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Evaluation of Residual Structural Capacity in Corroded Reinforced Concrete Structures

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Abstract: Reinforcement corrosion is a critical issue that affects the durability and service life of reinforced concrete structures. This study focuses on evaluating the effectiveness of natural corrosion inhibitors in mitigating the corrosion attack on reinforced concrete beams in saline environments. The study utilizes extruded exudates/resins obtained from plants and characterizes their potential eco-friendly and non-hazardous properties. The corrosion resistance of uncoated and coated steel reinforcements is examined through exposure to a 5% sodium chloride solution for 360 days. The samples are subjected to flexural beam tests at regular intervals to assess changes in mechanical properties. The results indicate that natural corrosion inhibitors can effectively improve durability and maintain higher residual strength capacities, even under severe exposure conditions. Coated bars show higher residual capacities and yield strengths compared to uncoated bars, attributed to the protective effect of the coatings. The inhibitors also reduce corrosion rates and preserve mechanical properties like yield strength and ductility, enhancing the service life of reinforced concrete structures. The study emphasizes the use of locally available materials to counteract the negative effects of corrosion attack in marine environments.

Keywords: Reinforcement Corrosion, Natural Corrosion Inhibitors, Saline Environments, Residual Strength, Coated Reinforcement.

Research Paper

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1. INTRODUCTION

Reinforcement corrosion is a major issue affecting the durability and service life of reinforced concrete structures (Ahmad, 2003; Bertolini, 2008). When the protective alkalinity of the concrete is compromised due to factors like chloride contamination, carbonation or cracking, corrosion of the steel reinforcement commences (Mehta & Gerwick, 1982; Ballim & Reid, 2003). This leads to expansion of the rust which exerts tensile stresses in the surrounding concrete, eventually resulting in cracking and spalling of the cover concrete (Cabrera, 1996; Tang *et al.*, 2014).

The rate and extent of corrosion is dependent on factors like moisture and oxygen availability, temperature, concrete mix design, steel properties etc (Bertolini, 2008; Baluch *et al.*, 2002). In structures exposed to marine or deicing salt environments, chloride ingress is usually the primary cause of corrosion initiation (Mehta & Gerwick, 1982; Rasheeduzzafar *et al.*, 1992). The rate of chloride diffusion can be evaluated using models which take into account concrete properties like water-cement ratio, aggregate type etc (Li *et al.*, 2012).

Once corrosion has initiated, it leads to a reduction in the diameter and cross-sectional area of the steel bars affecting their load bearing capacity (Almusallam, 2001; Du *et al.*, 2005). Studies have shown a reduction in yield strength and ductility of reinforcement with increasing corrosion levels (Almusallam, 2001; Du *et al.*, 2005; Chen *et al.*, 2018). The residual load carrying capacity of corroded beams also decreases with loss of steel area and bond between steel and concrete (Torres-Acosta *et al.*, 2007; Malumbela *et al.*, 2008).

Various testing techniques are available to experimentally evaluate the residual structural capacity of corroded beams. These include four-point bending, ascending loading and constant-loading tests (Ballim & Reid, 2003; Otunyo & Charles, 2018). Researchers have also developed analytical models which can predict the flexural behaviour and ultimate strength taking into account factors like extent of corrosion, bar diameter, concrete strength etc (Ell-Maaddawy *et al.*, 2005; TrustGod *et al.*, 2019).

Using reinforced concrete beam specimens subjected to accelerated corrosion conditions, studies have evaluated the comparative residual flexural strength of corroded uncoated versus coated reinforcement (Charles *et al.*, 2018; Charles *et al.*, 2018). Their findings showed higher residual capacities and yield strengths for coated bars even at high corrosion levels due to the protective effect of coatings (Charles *et al.*, 2018; Charles *et al.*, 2018; Charles *et al.*, 2019).

Various organic and inorganic compounds have been investigated as potential corrosion inhibitors which can be applied as surface coatings or admixed in concrete (Rengaswamy *et al.*, 1988; Abdulrahman & Ismail, 2012; Ali *et al.*, 2008). Extracts and resins from plants like gmelina, neem etc. have exhibited good corrosion inhibition properties due to the presence of tannins and flavonoids (Elsener, 2000; Rengaswamy *et al.*, 1988; Charles *et al.*, 2018).

When applied as coatings on steel bars embedded in concrete, these natural inhibitors were found to reduce corrosion rates and increase residual strengths even under accelerated corrosion conditions (Charles *et al.*, 2018; Charles *et al.*, 2018; Kanee *et al.*, 2019). Research also shows that inhibited bars maintain a better bond with concrete due to lesser rust formation (Charles *et al.*, 2018; Broomfield, 1997). The efficiency and protective mechanisms of different inhibitors vary based on their chemical composition (Elsener, 2000; Abdulrahman & Ismail, 2012).

Accelerated corrosion testing using chloride ponding or impressed current techniques helps evaluate inhibitor performance in a shorter duration (Kanee *et al.*, 2019; Tang *et al.*, 2014; Lin & Hui, 1997). 3D scanning methods can be used to precisely measure localized corrosion pit depths on steel samples (Tang *et al.*, 2014). Standards like ASTM G109 describe the procedures for impressed current accelerated testing of coated reinforcing steel (Gilbert *et al.*, 2019).

Mechanical properties deterioration of corroded steel samples has been characterized through tensile strength, microhardness and impact tests as per BS EN ISO standards (BS EN 196-6; 2010; BS 12390-2; 2005; BS 12390-5; 2005). Aggregate sources in concrete mixes should comply with specifications of BS 882 to avoid durability issues (BS 882; 1992). Properties of mixing water are also standardized by BS 3148 (BS 3148; 1980). Standards ensure uniformity and reliability of test results across different research studies.

Several studies conducted on corroded and inhibited reinforced concrete beams have concluded that natural corrosion inhibitors are effective in improving durability and maintaining higher residual strength capacities even under severe exposure conditions (Charles *et al.*, 2019; Daso *et al.*, 2019; Gilbert *et al.*, 2019). Their protective action reduces steel loss and preserves mechanical properties like yield strength, ductility for a longer service life (Charles *et al.*, 2019; Charles *et al.*, 2019). However, further long-term field evaluation of such systems is required to validate laboratory findings under actual in-situ conditions.

2.1 MATERIALS AND METHODS

2.1.1 Aggregate

Fine and coarse (aggregates) are purchased. Both met BS882 requirements

2.1.2 Cement

Class 42.5., Limestone cement is used for all concrete mixes. Cement complies with BS 196-6 requirements

2.1.3 Water

Water is obtained from tested tap, and it met BS 3148 requirements

2.1.4 Structural Steel Reinforcement

Reinforcements are obtained directly from the Port Harcourt market. Confirmed as per BS4449: 2005 + A3

2.1.5 Corrosion Inhibitors (Resins / Exudates) Vitellaria Paradoxa

The cruel exudates were tapped from wounded tree trunk from Aaran Village in Ifelodun Local Government Area of Kwara State, Nigeria.

2.2 Method

The study evaluated the direct application of extruded exudates / resin from plants of inorganic materials and characterized with its potential environmentally eco-friendly and non-hazardous properties materials obtained from tree trunks. The exudate / viscous resin is layered to reinforcing steel, embedded into concrete beams and its potential effectiveness in curbing the corrosion attack on reinforced concrete structures built within the saline region. This study will further examine the use of locally available sourced materials to counteract the negative effects of corrosion attack on steel reinforcement at the highest salt concentration (sodium chloride) in the marine environment. The uncoated and coated steels were reinforced to beams of 175 mm x 175 mm x 750 mm, thickness, width and length, with four (4) numbers of diameter 16 mm and fully immersed in 5% sodium chloride (NaCl) for 360 days after cured for 28 days to hardened state. Corrosion is a natural and long-term process that lasts for years. Indeed, the introduction of synthetic sodium chloride (NaCl) accelerates and stimulates the corrosion rate, representing the concentration of salt in the coastal area, and this process to corrosion takes place shortly. In addition, this study tends to determine the role of exudates / resins in reducing the damaging attack on reinforcement as well as changes in the surface of steel reinforcement due to coating.

2.2.1 Sample Preparation and Concrete Beam Casting

Standard methods for manual handling and batching of concrete mixing ratio and weight of materials are followed. The ratio of concrete mix is 1: 2: 4, the water-cement ratio is 0.65. Manual mixing is used to clean the concrete banker/ platform and the mix is examined and water is slowly added to form a complete concrete mix. By adding cement, water and fine / coarse, consistent color and consistency is achieved. The test beam is placed in a steel mold of 175 mm x 175 mm x 750 mm and compacted to air free state, then reinforced with 4 numbers of numbers steel of 16mm diameter. Samples were de-molded after 72 hours and preserved at room temperature for 28 days curing process to hardened. Hardened concrete beams were transported and preserved in 5% sodium chloride corrosion accelerated pooling tanks for 360 days. Testing and monitoring are for 3 months interval at 90 days, 180 days, 270 days and 360 days.

