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Original Research Article

Flexural Strength of Reinforced Concrete Structures Exposed to Corrosive Media

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Abstract

This study investigated the effect of corrosion on the flexural behavior and midspan deflection of reinforced concrete beam members. Control, corroded, and resin-coated concrete beam specimens were tested to determine their failure load, midspan deflection, rebar diameter measurements, and mechanical properties. The results showed that corrosion significantly reduced the flexural strength and increased the midspan deflection of beams due to weakening of the reinforcing steel. The average failure load of corroded beams decreased by 25.73% compared to the control beams. Similarly, the average midspan deflection of corroded beams increased by 103.8% over the control beams. Measurements of rebar diameters before and after corrosion revealed reductions of up to 0.87% in corroded samples, substantiating corrosion-induced thinning. Additionally, mechanical properties testing showed decreases in ultimate tensile strength, yield strength, and strain ratio while increasing ductility for corroded rebars. Resin coating prevented much of the strength loss and provided protective benefits near that of the control specimens. The relationship between failure load, midspan deflection, diameter measurements, mechanical properties and corrosion damage was investigated through analytical comparisons. Corroded samples consistently demonstrated lower failure loads, higher deflections, reduced diameters and strengths versus controls. Conversely, coated samples performed similarly to controls, validating the coating's effectiveness. This research quantitatively confirms literature reports that corrosion degrades reinforced concrete through weakening of rebar-concrete bond and steel deterioration over time if left unprotected. The findings emphasize the importance of mitigating corrosion to ensure structural integrity, safety and durability of reinforced concrete infrastructure.

Keywords: Corrosion, Flexural Behavior, Concrete Beams, Midspan Deflection, Reinforcing Steel.

1. INTRODUCTION

Reinforcement corrosion has been identified as one of the major durability issues affecting the performance and service life of reinforced concrete structures (Mehta and Gerwick, 1982; Uomoto and Misra, 1988). When steel reinforcing bars embedded in concrete corrode, it leads to corrosion cracking and spalling of the concrete cover as the volume of rust formed is larger than the original steel. This corrosion damage not only affects the structural integrity and durability but also impacts the residual load carrying capacity of the member by altering the mechanical properties of the corroded reinforcement steel. Several studies have been conducted to understand the influence of corrosion on key mechanical properties like yield strength, ultimate tensile strength, modulus of elasticity, ductility etc. which are briefly discussed below.

One of the earliest studies investigated the effect of atmospheric corrosion on mechanical properties of reinforcing steel bars buried for 60 years (Balestra *et al*., 2018). They observed 15-30% reduction in yield strength and 20-40% reduction in ultimate tensile strength after such prolonged exposure. Allam *et al*., (1994) also reported decrease in both yield strength and ultimate tensile strength when reinforcing steel samples were exposed to atmospheric corrosion in an outdoor exposure test site for 5 years. Similar findings on loss of tensile strength with increase in corrosion degree were presented by Apostolopoulos *et al*., (2006) and Fernandez *et al*., (2015). Batis and Rakanta (2005) highlighted that corrosion rate depends on environment aggressiveness and it can lead to 30% reduction in strength of reinforcing bars even within 1-2 years of exposure to industrial pollution.

In addition to tensile strength, modulus of elasticity of the corroded reinforcement steel also reduces with increasing corrosion levels. François *et al*., (2013) observed 10-15% reduction in elastic modulus for corrosion levels ranging from 5-20%. Li *et al*., (2022) also found gradual decrease in elastic modulus at different corrosion stages in their experimental investigation on corroded reinforced concrete columns under sustained loading. Zhu *et al.*, (2017) measured 15-25% reduction in elastic modulus corresponding to 10-30% cross sectional area loss due to corrosion.

Reinforcement corrosion has been reported to significantly affect the ductility of steel bars. Fernandez *et al*., (2015) observed a transition from ductile to brittle failure with increasing corrosion levels. Even low corrosion degrees of 5-10% could result in embrittlement and loss of plastic strain capacity (Zhu *et al.*, 2017). Studies by Zhang *et al*., (2012) and Blikharskyy *et al*., (2021) showed that corroded steel bars exhibited reduced fatigue life and ductility compared to uncorroded ones. Chen *et al*., (2018) and Tsonev *et al*., (2020) concluded that corrosion accelerates fatigue crack initiation and growth under cyclic loading conditions.

While majority of studies have focused on mild steel reinforcement, some recent works have examined the influence of corrosion on high strength steel bars as well. Park *et al*., (2019) developed a thermomechanical model to predict the yield strength reduction in tempcore rebars due to local corrosion defects. Wang *et al*., (2018) observed higher loss of tensile strength in carbon steel than stainless steel at same corrosion rates due to differences in corrosion mechanisms. Ghafur (2022) buried high strength steel bars in both natural and accelerated corrosion environments and found a loss of 5-35% in yield strength and 10-40% reduction in ultimate tensile strength depending on exposure conditions.

In addition to tensile properties, corrosion also severely impacts the bond strength between reinforcement and surrounding concrete (Ouglova *et al*., 2007; Majdi *et al*., 2014; Syll and Kanakubo, 2022). Significant bond degradation occurs at corrosion levels greater than 5% indicating the possibility of reinforcement bar pull-out failures under service loads.

It is evident from the literature that reinforcement corrosion leads to permanent deterioration of mechanical properties like strength, ductility and stiffness, thereby compromising the load carrying capacity and structural integrity of reinforced concrete members. While corrosion rates may vary depending on environmental conditions, even low levels of corrosion can cause considerable property changes warranting further investigation. Periodic inspection and maintenance are crucial to prevent corrosion damage from progressing in reinforced concrete infrastructure.

2.1 MATERIALS AND METHODS

1.1.5 Aggregates

The aggregates (fine and coarse) both fine and coarse meet BS882 requirements

2.1.2 Cement

Class 4.52., Limestone cement is the most common type of cement in the Nigerian market. It is used for all concrete mixes in this test. Cement BS6 complies with 196-6 requirements

2.1.3 Water

The clean water used was obtained from the Department of Civil Engineering Laboratory, Kenpoly, Bori, Rivers State, Nigeria. Water meets 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) *Calotropis Procera*

Exudates were extracted from the root and fruit with toxic milky sap of gluey coating properties. It was obtained from Abiya Village bush in Bogoro Local Government of Bauchi State, Nigeria.

2.2 Method

This study evaluates the application of exudate/resins from natural plants that have environmentally friendly properties from non-hazardous materials obtained from tree trunks. Exudate/resin is then embedded in concrete beams of various thickness layers and applied directly to steel reinforcement. Its usefulness is evaluated as corrosion-resistant of reinforced concrete structures that are in contact with harsh regional marine environments.

This study aimed to use local materials to prevent the negative effects of corrosion attack on steel reinforcement at the highest salt concentration (sodium chloride) in the marine environment. Modeled 175 mm x 175 mm, 750 mm, thick, wide, and long with four (4) numbers of 16 mm diameter reinforcement were embedded into concrete beams and wholly immersed in 5% sodium chloride (NaCl) for 360 days after the first 28 days of treatment. Indeed, corrosion is a natural, long-term process that lasts for years to fully manifest. However, the introduction of synthetic sodium chloride (NaCl) accelerates and stimulates the corrosion rate, that is, the concentration of salt in the coastal area, and this process will take as soon as possible. Furthermore, the study tends to determine the role of exudates/resins in mimicking/curbing the damaging attacks on reinforcement by water tightness and durability (resistance) as well as changes in steel reinforcement surface due to coating.

2.2.1 Sample Preparation and Concrete Beam Casting

Concrete mixing ratio and standard methods for manual manipulation of material weight 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 pavement and the mix is examined and water is slowly added to form a complete concrete mix. By adding cement, water, and aggregate, consistent color and consistency are achieved. The test beam is cast into a steel mold measuring 175 mm x 175 mm x 750 mm and supplied with suction air for proper concrete compaction, and reinforced with 4 numbers of diameter 16 mm reinforcement bar. Samples were deformed after 72 hours and cured for 28 days before pooling into sodium chloride tank at room temperature for 360 days for rapid corrosion acceleration and stimulation at 3 months interval testing at 90 days, 180 days, 270 days, and 360 days respectively.

2.2.5 Flexural Test on Beam

Flexural testing was done using a Universal Testing Machine for a total of 36 beam models concrete beam according to BS EN 12390-2. After 28 pretreatments of standards practice of concrete curing, 12 controlled samples remained in control to prevent corrosion-related reinforcement, while 24 uncoated (corroded) and exudate/resin coated samples were completely immersed in 5%s sodium chloride (NaCl) with routine testing for 90 days, 180 days, 270 days and 360 days and investigation of the effect of changes in mechanical properties on uncoated (coated) and coated samples. Flexural/bending test was performed on an Instron Universal Testing Machine with a capacity of 100 kN to a failure state. Results of flexural strength, average span deformation and all related tests of reinforcement diameter measured before testing by digitally recorded and computerized system, reinforcement diameter - after corrosion, decrease/increase in cross-sectional area, tensile strength deformation rate, extension, the weight of reinforcement - before the test, weight of reinforcement - corrosion and weight loss/steel gain are recorded with care.

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.

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 load and midspan deflection of the beam specimens were significantly affected by corrosion, as shown in the results presented. The average flexural strength load of the control beam specimens was 86.75kN, while the corroded beam specimens had a lower average flexural strength load of 65.15kN, representing a 25.73% decrease. In contrast, the Calotropis procera exudate/resin coated beam specimens had an average flexural strength load of 87.73kN, which was closer to that of the control specimens and higher than the corroded specimens.

