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Sustainable Corrosion Protection in Concrete Using Henna Coatings: An Environmentally Friendly Alternative to Zinc Coatings

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ABSTRACT

Corrosion of reinforcement bars in concrete compromises structural integrity and increases maintenance costs. This study investigates the effectiveness of organic (henna powder) and inorganic (zinc powder) corrosion inhibitor coatings in enhancing both corrosion resistance and bond strength retention of coated reinforcement bars embedded in concrete. The significance of the study lies in its approach to measure the bond strength retention of coated reinforcement bars in chloride induced environment. To evaluate the corrosion mitigation and bond strength retention of the coated bars, cylindrical specimens of M20 grade of concrete were casted having embedded coated and non-coated reinforcement bars having varying coating layers. Accelerated corrosion tests using 3.5% NaCl solution was applied to casted specimens to simulate aggressive environmental conditions. Bond strength retention was assessed through pull-out tests in accordance with IS 2770: Part 1 (1967). Results showed that reinforcement bars with four coats of henna delayed corrosion initiation by up to 14,525 minutes (~10 days) compared to 6,132 minutes (~5 days) for uncoated bars—representing a 137% improvement in corrosion resistance for 20% corrosion levels. Zinc coatings improved corrosion resistance by up to 65% with four coats for 20% corrosion levels. In bond strength tests, uncoated samples exhibited a 42% reduction in bond strength at 20% corrosion, while henna-coated samples retained up to 90% of their original bond strength, significantly outperforming zinc-coated samples, which retained approximately 84%. The superior performance of henna coatings is attributed to the formation of a protective passive layer containing organic tannins and polyphenolic compounds such as lawsone. Unlike conventional admixture-based or epoxy-based corrosion inhibitors, which are either dispersed within the concrete matrix or applied externally to hardened surfaces, this study pioneers the direct application of henna as a coating on reinforcement bars—targeting corrosion mitigation precisely at the steel–concrete interface without compromising bond strength. These findings highlight the potential of organic inhibitors as cost-effective solutions and presenting a viable alternative to traditional epoxy-coating based prevention methods for mitigating reinforcement corrosion while preserving bond strength, offering a promising approach for enhancing the durability of reinforced concrete structures. The study promotes the use of environmentally safe inhibitors to reduce the ecological footprint of reinforced concrete structures and supports the transition toward green and sustainable construction practices.

INTRODUCTION

Strength, durability and adaptability are the major factors driving the reinforced cement concrete as one of the most widely used construction material. The service life of reinforced cement concrete remains unhindered under ideal environmental conditions. However, in some cases, its performance is compromised due to factors such as inadequate design, poor construction practices, substandard material selection, or exposure to harsher environmental conditions than originally anticipated (Afandi et al. 2023). Among the many challenges faced by civil engineers, corrosion of reinforcement in concrete stands out as a significant concern, particularly when dealing with aging infrastructure. Addressing corrosion-related deterioration has become a crucial aspect of structural maintenance, creating a growing demand for specialized rehabilitation techniques (Arslan et al. 2024). While this presents opportunities for experts in the field, it also poses substantial challenges for those responsible for maintaining and restoring affected structures. The economic impact of corrosion is staggering. In the United States alone, it is estimated that corrosion-related damage to interstate highway bridges, primarily caused by deicing salts and marine exposure, amounts to approximately $150 billion. Additionally, difficulties in properly curing concrete further reduce the lifespan of reinforced concrete structures. In rapidly developing nations, cost-cutting measures in construction have led to lower-quality concrete and insufficient concrete cover over reinforcement, making structures more susceptible to carbonation-induced corrosion (Asaad et al. 2021, Bajaj & Khurpade 2024, Cai et al. 2022).

A more thought-provoking question might be: Why doesn’t steel corrode in concrete more frequently? It is well known that mild steel and high-strength reinforcing bars are prone to rusting when exposed to air and moisture. Given that concrete is a porous material containing water, one might expect embedded steel to corrode easily. However, under normal conditions, this is not the case. The key reason behind steel’s resistance to corrosion in concrete lies in the material’s inherent alkalinity. Unlike acids, which actively corrode metals, alkaline environments often provide protection against corrosion. Concrete contains microscopic pores filled with high concentrations of soluble calcium, sodium, and potassium oxides. When mixed with water, these oxides form hydroxides, creating a highly alkaline environment with a pH ranging between 12 and 13. This alkaline condition plays a crucial role in the durability of reinforced concrete structures by influencing the composition of pore water and controlling the movement of ions and gases through the concrete matrix (Çöğürcü & Uzun 2022, Courard et al. 2014). One of the most important protective mechanisms in reinforced concrete is the formation of a passive layer on the steel surface. This layer consists of a dense, impenetrable film, likely composed of metal oxides, hydroxides, and minerals derived from cement. Once fully developed, this passive layer significantly slows down the oxidation process, preventing corrosion. In fact, when properly maintained, this natural protective barrier can be more effective than artificial coatings like galvanization or fusion-bonded epoxy, which may degrade over time and expose the underlying steel to corrosion. However, this passivating environment is not always stable. Two primary mechanisms can disrupt it, leading to steel corrosion in concrete: carbonation and chloride attack. These processes alter the chemical balance within the concrete, weakening the protective layer and making the embedded steel vulnerable to corrosion. Understanding these degradation mechanisms is essential for developing strategies to enhance the longevity of reinforced concrete structures (Deliktas et al. 2024, Dybel & Walach 2017, El-Etre et al. 2005). As infrastructure continues to age and new structures are built in increasingly demanding environments, addressing the issue of corrosion in reinforced concrete remains a critical priority for engineers worldwide.