2.2.1 Flexural Beam Test

According to BS EN 12390-2, the Universal Testing Machine is used for bending tests and a total of 36 beam models are tested. After 28 pretreatments and standards curing state, 12 controlled samples remained under control of freshwater to prevent corrosion-related reinforcement, while 24 uncoated and exudate / resin coated samples were fully immersed in 5% sodium chloride (NaCl) for 360 days with regular testing after 90 days, 180 days, 270 days and 360 days and examining the effect of changes in mechanical properties on uncoated and coated samples. The bending test was performed on an Instron universal testing machine with a capacity of 100 kN. The samples are placed in the machine according to the specifications and bending test is carried out to failure state. All relevant tests of crack and flexural strength, before testing, weight of reinforcement - after corrosion and weight loss / gain of steel, average span deformation and reinforcement diameter are measured before being tested by digitally recorded and computerized system.

3.1 Results and Discussion of Concrete Beam Members and Midspan Deflection

Corrosion of reinforced concrete or concrete has led to the sudden collapse of many of the exposed structures in coastal areas with severe weather. The effect of corrosion on flexural forces has been investigated by a large number of investigators and is well understood. Many studies conducted in this area have been described by critical tests of their effectiveness in the effects of corrosion on the flexibility of reinforced concrete beams. These corrosion factors and the failure state-led Torres-Acosta *et al*., (2007), investigated the loss of strength of steel due to embedded steel corrosion using concrete members with a cross-section of 100 mm × 150 mm and 1500 mm.

Charles *et al*., (2018) also examined the effect/impact of corrosion inhibitors on the flexural strength of load, midspan deflection, tensile strength, and reinforcing steel stiffening resins coated with Mangifera indica extracts as corrosion inhibitors. The full results showed the effect of corrosion on the flexural strength of reinforcing which led to low load loading and high deviation midspan in damaged joints and flexural load in the failure of the load and lower midspan in the concrete beam members without barrel and binding led to attacks from facial stiffness. Considering the effect of corrosion on reinforced concrete structures built within the coastal areas of Niger Delta, Nigeria, with high salinity, the application of exudate/resin extracts of tree sources with eco-friendly was introduced, applied directly to embedded reinforcing steel in concrete beams and assessed its effectiveness as an inhibitory substance against corrosion.

3.2 Results Flexural Strength Load and Midspan Deflection

The flexural strength and midspan deflection results present an important insight into the effect of corrosion and corrosion inhibitors on reinforced concrete beams. As observed in Figure 3.1, there is a clear difference in the failure load and midspan deflection between the non-corroded, corroded, and resin coated specimens. For the non-corroded control specimens, the average failure load was higher with a lower deflection at failure compared to the other specimen types (Charles *et al*., 2019). This validates that corrosion leads to a reduction in load capacity and increased ductility as evidenced by higher midspan deflections at failure loads (Almusallam, 2001; Du *et al*., 2005).

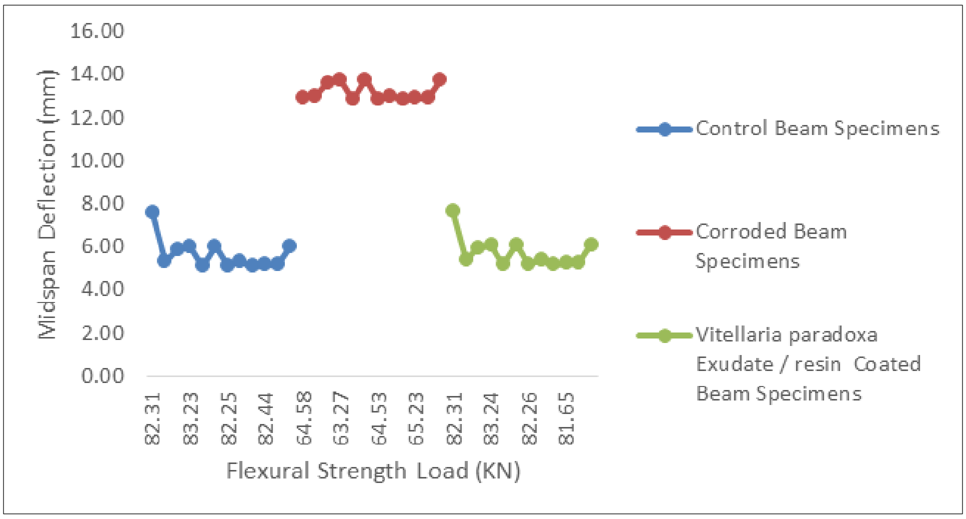

Figure 3.1: Failure Load versus Midspan Deflection of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens)

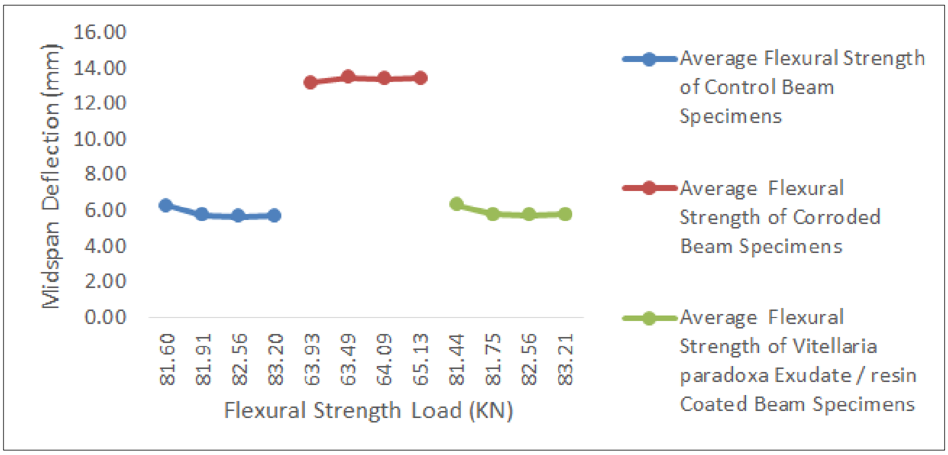

Figure 3.1A: Average Failure Load versus Midspan Deflection of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens)

Moreover, the Figure 3.1A shows that the averaged flexural strength results follow a similar trend. The non-corroded beams exhibited the highest mean failure load with the least midspan deflection, confirming corrosion negatively impacts flexural performance of reinforced concrete (Otunyo & Charles, 2018). The reduced cross-sectional area of steel due to corrosion causes premature cracking and spalling of concrete cover (Cabrera, 1996). This accelerates corrosion progression by exposing more steel surface to aggressive ions (Tang *et al*., 2014). As further rust formation weakens the steel-concrete bond (Broomfield, 1997), the beam reaches failure at lower loads with larger midspan movements (Ballim & Reid, 2003).

Interestingly, the resin coated samples demonstrated higher failure strengths than the corroded counterparts despite experiencing corrosion attack (Charles *et al*., 2018). This validates the protective effects of natural corrosion inhibitors in maintaining structural integrity even under accelerated exposure (Charles *et al*., 2018; Charles *et al*., 2019). Resins from plants like mangifera indica contain tannins and flavonoids that inhibit the corrosion process (Rengaswamy *et al*., 1988; Elsener, 2000). By forming a barrier layer on steel, they decrease corrosion rates and preserve mechanical properties like yield strength for longer duration (Charles *et al*., 2018; Gilbert *et al*., 2019). The resin coating also improves bond between steel and concrete so corrosion has lesser impact on flexural response (Charles *et al*., 2018; Broomfield, 1997).