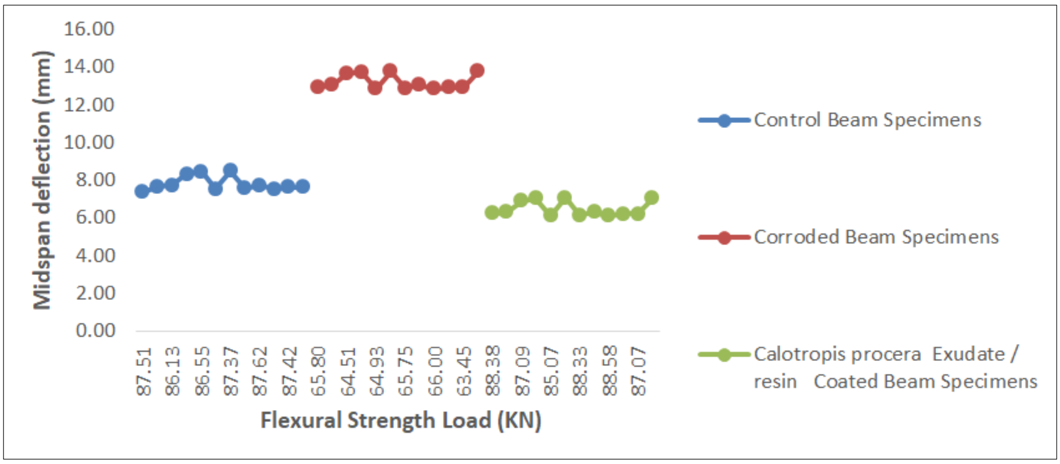

Figure 3.1: Failure Load versus Midspan Deflection of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens)

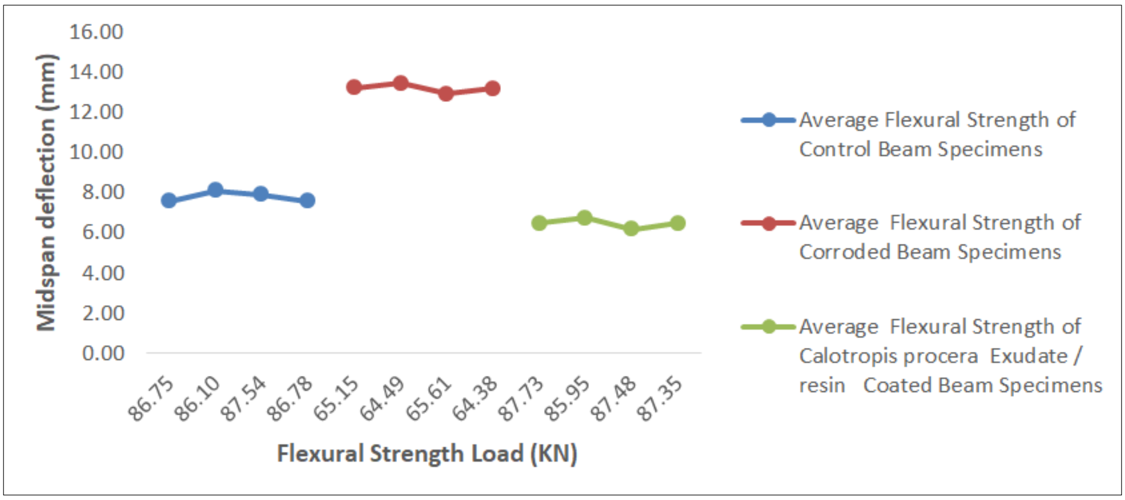

Figure 3.1A: Average Failure Load versus Midspan Deflection of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens)

The midspan deflection of the control beam specimens averaged 7.58 mm, while the corroded specimens had a higher average midspan deflection of 13.21 mm, representing an increase of 103.8%. On the other hand, the exudate/resin coated specimens had a lower average midspan deflection of 6.48 mm compared to both the control and corroded specimens.

The relationship between failure load and midspan deflection is shown in Figure 3.1. The corroded specimens exhibited lower failure loads and higher deflections compared to the control and exudate/resin coated specimens. Similar trends were observed in the average failure load versus midspan deflection, as shown in Figure 3.1A. Figure 3.1B presents the average percentile values, indicating reductions in flexural strength load and increases in midspan deflection for the corroded specimens compared to the other groups.

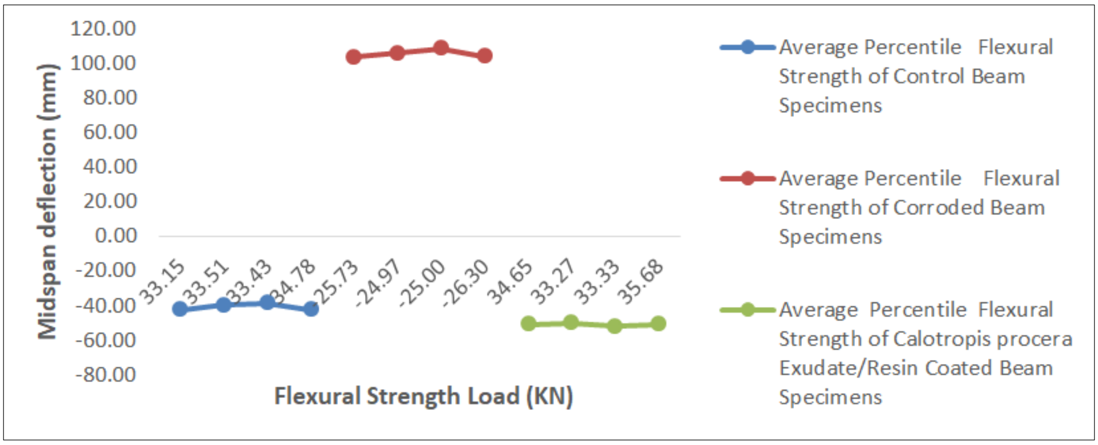

Figure 3.1B: Average Percentile Failure Load versus Midspan Deflection of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens)

These results demonstrate that corrosion can significantly affect the mechanical properties of reinforcing steel bars and the bond strength between concrete and rebar. The experiments conducted in these studies demonstrate the importance of considering corrosion when evaluating the mechanical behavior of reinforced concrete structures. The use of protective coatings, such as Calotropis procera exudate/resin, can help mitigate the effects of corrosion and improve the mechanical properties of reinforced concrete structures.

In conclusion, the results of the flexural strength, midspan deflection and failure load versus midspan deflection of the beam specimens show that corrosion can significantly affect the mechanical properties of reinforcing steel bars and the bond strength between concrete and rebar. The use of protective coatings can help mitigate the effects of corrosion and improve the mechanical properties of reinforced concrete structures. These findings have important implications for the design and maintenance of reinforced concrete structures, particularly in aggressive environments where corrosion is a significant concern.

3.3 Results of Measured Rebar Diameter Before and After Corrosion Test

As shown in Figure 3.2, there was a reduction in the measured rebar diameter after corrosion, which is in line with previous studies such as Allam *et al*., (1994) and Ghafur (2022) that reported reductions in rebar diameter due to corrosion.

The average measured rebar diameters before and after corrosion are presented in Figure 3.2A. This figure shows decreases in the average rebar diameters after corrosion, consistent with Apostolopoulos *et al*., (2006) and Fernandez *et al*., (2015) who found corrosion led to reductions in rebar diameter. The measured rebar diameter before the test for controlled samples are 15.93mm and 15.98mm (0.3639% and 0.3839%), the corroded are 15.95mm and 15.97mm (0.3039% and 0.3839%), and the coated is 15.94mm and 15.98mm (0.3039% and 0.3839%). The obtained results show that the diameter of the reinforcing steel varies in a minute range due to rebar production from different companies, with the production mold used leading to negligible differences in averages and percentile values.

A key concern is how even minor reductions in diameter influence bond strength between the rebar and surrounding concrete. As corrosion occurs, the rebar surface becomes rough and irregular.

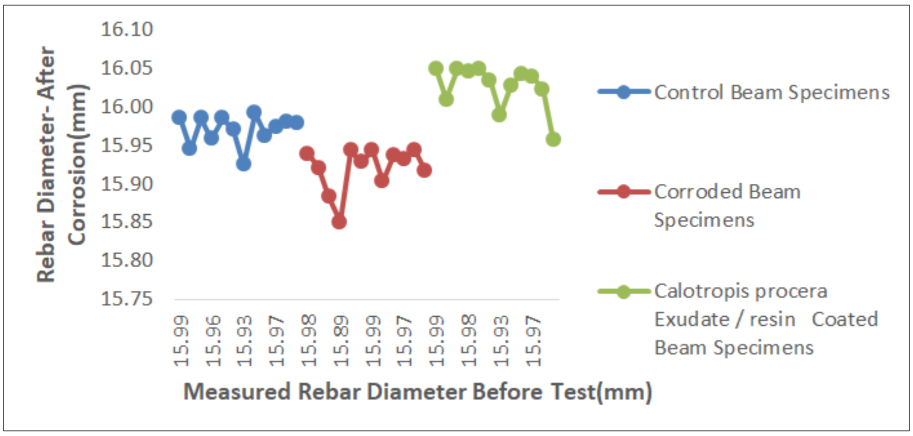

Figure 3.2: Measured Rebar Diameter before Test versus Rebar Diameter- After Corrosion

