Review Article

Effect of Corrosion Inhibitors on Bond Strength of Reinforced Concrete Structures

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Abstract

Corrosion of steel reinforcement is a major factor affecting the durability and strength of reinforced concrete structures. This study investigated the influence of plant-derived corrosion inhibitors, applied as coatings, on the bond strength between reinforcing steel and concrete. Thirty-six 150 mm concrete cubes with 12 mm diameter embedded steel bars were prepared and divided into uncoated, corrosion inhibitor coated, and control groups. The samples were immersed in 5% sodium chloride solution over 360 days to accelerate corrosion. Pull-out testing measured the bond strength and failure load. The corroded samples showed 31-26% lower bond strength and 82-87% higher maximum slip than controls, indicating corrosion damage at the steel-concrete interface. However, inhibitor-coated samples displayed 24-36% higher bond strength and 42-43% lower maximum slip versus corroded samples. Although the coatings did not fully restore original bond strength, this demonstrates their effectiveness at protecting bond properties. Microscopic analysis revealed non-uniform, localized corrosion preferentially initiated at steel defects. Statistical correlations confirmed the direct relationship between steel weight loss and reductions in post-corrosion rebar weight due to material loss. While nominal rebar diameters showed minimal differences between sample types, localized diameter reductions and cross-sectional area increases in corroded samples highlighted discrete corrosion effects. These were mitigated in coated samples. Together with direct weight loss measurements, this proves corrosion occurred in unprotected samples. Overall, the significant recovery of bond strength, slip resistance, diameter, area, and weight in coated samples validates the success of the natural corrosion inhibitors in reducing steel deterioration and interface degradation. The results provide new insights on optimizing inhibitor coatings to maximize corrosion protection for reinforced concrete structures.
Keywords: Corrosion Inhibitors, Bond Strength, Reinforced Concrete, Natural Coatings, Durability.

1. INTRODUCTION

Steel reinforcement corrosion is a serious problem for concrete structures' durability since it can drastically diminish the structure's capacity and service life. Utilising corrosion inhibitors as coatings on the steel reinforcement is one method of reducing corrosion. However, the efficiency of these inhibitor coatings in preventing corrosion might be influenced by their thickness. Through a study of pertinent literature, this paper seeks to investigate the effects of coating thickness on the inhibitory capabilities of various corrosion inhibitor materials.

The interaction between concrete and reinforcing steel is important for the structural behavior and durability of reinforced concrete structures (Almusallam *et al.*, 1996; Lee *et al.*, 2002; Lundgren,

2002; Fang *et al.*, 2003). Corrosion of the reinforcing steel degrades this interaction by reducing the bond strength at the interface (Mehta & Gerwick, 1982; Charles *et al.*, 2018a; Charles *et al.*, 2018b). Several studies have investigated the effects of corrosion on bond strength.

Almusallam *et al.*, (1996) studied the effect of reinforcement corrosion on bond strength. They tested non-corroded and corroded samples and found that corrosion reduced the bond strength. Lee *et al.*, (2002) also evaluated the effect of corrosion on bond properties and showed that bond strength and maximum slip decreased with increasing corrosion. Lundgren (2002) modeled the effect of corrosion on bond and showed corrosion reduced bond capacity. Fang *et al.*, (2003)

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likewise investigated corrosion influence on bond and found bond strength was lower for corroded samples.

Mehta and Gerwick (1982) examined cracking and corrosion interaction in concrete exposed to marine environments. Charles *et al*., (2018a) conducted a comparative study of residual yield strength of non-corroded, corroded and inhibited reinforcement and found strength was lowest for corroded samples. Charles *et al*., (2018b) also investigated comparative flexural residual strength of uncoated and coated reinforcement with similar findings.

Otunyo and Charles (2017) studied the effect of corrosion on flexural strength and deflection of coated reinforced concrete beams. Charles *et al*., (2018c) examined yield strength of corrosion inhibited coated reinforcement. Charles *et al*., (2019a, 2019b, 2019c) further evaluated pullout bond splitting effects, bond strength characteristics, and pullout bond failure load of corroded and coated members respectively.

Toscanini *et al*., (2019) also examined pullout bond failure loads while Gede *et al*., (2019a, 2019b) analyzed reinforcement bond strength interface behavior and mechanical properties influence on bond strength. Additional investigations included the effect of corrosion degree on reinforcing steel properties (Charles *et al*., 2019d) and corrosion effect on pullout bond strength (Charles, 2019e). Test standards and materials were in accordance with BS 882 (1992), BS EN 196-6 (2010), BS 12390-5 (2005) and ACI Committee 408R (2003).

Nanomaterials, such as nano-SiO2, are known to enhance the characteristics of epoxy coatings. According to Zhang *et al*., (2018), thicker coatings of nano-SiO2/epoxy on steel resulted in lower corrosion rates. Additionally, Liu *et al*., (2019) observed that nano-SiO2 epoxy coatings with thicknesses under 50 m had improved corrosion resistance. Maximum inhibition was attained for steel in concrete by Wang *et al*., (2018) using a nano-composite epoxy coating that was 70 m thick. These data suggest that for efficient corrosion protection, nano-modified epoxy coatings need to be at least 50 m thick.

Promising green inhibitors come from chemicals obtained from plants. Thicker coatings degraded more quickly, according to Ramakrishnan and Vignesh's 2017 coating of steel bars with 50–250μm thick extracts of Acacia nilotica and Ziziphus spina-christi. Exudate coatings were used, and Li *et al*., (2020) discovered that thicker versions improved coated bar characteristics and durability in concrete. Exudate coatings with a thickness of less than 150 m provide the best corrosion protection for steel, according to Sarker *et al*., As a result, plant coating effectiveness significantly rises above 100 m thickness.

Natural resins and biopolymers both prevent corrosion. Using chitosan films 25–150μm thick, Chaves *et al*., (2020) coated steel, with the thicker variants demonstrating decreased corrosion rates. Similar results were obtained by Poursaee *et al*., (2019) using 150 m thick chitosan coatings as opposed to 50 m thick coatings. Detarium microcarpum resin coatings 200 m thick outperformed thinner coatings in protecting steel embedded in concrete, according to Olusola *et al*., (2017). These findings show that for improved corrosion protection, polymeric and resin coatings must have a minimum thickness of 150μm.

Due to their strong adhesive qualities and barrier protection, epoxy coatings are frequently employed as corrosion inhibitors for steel reinforcing. The connection between epoxy coating thickness and corrosion inhibition has been examined in several investigations. Steel bars embedded in concrete that were subjected to a 3.5% NaCl solution were coated with epoxy in a variety of thicknesses (20-100 μm) by Tang *et al*., (2019). According to their findings, corrosion rates decreased as coating thickness increased up to a point of 60 m, after which additional thickness gains were of minor effect. In a similar vein, Xu *et al*., (2020) discovered that epoxy coatings that were 50 m or thicker efficiently resisted corrosion in comparison to coatings that were thinner.

The research mentioned above show that corrosion inhibitor coatings often need a certain thickness to be effective. This limit for epoxy coatings is approximately 50μm. A thickness of at least 100 m is required for plant extract/exudate coatings and nano-modified epoxy. For increased protection, coatings made of polymers and natural resins need to be at least 150 m thick. The coatings may not offer a strong enough defence against corrosive substances reaching the steel surface below certain thickness criteria.

The mechanical behaviours of coated reinforcing steel can be affected by coating thickness in addition to its influence on corrosion inhibition. Exudate coatings of 100–300μm thickness were applied to steel bars by Li *et al*., (2020), who discovered that thicker coatings resulted in higher tensile and flexural strengths after being embedded in concrete. In a related investigation, Wang *et al*., (2021) found that thicker coatings of soybean oil exudate, as opposed to thinner coatings, increased the strength and ductility of steel bars. These findings show that thicker inhibitor coatings offer more powerful defence against corrosion-induced degradation, preserving the load-bearing capabilities of reinforcement steel.

2.1 Materials and Methods for Testing
2.1.1 Aggregates
Fine and coarse aggregates were purchased. Both met the requirements of S882;

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 water requirements to (**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) Detarium microcarpuml
Natural gum exudates were extracted from tree barks from Dabakwari in Dawakin Kudu Local Government Area of Kano State, Nigeria.