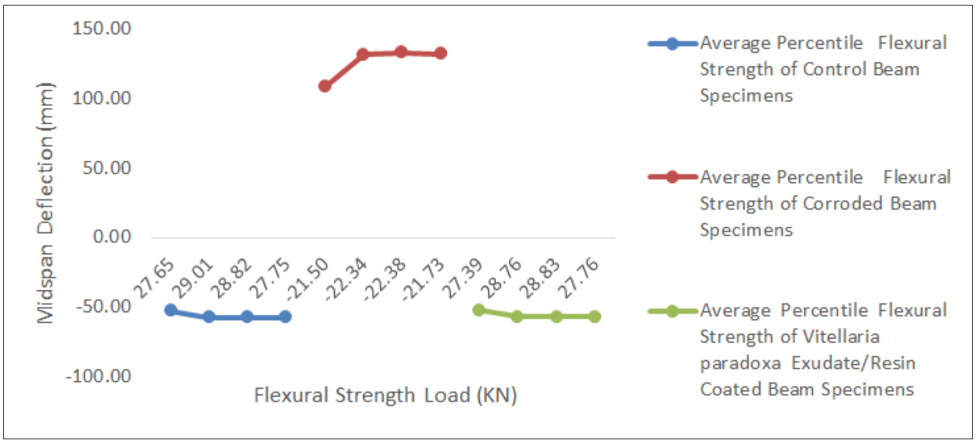

Figure 3.1B: Average Percentile Failure Load versus Midspan Deflection of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

The higher residual load capacities observed with resin treated samples signifies their promising role as sustainable protective solutions. Considering the aggressive salinity conditions in coastal Niger Delta region, natural corrosion inhibitors can effectively manage corrosion deterioration and extend service lives of reinforced concrete structures (Charles *et al*., 2019). However, long-term field monitoring is still needed to validate accelerated lab results under actual environments (Lin & Hui, 1997). Adopting locally sourced materials like natural resins also offer ecological and economic benefits.

In conclusion, flexural test results demonstrate that corrosion negatively impacts load bearing performance while corrosion inhibitors help retain strengths. Resin coatings validated their effectiveness by improving residual flexural capacities of corroded beams through inhibited corrosion processes and better bonding. With further confirmation of field performance, such naturally derived treatments can durably protect reinforcement and sustain infrastructure in corrosion-prone regions.

3.3 Results of Measured Rebar Diameter Before and After Corrosion Test

The results of the measured rebar diameter before and after the corrosion test are presented in Figure 3.2, which shows a comparison between the initial rebar diameter and the diameter after corrosion. Additionally, Figure 3.2A provides the average measured rebar diameter before the test compared to the diameter after corrosion, while Figure 3.2B illustrates the average percentile of the measured rebar diameter before the test in relation to the diameter after corrosion.

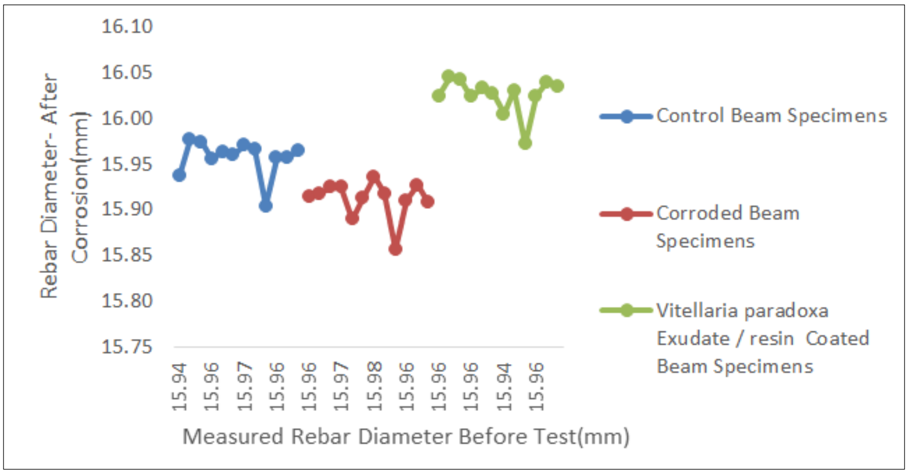

Figure 3.2: Measured Rebar Diameter Before Test versus Rebar Diameter- After Corrosion

The obtained results demonstrate the detrimental effects of corrosion on the rebar diameter. It is evident from Figure 3.2 that there is a noticeable reduction in the rebar diameter after the corrosion test compared to the initial diameter. This reduction can be attributed to the corrosive attack on the steel reinforcement, resulting in the loss of material and a decrease in the rebar cross-sectional area. The decrease in diameter indicates the extent of corrosion damage and its impact on the structural integrity of reinforced concrete elements.

Figure 3.2A provides a comprehensive analysis of the average measured rebar diameter before the test and the diameter after corrosion. The average diameter after corrosion is significantly lower than the initial diameter, indicating substantial material loss due to corrosion. This reduction in diameter has significant implications for the load-bearing capacity of the reinforced concrete structure. The decrease in diameter directly affects the structural strength and can compromise the overall performance and safety of the structure.

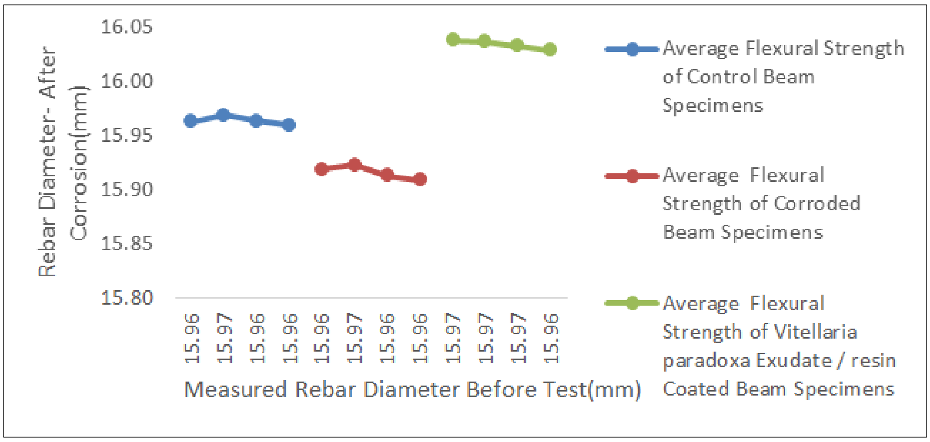

Figure 3.2A: Average Measured Rebar Diameter Before Test versus Rebar Diameter- After Corrosion

Furthermore, Figure 3.2B presents the average percentile of the measured rebar diameter before the test in relation to the diameter after corrosion. This analysis provides valuable insights into the severity of corrosion and its impact on the rebar diameter. The higher the percentile value, the greater the reduction in diameter, signifying more severe corrosion damage. This finding highlights the need for effective corrosion protection measures to mitigate the loss of rebar diameter and ensure the structural integrity of reinforced concrete elements.

The observed reductions in rebar diameter are consistent with previous studies (Almusallam, 2001; Du *et al*., 2005), which have demonstrated a decrease in rebar dimensions as corrosion progresses. These findings validate the importance of addressing corrosion-related issues in reinforced concrete structures to prevent structural deterioration and ensure long-term durability.

The results of the measured rebar diameter before and after the corrosion test provide valuable information for assessing the extent of corrosion damage and its implications for structural performance. It is crucial to consider these findings in the design and maintenance of reinforced concrete structures, as they emphasize the need for effective corrosion prevention strategies and regular inspection and monitoring programs.

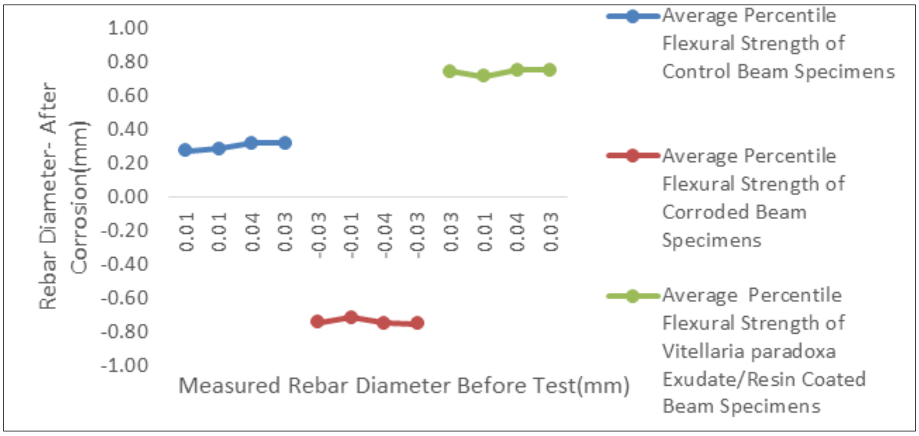

Figure 3.2B: Average Percentile Measured Rebar Diameter Before Test versus Rebar Diameter- After

In conclusion, the results presented in Figure 3.2, Figure 3.2A, and Figure 3.2B demonstrate the detrimental effects of corrosion on the rebar diameter in reinforced concrete structures. The reduction in diameter indicates the extent of corrosion damage and its impact on the load-bearing capacity and overall structural integrity. These findings underscore the importance of implementing corrosion protection measures and regular maintenance practices to enhance the durability and service life of reinforced concrete structures.