Several factors have been researched that affect the corrosion of rebars embedded in concrete. Quality of concrete, environmental conditions, specific construction practices carried out are key among these. It is the surface at the steel/concrete interface and its relationship with water content, pore structure and the component of the local environment which largely determines the onset and propagation of corrosion. In addition, the required critical chloride content for initiation of corrosion is not a fixed value and is affected by several variables, resulting in very complex predictions of corrosion rates (Fernando et al. 2023, Ye et al. 2020, Zhao & Luo 2024). Different methods of protection for rebars have been developed and studied over the years to combat these issues. Some common methods include protective coating, sacrificial anode or impressed current system. Efficacy of these techniques has been measured through experimental studies that ascertain thus how these techniques can limit corrosion in a variety of concrete environments. For example, the small scale projects have widely used protective coatings while for harsher environment, sacrificial anodes are suggested. In addition, corrosion inhibitors for concrete have been examined as a possible alternative way to improving the durability of reinforced structures. If applied properly these inhibitors can have a massive effect on extending the lifespan of concrete constructions by cutting the corrosion rate down to a low value. These coatings will operate most effectively if the type of inhibitor used and its compatibility with the concrete mix design are taken into consideration. In determining the durability and structural integrity of reinforced concrete structures, one of the critical factors contributing to this is the bond strength of reinforcement bars in concrete. A few studies have also been conducted to evaluate the effect of corrosion inhibitors, carbonation and other binder materials on bond strength (Julio et al. 2004, Suguma & Pyatina 2017, Yan et al. 2016). Traditional corrosion mitigation strategies, such as epoxy coatings or corrosion-inhibiting admixtures, face limitations such as poor bond strength retention or imprecise delivery to corrosion-prone areas. While plant-based corrosion inhibitors have been explored in various forms, their use has been mostly limited to admixture inclusion or surface application (Suguma & Pyatina 2017). This study presents a novel strategy by applying henna powder directly onto the reinforcement bars as a protective coating. This direct-contact application is significant because it actively targets the corrosion initiation zone at the steel–concrete interface, potentially offering both improved corrosion resistance and bond retention—an area not sufficiently explored in existing literature.

For a better understanding of the utilization of corrosion inhibitors in concrete, an in-depth literature review was done and the papers were analyzed from 2004 to 2024 as shown in Fig. 1. As per the database made form Google Scholar, the number of articles published on use of corrosion inhibitors in concrete, year wise were:

2004 – 2009: 9,543

2010 – 2014: 13,287

2015 – 2019: 16,785

2020 – to present: 21,124

As evident from these increasing numbers, it further highlights the importance of studying the effect of corrosion in concrete. The various keywords used to conduct the search of the varied literature were “Corrosion Inhibitors”, “corrosion mitigation”, “corrosion”, “durability of concrete” and “inhibitors”.

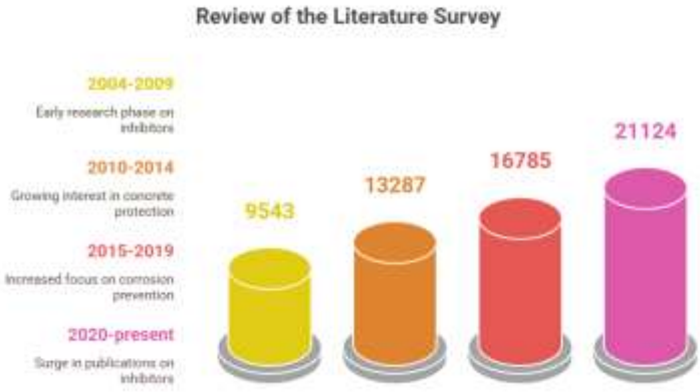


Fig. 1: Review of Literature Survey.

The study of the various phytochemicals responsible for showing corrosion inhibition properties in plant based inhibitors when used in concrete is very important. Fig. 2 below highlights the five key important classes of phytochemicals, i.e. Alkaloids, Phenolic Acids, Carbohydrates, Terpenoids, and Lipids which are responsible for exhibiting corrosion inhibition properties. Alkaloids such as glucosinolates and indole are known for their bioactive properties, while Phenolic Acids like flavonoids and quinones are notable for their antioxidant and metal-chelating capabilities. Carbohydrates including monosaccharides and polysaccharides can form protective layers on metal surfaces. Terpenoids like carotenoids and monoterpenoids contribute to corrosion resistance through their hydrophobic characteristics. Lastly, Lipids, including saturated and unsaturated fats, can create protective barriers that reduce moisture penetration. This comprehensive classification underscores the diverse chemical nature of plant extracts and their promising role in enhancing the durability of reinforced concrete and metal structures. Conventional corrosion inhibitors often involve synthetic or heavy metal-based compounds that pose disposal and leaching concerns. In contrast, natural inhibitors like henna, being biodegradable and non-toxic, present a viable green alternative. Their use aligns with global efforts to minimize environmental degradation in construction activities.