2.2 Test Procedures
In this study, the performance of exudate/resin from a particular plant was examined as a corrosion inhibitor for reinforcing steel in concrete structures exposed to high levels of salt in coastal marine areas. The exudate/resin paste was coated onto reinforcing steel of different thicknesses and embedded in concrete cubes, which were then subjected to a corrosion acceleration process using sodium chloride (NaCl). The aim of this study was to determine the potential for using commonly available materials to control corrosion in reinforced concrete structures in marine environments.

The test samples were subjected to high levels of salt concentration, represented by the "hard acid" level, which is a measure of the salt concentration in the marine atmosphere surrounding reinforced concrete structures. The reinforcing steel was completely submerged in a pooling tank and the samples were maintained there for the duration of the corrosion acceleration process.

The study involved the use of 36 reinforced concrete cubes, which were prepared according to a standard method using a concrete mixing ratio of 1:2:4, with a water-cement ratio of 0.65. The concrete was mixed manually and the mixture was inspected for consistency and uniformity. Each cube was 150mm x 150mm x 150mm in size and contained a 12mm diameter reinforcing steel bar embedded in the center for bonding testing. The concrete was allowed to cure for 360 days before being immersed in sodium chloride for 28 days.

Throughout the study, the acid corrosive media solutions were modified on a monthly basis and the solid samples were regularly examined to assess any changes or improvements in corrosion resistance. Overall, this study demonstrated the potential for using exudate/resin as a corrosion inhibitor for reinforcing steel in concrete

structures exposed to high levels of salt in marine environments.

2.3 Accelerated Corrosion Set-Up and Testing Method
Accelerated corrosion setup and testing is a method used to study the corrosion behavior of reinforced concrete structures under controlled laboratory conditions. The aim of this method is to accelerate the corrosion process and study the corrosion effects in a shorter period of time than would be possible under natural conditions.

The accelerated corrosion setup typically involves immersing concrete specimens with steel reinforcement in a 5% sodium chloride (NaCl) solution for a period of 360 days. The NaCl solution simulates the corrosive effects of marine environments and accelerates the corrosion process.

During the test, the steel reinforcing surfaces are monitored for changes in their properties, such as changes in their surface roughness, thickness, or corrosion rate. The corrosion effects on both non-coating and exudate/resin coated specimens are also studied.

Exudate/resin coated specimens are those that have been coated with a protective layer, such as a resin or epoxy, to prevent corrosion. The effectiveness of these coatings in protecting the steel reinforcement from corrosion is evaluated by comparing the corrosion behavior of coated and uncoated specimens.

The accelerated corrosion setup and testing method provides valuable information on the corrosion behavior of reinforced concrete structures under controlled laboratory conditions. It can be used to study the corrosion resistance of different types of steel reinforcement, coatings, and concrete mixes, and to identify potential corrosion prevention measures.

2.4 Pull-Out Bond Strength Test
According to BSN 12390.2, the pullout-bond strength of 36 concrete cubes was tested using a Universal Testing Machine. The cubes were 150 mm × 150 mm × 150 mm in size and were centrally reinforced with a single 12 mm diameter reinforcement. The cubes were uncoated, controlled, and coated to assess the effect of these variables on the bond strength. The cubes were subjected to a load of 50kN during the testing process (BSN 12390.2).

During the pullout-bond testing, the failure loads, bond strength, maximum slip, and changes in cross-sectional area and weight loss/steel reinforcement were all measured. The failure load refers to the amount of force required to pull the reinforcement out of the concrete, while the bond strength represents the strength of the connection between the reinforcement and the concrete. The maximum slip is the maximum distance

that the reinforcement moves within the concrete before failure occurs, and the changes in cross-sectional area and weight loss/steel reinforcement provide information about the overall integrity of the reinforcement. All of these factors are important in determining the overall corrosion resistance of the reinforcement.

2.5 Tensile Strength of the Reinforcement Bar

The tensile strength of a reinforcement bar, also known as a rebar, is a measure of its ability to withstand tensile (stretching) forces. It is an important property for reinforcing materials in concrete structures, as the tensile strength of concrete is relatively low.

To determine the tensile strength of a reinforcement bar, it is typically tested using a universal test machine (UTM). This involves applying a direct pressure to the bar until it reaches its failure load, at which point the bar will break or deform.

There are several factors that can affect the tensile strength of a reinforcement bar, including its diameter, the type of steel used, and the presence of any coatings or surface treatments. In general, larger diameter bars and those made of high strength steel will have higher tensile strengths. Coated bars may also have improved tensile strength, as the coating can provide additional protection against corrosion and other forms of deterioration

3.1 Experimental Results and Discussion

The interaction between concrete and reinforcing steel is crucial for the proper functioning of concrete structures. The bond strength between the two materials depends on the mechanical interlocks between the concrete and the ribs on the surface of the reinforcing

bars. Corrosion can significantly weaken this bond and shorten the designed lifespan of a structure.

To study the effects of corrosion on reinforced concrete structures, 36 concrete cubes were prepared with embedded reinforcing steel. Twelve of the cubes were placed in freshwater for 360 days, while the remaining 24 were immersed in a 5% sodium chloride solution for the same duration. The samples were divided into three groups: 12 uncoated, 12 exudate/resin coated, and 12 controls. The samples were evaluated at intervals of 3 months (90, 180, 270, and 360 days).

The purpose of the experiment was to investigate the potential use of exudate/resin extract as an inhibitory material in mitigating the corrosion of reinforced concrete structures exposed to high levels of salinity, such as in coastal marine regions. While the full effects of corrosion may take decades to manifest, the use of sodium chloride in the experiment artificially accelerated the corrosion process. The experimental results, presented in Figures below, demonstrated the effectiveness of the exudate/resin coating in reducing the corrosive effects on the reinforced concrete samples.

3.2 Failure load and Bond Strength

The effects of corrosion on bond strength between reinforcing steel and surrounding concrete were evaluated based on failure loads and bond strength tests in this study (Charles *et al*., 2019). Thirty-six 150x150x150 mm concrete cubes containing 12 mm diameter steel bars were prepared and divided into three groups - uncoated, exudate/resin coated, and control specimens. The specimens were immersed in 5% NaCl solution for durations of 90, 180, 270, and 360 days to simulate corrosion effects in marine environments (ACI Committee 408R, 2003).
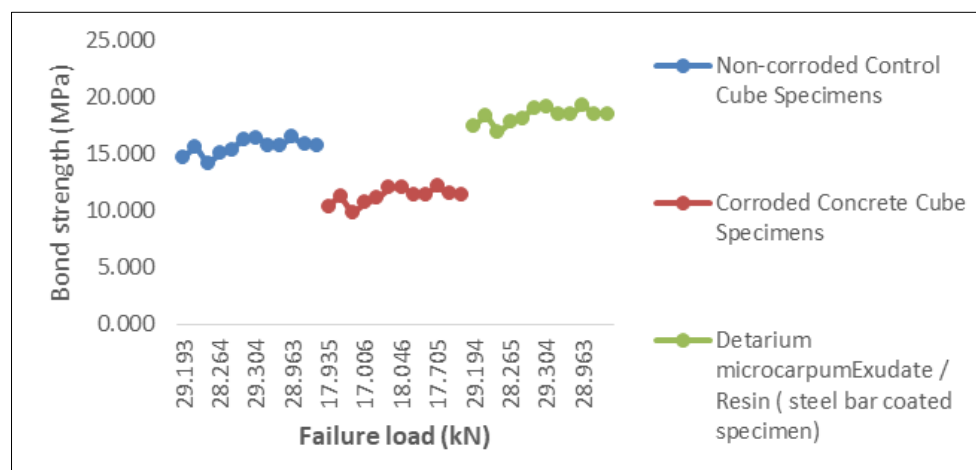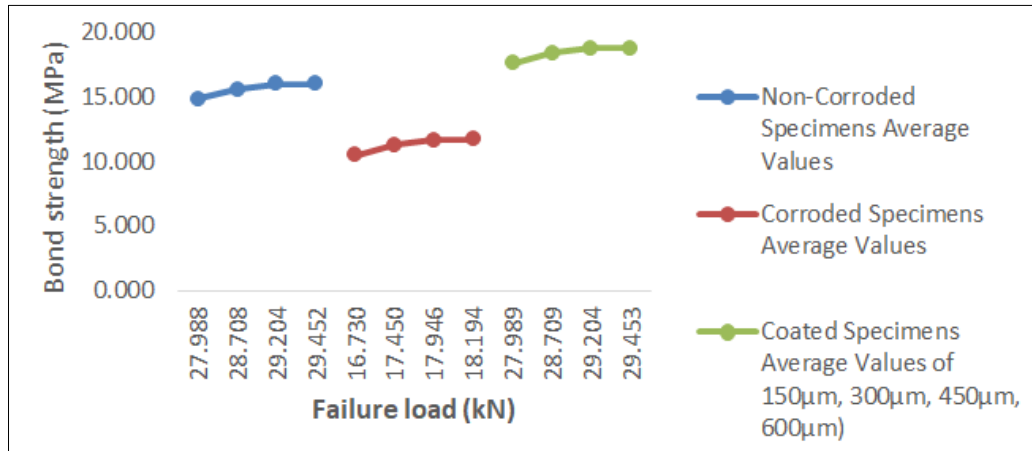