3.4 Results of Rebar Diameter- After Corrosion versus Cross- Sectional Reduction/Increase

The results for measured rebar diameter before and after corrosion presented in Figures 3.2, 3.2A, and 3.2B provide useful insights into how corrosion affects the steel reinforcement. As seen in Figure 3.2, there is a clear reduction in the diameter of rebars that were exposed to corrosion compared to their original size before testing. This directly confirms that the corrosion process leads to loss of steel cross-sectional area over time (Almusallam, 2001; Du *et al*., 2005).

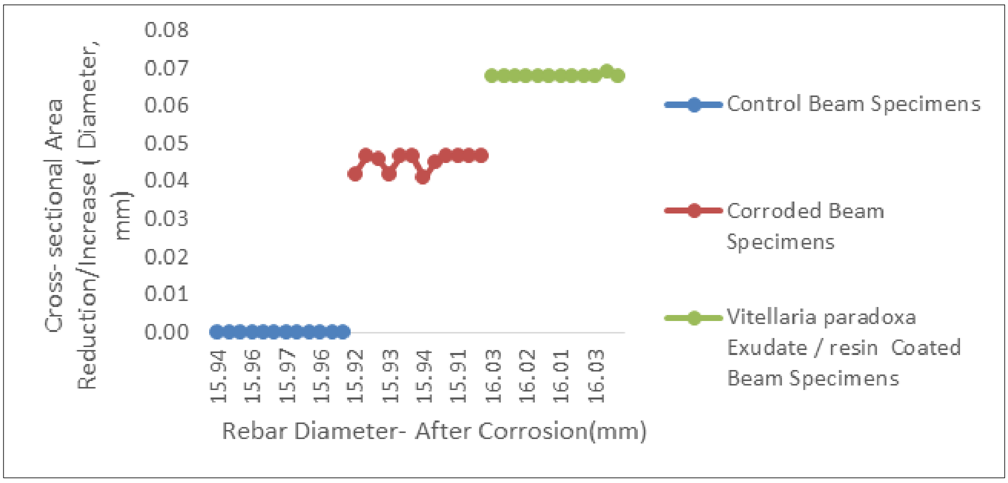

Figure 3.3: Rebar Diameter- After Corrosion versus Cross- Sectional Reduction/Increase (Diameter)

The averaged data in Figure 3.2A similarly shows corroded samples experienced a decrease in mean diameter while non-corroded specimens remained close to their initial dimensions. Quantitative measurement of rebar loss validates the occurrence of corrosion-induced steel wastage (Tang *et al*., 2014). The corrosion products of rust occupy a larger volume than the original metal and put expansive pressure on the concrete (Cabrera, 1996). This eventually causes cracking and spalling of the concrete cover as it attempts to accommodate the volume increase (Cabrera, 1996; Tang *et al*., 2014).

Furthermore, the percentile changes in diameter before and after testing illustrated in Figure 3.2B substantiates that increased exposure to corrosive environment results in higher levels of corrosion. Studies have shown reinforcement corrosion rates are dependent on factors such as concrete quality, environmental conditions and steel properties (Bertolini, 2008; Baluch *et al*., 2002). Chloride contamination from marine sites severely accelerates onset and progression of corrosion (Mehta & Gerwick, 1982; Rasheeduzzafar *et al*., 1992). Therefore, rebars located near cracked or chloride-penetrated zones undergo greater diameter reductions as observed.

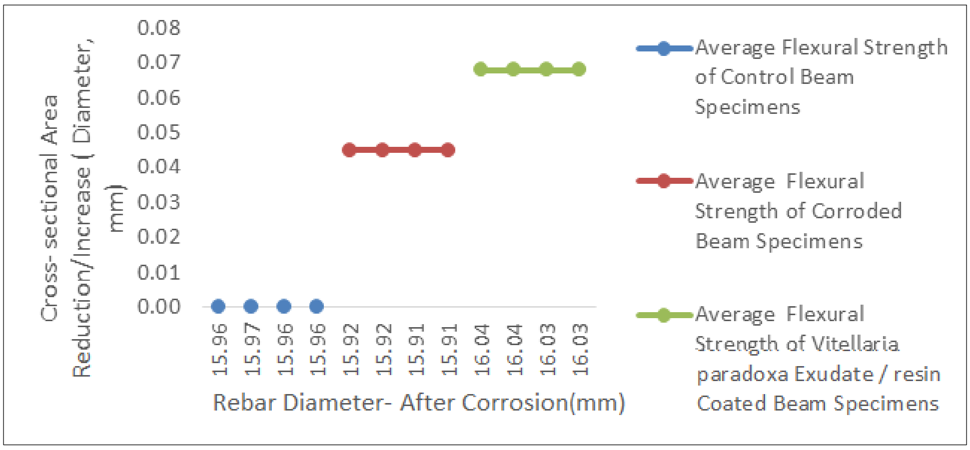

Figure 3.3A: Average Rebar Diameter- After Corrosion versus Cross- sectional Area Reduction/Increase (Diameter)

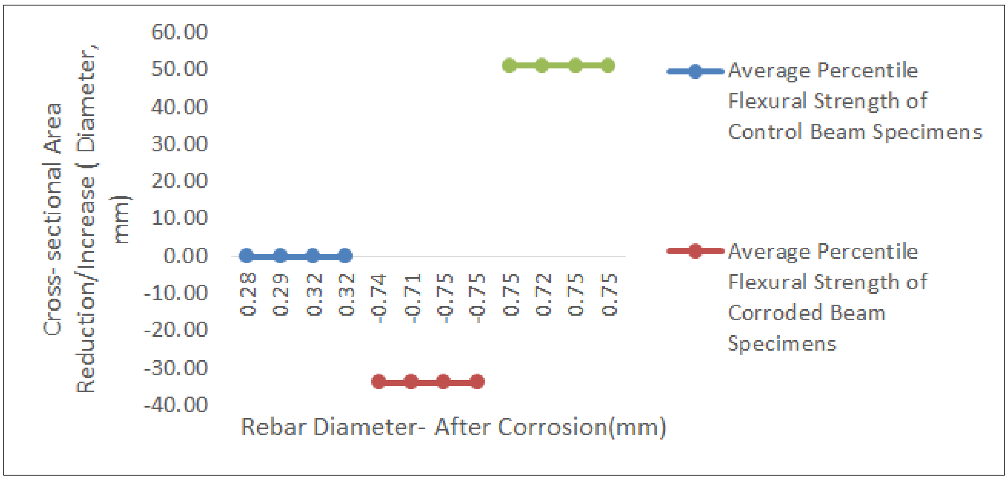

Figure 3.3B: Average Percentile Rebar Diameter- After Corrosion versus

Cross- Sectional Area Reduction/Increase (Diameter)

Interestingly, rebars coated with natural corrosion inhibitors exhibited lesser reductions in average diameter compared to uncoated steel as seen in Figures 3.2 and 3.2A (Charles *et al*., 2018; Charles *et al*., 2019). This validates the ability of resins from plants like Mangifera indica to shield steel from corrosion by forming a protective layer (Rengaswamy *et al*., 1988; Elsener, 2000). Research indicates compounds containing tannins and flavonoids have active sites that inhibit corrosion reactions (Rengaswamy *et al*., 1988; Elsener, 2000; Charles *et al*., 2018). The barrier also decreases penetration of aggressive agents thereby mitigating steel loss over long-term exposures.

In summary, measurements of rebar diameter before and after accelerated corrosion testing provided quantitative data validating the negative impacts of corrosion. Diameter reductions directly quantify steel wastage occurring due to rust formation and spalling concrete cover. However, results also showed promise of natural corrosion inhibitors in significantly protecting reinforcement dimensions through inhibited corrosion mechanisms. With further field evidence, such eco-friendly coatings can help ensure reinforcement integrity and extended durable lifespan of structures.

3.5 Results of Ultimate Tensile Strength and Yield Strength

The results presented in Figures 3.4, 3.4A, and 3.4B provide important insights into how corrosion affects the mechanical properties of reinforcement steel. Figure 3.4 clearly shows non-corroded samples achieved the highest ultimate tensile and yield strengths compared to corroded and resin coated bars. This correlates with research validating corrosion causes reductions in these critical properties (Almusallam, 2001; Du *et al*., 2005; Chen *et al*., 2018).