Fig. 2: Phytochemicals in Plant-Based Extracts for Corrosion Inhibition (Kadhim et al. 2021, Kumar et al. 2019, Kumar et al. 2025, Shunmuga & Ammasi 2023, Söylev & Richardson 2008).

2. RESEARCH GAP AND RESEARCH SIGNIFICANCE

Although corrosion inhibitors have been widely used in previous studies—mainly as admixtures mixed into concrete or surface-applied on hardened structures—the direct application of plant-based inhibitors such as henna as a coating on reinforcement bars remains largely unexplored. Common methods include epoxy coatings, admixtures, and surface-applied treatments. While these methods improve corrosion resistance, they may compromise bond strength or incur high costs. Organic inhibitors such as plant extracts have shown potential in corrosion mitigation, but their direct application as coatings on reinforcement bars has not been explored extensively. Previous studies primarily focus on corrosion inhibitors mixed within concrete or applied on hardened concrete surfaces, but their performance as direct coatings on reinforcement bars has not been adequately investigated. Unlike epoxy coatings, which may act as a barrier to mechanical bonding, or admixtures that rely on diffusion throughout the concrete, henna as a direct coating combines physical barrier protection with chemical inhibition at the precise corrosion-prone interface—without negatively affecting bond strength. This study introduces a novel approach of applying organic (henna powder) and inorganic (zinc powder) corrosion inhibitor coatings directly to reinforcement bars to simultaneously enhance corrosion resistance and preserve bond strength. The dual-benefit strategy, combined with quantitative performance data, addresses a critical gap in existing research and offers a practical solution for improving the durability of reinforced concrete structures. The application of organic (henna) and inorganic (zinc) inhibitor coatings directly on reinforcement bars represents a novel approach that addresses corrosion mitigation at its source—the steel-concrete interface. This research extends existing knowledge by demonstrating that these coatings significantly enhance corrosion resistance while also improving bond strength retention. This insight fills a research gap regarding the dual benefit of corrosion control and bond strength preservation. Henna contains organic tannins and polyphenolic compounds such as lawsone (2-hydroxy-1,4-naphthoquinone) (Kamarska 2024, Kumar 2020). These compounds form a protective passive layer on the steel surface, which acts as a physical barrier, limiting the diffusion of chloride ions, oxygen, and moisture. These active constituents in Henna, have chelating properties that allow them to bond with metal ions. This forms a stable complex that reduces the reactivity of the metal surface, thus minimizing corrosion. The coatings were prepared by mixing used engine oil with the powdered inhibitors. The Henna coating exhibits hydrophobic characteristics when mixed with binder like engine oil. This property further reduces moisture ingress to the reinforcement surface, a critical factor in corrosion prevention. Consequently, the primary objective of this study is to investigate the effectiveness of organic (henna powder) and inorganic (zinc powder) corrosion inhibitor coatings on reinforcement bars embedded in concrete (Kumar et al. 2024, Monticelli et al. 2000). The focus is to assess the ability of these coatings to mitigate corrosion in concrete using accelerated corrosion techniques, evaluate the influence of these coatings on bond strength retention under varying corrosion levels, and compare the performance of organic and inorganic coatings to identify the most effective solution for corrosion mitigation and bond strength retention in reinforced concrete structures.

3. MATERIALS AND METHOD

To conduct the research two different corrosion inhibitors, i.e. organic and inorganic inhibitors were used to provide coatings on the reinforcement bars of grade HYSD Fe 415. The organic inhibitor used in the study is Henna Powder and the inorganic corrosion inhibitor used for the study is Zinc powder. Henna (Lawsonia inermis) used in this study is derived from plant sources and is biodegradable, non-toxic, and harvested with minimal environmental impact. This supports the circular economy and aligns with principles of green chemistry. Henna powder used in this study had a specific gravity of 0.95 and particle size between 75 to 150 micron (micro-level) ensuring a finer particle size which is required for better surface coverage and uniform application on the surface of the steel reinforcement. Henna powder was mixed with engine oil at a concentration ratio of 1:1 by weight to create a uniform paste. The pH of the Henna paste was maintained between 6.5 and 7.5 to optimize the stability of tannins and polyphenolic compounds, which are responsible for corrosion inhibition. Prior to coating, the reinforcement bars were subjected to a standardized surface preparation protocol to ensure proper adhesion. The bars were first mechanically cleaned using a rotary wire brush to remove rust, and other contaminants. After mechanical cleaning, the bars were degreased using acetone and wiped clean to remove any residual oils or dust to obtain a bright clear surface. The prepared bars were then air-dried under ambient conditions for 1 hour before coating was applied. The procedure followed for the surface preparation of the reinforcement bar for application of coatings were as per IS 9077:1979. For samples with two coats, the total thickness was approximately 0.3 – 0.5 mm, while samples with four coats reached a total thickness of approximately 0.6 – 0.8 mm. The thickness was measured by using digital Vernier caliper at multiple points along the length of the bar and finally taking the average of the readings obtained. The prepared paste was evenly applied to cleaned reinforcement bars using a brush. Each coating layer was air-dried for 24 hours before applying the next layer to ensure proper adhesion. The corrosion protection mechanism of henna coating is attributed to both physical barrier formation and chemical interaction with the steel surface. Henna paste, when applied as a coating, dries to form a dense, adherent layer on the reinforcement bar. This layer physically isolates the steel surface from aggressive agents like chlorides, oxygen, and moisture, which are key factors in corrosion initiation. Furthermore, Henna contains bioactive compounds such as lawsone (2-hydroxy-1,4-naphthoquinone), flavonoids, and phenolic compounds. These components play a crucial role in corrosion inhibition through adsorption and film formation. The oxygen (O) and hydroxyl (–OH) groups in lawsone molecules have a strong affinity for metal surfaces. These functional groups form coordinate bonds with the iron (Fe) atoms on the steel bar. This adsorption process results in the formation of a stable, protective layer, reducing the anodic and cathodic reactions responsible for corrosion. Further when henna is mixed with a binder agent, i.e. engine oil it increases the hydrophobic characteristics of the paste, which repel moisture from the coated surface. This minimizes water penetration into the concrete-rebar interface, further reducing the risk of corrosion. The reinforcement sample of 16mm diameter and 500mm length were used for the study. A total of 45 reinforcement samples were used for the study and coated with 2 and 4 layers of the inhibitors. 45 reinforcement samples were divided in 5 batches, each containing 9 reinforcement samples. Batch 1 contained of 9 samples having no coated reinforcement bars, Batch 2 contained 9 reinforcement samples coated with 2 coats of Henna powder, Batch 3 contained 9 reinforcement bars coated with 4 coats of Henna Powder, Batch 4 contained 9 reinforcement samples with 2 coats of Zinc powder and Batch 5 contained 9 reinforcement samples of 4 coats of Zinc powder. Fig. 3 explains the coating treatments of the reinforcement samples.