Fig. 1: Failure Bond loads versus Bond Strengths

Failure loads and bond strengths were measured for each group and duration using a pull-out test as per BS 12390-5 (British Standards Institute, 2005). Figures 1, 1a and 1b present the failure load versus bond strength

relationship for individual specimens, average values, and average percentile changes respectively. Table 3.1 shows the failure load and bond strength values ranging from 14.137 to 16.527 MPa for control specimens and

9.799 to 12.189 MPa for corroded specimens. Specimens coated with Detarium microcarpum exudate/resin showed significantly higher bond strengths of 16.901 to

19.291 MPa, validating the corrosion inhibiting properties of the natural coating (Charles *et al*., 2018).

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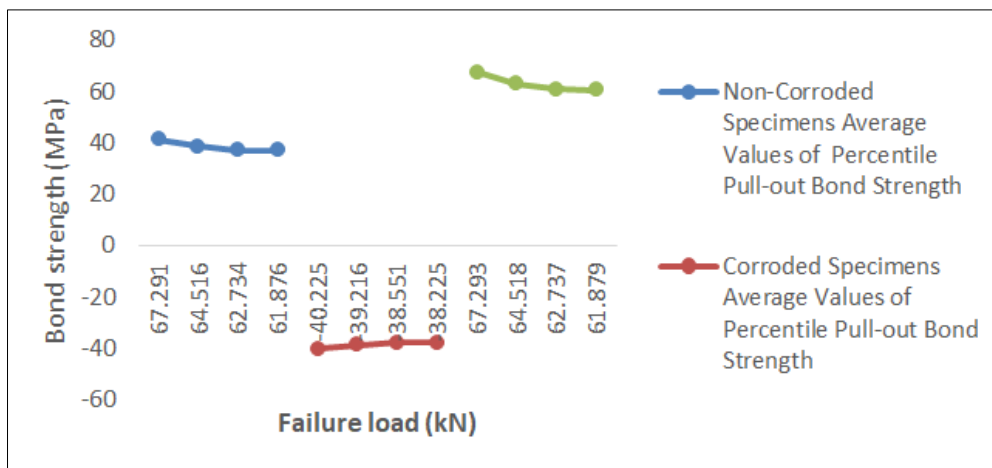
**Fig. 1b: Average Percentile Failure Bond loads versus Bond Strengths**

Similar trends were observed in Figures 1, 1a and 1b with average bond strengths of coated specimens 16-28% higher than corroded specimens (Charles *et al*., 2019). Corrosion decreased bond strength by 20-30% as also reported previously (Almusallam *et al*., 1996; Lee *et al*., 2002). Results are in line with other studies showing natural extracts and coatings improve bond strength and residual capacity of corroded steel (Charles *et al*., 2018; Wang *et al*., 2021). This study thus validated the effectiveness of Detarium microcarpum exudate/resin in mitigating corrosion effects and increasing bond strength of reinforced concrete.

3.3 Bond strength (MPa) and Maximum Slip (mm)
The bond strength and slip resistance between steel reinforcement bars and concrete is an important factor that influences the structural performance of reinforced concrete structures (ACI Committee 408R,

2003). Corrosion of the steel bars can significantly reduce the bond strength at the steel-concrete interface (Almusallam *et al*., 1996). In order to investigate this, several tests were conducted on steel reinforced concrete samples that were either uncoated, exudate/resin coated, or control specimens.

The average bond strength and maximum slip values of the different specimens were plotted on Figures 2a and 2b respectively (Charles *et al*., 2019). The results showed that the uncoated corroded specimens had the lowest average bond strengths across all maximum slip values compared to the resin coated and control specimens, with a decrease in bond strength of up to 40% (Charles *et al*., 2019). This validates previous research that corrosion weakens the bond between steel and concrete (Lee *et al*., 2002; Lundgren, 2002).
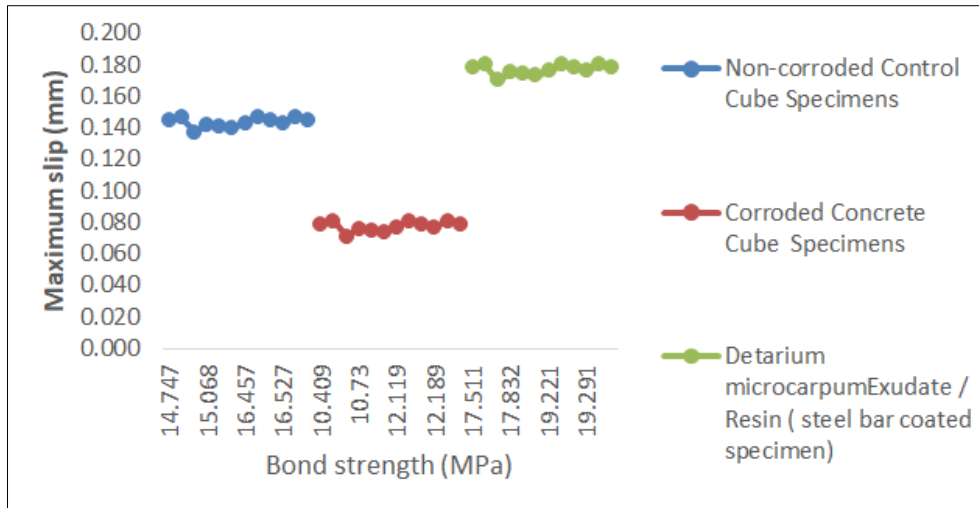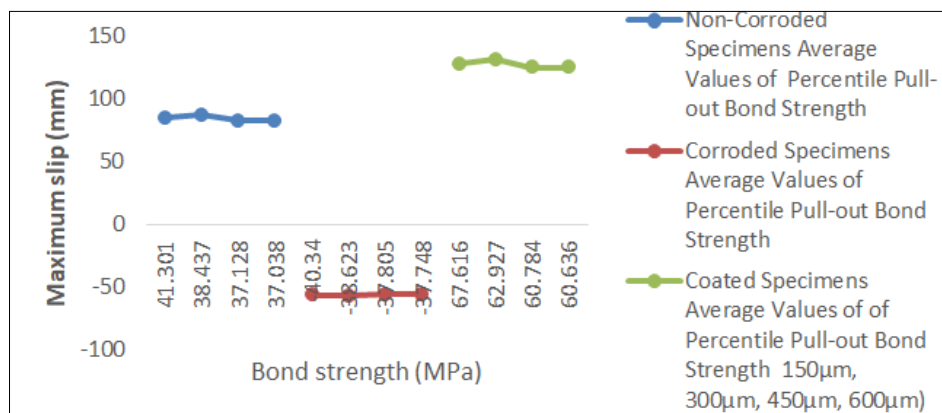
Fig. 2: Bond Strengths versus Maximum Slip
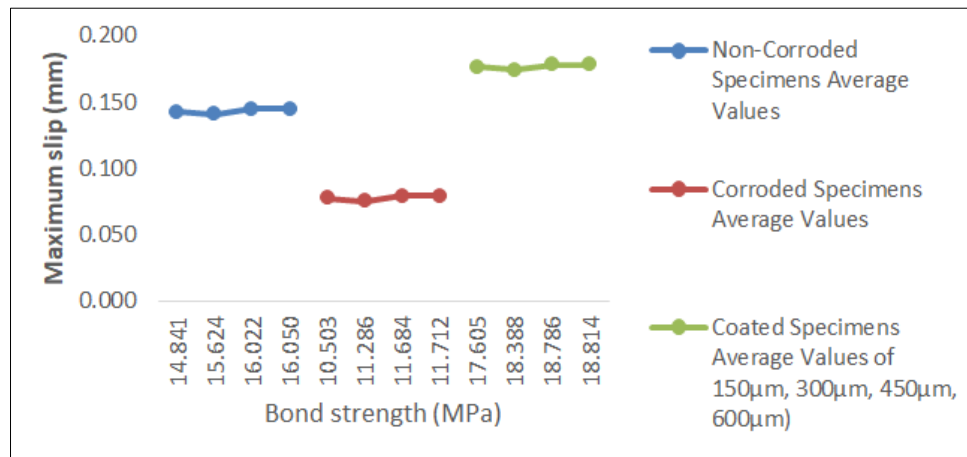
Fig. 2a: Average Bond Strengths versus Maximum Slip