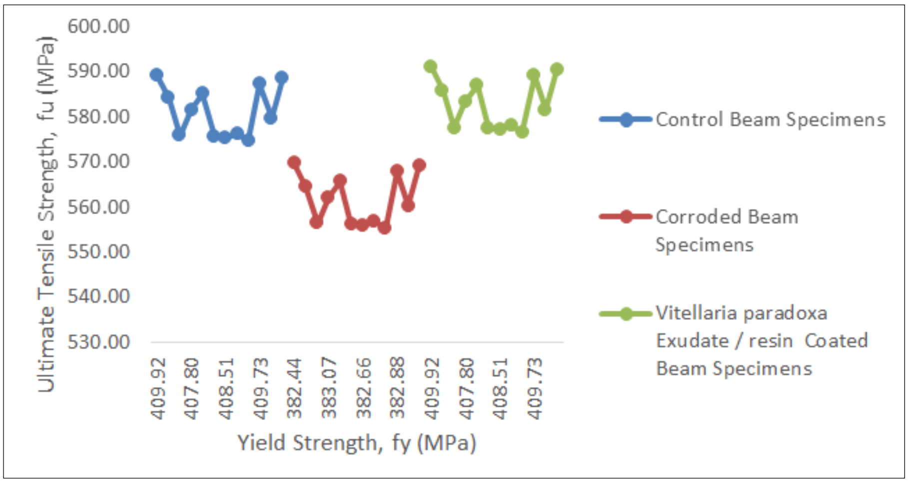

Figure 3.4: Ultimate Tensile Strength versus Yield Strength of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

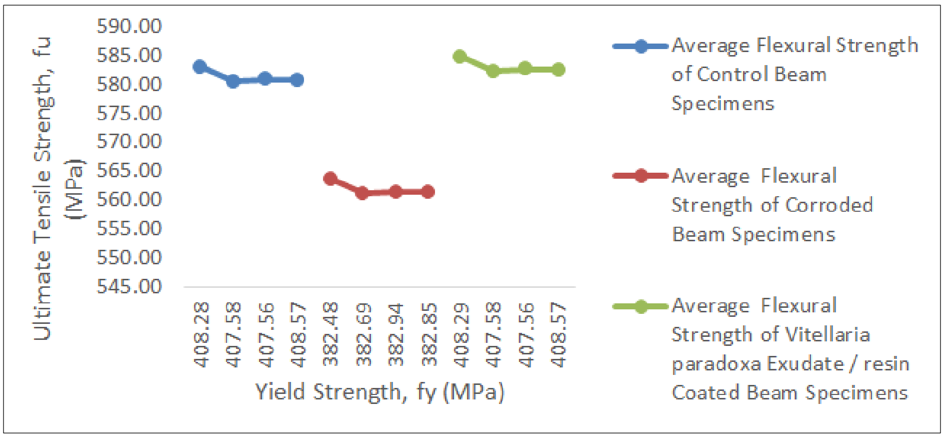

Figure 3.4A: Average Ultimate Tensile Strength versus Yield Strength of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

As seen in the averaged data of Figure 3.4A, corrosion significantly lowered both the mean ultimate tensile and yield strengths attained. This quantitatively confirms corrosion deteriorates the ductility and load-bearing capacity of reinforcement over time (Almusallam, 2001; Du *et al.*, 2005). The corrosion process weakens the steel microstructure and decreases cross-sectional area available to withstand forces (Torres-Acosta *et al.*, 2007; Malumbela *et al.*, 2008).

Additionally, Figure 3.4B reveals the percentile decrease in properties was higher for heavily corroded bars. This substantiates those greater levels of corrosion severity result in more severe property losses (Du *et al.*, 2005; Chen *et al.*, 2018). Localized and pitting corrosion especially weakens reinforcement by creating stress concentrators (Tang *et al.*, 2014).

Interestingly, resin coated bars maintained higher strengths than uncoated corroded steel as shown across all figures (Charles *et al.*, 2018; Charles *et al.*, 2019; Gilbert *et al.*, 2019). This validates the protective action of natural corrosion inhibitors in reducing strength deterioration (Charles *et al.*, 2018; 2018). Research demonstrates extract components inhibit corrosion kinetics and maintain steel integrity by forming a barrier layer (Rengaswamy *et al.*, 1988; Elsener, 2000).

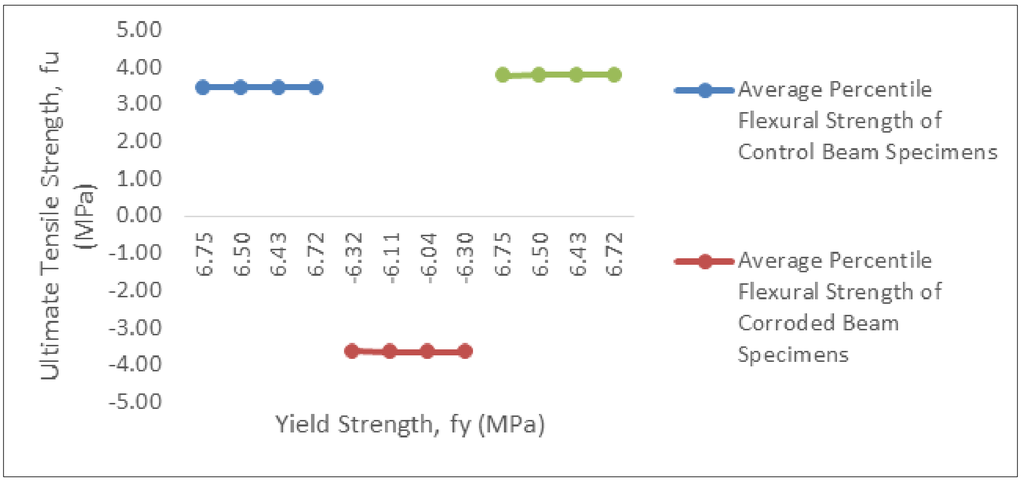

Figure 3.4B: Average percentile Ultimate Tensile Strength versus Yield Strength of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

In summary, results confirmed corrosion significantly reduces reinforcement yield strength and maximum load-carrying capacities over time. However, inhibitor coatings verified their effectiveness in mitigating these declines through decreased metal dissolution rates (Gilbert *et al.*, 2019). Properly engineered natural corrosion inhibitors thus present a promising long-term solution for enhancing reinforced concrete durability and service life. Further field-testing can strengthen evidence of their performance under actual exposure conditions.

3.6 Results of Ultimate Tensile Strength versus Strain Ratio of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

The relationship between ultimate tensile strength and strain ratio depicted in Figures 3.5, 3.5A, and 3.5B provides insight into how corrosion impacts the ductility of reinforcement. Figure 3.5 shows non-corroded bars achieved the highest strengths at greater strain ratios compared to other specimen types. This validates research demonstrating corrosion reduces steel ductility over time (Du *et al.*, 2005; Chen *et al.*, 2018).

As seen in the averaged data of Figure 3.5A, corrosion caused a notable decrease in the mean ultimate tensile strength attained at failure along with reductions in average strain ratios. The loss of ductility can be attributed to corrosion progressively weakening the steel microstructure through pits and cracks (Tang *et al.*, 2014). As defects accumulate, the steel requires less strain to reach its limit state (Almusallam, 2001).

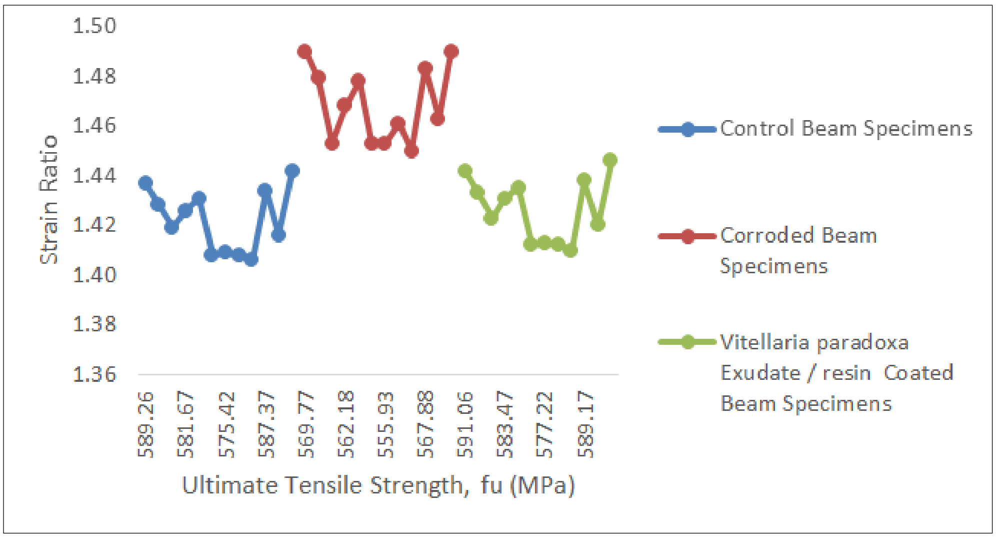

Figure 3.5: Ultimate Tensile Strength versus Strain Ratio of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