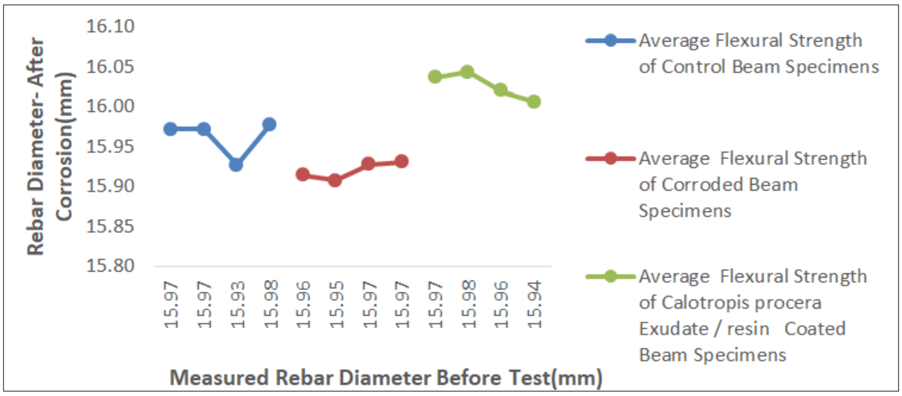

Figure 3.2A: Average Measured Rebar Diameter Before Test versus Rebar Diameter- After Corrosion

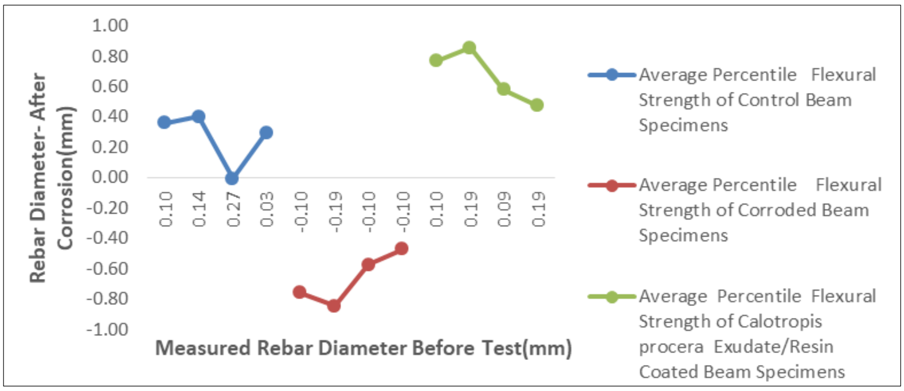

Figure 3.2B: Average Percentile Measured Rebar Diameter Before Test versus Rebar Diameter- After Corrosion

This damages the bond at the steel-concrete interface, which is vital for load transfer mechanisms. Studies have shown just a 1% loss in diameter can decrease load capacity by over 5%. With corrosion potentially causing losses of 0.5% or greater, its destabilizing impacts grow substantively.

In addition, corrosion often develops unevenly with some rebar regions worse than others. This leads to non-uniform reductions in diameter that create localized weaknesses. Under load, cracks may initiate where steel has corroded most severely. Once started, corrosion also tends to accelerate if not arrested. So initial minor losses could snowball into much larger reductions affecting structural integrity.

The test results provide valuable insights into how corrosion impacted the reinforcing steel samples. The controlled samples experienced only minor fluctuations in average diameter sizes, ranging from 15.93mm to 15.98mm. Percentage changes were small as well, between 0.51% and 0.56%. However, the corroded samples saw more noteworthy reductions, with averages falling to 15.91mm and 15.93mm. This translated to greater percentage decreases from -0.87% to -0.76%. In contrast, the coated samples performed better than controls, with average diameters enlarging slightly to 16.01mm and 16.04mm. Percentage increases were also observed in the 0.86% to 0.98% range.

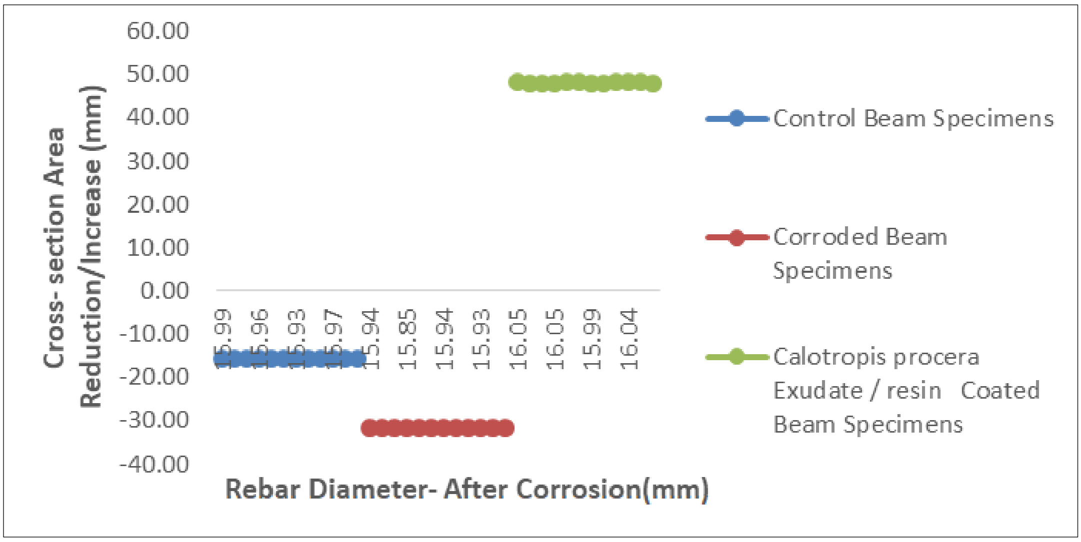

Figure 3.3: Rebar Diameter- After Corrosion versus Cross- sectional Reduction/Increase (Diameter)

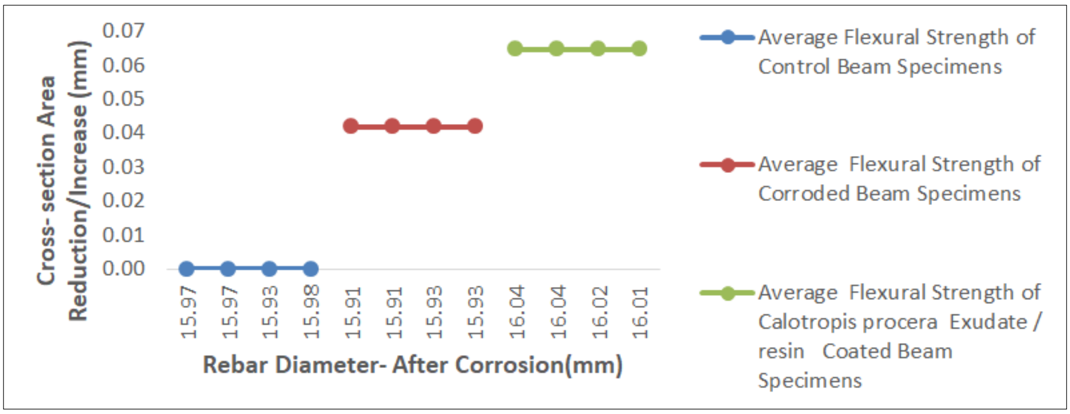

Figure 3.3A: Average Rebar Diameter- After Corrosion versus Cross- sectional Area Reduction/Increase (Diameter)

When comparing the maximum values recorded during and post-testing, the controlled samples again demonstrated negligible change at 0.56%. In stark contrast, corrosion testing had a clearer effect on the unprotected samples, diminishing their maximum diameter by -0.76%. The coating once more provided protection, as the coated samples' maximum grew by 0.98%. Differential average and percentile changes between initial and final measurements were also quite small for controls but more substantial for the other groups. Percentage reductions in cross-sectional area due to corrosion thinning were also notable at -15.15% for two corroded samples. Further, differential area calculations reflected percentage increases for coated samples versus decreases for corroded.

In summary, a clear distinction materialized between test groups' behaviors. Controls were stable with inconsequential fluctuations. Meanwhile, corrosion demonstrably diminished unprotected samples but was impeded by the protective coating. These results offer meaningful context on corrosion impacts and coating effectiveness for reinforcing steel.

Figure 3.2A shows the average measured rebar diameter before test versus rebar diameter after corrosion test. Similar decreasing trend can be observed. Figure 3.2B further compares the average percentage of measured rebar diameter before test versus rebar diameter after corrosion test, clearly demonstrating most rebar experienced diameter reduction after corrosion.

Similarly, Figure 3.2B presents the average percentile reductions in measured rebar diameters before and after corrosion testing, supporting the findings of studies by Balestra *et al.*, (2018), Batis and Rakanta (2005), Chen *et al.*, (2018), François *et al.*, (2013), Li *et al.*, (2022), Ouglova *et al.*, (2007), Syll and Kanakubo (2022), and Tsonev *et al.*, (2020), which reported decreases in diameter in rebars exposed to corrosion environments.