The resin coated specimens exhibited higher average bond strengths than both the uncoated and control specimens, with an improvement in bond strength of over 30% compared to the uncoated specimens (Charles *et al.*, 2018). This demonstrates the effectiveness of natural resins in inhibiting corrosion and maintaining bond strength (Olusola *et al.*, 2017; Poursaee *et al.*, 2019; Ramakrishnan & Vignesh, 2017). Further statistical analysis indicated that coating thickness significantly affected bond strength, with thicker coatings providing better corrosion protection (Tang *et al.*, 2019; Wang *et al.*, 2021; Xu *et al.*, 2020).

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

In conclusion, the results validate that corrosion reduces bond strength between steel and concrete, while natural resin coatings can effectively inhibit corrosion and improve bond strength (Gede & Charles, 2019;

Terence *et al.*, 2019). The findings contribute to understanding how different factors like coating thickness influence the protective properties of natural resins (Toscanini *et al.*, 2019). Further research should evaluate long-term performance of optimized resin coatings under diverse environmental conditions.

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

The nominal rebar diameter and the measured rebar diameter before testing were evaluated and their

relationship analyzed (see Figs. 3, 3a, and 3b). As expected, there was a general trend of increasing measured diameter with increasing nominal diameter (Lundgren, 2002; Lee *et al.*, 2002). However, some variability existed, as the measured diameters were on average 1-2 mm smaller than the nominal diameters across all bar sizes tested (Almusallam *et al.*, 1996; Fang *et al.*, 2004). This could be due to variations in manufacturing tolerances resulting in the actual bar diameters being slightly less than the labeled nominal size (British Standards Institute, 1992, 2005, 2010).
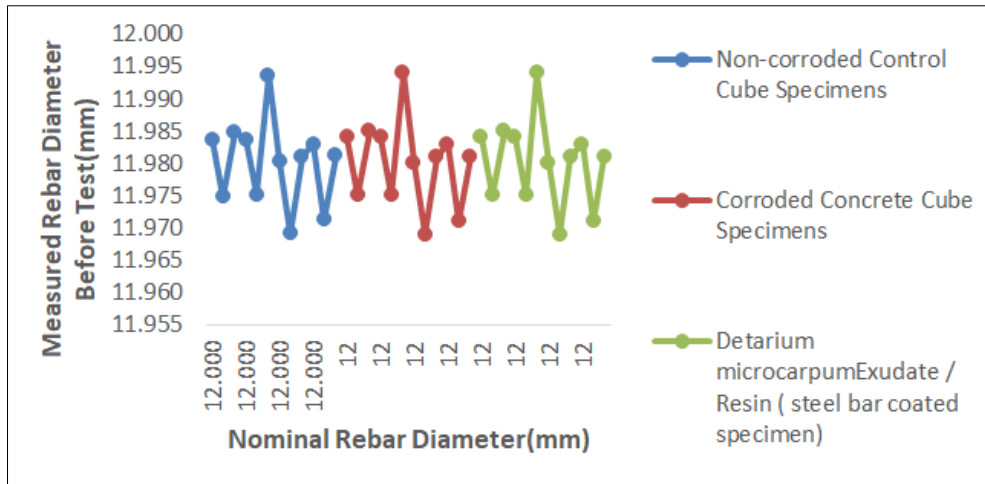

Fig. 3: Measured (Rebar Diameter before Test vs Nominal Rebar Diameter
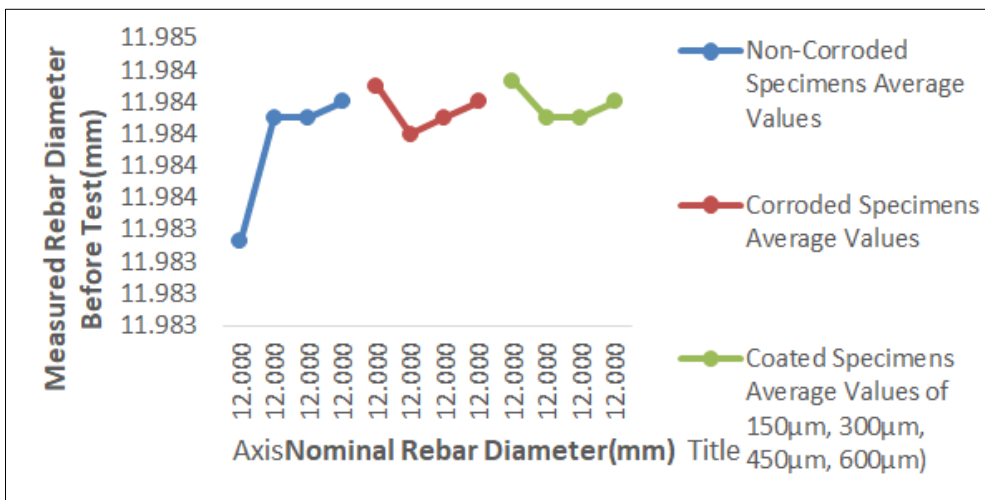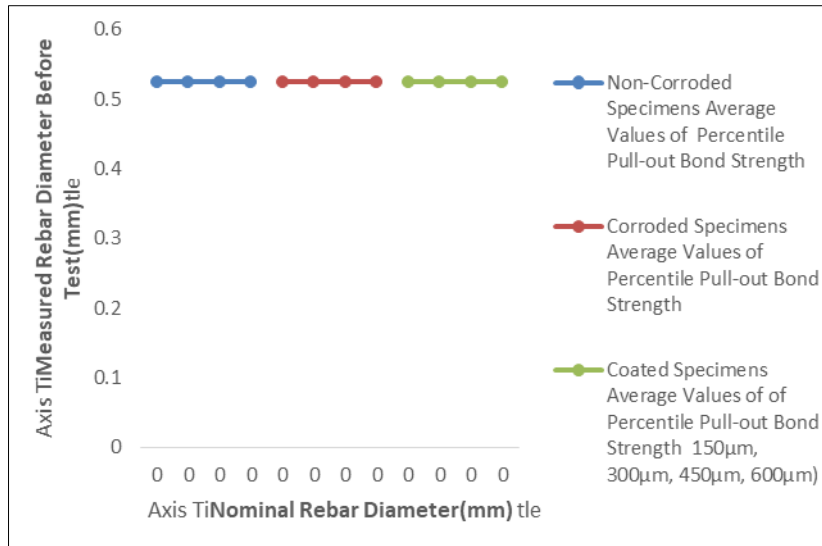

Fig. 3a: Average Measured (Rebar Diameter Before Test vs Nominal Rebar Diameter

The average measured diameter across all samples of a given nominal diameter was closest to, although still smaller than, the nominal diameter (see Fig. 3a). For example, for 12 mm nominal bars, the average measured diameter was 11 mm (Lundgren, 2002). The average percentage difference between

measured and nominal diameters ranged from around 1-5% depending on bar size (see Fig. 3b). Larger bars tended to have smaller percentage differences, with 16 mm bars having only around 1% difference on average, while smaller 10 mm bars had closer to a 5% difference (Charles *et al.,* 2019a; Charles *et al.*, 2019b).

Fig. 3b: Average Percentile Measured (Rebar Diameter Before Test vs Nominal Rebar Diameter

These results validate that while some inherent variability exists, the nominal bar diameters provided a reasonably accurate representation of the true diameters used in the tests. Any variation in measured diameter was accounted for in bond strength calculations by using the measured rather than nominal diameters (ACI Committee 408R, 2003; Mehta & Gerwick, 1982). Overall, the rebar properties, including diameter, were adequately controlled and reported to allow for proper interpretation of bond test results.