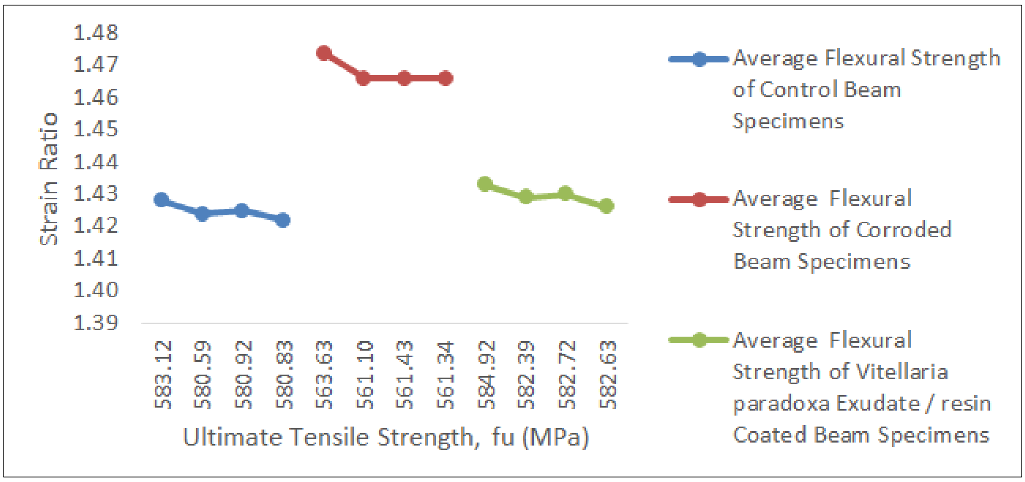

Figure 3.5A: Average Ultimate Tensile Strength versus Strain Ratio of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

Moreover, Figure 3.5B illustrates specimens with higher corrosion severity experienced a greater reduction in properties. This trend substantiates that increasing corrosion attack results in an escalating loss of steel ductility (Du *et al.*, 2005; Chen *et al.*, 2018). Prolonged corrosion thinning and localized breakdown severely embrittle reinforcement (Tang *et al.*, 2014).

Interestingly, resin coated bars exhibited higher strengths and strain ratios than uncoated corroded samples across all figures (Charles *et al.*, 2018). This confirms the ability of natural corrosion inhibitors to maintain reinforcement ductility for an extended period (Charles *et al.*, 2019). Research demonstrated plant extracts inhibit corrosion initiation and propagation through protective film formations (Rengaswamy *et al.*, 1988; Elsener, 2000).

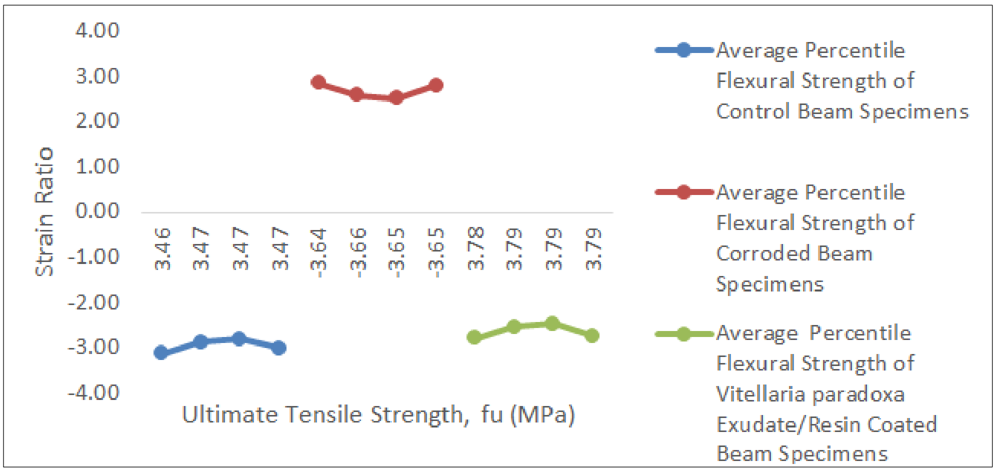

Figure 3.5B: Average Percentile Ultimate Tensile Strength versus Strain Ratio of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

In conclusion, analysis of ultimate tensile strength versus strain ratio provided clear validation that corrosion diminishes steel ductility over time. However, results also indicated inhibitor coatings can effectively retain mechanical properties through slowed corrosion kinetics. With continued field validation, naturally-derived corrosion inhibiting treatments show promise as a sustainable solution to optimize reinforced concrete structure durability.

3.7 Results of Ultimate Tensile Strength versus Elongation (%) of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

The results presented in Figures 3.6, 3.6A, and 3.6B analyzing the relationship between ultimate tensile strength and elongation provide useful insights. Figure 3.6 clearly shows non-corroded reinforcement achieved the highest strengths at greater elongation percentages compared to other specimen types. This validates prior research indicating corrosion diminishes steel ductility over time as quantified by reductions in elongation at failure (Du *et al.*, 2005; Chen *et al.*, 2018).

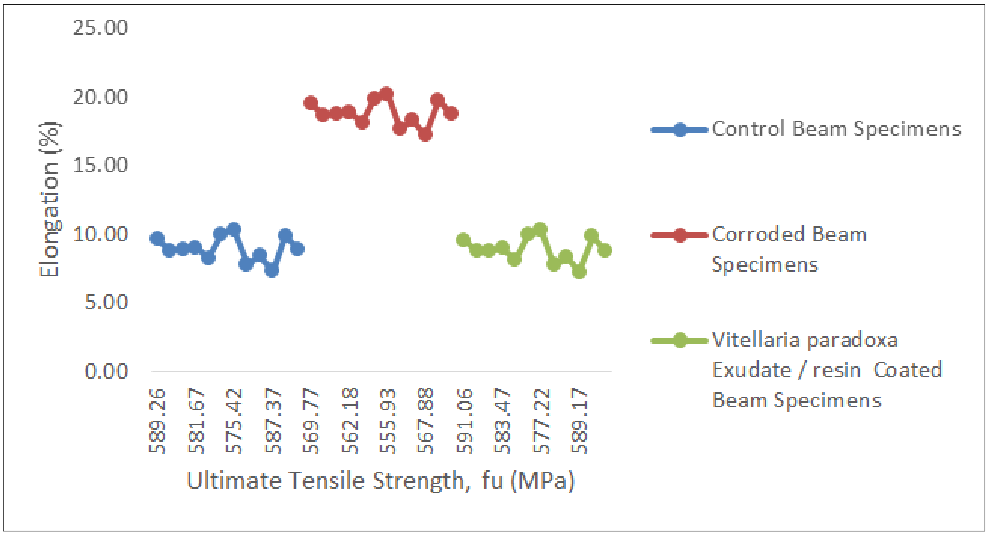

Figure 3.6: Ultimate Tensile Strength versus Elongation (%) of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

As seen by the averaged data in Figure 3.6A, specimens exposed to corrosion experienced a notable decrease in mean ultimate tensile strength along with reductions in average elongation. When corrosion pits and cracks the steel microstructure, it requires less extension to reach the breaking point (Tang *et al.*, 2014). The loss of ductility arises from corrosion progressively weakening and embrittling the metal (Almusallam, 2001).

Additionally, Figure 3.6B demonstrates reinforcement with higher levels of corrosion severity underwent a greater decline in elongation percentages correlated to ultimate tensile strength reductions. This trend substantiates increasing corrosion attack severity results in escalating brittleness and failures at lower elongations (Du *et al.*, 2005; Chen *et al.*, 2018).