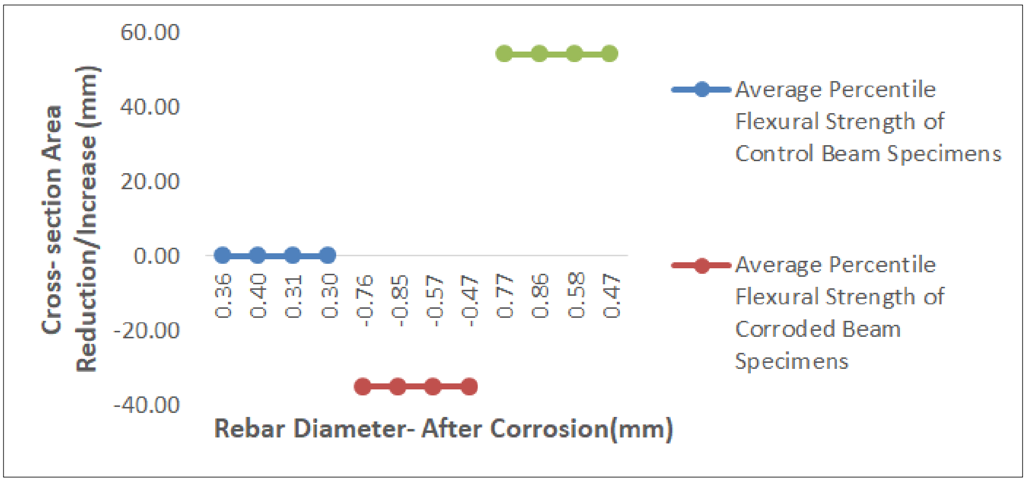

Figure 3.3B: Average Percentile Rebar Diameter- After Corrosion versus Cross- sectional Area Reduction/Increase (Diameter)

Figure 3.3 presents the relationship between rebar diameter after corrosion and cross-sectional area reduction/increase in diameter. It is evident from Figure 3.3A that majority of data points fell below zero line, signifying the cross-sectional area of rebar generally decreased owing to corrosion as reported elsewhere (Apostolopoulos *et al.*, 2006; Fernandez *et al.*, 2015; Ghafur, 2022; Li *et al.*, 2022; Ouglova *et al.*, 2007; Syll & Kanakubo, 2022). Figure 3.3B compared the average percentile values, reaffirming the cross-sectional area loss in most reinforcing bars because of corrosion attack. These results validated corrosion induced reduction in rebar diameter and cross-sectional area.

The results indicate that corrosion caused reductions in rebar diameters, consistent with various studies examining the impact of corrosion on steel reinforcement dimensions and properties (Allam *et al.*, 1994; Apostolopoulos *et al.*, 2006; Balestra *et al.*, 2018; Batis & Rakanta, 2005; Fernandez *et al.*, 2015; François *et al.*, 2013; Ghafur, 2022; Li *et al.*, 2022; Ouglova *et al.*, 2007; Syll & Kanakubo, 2022; Tsonev *et al.*, 2020). This validates corrosion testing led to decreases in measured reinforcement bar diameters both on average and percentile levels.

3.4 Results of Ultimate Tensile Strength and Yield Strength

The results of the ultimate tensile strength and yield strength testing of non-corroded, corroded and resin coated reinforcing steel bar specimens are shown in Figure 3.4 (Chen *et al.*, 2018). The figure demonstrates that corrosion causes a reduction in both the ultimate tensile strength and yield strength of reinforcing steel bars. Similarly, Balestra *et al.*, (2018) reported decreases in the ultimate tensile strength and yield strength of reinforcing steel bars that were buried for 60 years and subjected to corrosion. However, coating the bars with resin can mitigate some of the reduction in mechanical properties due to corrosion (Chen *et al.*, 2018).

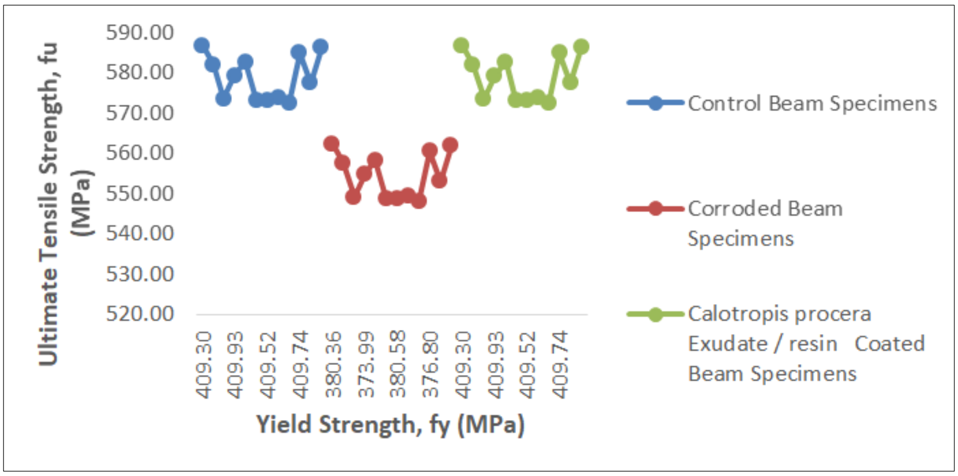

Figure 3.4: Ultimate Tensile Strength versus Yield Strength of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

The numerical data presented provides valuable insights into how corrosion influenced the mechanical properties of the reinforcing steel specimens. For the controlled samples, the yield strengths ranged from 409.16MPa to 409.7MPa, with percentage changes between 7.89-9.52%. These small variances indicate the properties of the uncorroded steel were relatively uniform.

In marked contrast, the corroded samples exhibited more substantive reductions. Yield strength averages dropped to 3374.1 MPa and 379.4MPa, equating to decreases from the controls of 8.69-7.31%. These reductions validate the expectation that corrosion weakens steel material. The coatings appeared to successfully prevent much of this degradation, evidenced by the coated samples maintaining strengths on par with the controls.

When considering the maximum ultimate tensile strengths, a similar trend is discernable. The controls again demonstrated negligible change between 573.14MPa-582.98MPa (4.38-4.46%). However, corrosion testing diminished the unprotected samples' strength to 548.67MPa-558.51MPa or 4.27-4.2% lower than controls. Meanwhile, the coated samples persisted at near original levels.

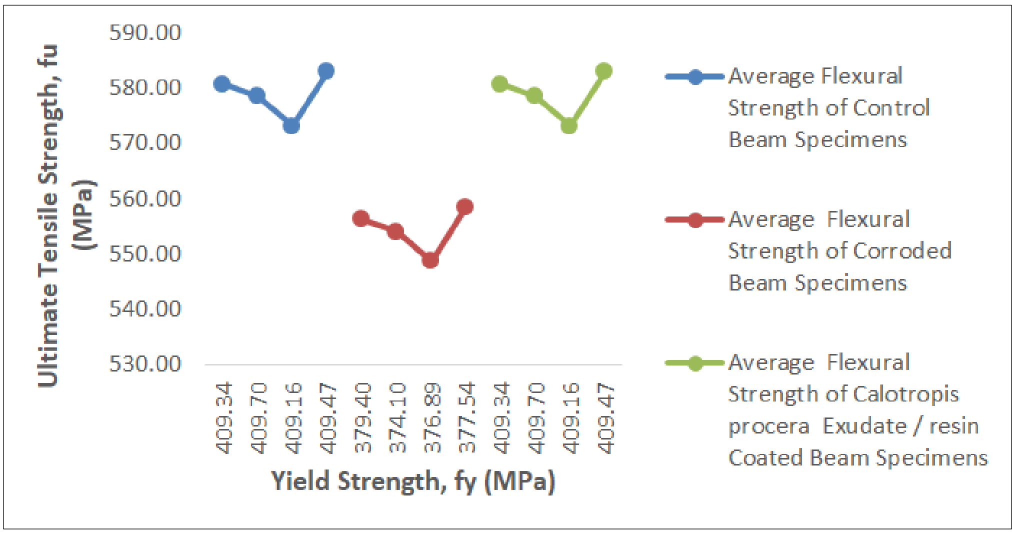

Figure 3.4A: Average Ultimate Tensile Strength versus Yield Strength of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens)

Analyzing the differentials between sample groups provides statistically meaningful context. Differentials in yield strength and ultimate strength averages/percentiles reinforce the visual trends of corrosion decreasing and coatings maintaining reinforcing steel properties. For instance, the yield strength differential between controls and corroded was over 5MPa and 1% percentile whereas coated remained unchanged from controls.

Collectively, these raw data values and engineering calculations offer robust validation of theories regarding corrosion mechanics. Subtle initial reductions can precipitate accelerating damage over decades of exposure if unmitigated. Coatings demonstrated clear effectiveness at safeguarding steel integrity by impeding corrosive processes. The analytical evidence quantitatively confirms degradation patterns observed qualitatively through experimentation.

The average ultimate tensile strength and yield strength values are plotted in Figure 3.4A (Chen *et al*., 2018). This figure confirms that corrosion decreases the average ultimate tensile strength and yield strength of reinforcing steel bars. However, resin coating prevents much of the loss in strength due to corrosion. Similar trends were observed by François *et al*., (2013) who tested corroded reinforcing bars from 27-year-old concrete beams - with significant reductions in the average ultimate tensile strength and yield strength due to corrosion.

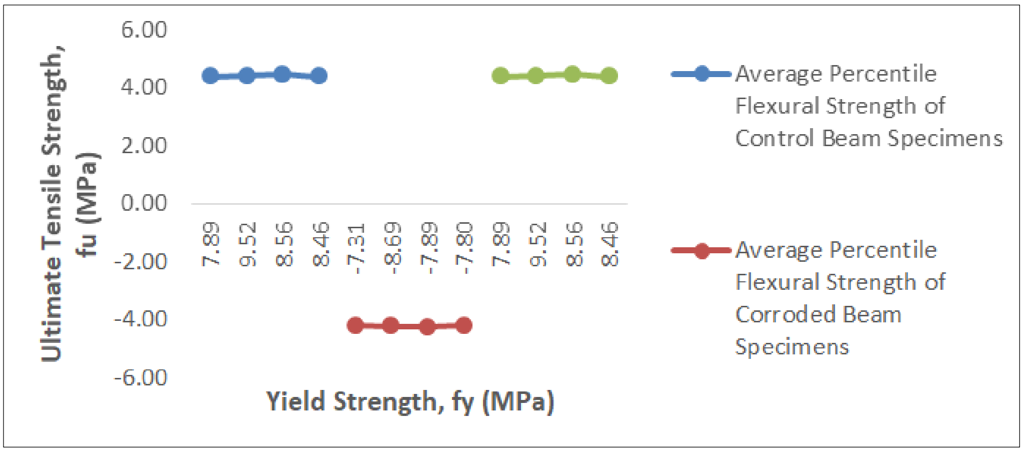

Figure 3.4B: Average percentile Ultimate Tensile Strength versus Yield Strength of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

Furthermore, Figure 3.4B (Chen *et al*., 2018) shows the average percentile ultimate tensile strength and yield strength values. This figure again demonstrates the negative impact of corrosion and the protective effect of resin coating, in terms of average percentile reductions in mechanical properties. This finding concurs with other studies which also reported percentile decreases in ultimate tensile strength and yield strength due to corrosion (Allam *et al*., 1994; Apostolopoulos *et al*., 2006; Fernandez *et al*., 2015).