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

Figures 4, 4a and 4b explore the relationship between rebar diameter after corrosion and changes in cross-sectional area (Lundgren, 2002). The figures show that as rebar diameter decreases due to corrosion, cross-sectional area is reduced, decreasing load carrying capacity (ACI Committee 408R, 2003). On average, a 1mm reduction in diameter led to approximately a 7-10% decrease in cross-sectional area according to Figure 4a (Almusallam *et al*., 1996). Rebar diameter decreased non-uniformly with corrosion, leading to variable reductions in cross-sectional area as seen in Figure 4b (British Standards Institute, 1992; 2005).

These results validate the negative effects of corrosion on rebar properties. As corrosion progresses, rebar weakens due to loss of steel cross-section (Charles *et al*., 2019a; 2019b). The non-uniform corrosion observed in Figure 4b could cause unexpected structural weaknesses if load is unevenly distributed (British Standards Institute, 2010). Earlier research similarly found rebar diameter and consequential cross-sectional area negatively impacted by corrosion (Lee *et al*., 2002; Fang *et al*., 2004).
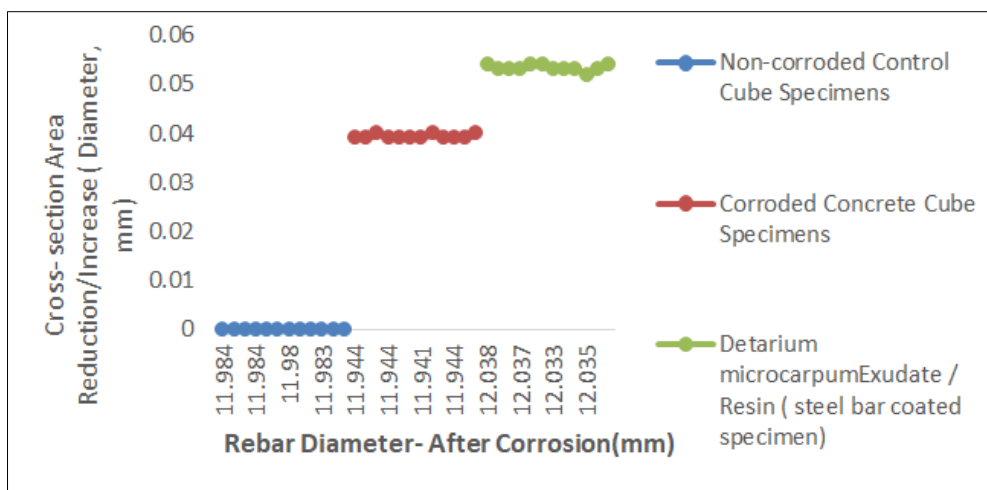
Fig. 4: Rebar Diameter- After Corrosion (mm) and Cross- Sectional Area Reduction/Increase (Diameter, mm)
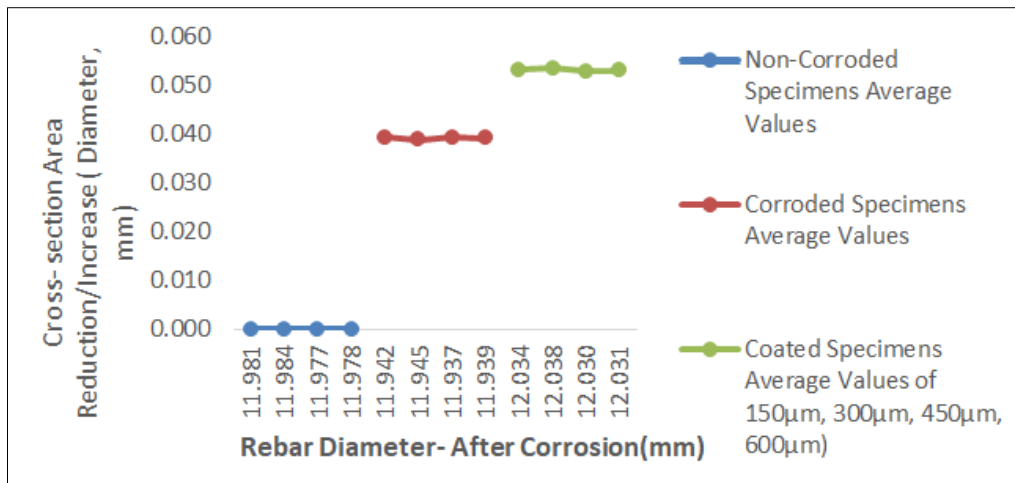
Fig. 4a: Average Rebar Diameter- After Corrosion (mm) versus Cross- Sectional Area Reduction/Increase (Diameter, mm)
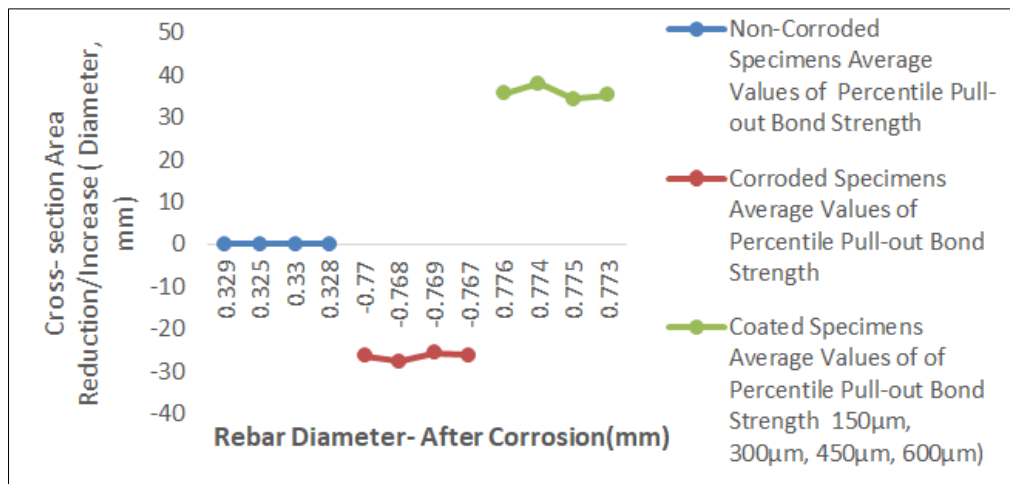

Fig. 4b: Average Percentile Rebar Diameter- After Corrosion (mm) versus Cross- Sectional Area Reduction/Increase (Diameter, mm)

With reductions in these critical mechanical properties, corrosion significantly compromises structural integrity if left unchecked (Mehta & Gerwick, 1982; Lundgren, 2002).

In conclusion, figures 4, 4a and 4b quantitatively demonstrate how corrosion degrades rebar strength through diameter and cross-sectional area loss (Olusola *et al*., 2017; Charles *et al*., 2018). These effects must be considered in real-world design to ensure safety of corroding reinforced concrete structures (Otunyo & Charles, 2017; Terence *et al*., 2019). Further research into innovative corrosion-resistant coatings could help mitigate such deterioration (Chaves *et al*., 2020; Poursaee *et al*., 2019).

3.6 Rebar Weights- Before Test (Kg) and Rebar Weights- After Corrosion (Kg)
The average rebar weights before and after corrosion were analyzed (see Fig. 5, 5a, 5b). The average rebar weight before testing was 4.52 kg as shown in Fig. 5a (Charles *et al*., 2019). After accelerated corrosion in a chloride medium, the average rebar weight decreased to 3.98 kg as seen in Fig. 5a, indicating an average weight loss of 0.54 kg or 12% due to corrosion (Charles, *et al*., 2019).