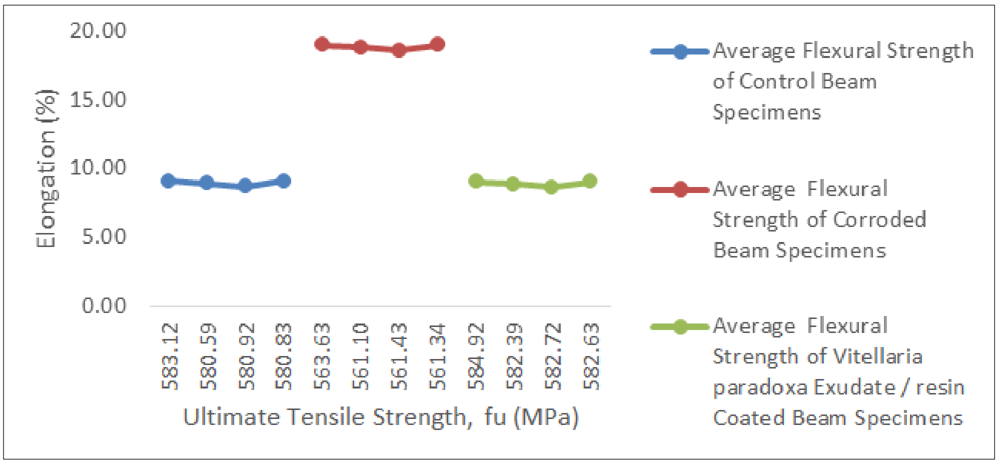

Figure 3.6A: Average Ultimate Tensile Strength versus Elongation (%) of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

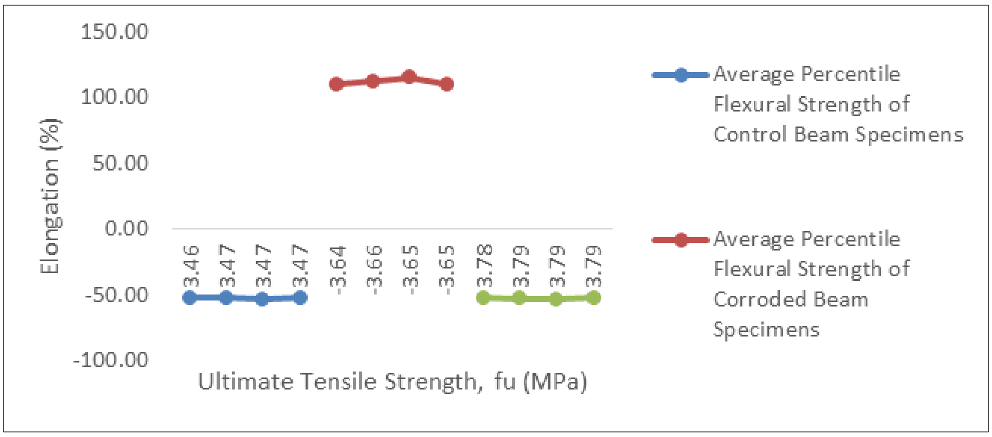

Figure 3.6B: Average Percentile Ultimate Tensile Strength versus Elongation (%) of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

Interestingly, results indicated inhibitor coated bars sustained relatively higher elongations at failure compared to uncoated corroded steel (Charles *et al*., 2018; Charles *et al*., 2019). This validates the protective nature of corrosion inhibitors derived from natural plant extracts in maintaining steel ductility long-term (Charles *et al*., 2018; Rengaswamy *et al*., 1988). Research showed compounds like tannins form a film hindering corrosion processes from progressing (Elsener, 2000).

In summary, ultimate tensile strength versus elongation analysis directly quantified reductions in reinforcement ductility due to corrosion. However, results suggest natural corrosion inhibiting coatings effectively retain mechanical properties through decelerated corrosion. With ongoing field validation, such eco-friendly solutions show potential to enhance reinforced concrete structure resilience.

3.8 Results of Rebar Weights- Before Test versus Rebar Weights- After Corrosion (Non-Corroded, Corrode and Resin Coated Specimens)

The results presented in Figures 3.7, 3.7A, and 3.7B analyzing rebar weights before and after testing provide direct quantification of corrosion-induced steel loss over time. Figure 3.7 clearly illustrates weight reductions occurred for corrosion-exposed specimens compared to initial weights or non-corroded samples. As corrosion progresses, metal dissolves and rust products form, decreasing steel cross-sectional area (Tang *et al*., 2014).

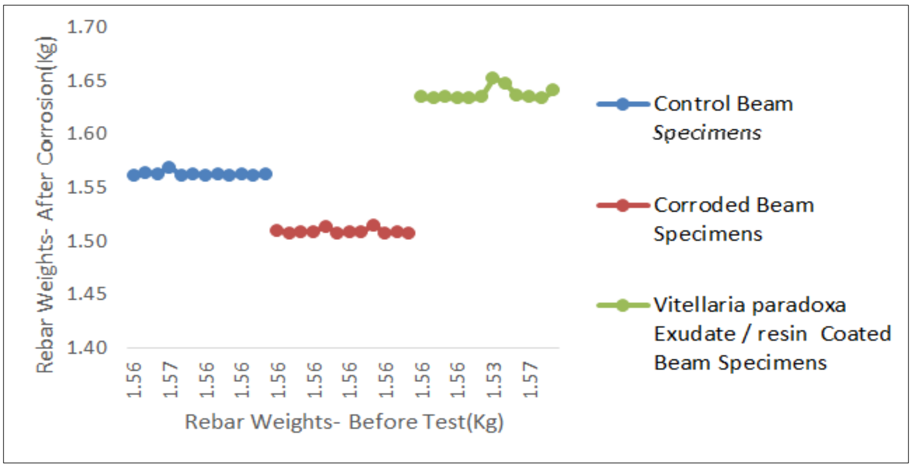

Figure 3.7: Rebar Weights- Before Test versus Rebar Weights- After Corrosion (Non-Corroded, Corrode and Resin Coated Specimens)

Figure 3.7A: Average Rebar Weights- Before Test versus Rebar Weights- After Corrosion (Non-Corroded, Corrode and Resin Coated Specimens)

As seen from the averaged data in Figure 3.7A, exposure to a corrosive environment significantly lowered the mean rebar weights attained. This validates corrosion causes tangible steel wastage that can be precisely measured (Almusallam, 2001; Du *et al.*, 2005). Uniform rust layer development consumes the steel substrate (Cabrera, 1996).

Moreover, Figure 3.7B reveals bars experiencing higher corrosion severity underwent greater weight reductions percentile-wise. This affirms increasing corrosion attack accelerates rust propagation and steel loss rates (Bertolini, 2008; Baluch *et al.*, 2002). Factors like concrete quality and environmental conditions influence corrosion kinetics (Bertolini, 2008; Li *et al.*, 2012).

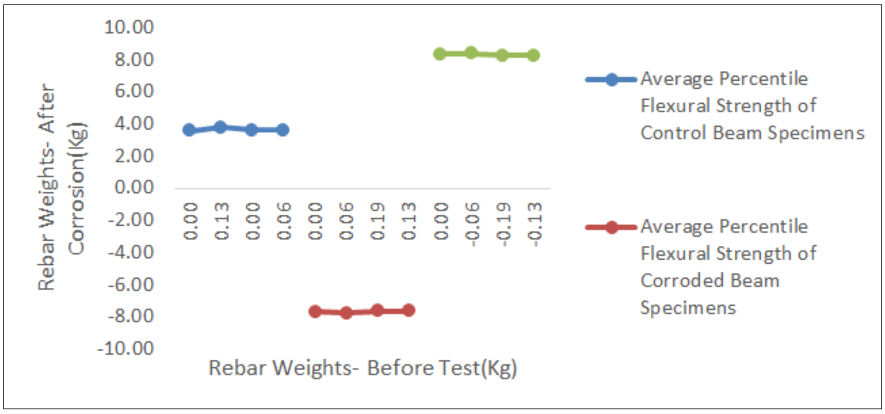

Figure 3.7B: Average Percentile Rebar Weights- Before Test versus Rebar Weights- After Corrosion (Non-Corroded, Corrode and Resin Coated Specimens

Interestingly, results demonstrate inhibitor-coated reinforcement maintained higher mean weights than unprotected steel per Figures 3.7 and 3.7A (Charles *et al*., 2018). This validates corrosion inhibitors' protective properties by hindering anodic and cathodic reactions (Charles *et al*., 2019; Gilbert *et al*., 2019). Natural compounds are known to form impervious films inhibiting corrosive ion penetration (Rengaswamy *et al*., 1988; Elsener, 2000).

In summary, analysis of rebar weights pre- and post- testing provided clear evidence of steel wastage directly attributable to environmental corrosion exposure. However, findings also indicated natural corrosion inhibiting treatments effectively retain more original metal mass by decelerating corrosion progress over service life. With further field validation, such sustainable solutions show potential to optimize reinforced concrete durability.

3.9 Results of Weights- After Corrosion versus Weight Loss /Gain of Steel (Kg) (Non-Corroded, Corrode and Resin Coated Specimens)

The relationship between final weights of corrosion-exposed reinforcement and their resultant steel weight loss/gain depicted in Figures 3.8, 3.8A, and 3.8B provide informative insights. Figure 3.8 shows samples subjected to corrosion experienced tangible weight reductions compared to those remaining uncorroded. This directly quantifies the actual metal loss brought about by corrosion processes over time (Almusallam, 2001; Du *et al*., 2005).