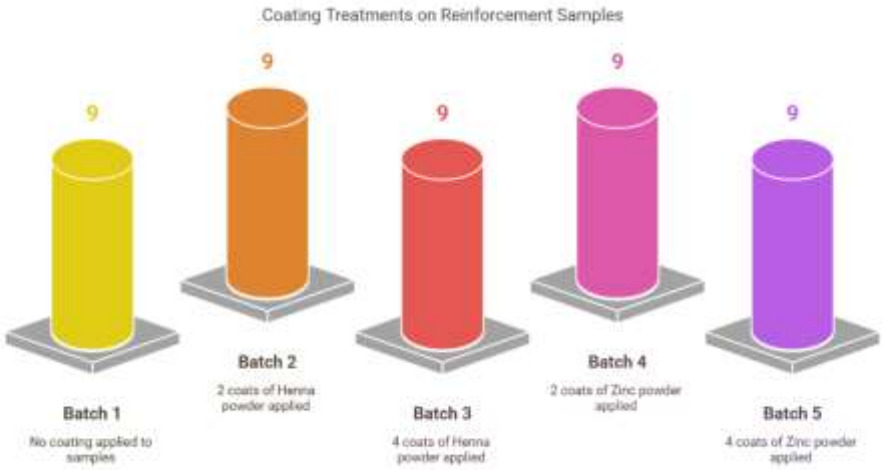
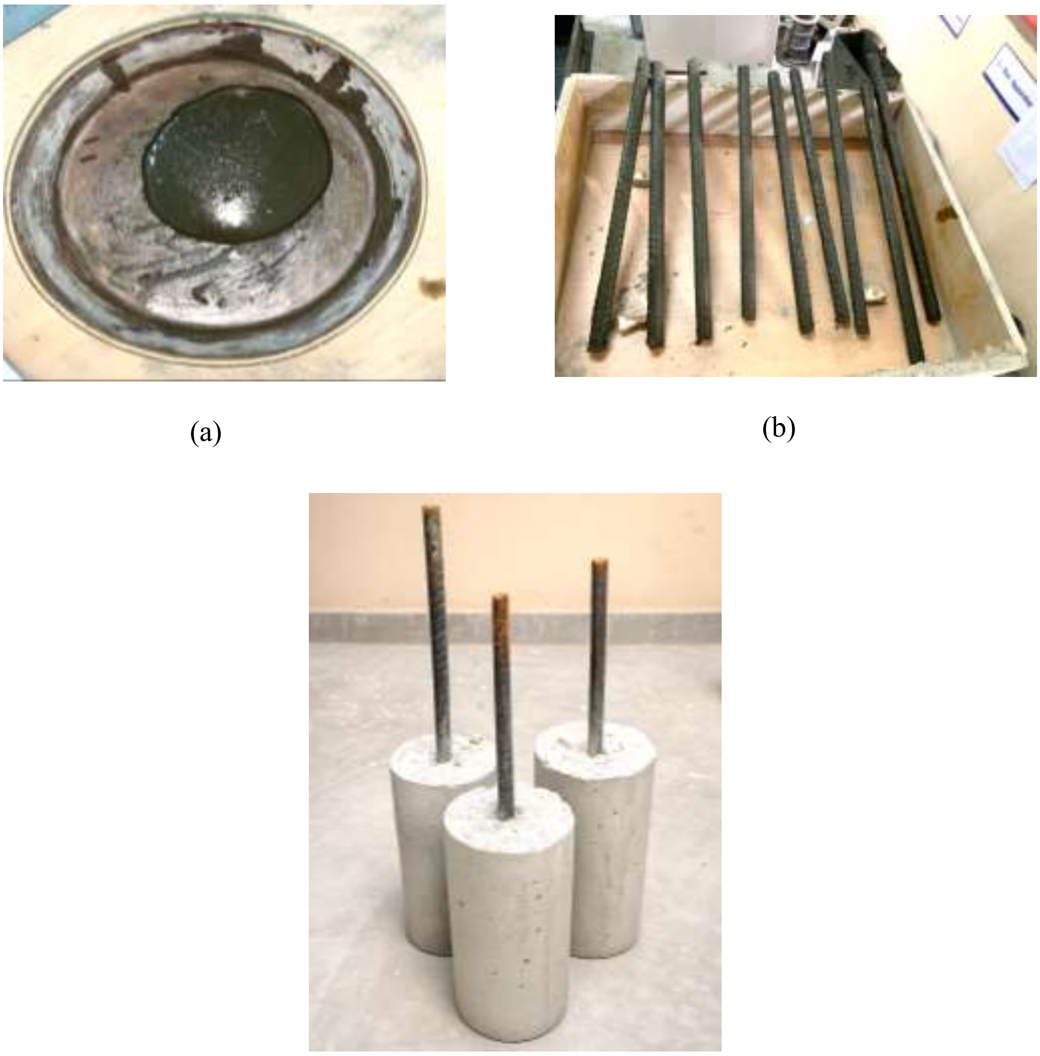