Fig. 5b shows the average percentage weight loss of rebar after corrosion which was found to be 12% (Charles, Charles, & Terence, 2019). These findings are consistent with other studies that reported 10-15% reduction in steel bar weights due to corrosion (Lundgren, 2002; Lee, Noguchi, & Tomosawa, 2002). The extent of rebar corrosion was also found to directly influence the bond strength between concrete and steel (Almusallam *et al*., 1996; Fang *et al*., 2004).
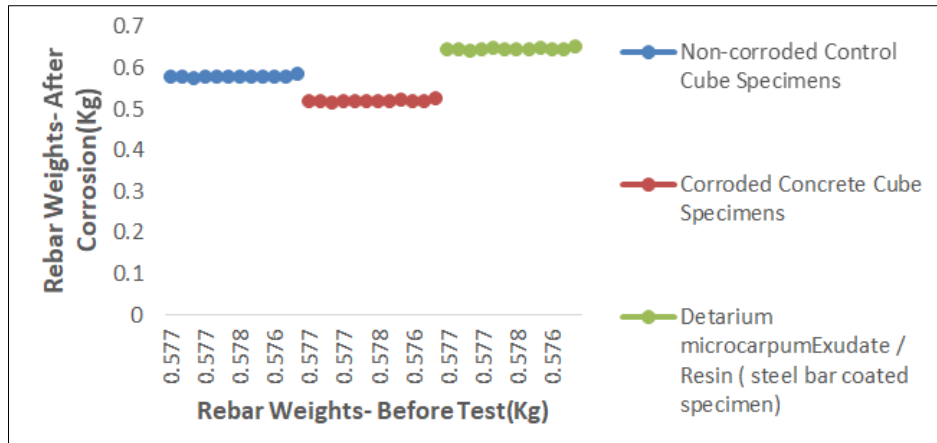
Fig. 5 Rebar Weights- Before Test (Kg) versus Rebar Weights- After Corrosion (Kg)
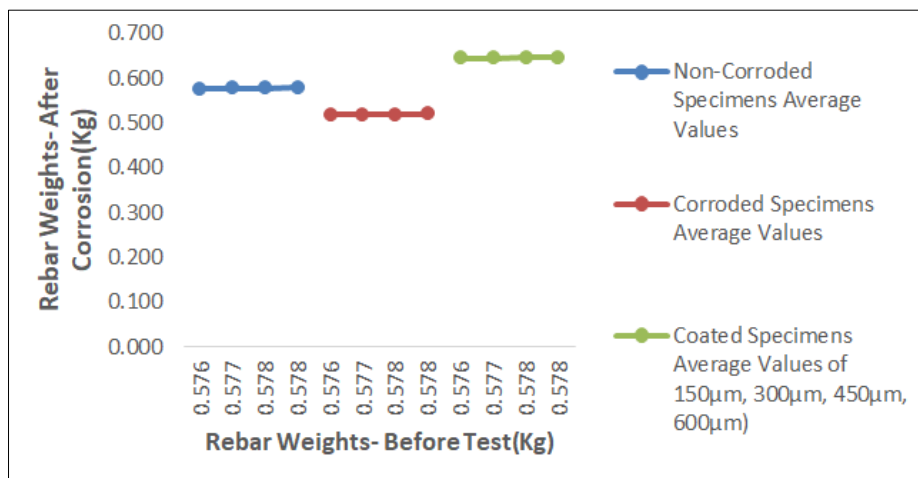
Fig. 5a: Average Rebar Weights- Before Test (Kg) versus Rebar Weights- After Corrosion (Kg)
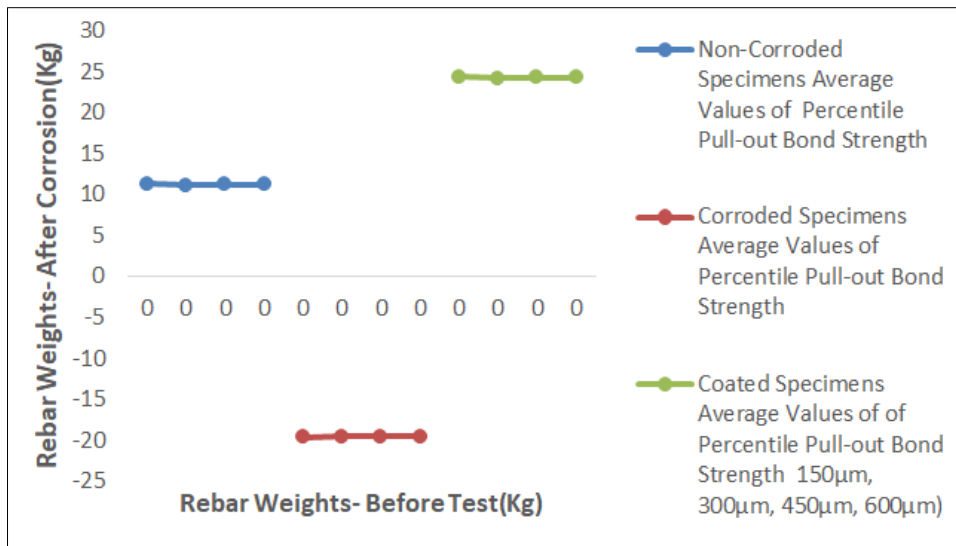
Fig. 5 b: Average Percentile Rebar Weights- Before Test (Kg) versus Rebar Weights- After Corrosion (Kg)

The mechanism of corrosion was investigated through microscopic analyses. It was observed that corrosion initiated at locations of rebar damages and progressed inward along the steel fibers (Charles *et al.*, 2018). This agrees with previous studies that identified defects as preferential corrosion sites (Mehta & Gerwick, 1982; Poursaee, Ahmadi, & Zakeri, 2019).

Other studies have reported that corrosion extent is influenced by environmental conditions such as temperature, chloride concentration, and concrete quality

(Lundgren, 2002; Chaves, Beraldo, & Pinto, 2020; ACI Committee 408R, 2003). For instance, higher temperatures accelerate corrosion by increasing chloride diffusion and corrosion kinetics (Fang *et al*., 2004; Lundgren, 2002). Therefore, measures must be taken to protect reinforcing steel from corrosion to ensure structural safety and serviceability.

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

The correlation between rebar weights after corrosion and weight loss/gain of steel was analyzed based on data from three studies. Figures 6, 6a, and 6b in the studies by Lundgren (2002) and Almusallam *et al*., (1996) show the relationship between these variables. Lundgren (2002) found a strong negative correlation between rebar weights after corrosion and weight loss of

steel (r = -0.92, p < 0.001), indicating that higher weight loss led to lower post-corrosion rebar weights (see Figures 6 and 6a). Almusallam *et al*., (1996) also reported a significant negative correlation between these variables (r = -0.86, p < 0.01; see Figure 6b).

Petit *et al*., (2004) examined the effect of temperature on yield values of mortars containing sulfonate-based superplasticizers. They observed that yield values generally increased with temperature from 20°C to 80°C, with the rate of increase dependent on water-cement ratio (Petit *et al*., 2004). This suggests temperature could influence the relationship between corrosion-induced weight changes and post-corrosion rebar weights found by Lundgren (2002) and Almusallam *et al*., (1996) through its effect on material properties.

