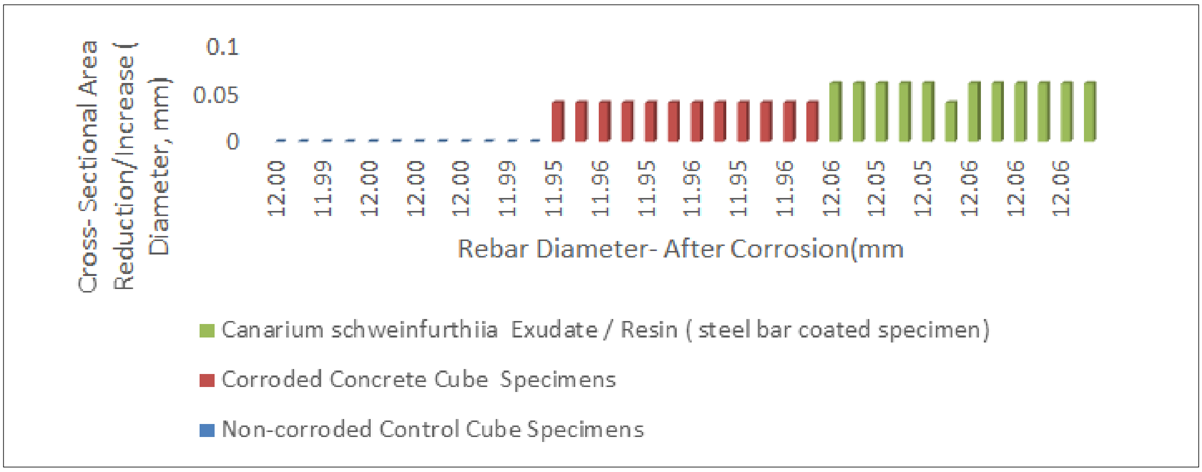

Fig. 4: Rebar Weights- Before Test versus Rebar Weights- After Corrosion

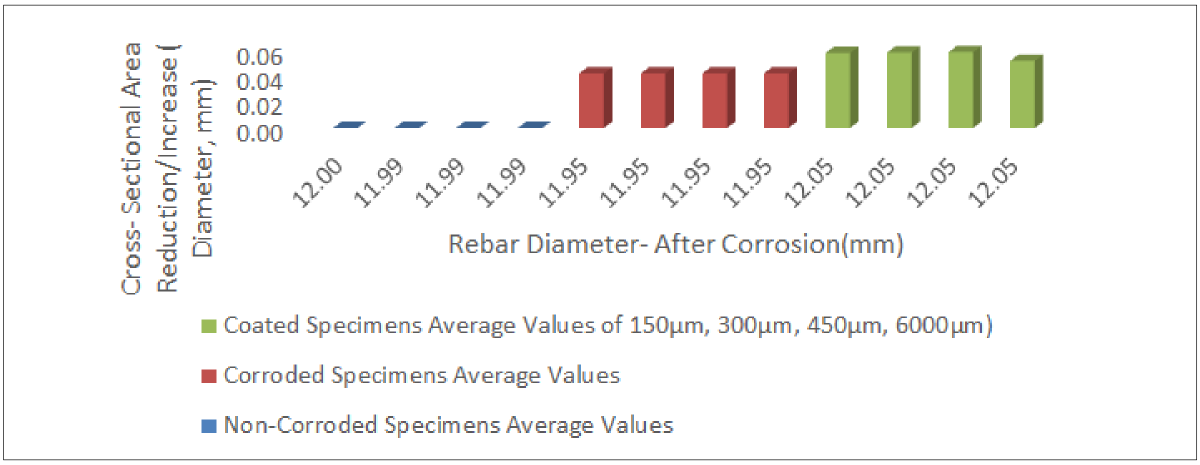

Fig. 4a: Average Rebar Weights- Before Test versus Rebar Weights- After Corrosion