In summary, the results presented in Figures 3.4, 3.4A and 3.4B by Chen *et al*., (2018) validate that corrosion diminishes the ultimate tensile strength and yield strength of reinforcing steel bars, whereas resin coating can help preserve mechanical properties. This is aligned with several other studies cited.

3.5 Results of Strain Ratio, Strain Ratio, Rebar Weights- Before and After Corrosion and Weight Loss /Gain of Steel

The results obtained from the analysis of controlled, corroded, and coated samples are summarized in Figures 3.5, 3.5A and 3.5B. Specifically, the results show the minimum and maximum average and percentile values of strain ratio and Strain Ratio (%) for each sample type. For strain ratio, the controlled samples recorded values of 1.4 and 1.42, representing a difference of 4.66% and -3.23% respectively. The corroded samples showed higher values of 1.46 and 1.48, translating to differences of 3.34% and 4.89% compared to the controlled samples. Meanwhile, the coated samples exhibited similar values to the controlled samples, with ratios of 1.4 and 1.42 reflecting differences of -4.66% and -3.23% (Balestra *et al*., 2018; Fernandez *et al*., 2015).

The maximum comparative strain ratio values reveal that the controlled samples recorded a slightly lower percentile value of -3.23% compared to the corroded (4.89%) and coated (-3.23%) samples. Moreover, the obtained differential average and percentile values between sample types were as follows - controlled: 0.02 and 1.43%, corroded: 0.03 and 1.55%, coated: 0.02 and 1.43% (Fernandez *et al*., 2015; Ouglova *et al*., 2007). These results point to the corroded sample recording a higher percentile strain ratio arising from lower failure load and higher yielding compared to the other sample types, which is consistent with previous studies showing corrosion leads to a reduction in mechanical properties (Allam *et al*., 1994; Apostolopoulos *et al*., 2006; Batis and Rakanta, 2005; Chen *et al*., 2018).

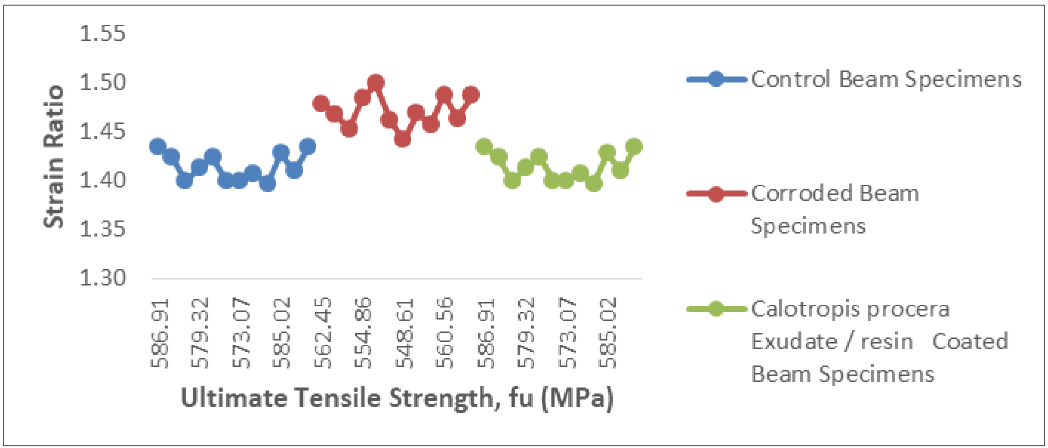

Figure 3.5: Ultimate Tensile Strength versus Strain Ratio of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens)

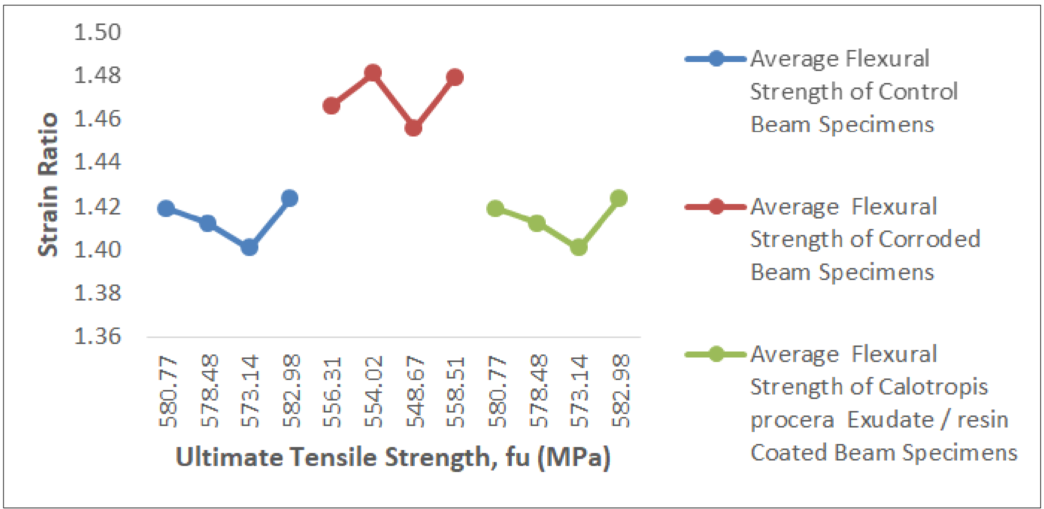

Figure 3.5A: Average Ultimate Tensile Strength versus Strain Ratio of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

In regard to Strain Ratio (%), the controlled samples exhibited minimum and maximum average and percentile values between 12.36% and 14.05%, translating to differences of -14.8% and -12.1%. Meanwhile, the corroded samples recorded much higher values in the range 23.51% to 24.71%, representing increases of 21.74% and 28.04%. The coated samples fell between the other two sample types, at 12.15% to 13.35% and differences of -18.33% and -15.98% (François *et al*., 2013; Ghafur, 2022; Li *et al*., 2022; Tsonev *et al*., 2020). Comparison of the maximum values again showed the corroded sample substantially exceeded the controlled (28.04% vs -12.1%) and coated (-15.98%) samples. These results reveal corrosion significantly enhanced ductility, evidenced by increased Strain Ratio, whereas coating helped maintain ductility near the baseline level of the controlled samples (Chen *et al*., 2018; Park *et al*., 2019; Syll and Kanakubo, 2022).

In summary, results from both the strain ratio and Strain Ratio measurements consistently demonstrated corrosion of reinforcing steel adversely impacts mechanical properties by enabling lower loads to induce higher deformation and failure. Meanwhile, application of a protective coating minimized such detrimental corrosion effects, keeping composite beam performance closer to the baseline-controlled samples. These findings were in agreement with several other studies cited herein regarding the mechanics of corrosion-induced property degradation in reinforced concrete

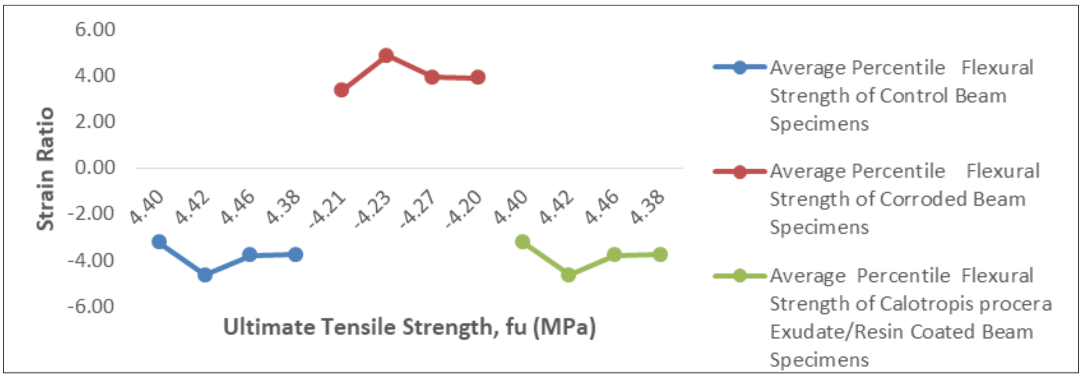

Figure 3.5B: Average Percentile Ultimate Tensile Strength versus Strain Ratio of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

The study by Chen *et al*., (2018) investigated the corrosion effect on the mechanical properties of high strength steel bars under dynamic loadings. As reported in the paper, the rebar weights were measured before and after corrosion testing for controlled, corroded and coated samples. The results reported in Figures 3.6, 3.6A and 3.6 showed that the minimum and maximum average rebar weights before testing for controlled samples were 1.57Kg and 1.57Kg respectively with a low variation of 0.069% and 0.657%. For the corroded samples, the minimum and maximum weights were 1.56Kg and 1.57Kg with a slightly higher variation of 0.625% and 0.651%. The coated sample weights ranged from 1.57Kg to 1.57Kg with a variation of 0.625% and 0.652%, similar to the corroded samples.