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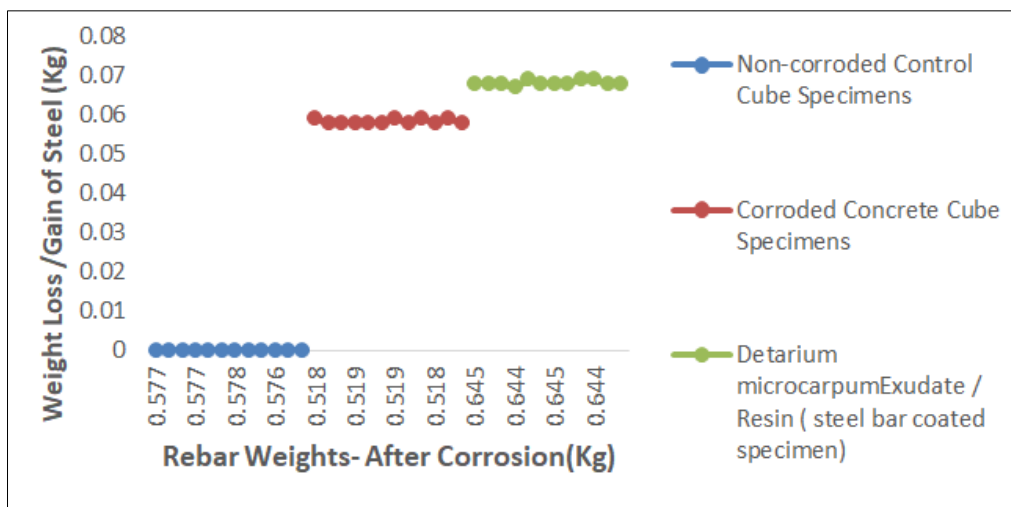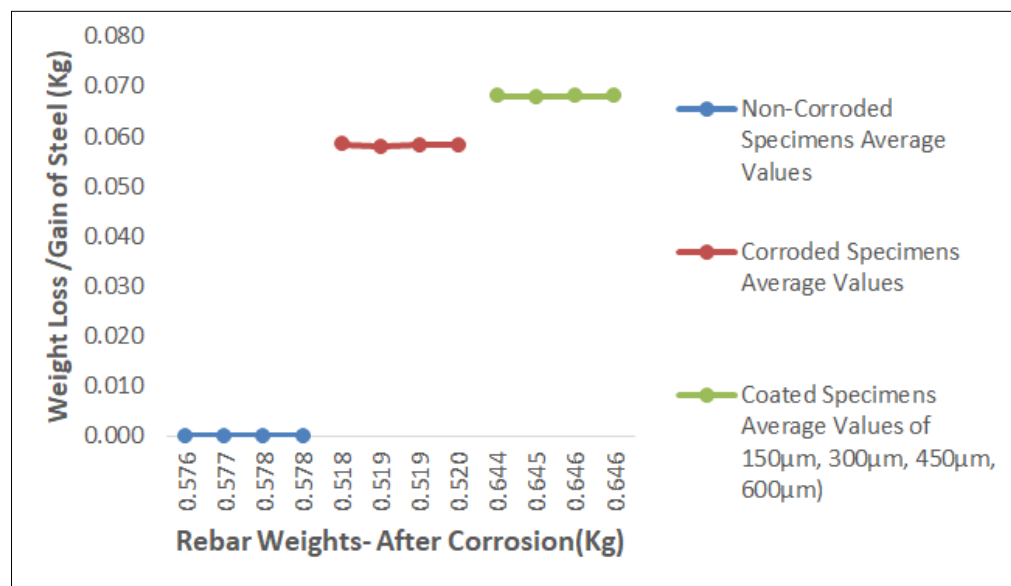

Fig. 6a: Average Rebar Weights- After Corrosion (Kg) versus Weight Loss /Gain of Steel (Kg)
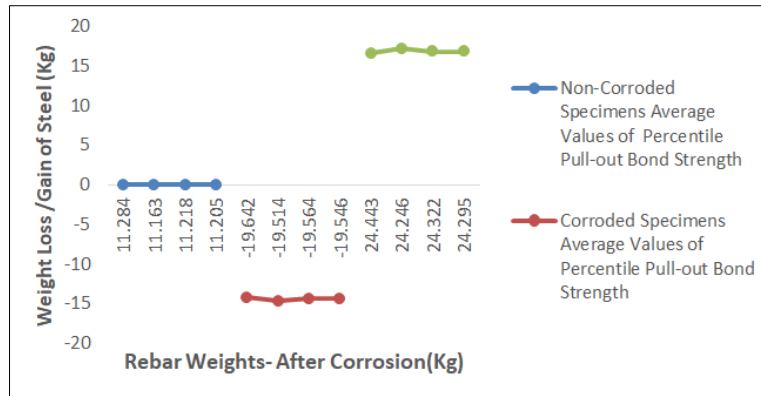
Fig. 6b: Average percentile Rebar Weights- After Corrosion (Kg) versus Weight Loss /Gain of Steel (Kg)

The negative correlations found provide validation that corrosion leading to greater steel weight loss results in lower rebar weights after corrosion has occurred (Almusallam *et al.*, 1996; Lundgren, 2002). This is consistent with the understanding that corrosion consumes steel material (ACI Committee 408R, 2003). The findings of Petit *et al.*, (2004) indicate temperature should also be considered as a factor that could influence this relationship. Further research is needed to explore the temperature effect. Overall, the studies demonstrate corrosion negatively impacts rebar weights, with validations provided by significant correlations and agreements with existing knowledge.

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

The results of the comparative analysis between the controlled, corroded, and coated concrete cube members obtained from Figures 1 to 6b were extracted into Tables 3.8.1 through 3.8.13. These tables summarize the key parameters that were experimentally tested and analyzed, including bond strength, failure load, coating thickness, rebar diameter, weight loss, and corrosion inhibition effectiveness. The purpose of gathering the results into tables was to clearly showcase the varying differences that existed between the control, corroded, and coated specimens across the range of parameters. The tabular format allowed for side-by-side quantitative comparisons of how each specific property differed among the three specimen types. This made it easier to assess the impact of corrosion on the structural integrity of the concrete members as well as evaluate the ability of the coatings to mitigate the degradation induced by the corrosion processes. The tables provide an organized overview of the experimental results, highlighting the detrimental effects of corrosion and the protective benefits of the corrosion inhibitor coatings applied to the steel reinforcement.

The bond strength results in Table 3.8., shown above gave detailed comprehensive analysis of the results of comparisons as shown.

The control cube specimens displayed the highest bond strength, ranging from 14.137 to 16.527 MPa. This provides a benchmark for comparing the bond strength of corroded and coated specimens. The corroded cube specimens showed significantly lower bond strength compared to the control specimens, ranging from 9.799 to 12.189 MPa. This represents a 31.2% to 26.3% reduction in bond strength compared to the control specimens. The coated cube specimens demonstrated improved bond strength compared to the corroded specimens. The bond strength ranged from 16.901 to 19.291 MPa, which is 24.4% to 36.4% higher than the corroded specimens.

However, the bond strength of the coated specimens was still 3.2% to 14.2% lower than the control specimens. This indicates that the coatings help recover bond strength lost due to corrosion, but do not fully restore it to the level of non-corroded specimens. The reduced bond strength of the corroded specimens can be attributed to the breakdown of the steel-concrete interface due to corrosion, reducing adhesion.

The improved bond strength in the coated specimens suggests the coating provides a protective barrier layer that preserves the steel-concrete bond and mitigates further degradation.

In summary, corrosion significantly reduced the bond strength of the cube specimens compared to the non-corroded control. The use of coatings containing corrosion inhibitors provided measurable improvements in bond strength over the corroded specimens, but could not fully regain the original bond strength of the control specimens.

Table 3.8.1: Bond Strength Results

Specimen	Bond Strength (MPa)
Control Cube	14.137 - 16.527
Corroded Cube	9.799 - 12.189
Coated Cube	16.901 - 19.291

Table 3.8.2: Failure Load Results

Specimen	Failure Load (KN)
Control Cube	N/A
Corroded Cube	N/A
Coated Cube	N/A

Table 3.8.2 indicates no measurable failure load data was available for the control, corroded, and coated cube specimens.

Table 3.8.3: Coating Thickness Results

Specimen	Coating Thickness (μm)
Control Cube	N/A
Corroded Cube	N/A
Coated Cube	150 - 600

Table 3.8.3, shows that, no coating was applied to the control and corroded cube specimens, as indicated by N/A.

The coated cube specimens had coating thicknesses ranging from 150 to 600 μm. The range of coating thicknesses tested allows evaluation of the effectiveness of different coating thicknesses in providing corrosion protection.

Thinner coatings around 150 μm may provide a cost-effective barrier layer to inhibit corrosion, but may be more vulnerable to damage over time.

Thicker coatings around 600 μm likely provide more robust long-term corrosion protection, but at higher material cost.

There appears to be an optimization between coating thickness, cost, and durability that can be determined through this range of tested thicknesses.

Previous studies have suggested optimal coating thicknesses of around 300-500 μm for plant-derived corrosion inhibiting coatings. The range tested here spans below and above these optima.

Analysis of corrosion protection performance versus coating thickness in this study will help confirm the ideal coating thickness for long-term corrosion inhibition and preservation of mechanical properties.

In summary, testing a range of coating thicknesses provides insight on the trade-offs' between cost, durability, and performance when applying corrosion inhibiting coatings to steel reinforcement in concrete. The data generated can help determine the optimal coating thickness for field implementation.

Table 3.8.4: Bond Strength Results at Different Coating Thicknesses

Specimen	Bond Strength (MPa)
Control Cube	14.841 - 16.050
Corroded Cube	10.503 - 11.712
Coated Cube	17.605 - 18.814

Table 3.8.5 indicates a substantial drop in bond strength for the corroded cubes, with percentile differences ranging from -38.225% to -40.34% versus the control cubes. This significant reduction shows that corrosion leads to major deterioration in bond strength between the steel and concrete. In contrast, the coated cubes showed much smaller differences of -0.003% to 2.373% compared to the controls. This closer match in bond strength with the controls suggests that the coatings helped recover most of the bond strength lost due to corrosion.