Fig. 3: Coating Treatment on Reinforcement Samples

Once the specimen was coated their initial weight was recorded. Further the test specimens to measure the bond strength of concrete were casted in accordance with IS 2770: Part 1(1967), with a single reinforcement bar embedded vertically along the central axis of the specimen. The grade of the concrete taken for the study was M20 grade mix and its details are mentioned in Table 1 below. The reinforcement bar used projected down at a distance of 10mm from the bottom face and extended above suitable as per the dimensions of the cylinders. The samples were then cured for 28 days under normal conditions maintaining a temperature of 24° ± 2° Celsius and a relative humidity of approximately 95% to ensure continuous hydration of cement. The casting is explained in Fig. 4(a), (b) and (c) below.

Table 1: Mix Proportioning

Proportioning of Mix – M20 grade	
Grade of Concrete	M20
Proportioning	1:1.5:3
Water/Cement Ratio	0.5
Cement	320 kg/m^3
Fine Aggregate	480 kg/m^3
Coarse Aggregate	960 kg/m^3



(a) (b)

(c)

Fig. 4: a) Corrosion Inhibitor Paste, b) Coated Reinforcement Bars, c) Casted Samples

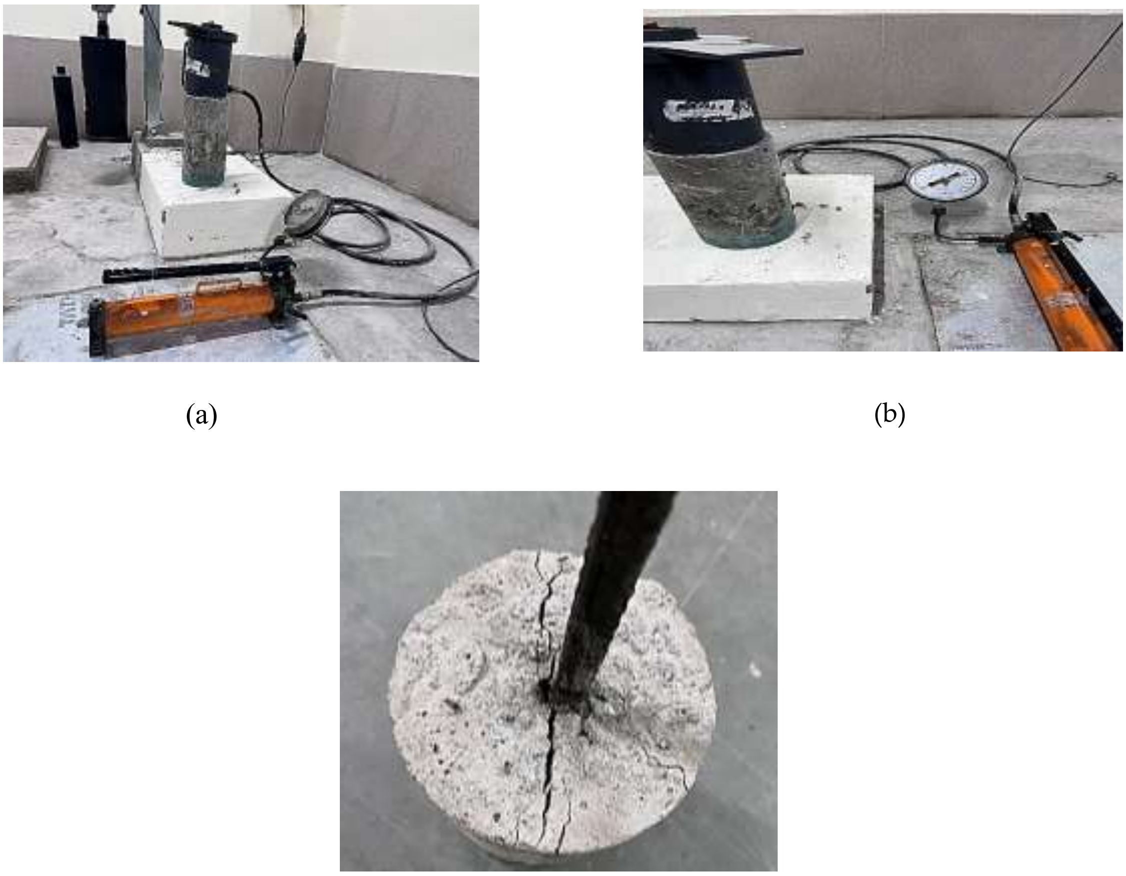
3.1. Accelerated Corrosion Setup

To simulate the corrosive environment, the casted samples were subjected to impressed current method. The samples were subjected to direct current, with the help of the embedded reinforcement bar, which in turn accelerated the corrosion process. To simulate the corrosive environment, the samples were immersed in a 3.5% NaCl solution and subjected to an impressed current corrosion setup in accordance with ASTM G109-21 and modified ASTM C876-15 standards. A direct current was applied using a DC power supply with the embedded reinforcement bars acting as anodes and a reference reinforcement rod as the cathode. The current density was maintained at approximately 145 $\mu A/cm^2$ of exposed steel surface, as the exposed steel surface had an approximate area of 145.6cm^2, a value chosen to balance accelerated corrosion with realistic damage progression. The corrosion process was monitored over a maximum exposure period of 10 days, during which the current was continuously applied. The exposure time required to reach predefined corrosion levels (5%, 10%, 15%, and 20%) was recorded for each test batch and is detailed in Table 2. A reference reinforcement rod was immersed in the solution was used as a cathode, i.e. the negative terminal and exposed end of the reinforcement bar in the casted samples were used as anode, i.e. postive terminal as explained in Fig. 5.