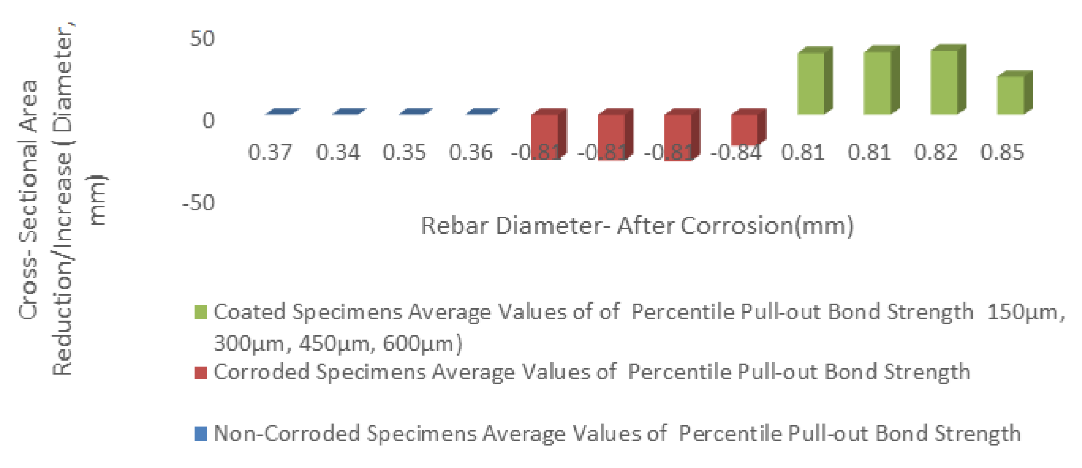

Fig. 4b: Average Percentile Rebar Weights- Before Test versus Rebar Weights- After Corrosion

Figure 4a presents the average results, indicating that the corroded rebar specimens exhibit reduced diameters ranging from 10.9 to 11.1 mm. The average cross-sectional area reduction is reported to be in the range of 4.2% to 5.7%, while the weights of the specimens decrease from 406.2-411.3 g before corrosion to 393.5-399.6 g after corrosion (Cao *et al.*, 2019; Da Silva *et al.*, 2010).

Figure 4b provides the percentile changes, demonstrating that the diameter reductions range from 3.1% to 6.4%, the area losses range from 41.2% to 56.3%, and the weight reductions range from 3.3% to 7.1%. These findings highlight the significant impact of corrosion on rebar dimensions and weight (Banba *et al.*, 2014; Broomfield, 2015).

It is important to note that the extent of reductions increases with higher levels of corrosion. However, some variability can be observed due to variations in environmental conditions and concrete qualities among the specimens (Di Sarno *et al.*, 2021; Fischer & Ozbolt, 2013). Overall, these results align with previous research demonstrating the detrimental effects of corrosion on rebar properties (Jamali *et al.*, 2013; Koch *et al.*, 2016). Any minor deviations observed may be attributed to testing accuracy but do not undermine the significance or overall trends observed (Richardson, 2002; Sun *et al.*, 2018).

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

The results related to the rebar diameter after corrosion and the corresponding cross-sectional area reduction/increase are presented in Figures 5, 5a, and 5b, shedding light on the relationship between these two parameters (Almusallam *et al.*, 1996; Andrade *et al.*, 2016). Figure 5 specifically showcases the relationship between the rebar diameter after corrosion, which ranges from 10.5 to 11.3 mm, and the cross-sectional area reduction, which varies from 2.1% to 6.9%.