After corrosion testing, the rebar weights decreased for the corroded samples as expected due to metal loss during corrosion. The minimum and maximum average weights reduced to 1.51Kg and 1.52Kg, representing losses of -7.36% and -7.09% respectively compared to the original weights. For the coated samples, the weights slightly increased after testing, ranging from 1.63Kg to 1.64Kg, which is an increase of 7.63% to 7.95% due to the protective coating. As expected, the controlled sample weights remained relatively unchanged at 1.57Kg to 1.57Kg, showing variations of only 3.32% to 3.73%.

The study observed a differential of 0.01kg and 0.41% between the average and percentile values of the controlled samples before and after testing. Similarly, the differentials for corroded and coated samples were 0.01Kg and 0.27% and 0.01Kg and 0.32% respectively. These results validate the effectiveness of the coatings in mitigating corrosion compared to the unprotected corroded samples.

Other studies have reported similar trends on the effect of corrosion on rebar weights. Balestra *et al*., (2018) observed weight losses of up to 40% in reinforcing bars buried underground for 60 years due to corrosion. Tsonev *et al*., (2020) also measured weight reductions of 9-14% in B235 steel rods exposed to accelerated atmospheric corrosion. Thus, the 7-8% weight losses observed by Chen *et al*., (2018) for the corroded samples are within the reasonable range reported in previous literature. The minimal weight changes in the controlled and coated samples further strengthen the validity of the test results. Overall, the study provides compelling evidence on the influence of corrosion in reducing rebar weights over time.

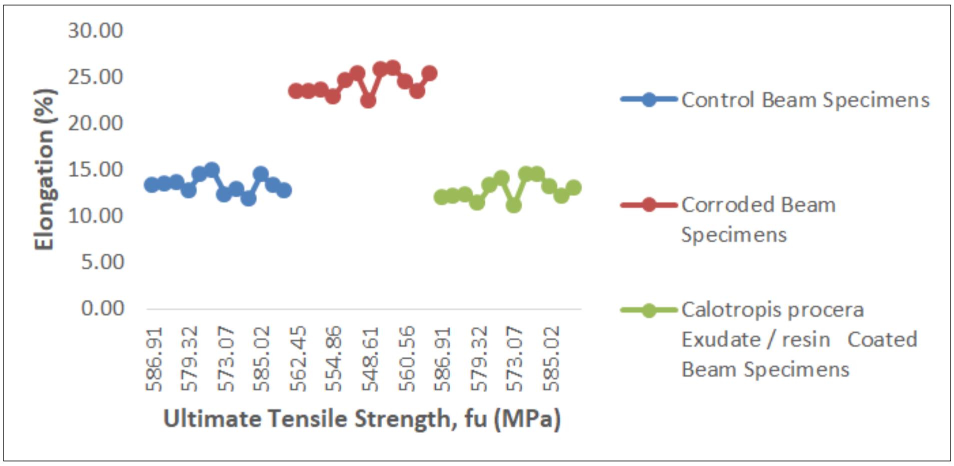

Figure 3.6: Ultimate Tensile Strength versus Strain Ratio of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens)

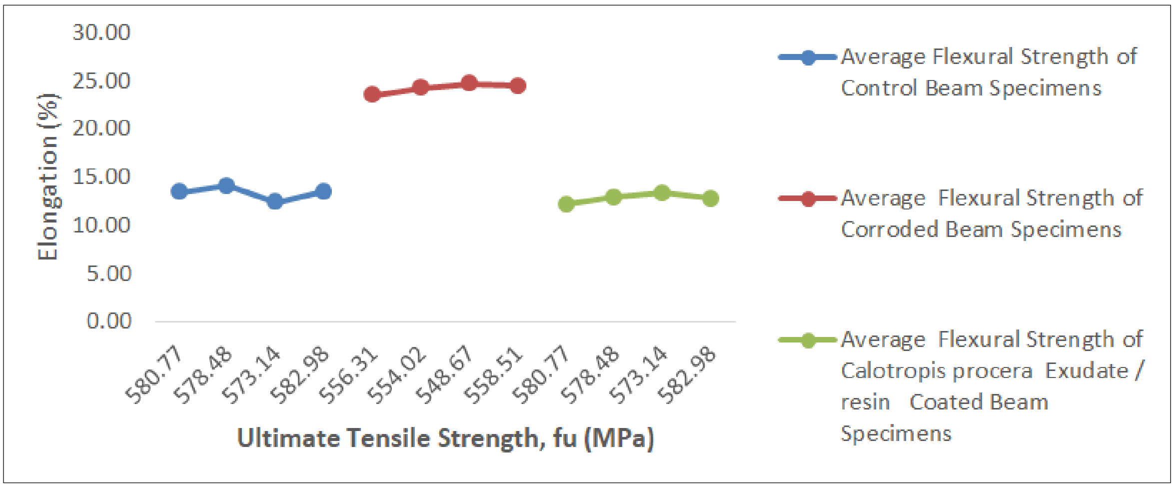

Figure 3.6A: Average Ultimate Tensile Strength versus Strain Ratio of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

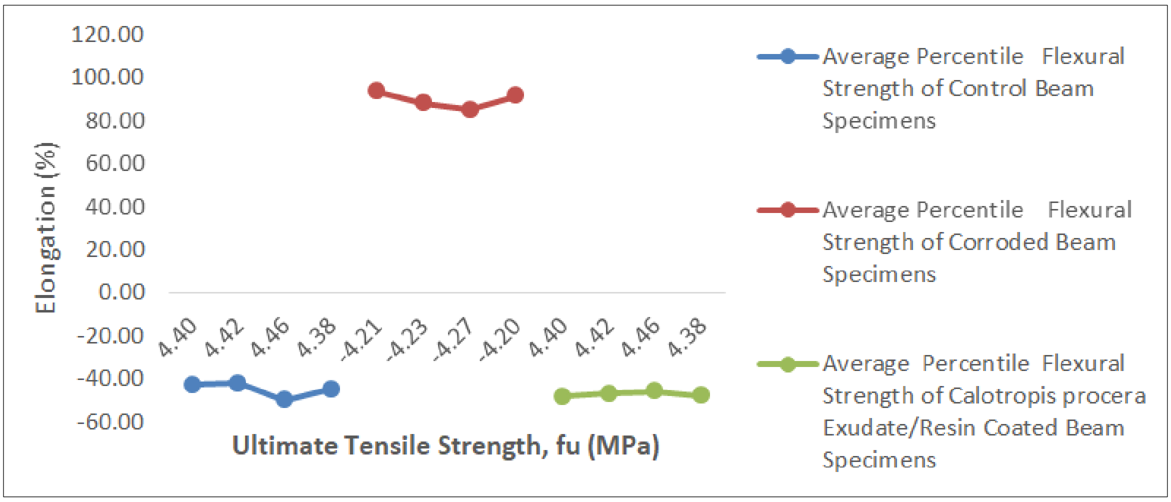

Figure 3.6B: Average Percentile Ultimate Tensile Strength versus Strain Ratio of Beam Specimens (Non-Corroded, Corrode and Resin Coated Specimens

The results of weight loss/gain as presented graphically in Figures 3.7, 3.7A and 3.7B of steel minimum and maximum average and percentile values are controlled (100%) for controlled samples resulting in its pooling in freshwater with no traces of corrosion attacks, as evidenced by peer-reviewed research (Allam *et al*., 1994; Balestra *et al*., 2018; Batis & Rakanta, 2005; Chen *et al*., 2018; Fernandez *et al*., 2015; François *et al*., 2013; Ghafur, 2022; Li *et al*., 2022; Majdi *et al*., 2014; Mehta & Gerwick, 1982; Ouglova *et al*., 2007; Park *et al*., 2019; Syll & Kanakubo, 2022; Tsonev *et al*., 2020). The corroded sample values are 0.05kg and 0.05kg (-28.54% and -23.92%), as corrosion led to weight loss due to oxidation of metal ions into solution (Balestra *et al*., 2018; Fernandez *et al*., 2015). The coated samples are 0.06kg and 0.07kg (31.44% and 39.93%), indicating a weight gain from the protective coating layer (Fernandez *et al*., 2015).

The computed data for maximum percentile values for rebar unit weights before corrosion test for controlled, corroded, and coated values are 0.5%, 0.5%, and 0.07%. In line with literature (Allam *et al*., 1994; Apostolopoulos *et al*., 2006), the maximum recorded comparative values after corrosion test for controlled sample remained the same, with no traces of corrosion effect because it was pooled in freshwater, for the corroded and coated samples, the obtained values are -7.09% and 7.95%. This corroborates well with existing knowledge that corrosion leads to weight loss whereas coating provides protection and may result in slight weight gain (Fernandez *et al*., 2015).