Fig. 5: Accelerated Corrosion Setup

3.2. Pull out Test

After the completion of the accelerated corrosion test, the samples were then tested for bond strength through the standard pull out test. The pull out test on the samples casted were performed in accordance with IS 2770: Part 1(1967) as shown in Fig. 6(a) and 6(b) below. Fig. 6(c) shows the failure pattern observed in the sample after the pullout test was completed.



(a) (b)

(c)

Fig. 6: a) Pull out test on sample, b) Pull out test on sample, c) Failure Pattern after Pull out test

4. RESULTS AND DISCUSSION

4.1. Accelerated Corrosion Results

The samples subjected to accelerated corrosion setup gave the insights on how the corrosion inhibitor coatings perform in a corrosive environment. The direct current was adjusted in such a way to observe maximum corrosion that can take place in samples for a period of 10 days. The avergae potential values in (-mV) were obtained form the Half-Cell Potentiometer Test as per ASTM C876-15 standards. The amount of time required to reach the various levels of corrosion is explained in the Table 2 below:

Table 2: Corrosion measurements in casted samples

S.No	**Sample**	**Coatings**	**Time taken for corrosion (min)**	**No. of days (approx.)**	**Average Measured Potential (-mV)**
			5 % corrosion levels		
1	Batch 1	No Coating	1482	1	**364.5**
2	Batch 2	2 coats of Henna	3102	2	**230.3**
3	Batch 3	4 coats of Henna	5124	3.5	**179.4**

4	Batch 4	2 coats of Zinc	2322	1.5	**290.2**
5	Batch 5	4 coats of Zinc	3721	2.5	**234.6**
			10% corrosion levels		
1	Batch 1	No Coating	2954	2	**472.8**
2	Batch 2	2 coats of Henna	5812	4	**260.7**
3	Batch 3	4 coats of Henna	7933	5.5	**190.3**
4	Batch 4	2 coats of Zinc	3782	2.5	**310.4**
5	Batch 5	4 coats of Zinc	4932	3.5	**276.9**
			15% corrosion levels		
1	Batch 1	No Coating	4951	3.5	**512.3**
2	Batch 2	2 coats of Henna	7521	5.5	**275.4**
3	Batch 3	4 coats of Henna	9451	6.5	**210.8**
4	Batch 4	2 coats of Zinc	5612	4	**320.4**
5	Batch 5	4 coats of Zinc	7869	5.5	**293.5**
			20% corrosion levels		
1	Batch 1	No Coating	6132	5	**534.8**
2	Batch 2	2 coats of Henna	10430	7	**291.5**
3	Batch 3	4 coats of Henna	14525	10	**225.4**
4	Batch 4	2 coats of Zinc	9385	6.5	**340.2**
5	Batch 5	4 coats of Zinc	10142	7	**325.5**