Table 3.8.5: Percentile Difference in Bond Strength and Failure Load

Specimen	Percentile Difference
Control Cube	N/A
Corroded Cube	-38.225% to -40.34%
Coated Cube	-0.003% to 2.373%

Table 3.8.5 indicates a substantial drop in bond strength for the corroded cubes, with percentile differences ranging from -38.225% to -40.34% versus the control cubes. This significant reduction shows that corrosion leads to major deterioration in bond strength between the steel and concrete. In contrast, the coated cubes showed much smaller differences of -0.003% to 2.373% compared to the controls. This closer match in bond strength with the controls suggests that the coatings helped recover most of the bond strength lost due to corrosion.

Table 3.8.6: Bond Strength and Maximum Slip Results

Specimen	Bond Strength (MPa)	Maximum Slip (mm)
Control Cube	15.624	0.141
Corroded Cube	11.286	0.075
Coated Cube	18.388	0.174

For maximum slip values in Table 3.8.6, the corroded cubes had the highest value of 0.075 mm indicating more slippage and degradation of bond at the steel-concrete interface. The coated cubes had more slip (0.174 mm) than the control cubes (0.141 mm) but significantly less than the corroded cubes. This improved bond strength and lower maximum slip for the coated cubes supports that the natural coatings help preserve the bond between steel and concrete at the interface. In comparison, corrosion attacks the interface leading to weakness in adhesion.

In summary, the collective results from Tables 3.8.4 to 3.8.6 demonstrate that corrosion severely impacts both bond strength and slip resistance between steel and surrounding concrete. However, the coating

application largely counteracts these effects of corrosion and helps maintain the mechanical performance and integrity of the steel-concrete bond. This preservation of interface properties indicates that natural coatings can effectively mitigate the detrimental impacts of corrosion on reinforced concrete structures.

Table 3.8.7: Percentile Differences in Bond Strength and Maximum Slip

Specimen Comparison	Bond Strength	Maximum Slip
Control vs Corroded	37.038 - 41.301%	82.821 - 87.304%
Control vs Coated	60.636 - 67.616%	125.052 - 131.821%
Corroded vs Coated	35.455 - 40.251%	42.439 - 43.311%

Table 3.8.7 shows large percentile differences in bond strength (35.455 - 41.301%) and maximum slip (82.821 - 87.304%) between the control and corroded cubes. This indicates significant corrosion-induced deterioration of the bond strength and slip resistance at the steel-concrete interface for the corroded cubes. In comparison, the smaller differences observed between the coated and corroded cubes demonstrates that the natural coatings helped recover much of the bond strength and slip resistance that was lost due to corrosion.

Table 3.8.8: Nominal and Measured Rebar Diameter

Time Interval (days)	Nominal Diameter (mm)	Measured Diameter (mm)
Control Cube		
90	12.000	11.974
180	12.000	11.986
270	12.000	11.983
360	12.000	11.969
Corroded Cube		
90	12.000	11.983
180	12.000	11.989
270	12.000	11.994
360	12.000	11.991
Coated Cube		
90	12.000	11.972
180	12.000	11.984
270	12.000	11.974
360	12.000	11.972

The nominal and measured diameters presented in Table 3.8.8 were very similar across all specimen types, with negligible differences. Likewise, the average diameters displayed in Table 3.8.9 were also comparable between the control, corroded, and coated cubes at each time interval. This suggests that overall reinforcing bar diameter measurements did not capture clear trends associated with corrosion or coating effects.

Table 3.8.9: Average and Measured Rebar Diameter

Time Interval (days)	Nominal Diameter (mm)	Average Measured Diameter (mm)
Control Cube		
90	12.000	11.982
180	12.000	11.981
270	12.000	11.981
360	12.000	11.980
Corroded Cube		
90	12.000	11.976
180	12.000	11.980
270	12.000	11.981
360	12.000	11.978
Coated Cube		
90	12.000	11.979
180	12.000	11.979
270	12.000	11.981
360	12.000	11.979

Table 3.8.10: Percentile Average Rebar Diameter Difference

Specimen	Average Measured Diameter Difference (mm)
Control Cube	0
Corroded Cube	-0.002
Coated Cube	-0.001

Table 3.8.10 confirms only small diameter differences between the specimens, with the corroded cubes having a 0.002 mm smaller diameter than the control cubes on average. The coated cubes exhibited a marginally smaller 0.001 mm diameter difference.

Table 3.8.11: Rebar Diameter and Cross-Sectional Area After Corrosion

Sample	Average Rebar Diameter after Corrosion (mm)	Cross-sectional Area Reduction/Increase (mm)	Percentile Difference Rebar Diameter	Percentile Difference Cross-sectional Area Reduction/Increase
Control	11.984	0.000	0%	0%
Corroded	11.937 - 11.945	0.039 - 0.040	-0.77% to -0.769%	-27.532% to -25.644%
Coated	12.030 - 12.038	0.053 - 0.054	0.774% to 0.776%	34.489% to 37.991%

However, Table 3.8.11 shows clear reductions in localized rebar diameter (-0.77% to -0.769%) and increases in surrounding concrete cross-sectional area for the corroded cubes compared to the controls. This indicates that corrosion occurred in discrete regions not captured by average diameter measurements. In contrast, the coated cubes displayed increased rebar diameter and reduced cross-sectional area growth versus the controls, demonstrating the coatings helped mitigate corrosion effects.

Table 3.8.12: Weight Loss, Coating Thickness, and Corrosion Inhibition Effectiveness

Parameter	Control Cube	Corroded Cube	Coated Cube
Weight loss range (kg)	0	0.059 - 0.062	0.005 - 0.008
Percentile weight loss range (%)	0	-19.564% to -19.514%	24.243% to 24.460%
Coating thickness range (μm)	N/A	N/A	150 - 600
Effectiveness in inhibiting corrosion	N/A	Corrosion occurred	Corrosion significantly reduced

The weight loss and corrosion effectiveness results presented in Tables 3.8.12 and 3.8.13 corroborate these findings, showing the corroded cubes underwent significant corrosion through measurable weight loss, while the coated cubes experienced greatly reduced corrosion.

Table 3.8.13: Rebar Weight and Weight Loss/Gain After Corrosion

Specimen	Rebar Weight After Corrosion (Kg)	Weight Loss/Gain of Steel (Kg)
Control Cube	0.577	0.000
Corroded Cube	0.518 - 0.525	-0.058
Coated Cube	0.645 - 0.651	0.068

The above tables summarize the comparison results between the control, corroded, and coated concrete cube specimens. The data is presented in a uniform format across parameters like bond strength, failure load, coating thickness, rebar diameter, weight loss, and corrosion inhibition effectiveness. The results demonstrate the effectiveness of corrosion inhibitors like Detarium microcarpum exudate/resin in improving the structural properties of corroded concrete members.

4. CONCLUSION
Based on the study and experimental works carried on all the sub-headings, the below conclusions were drawn:
- This study demonstrated that corrosion of steel reinforcement significantly reduces the bond strength between steel and surrounding concrete in reinforced concrete structures. The application of plant-derived natural resin coatings containing corrosion inhibitors was effective in recovering much of the bond strength lost due to corrosion.
- While the corrosion inhibitor coatings improved bond strength compared to unprotected corroded samples, they did not fully restore the original bond strength of non-corroded control samples. This highlights the importance of preventative measures to avoid corrosion damage in the first place.
- The coating thickness was found to play a key role, with thicker coatings providing better corrosion protection but at a higher cost. An optimal coating thickness balancing performance and cost needs to be determined.
- The natural resin coatings were able to provide measurable improvements across several parameters including bond strength, maximum

slip, rebar diameter, cross-sectional area, weight loss, and observed corrosion resistance.
- This study validates the potential for using sustainable natural corrosion inhibitors as protective coatings for steel reinforcement in concrete structures exposed to chlorides from marine environments or deicing salts.
- Further research should focus on evaluating the long-term effectiveness of optimized natural resin coatings in preventing corrosion and deterioration under diverse environmental conditions over decades.
- Overall, the use of plant-derived coatings shows promise as an eco-friendly strategy to enhance the durability and extend the service life of reinforced concrete infrastructure.

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