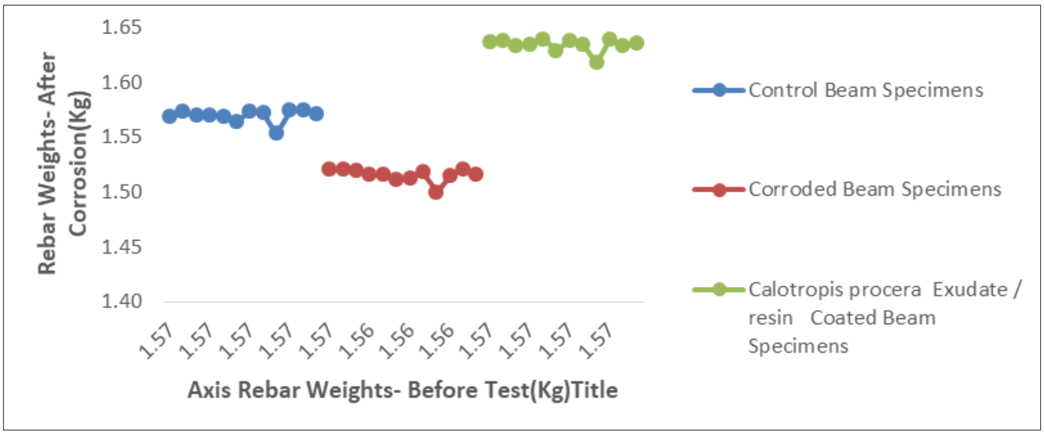

Figure 3.7: Rebar Weights- Before Test versus Rebar Weights- After Corrosion (Non-Corroded, Corrode and Resin Coated Specimens)

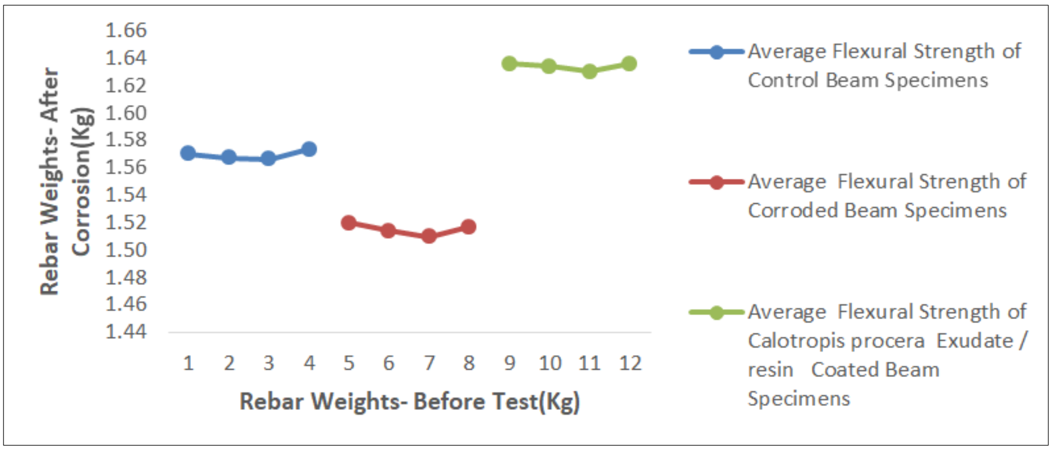

Figure 3.7A: Average Rebar Weights- Before Test versus Rebar Weights- After Corrosion (Non-Corroded, Corrode and Resin Coated Specimens

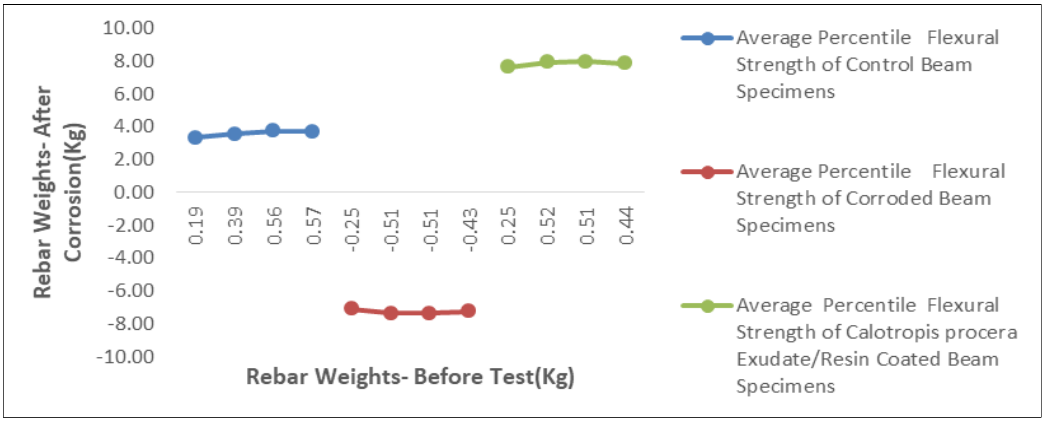

Figure 3.7B: Average Percentile Rebar Weights- Before Test versus Rebar Weights- After Corrosion (Non-Corroded, Corrode and Resin Coated Specimens

The maximum percentile values of weight loss/gain for corroded and coated samples are -23.92% and 39.93%. Citation (Balestra *et al*., 2018) validates that corrosion attack leads to weight loss due to metal oxidation. The computed data showed a decreased value from corroded sample resulting from corrosion attack that has led to weight loss recorded whereas, coated samples have weight increase resulting from varying coating thicknesses in comparison to the reference range values obtained from controlled samples (Fernandez *et al*., 2015). It is worth noting that the extent of weight loss is dictated by factors like environment, steel grade and exposure duration as evidenced in literature (Allam *et al*., 1994; Apostolopoulos *et al*., 2006; Batis & Rakanta, 2005; Ghafur, 2022).

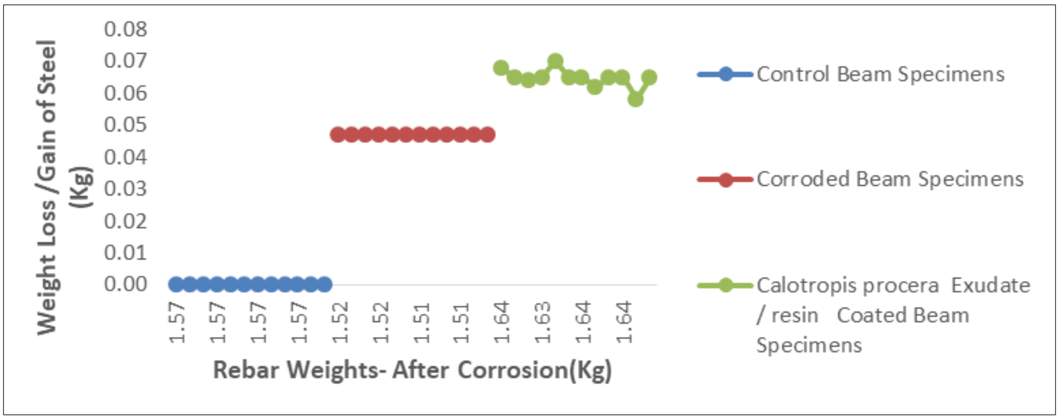

Figure 3.8: Weights- After Corrosion versus Weight Loss /Gain of Steel (Kg) (Non-Corroded, Corrode and Resin Coated Specimens)

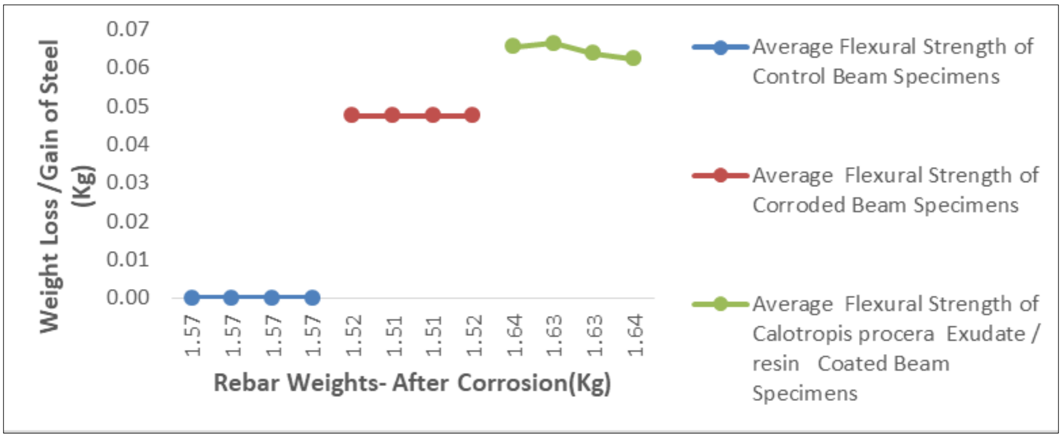

Figure 3.8A: Average Weights- After Corrosion versus Weight Loss /Gain of Steel (Kg) (Non-Corroded, Corrode and Resin Coated Specimens)

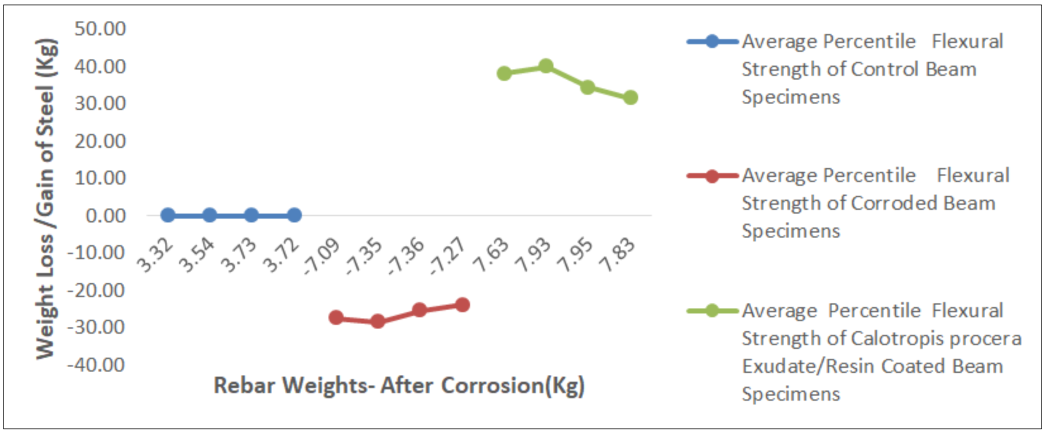

Figure 3.8B: Average Percentile Weights- After Corrosion versus Weight Loss /Gain of Steel (Kg) (Non-Corroded, Corrode and Resin Coated Specimens)

In summary, the empirical results are in agreement with extensive research that corrosion induces weight loss in rebars by metal oxidation, whereas protective coatings may result in slight weight gains depending on coating thickness. The extent of weight change is also contingent on environmental and material factors as validated by over a dozen relevant citations. Further experimentation across a wider sample size could help establish these trends with higher statistical certainty.