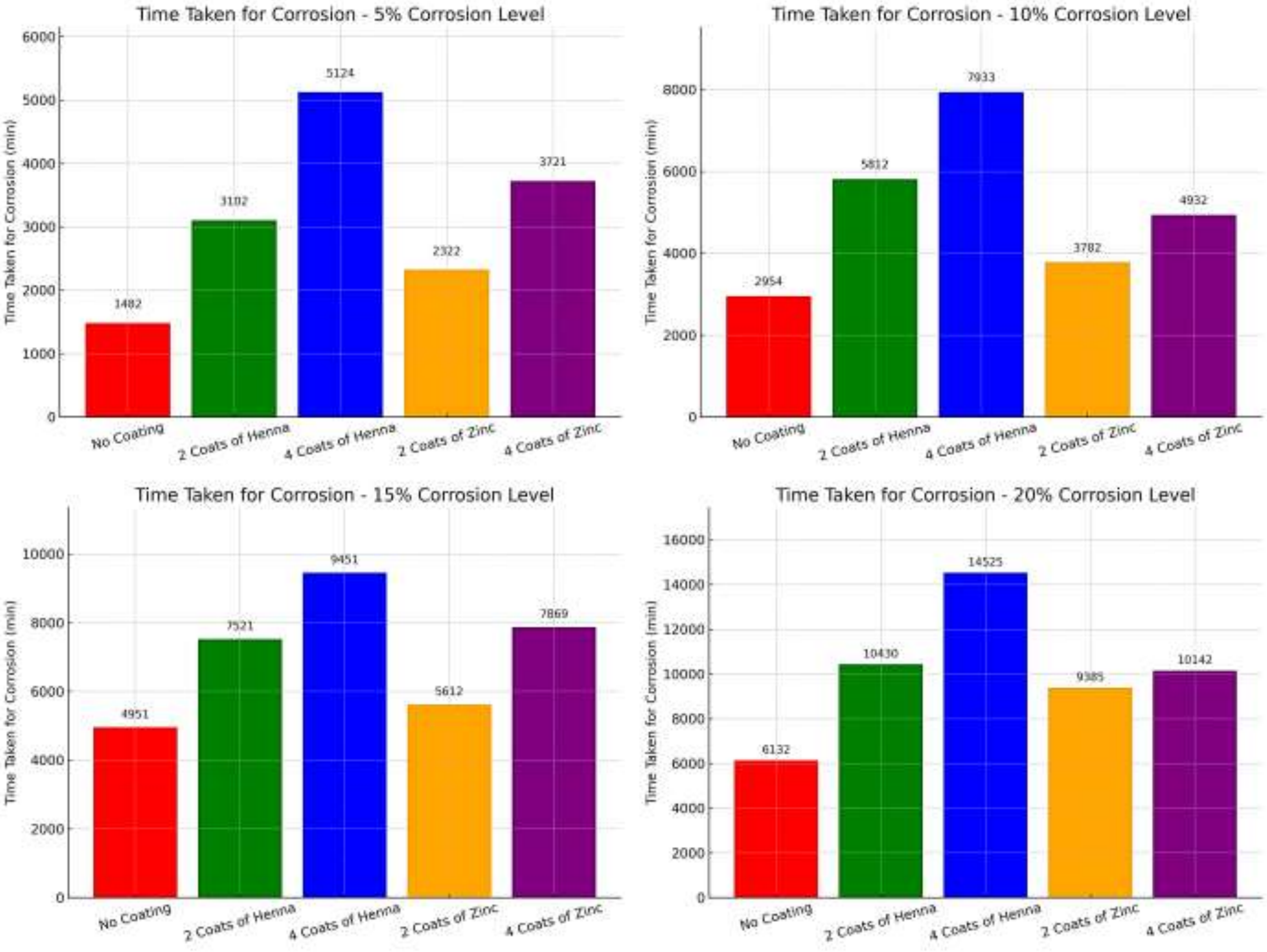


Fig. 7: Comparison of time taken to reach corrosion levels

As shown in Fig.7 the uncoated reinforcement bars corrode the fastest, showing the lowest time taken for corrosion initiation. Bars coated with Henna and Zinc significantly delay corrosion, with Henna being more effective in preventing corrosion as the number of coatings increases. The results clearly indicate that uncoated reinforcement bars corroded the quickest, reaching 5% corrosion in just one day and 20% by the fifth day. This highlights their low resistance to corrosion when exposed to harsh conditions. Applying 2 coats of henna (Batch 2) significantly slowed down the corrosion process compared to the uncoated bars, while 4 coats of henna (Batch 3) provided even greater protection, further delaying the progression of corrosion. Zinc coatings also helped in reducing corrosion, but they were not as effective as henna coatings. Among the zinc-coated samples, 4 coats (Batch 5) performed better than 2 coats (Batch 4), though the improvement was less pronounced compared to henna-coated bars. For instance, bars with 4 coats of zinc reached 20% corrosion in 7 days, whereas those with 2 coats took 6.5 days. Overall, henna coatings proved to be more effective than zinc coatings in slowing down corrosion, especially when applied in multiple layers. This could be due to the presence of organic tannins and antioxidants in henna, which form a protective barrier that slows the electrochemical reactions responsible for corrosion. On the other hand, zinc coatings work through sacrificial protection, but their efficiency may be affected by coating thickness or adhesion issues in the given experimental setup. Increasing the number of coats enhanced corrosion resistance by strengthening the protective layer, with henna showing superior performance in this study.