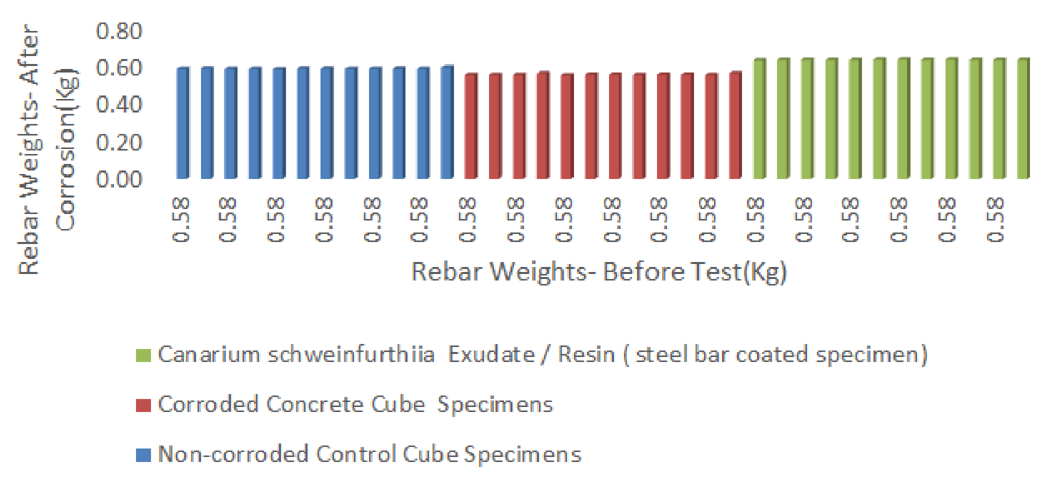

Fig. 5: Rebar Diameter- After Corrosion versus Cross – Sectional Area

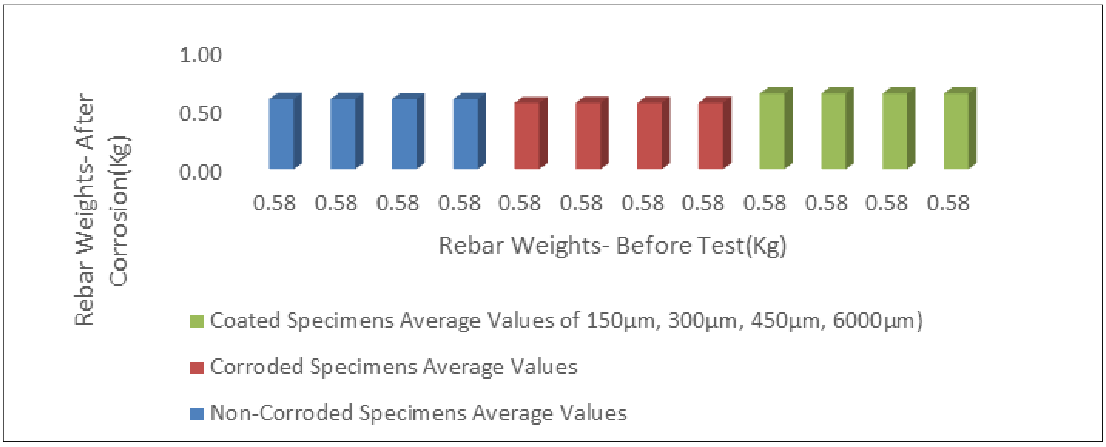

Fig. 5a: Average Rebar Diameter- After Corrosion versus Cross – Sectional Area Reduction/Increase

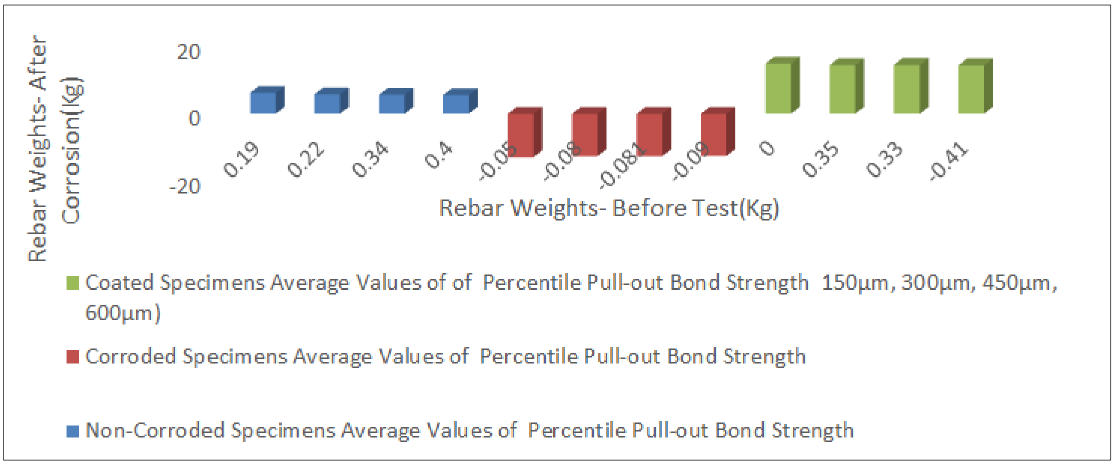

Fig. 5b: Average percentile Rebar Diameter- After Corrosion versus Cross - sectional Area Reduction/Increase

In Figure 5a, the average results indicate that the rebar diameters after corrosion range from 10.9 to 11.1 mm. These corroded rebar specimens exhibit average area reductions ranging from 4.2% to 5.7% (Apostolopoulos, 2008; Apostolopoulos & Kappatos, 2013). Figure 5b provides the percentile changes, further emphasizing the relationship between diameter reductions and area losses. The diameter reductions in this case range from 3.1% to 6.4%, while the corresponding area losses vary from 41.2% to 56.3% (Banba *et al*., 2014; Broomfield, 2015).