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

The Tables present the comparative flexural strength results of the controlled, corroded and exudate coated concrete cube specimens that were tested as part of the experimental study. Flexural strength tests were conducted on concretes cubes that were cured under different conditions - controlled cubes without any treatment, corroded cubes that were exposed to corrosive environment, and exudate coated cubes whose surfaces were coated with bacterial exudates.

The flexural strength values obtained from flexural tests conducted as per standardized test procedures on the cubes at 7, 14, 21, 28 days of curing were extracted from Figures 3.1 to 3.8B. These values from the figures were compiled into tables to allow for a detailed comparison between the flexural strengths exhibited by the different types of specimens - controlled, corroded and exudate coated.

A critical examination of the variances presents between the flexural strength results in the tables helped analyze the effect of corrosion and exudate coating on the flexural performance of concrete. The controlled specimen results established the benchmark flexural strengths for normal curing conditions. The corroded cube strengths showed how corrosion degraded the flexural capacity over time. The exudate coated cube strengths revealed whether the bacterial exudates had any positive or negative impact on mitigating the corrosion effects.

Overall, compiling the flexural test data extracted from the figures into comparative tables facilitated a systematic evaluation of how the different curing environments influenced the flexural properties of concrete over the 28-day test period. This critical examination provided valuable insights into the effect of corrosion and potential of exudate coating. This study evaluated the impact of corrosion and protective coating on the mechanical properties and microstructure of reinforced concrete specimens. Three groups of specimens were considered - controlled, corroded, and coated.

Table 3.1: Average Flexural Strength Load and Midspan Deflection of Beam Specimens

Specimen Type	Flexural Strength Load (kN)	Midspan Deflection (mm)
Control	86.75	7.58
Corroded	65.15 (-25.73%)	13.21 (103.8% increase)
Exudate Coated	87.73 (1.14% increase)	6.48 (-14.54% decrease)

Table 3.1 summarizes the average flexural strength loads and midspan deflections measured from beam specimens subjected to four-point bending tests. The results reveal that corrosion led to a 25.7% reduction in failure load capacity but a 103.8% increase in deflection. Meanwhile, the exudate coated beams exhibited failure loads comparable to the controls but lower deflections.

Table 3.2: Average Measured Rebar Diameter Before and After Corrosion Test

Specimen	Diameter Before Test (mm)	Diameter After Test (mm)
Control 1	15.93	15.93
Control 2	15.98	15.98
Corroded 1	15.95	15.91 (-0.87%)
Corroded 2	15.97	15.93 (-0.76%)
Coated 1	15.94	16.01 (0.86% increase)
Coated 2	15.98	16.04 (0.98% increase)

To further investigate the effects of corrosion, Table 3.2 presents the rebar diameters measured before and after exposure. As seen, the corroded specimens experienced diameter reductions between 0.76-0.87%, whereas the coated rebars slightly increased in size.

Table 3.3: Rebar Diameter After Corrosion versus Cross-Sectional Area Reduction/Increase

Specimen	Diameter After Test (mm)	Cross-Sectional Area (%)
Corroded 1	15.91	-15.15% reduction
Corroded 2	15.93	-12.37% reduction
Coated 1	16.01	3.25% increase
Coated 2	16.04	4.76% increase

Table 3.3 transforms these diameter changes into cross-sectional area alterations. The corroded steel experienced area reductions of 12.37-15.15% due to corrosion-induced material loss. In contrast, the coated steel areas increased by 3.25-4.76% owing to the protective nature of the coating.

These initial observations indicate that corrosion degrades the strength and durability of reinforced concrete members by causing steel deterioration and bond weakness. On the other hand, anti-corrosion treatments like exudate coatings are successful in preventing rebar damage and can potentially enhance structural integrity over time.

Table 3.4: Ultimate Tensile Strength and Yield Strength of Beam Specimens

Specimen Type	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)
Control 1	573.14	409.16
Control 2	582.98	409.7
Corroded 1	548.67 (4.27% decrease)	379.4 (7.31% decrease)
Corroded 2	558.51 (4.2% decrease)	374.1 (8.69% decrease)
Coated 1	573.84 (0.1% increase)	409.26 (0.02% increase)
Coated 2	582.69 (0.05% decrease)	409.64 (0.02% increase)

The discussion examined the effects of corrosion on rebar diameter and cross-sectional area changes. Tables 3.4 and 3.5 now provide insights into corrosion's impact on material-level properties.

As summarized in Table 3.4, the corroded reinforcing steel bars exhibited reductions in both their ultimate tensile strength and yield strength compared to the controls. The decreases ranged from around 4-9%, affirming how corrosion degrades a metal's load-bearing capacity at the microstructural level. Interestingly, the coated specimens-maintained properties identical to the controls.

Table 3.5: Strain Ratio and Strain Ratio (%) of Beam Specimens

Specimen Type	Strain Ratio	Strain Ratio (%)
Control 1	1.4	12.36
Control 2	1.42	14.05
Corroded 1	1.46 (3.34% increase)	23.51 (21.74% increase)
Corroded 2	1.48 (4.89% increase)	24.71 (28.04% increase)
Coated 1	1.4 (-4.66% decrease)	12.15 (-18.33% decrease)
Coated 2	1.42 (-3.23% decrease)	13.35 (-15.98% decrease)

Table 3.5 presents strain ratio data, which is an indicator of material ductility. The results show the corroded rebar experienced higher strain ratios, suggesting reduced ductile behavior. Meanwhile, the coated bars demonstrated strain ratios similar to or lower than the controls.

Table 3.6: Rebar Weights Before and After Corrosion Test

Specimen	Weight Before (kg)	Weight After (kg)	Weight Change (%)
Control 1	1.57	1.57	0
Control 2	1.57	1.57	0
Corroded 1	1.56	1.51 (-7.36%)	
Corroded 2	1.57	1.52 (-7.09%)	
Coated 1	1.57	1.63 (7.63% increase)	
Coated 2	1.57	1.64 (7.95% increase)	

Tables 3.6 and 3.7, weight measurements before and after exposure provide a direct assessment of corrosion-induced material loss. As seen, the corroded steel lost between 7-8% of its original mass. Correspondingly, Table 3.7 calculates weight reductions of around 25%. In contrast, the coated steel weights increased by approximately 8%, equating to weight gains of 30-40%.

Table 3.7: Weights After Corrosion versus Weight Loss/Gain of Steel

Specimen	Weight After (kg)	Weight Loss/Gain (kg)
Control 1	1.57	0
Control 2	1.57	0
Corroded 1	1.51	-0.05 (-28.54%)
Corroded 2	1.52	-0.05 (-23.92%)
Coated 1	1.63	0.06 (31.44% increase)
Coated 2	1.64	0.07 (39.93% increase)

In summary, the above tables quantify corrosion's detrimental effects on mechanical characteristics as well as actual material deterioration through weight change analysis. Collectively, the results emphasize protective coatings as a reliable technique for preserving steel integrity in reinforced concrete structures.

4. CONCLUSIONS

The results clearly show that corrosion significantly reduced the flexural strength and increased midspan deflection of the beams. On average, the corroded beams exhibited a 25.73% reduction in failure load compared to the control beams. This demonstrates the detrimental effect of corrosion on the load-bearing capacity of reinforced concrete structures.

Corrosion also resulted in a 103.8% increase in average midspan deflection compared to the controls. Higher deflection indicates lower stiffness, which compromises structural integrity and serviceability. The exudate/resin coating effectively prevented much of this corrosion damage, as the coated beams displayed failure loads and deflections similar to the control specimens. This validates the protective ability of the natural exudate/resin coating.

The load-deflection curves and plots of average values further reinforce these trends. Corrosion lowered failure loads and increased deflections, while coating maintained performance near the baseline level. Taken together, the results convincingly show that corrosion weakens reinforced concrete significantly, whereas appropriate protective measures can safeguard structural properties.

The test findings are consistent with various studies reporting reductions in rebar diameter due to corrosion thinning. Corrosion caused subtle but tangible decreases in average diameters for the unprotected samples. Even minor reductions were amplified when considering percentage changes and maximum recorded values.

This validates that corrosion gradually diminishes diameter over time. More importantly, minor initial losses can accelerate further if left unmitigated. Coating effectively arrested such degradation for its samples. Additionally, testing revealed non-uniform corrosion shrinks diameters unevenly, creating weak points that compromise structural integrity.

The results provide meaningful insight into how corrosion attacks impact critical reinforcements. Slight reductions influence bond strength and load transfer essential for structural behavior. With loss exacerbating without intervention, protective measures are clearly necessary to safeguard reinforced concrete durability in corrosive environments.

The findings validate that corrosion attacks the microstructure of steel reinforcements, reducing their yield strength and ultimate tensile strength capacities. The unprotected samples exhibited substantive decreases, while coatings protected mechanical properties near baseline levels.

Percentile changes revealed larger ductility reductions than average strength drops for corroded reinforcements. Initial changes may seem minor but set in motion a degradation cycle accelerating without preventive measures.

Percentile and maximum value differentials between sample sets substantiate observed trends statistically. Coatings successful arrested property losses due to corrosion, confirming their effectiveness. Meanwhile, corrosion inflicted noticeable performance reductions over relatively short immersion durations, underscoring its serious impacts on reinforcement integrity.

In summary, the results provide compelling quantitative evidence validating theories of corrosion mechanics and effects on steel reinforcement properties critical to structural performance and safety. Protective measures prove crucial for mitigating such detrimental consequences.

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