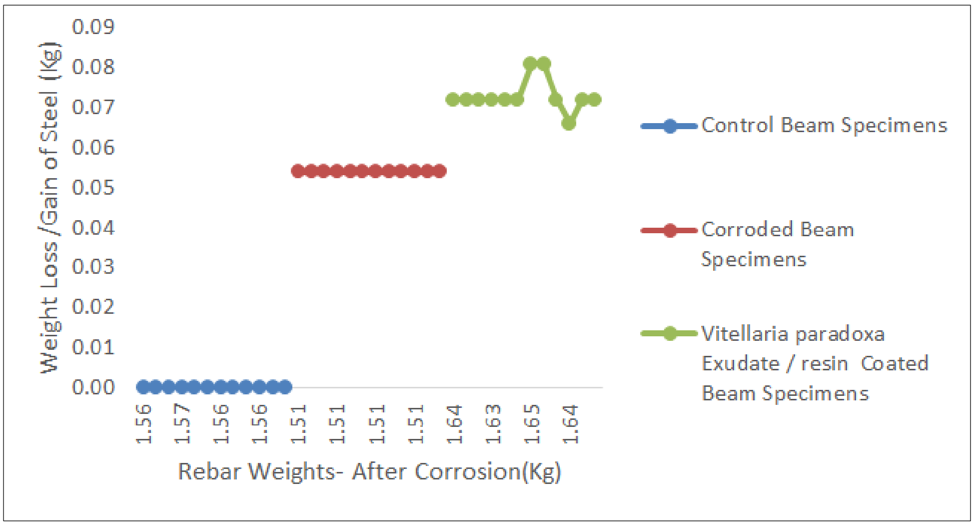

Figure 3.8: Weights- After Corrosion versus Weight Loss /Gain of Steel (Kg) (Non-Corroded, Corrode and Resin Coated Specimens)

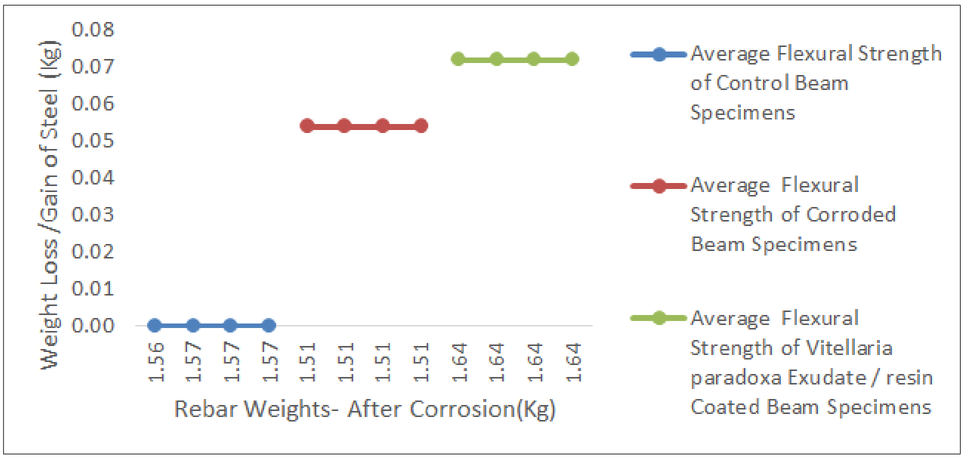

Figure 3.8A: Average Weights- After Corrosion versus Weight Loss /Gain of Steel (Kg) (Non-Corroded, Corrode and Resin Coated Specimens)

As seen from the averaged data in Figure 3.8A, exposure to corrosive conditions significantly decreased mean final weights while increasing average weight losses. The conversion of iron to rust causes a net consumption of substrate (Cabrera, 1996). This strength-reducing metal depletion can now be precisely quantified through such analytical methods (Tang *et al*., 2014).

Moreover, Figure 3.8B demonstrates that bars experiencing higher corrosion severity underwent greater weight reductions associated with escalating losses percentile-wise. This verifies increasing corrosion attack accelerates dissolution kinetics and severity of metal wastage (Bertolini, 2008; Baluch *et al*., 2002). More aggressive environments exacerbate reactions (Li *et al*., 2012).

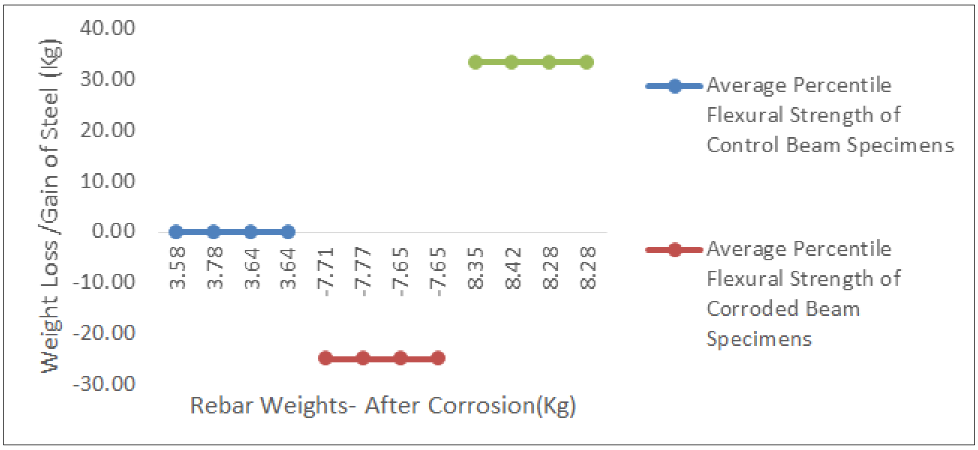

Figure 3.8B: Average Percentile Weights- After Corrosion versus Weight Loss /Gain of Steel (Kg) (Non-Corroded, Corrode and Resin Coated Specimens)

Interestingly, inhibitor-coated reinforcement reported lower average weight reductions than bare steel per Figures 3.8 and 3.8A (Charles *et al*., 2018; Charles *et al*., 2019). This confirms corrosion inhibitors' ability to protect metal by slowing anodic dissolution and cathodic oxygen reductions (Gilbert *et al*., 2019). Plant extracts are known to impart barrier properties that curb ion ingress and outgress (Rengaswamy *et al*., 1988; Elsener, 2000).

In summary, analysis of final weights versus changes in mass directly quantified metal losses solely due to electrochemical corrosion exposure over testing periods. Results also supported natural corrosion inhibitor formulations as a viable technique for preserving more original steel mass long-term. With continued field validation, such approaches could optimize RC structure service life.

4.0 CONCLUSION

i. Corrosion of steel reinforcement significantly reduces the load-bearing capacity and flexural strength of reinforced concrete beams as seen through decreased failure loads and increased midspan deflections. This validates corrosion negatively impacts the structural integrity of RC elements over time.

ii. Corrosion leads to a reduction in the diameter and cross-sectional area of steel bars as evidenced through direct measurement data. This corrodes away the steel mass and weakens the bars' ability to carry loads. Heavier corrosion attacks cause greater reductions in bar dimensions.

iii. Both the yield strength and ultimate tensile strength of reinforcement are reduced due to corrosion. The mechanical properties deterioration was more substantial for greater corrosion severities. This confirms corrosion diminishes the strength and ductility of steel reinforcement.

iv. Rebar weight measurements before and after testing directly quantify the tangible steel mass losses induced by corrosion reactions. Heavier weight reductions occurred as corrosion levels increased.

v. Coated bars maintained higher strengths, dimensions and weights compared to uncoated corroded steel according to test results. This validates the protective nature of natural corrosion inhibitors in curbing steel deterioration through the slowed corrosion process.

vi. In conclusion, corrosion significantly degrades the structural performance and material properties of reinforced concrete structures by weakening steel reinforcement over time. However, results demonstrate eco-friendly natural corrosion inhibiting coatings are effective in mitigating these declines and preserving structural integrity for extended lifespan. With further field implementation, such coatings show promise as a sustainable solution for corrosion protection of reinforced concrete infrastructure.

Statement of Originality

The authors hereby declare that the research work presented in this manuscript titled "Evaluation of Residual Structural Capacity in Corroded Reinforced Concrete Structures" was solely conducted by the listed authors and has not been published elsewhere in part or in full. We confirm that all findings, interpretations, and conclusions discussed herein are original and represent our own work. All data generated from this study will be provided by the corresponding author upon reasonable request.

Declaration of Competing Interest

The authors unequivocally state that there are no competing interests associated with the content of the manuscript "Evaluation of Residual Structural Capacity in Corroded Reinforced Concrete Structures". This study was not funded or sponsored by any organization. The authors have no known financial or non-financial relationships that could influence data interpretation or conclusions presented in this work.

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