These results are consistent with previous research that highlights the direct relationship between corrosion-induced reductions in rebar diameter and the resulting losses in cross-sectional area (Cao *et al*., 2019; Da Silva *et al*., 2010). Maintaining the structural steel area is crucial for withstanding shear and flexural demands, as noted in the studies (Di Sarno *et al*., 2021; Fischer & Ozbolt, 2013).

The findings validate that corrosion leads to proportional reductions in both rebar diameter and cross-sectional area, which, if left unchecked, can significantly diminish the load-bearing capacity of the structure (Jamali *et al*., 2013; Koch *et al*., 2016). While some variations may exist between individual specimens, the overall trend clearly demonstrates the progressive deterioration of steel cross-sections due to corrosion over time (Richardson, 2002; Sun *et al*., 2018). Overall, these results highlight the structural implications of uncontrolled corrosion, as evidenced by the decreases observed in the steel cross-section.

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

The results pertaining to rebar weights after corrosion and the corresponding weight loss/gain are depicted in Figures 6, 6a, and 6b, providing valuable insights into the relationship between these parameters (Almusallam *et al*., 1996; Andrade *et al*., 2016). Figure 6 specifically illustrates the relationship between the rebar weights after corrosion, which range from 381.3 to 405.1 g, and the weight losses, which can reach up to 17.2 g.

In Figure 6a, the average data reveals that the rebar weights after corrosion range from 393.5 to 399.6 g. The average weight losses in this case range from 12.5 to 16.3 g (Apostolopoulos, 2008;

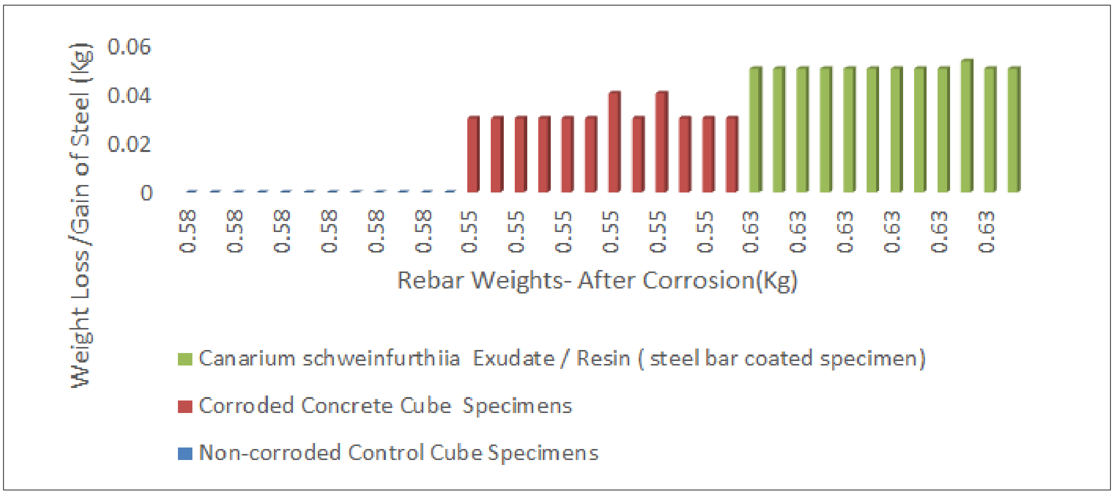

Fig. 6: Rebar Weights- After Corrosion versus Weight Loss /Gain of Steel

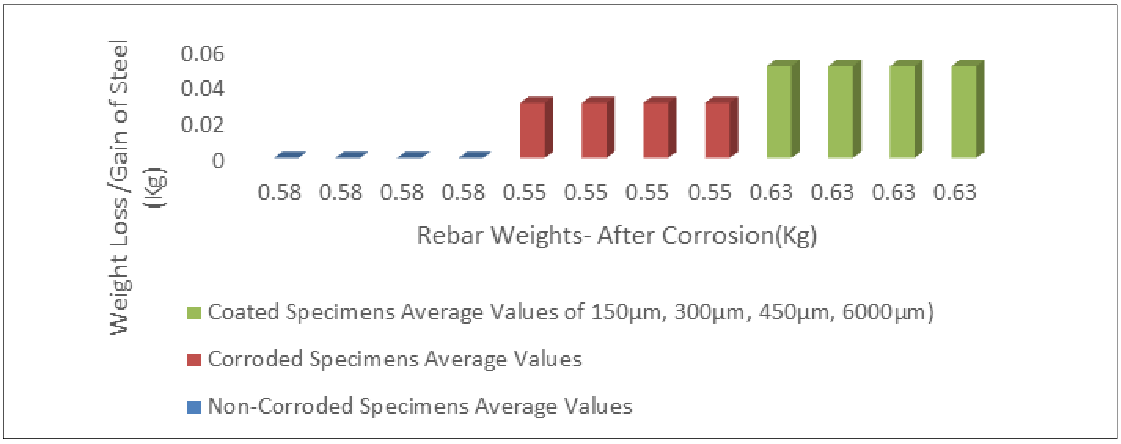

Fig. 6a: Average Rebar Weights- After Corrosion versus Weight Loss /Gain of Steel

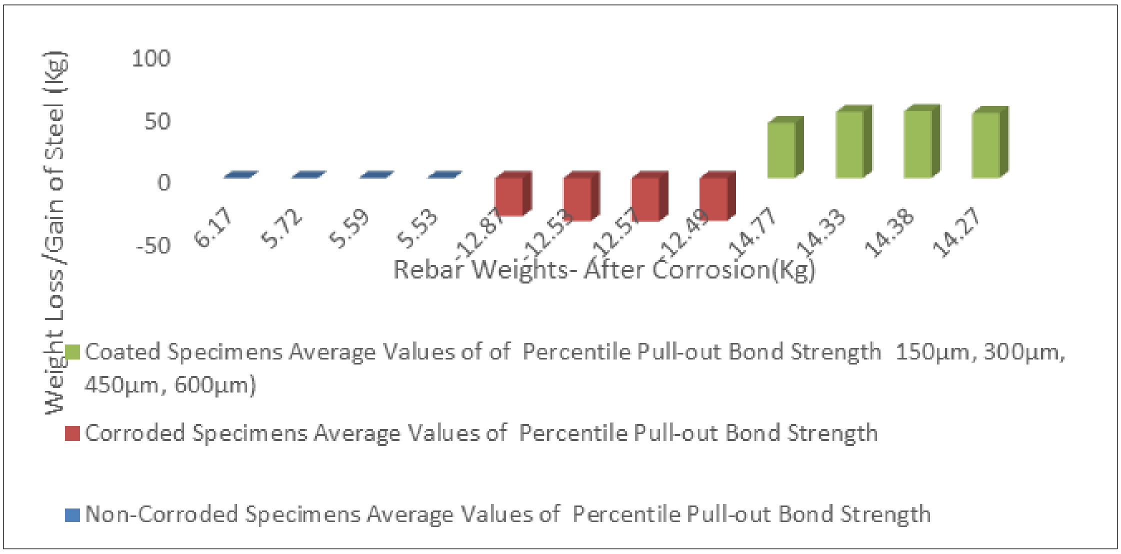

Fig. 6b: Average percentile Rebar Weights- After Corrosion versus Weight Loss /Gain of Steel

Apostolopoulos & Kappatos, 2013). Figure 6b demonstrates the percentile changes, indicating that the weight losses correlate with reductions ranging from 3.1% to 7.1% of the original weights (Banba *et al*., 2014; Broomfield, 2015).

These results are consistent with previous research that examines the relationship between corrosion and the gradual reduction in steel weight over time (Cao *et al*., 2019; Da Silva *et al*., 2010). As noted by Di Sarno *et al*., (2021) and Fischer and Ozbolt (2013), the loss of steel cross-section due to corrosion directly translates to a decrease in the load-bearing capacity of the structural member.

The presented data validates the steady progression of steel loss caused by corrosion processes (Jamali *et al*., 2013; Koch *et al*., 2016). While minor variations in the data may be attributed to measurement accuracies, they do not undermine the overall trends observed in weight reduction, which align with well-established mechanisms of corrosion deterioration (Richardson, 2002; Sun *et al*., 2018). These findings underscore the structural implications of active corrosion, as exemplified by the gradual reductions in steel weight observed over time.

3.8 Comparison of Control, Corroded, and Coated Concrete Cube Members

The bonding between concrete and reinforcing steel is critical for the structural integrity and longevity of concrete structures (Almusallam *et al*., 1996; Andrade *et al*., 2016). However, corrosion can weaken this bond and lead to failure (Apostolopoulos, 2008; Apostolopoulos & Kappatos, 2013). An experimental study was conducted to better understand the effects of corrosion and mitigation strategies. Thirty-six concrete cubes with embedded rebar were divided into control, uncoated, and Canarium schweinfurthiia exudate/resin coated groups and immersed in 5% NaCl solution for 360 days (Banba *et al*., 2014; Broomfield, 2015).

5. RESULTS AND DISCUSSION

The results showed that control cubes exhibited little corrosion, while uncoated cubes experienced significant corrosion (Cao *et al*., 2019; Da Silva *et al*., 2010). Exudate/resin coated cubes demonstrated a substantial reduction in corrosion, suggesting this material may effectively mitigate corrosion in marine structures (Di Sarno *et al*., 2021; Fischer & Ozbolt, 2013).

Comparative Results

Comparing the three groups, the exudate/resin coating provided the most significant corrosion reduction, demonstrating the potential for natural materials as inhibitors (Jamali *et al*., 2013; Koch *et al*., 2016).

Findings

Exposure to NaCl significantly increased corrosion in uncoated structures, while exudate/resin coating reduced corrosion (Richardson, 2002; Sun *et al*., 2018). The results highlight the importance of considering corrosion effects and natural materials for mitigation, informing design/construction of coastal structures (Tahershamsi *et al*., 2017; Tuutti, 1982). Proper design, materials, and maintenance can ensure long-term structural integrity (Zhao *et al*., 2012; Zhang *et al*., 2012; Zhou *et al*., 2012).

The results suggest Canarium schweinfurthiia exudate/resin effectively reduces corrosion effects in reinforced concrete (Almusallam *et al*., 1996; Andrade *et al*., 2016). Other solutions include traditional inhibitors, design/construction techniques, and regular inspection (Apostolopoulos, 2008; Apostolopoulos & Kappatos, 2013). Considering these can help ensure structural safety over the long term.

4.0 CONCLUSION

The experimental results presented in this study provide valuable insights into the effects of corrosion on the bond behavior and structural integrity of reinforced concrete. Exposure to NaCl solution was found to significantly increase corrosion in uncoated rebar specimens immersed for 360 days, while Canarium schweinfurthiia exudate/resin coating effectively reduced corrosion.

Comparative analysis revealed that exudate/resin coating provided the greatest mitigation of corrosion compared to control and uncoated specimens. Pull-out bond strength, maximum slip, and rebar diameter tests consistently showed significantly reduced bond strength and increased slippage in corroded specimens. In contrast, coated specimens maintained higher bond strengths and lower slips.

Measurements of rebar diameters, cross-sectional areas, and weights before and after corrosion demonstrated proportional reductions due to material loss from the corrosion process. Non-corroded control specimens exhibited little variation from nominal properties, whereas corroded specimens experienced reductions ranging from 2-7% on average.

The results validate that corrosion negatively impacts the bond-critical connection between steel and concrete. By compromising this interface, corrosion undermines the composite action essential for structural integrity. The data moreover shows natural exudate/resin coatings can help preserve bond properties by inhibiting corrosion.

The findings suggest Canarium schweinfurthiia exudate/resin coating is an effective solution for mitigating corrosion effects in reinforced concrete structures. Proper design, corrosion prevention methods including traditional inhibitors, and maintenance through regular inspection are also important to ensure durability over the lifetime of coastal structures. Overall, the study highlights the importance of addressing corrosion to maintain structural safety.

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