4.2. Pull out test Results

After performing the pull out test, the following results were obtained showing the effect on bond strength of concrete due to the corrosion levels and the presence of corrosion inhibitor coatings on the surface of the reinforcement. The results are formulated in the Table 3 below:

Table 3: Pullout Test Results

S.No	Sample	Embedded Bar Length (mm)	Diameter of Bar (mm)	Corrosion Percentage	Coating	Average Slippage at ultimate load (mm)	Average Ultimate Load (kN)	Average Ultimate Bond Strength (MPa)
1	Batch 1	290	16	0	No Coating	6.78	48.31	0.331
2	Batch 2	290	16	0	2 coats of Henna	5.23	47.91	0.329
3	Batch 3	290	16	0	4 coats of Henna	5.04	48.12	0.330
4	Batch 4	290	16	0	2 coats of Zinc	6.12	47.21	0.324
5	Batch 5	290	16	0	4 coats of Zinc	5.89	47.11	0.323
6	Batch 1	290	16	5	No Coating	6.28	42.11	0.289
7	Batch 2	290	16	5	2 coats of Henna	5.21	46.12	0.316
8	Batch 3	290	16	5	4 coats of Henna	5.01	47.12	0.323
9	Batch 4	290	16	5	2 coats of Zinc	5.91	46.23	0.317
10	Batch 5	290	16	5	4 coats of Zinc	6.01	45.89	0.315
11	Batch 1	290	16	10	No Coating	4.13	38.12	0.262
12	Batch 2	290	16	10	2 coats of Henna	4.89	45.12	0.310
13	Batch 3	290	16	10	4 coats of Henna	4.91	47.1	0.323
14	Batch 4	290	16	10	2 coats of Zinc	4.31	43.21	0.296
15	Batch 5	290	16	10	4 coats of Zinc	4.41	44.17	0.303
16	Batch 1	290	16	15	No Coating	3.51	31.41	0.215
17	Batch 2	290	16	15	2 coats of Henna	4.65	43.12	0.296
18	Batch 3	290	16	15	4 coats of Henna	4.83	45.13	0.310
19	Batch 4	290	16	15	2 coats of Zinc	4.15	40.13	0.275
20	Batch 5	290	16	15	4 coats of Zinc	3.92	41.21	0.283
21	Batch 1	290	16	20	No Coating	3.13	28.17	0.193
22	Batch 2	290	16	20	2 coats of Henna	4.51	42.14	0.289
23	Batch 3	290	16	20	4 coats of Henna	4.78	43.05	0.295
24	Batch 4	290	16	20	2 coats of Zinc	3.81	38.12	0.262
25	Batch 5	290	16	20	4 coats of Zinc	3.51	39.61	0.272

Uncoated reinforcement shows the most significant decline in bond strength, reducing from 0.331 MPa (0% corrosion) to 0.193 MPa (20% corrosion). Coated reinforcement exhibits relatively better retention of bond strength. 2 and 4 coats of Henna provide significant protection, reducing bond strength loss. At 0% corrosion, bond strength for 4 coats of Henna is 0.330 MPa, almost equal to uncoated bars. At 20% corrosion, bond strength remains at 0.295 MPa, which is 53% higher than uncoated bars. Zinc-coated samples show better performance than uncoated but slightly lower than Henna-coated samples. 2 coats of Zinc at 0% corrosion result in a bond strength of 0.324 MPa, slightly lower than 2 coats of Henna (0.329 MPa). At 20% corrosion, 4 coats of Zinc retain 0.272 MPa, which is 40% higher than uncoated samples as evident from Fig. 8 and 9. 4 coats of Henna consistently show the highest bond strength at each corrosion level, followed by 4 coats of Zinc. 2 coats of each inhibitor perform better than uncoated bars but are less effective than 4 coats. Rust formation increases volume, causing internal stresses that reduce adhesion. Henna, an organic inhibitor, forms a passive layer that delays chloride and oxygen penetration. Zinc coating provides a sacrificial protective barrier, reducing oxidation of the underlying steel. Ultimate load decreases with increasing corrosion, similar to bond strength trends. Uncoated bars exhibit the sharpest drop, from 48.31 kN (0% corrosion) to 28.17 kN (20% corrosion). Henna-coated bars maintain the highest load capacity, with 4 coats of Henna performing best across all corrosion levels. Zinc-coated bars also show improved performance over uncoated samples, but slightly lower than Henna-coated samples.

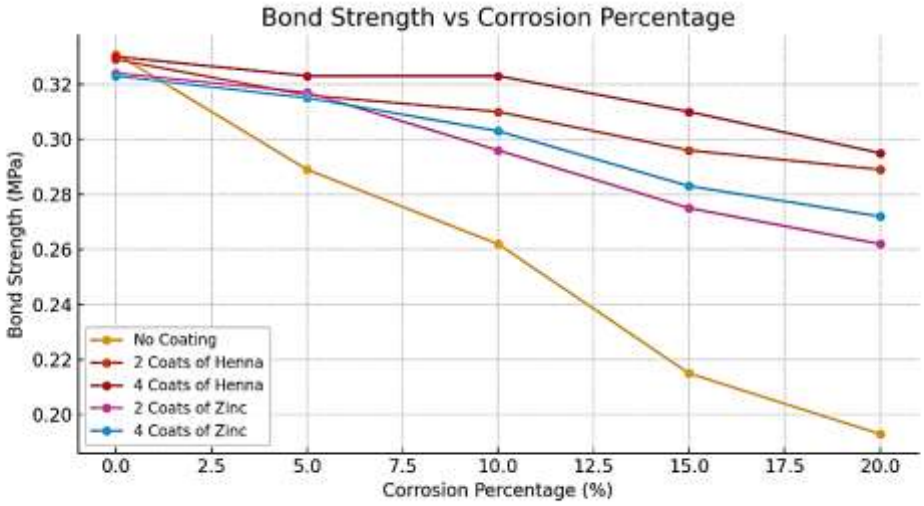


Fig. 8: Bond Strength vs. Corrosion Percentage

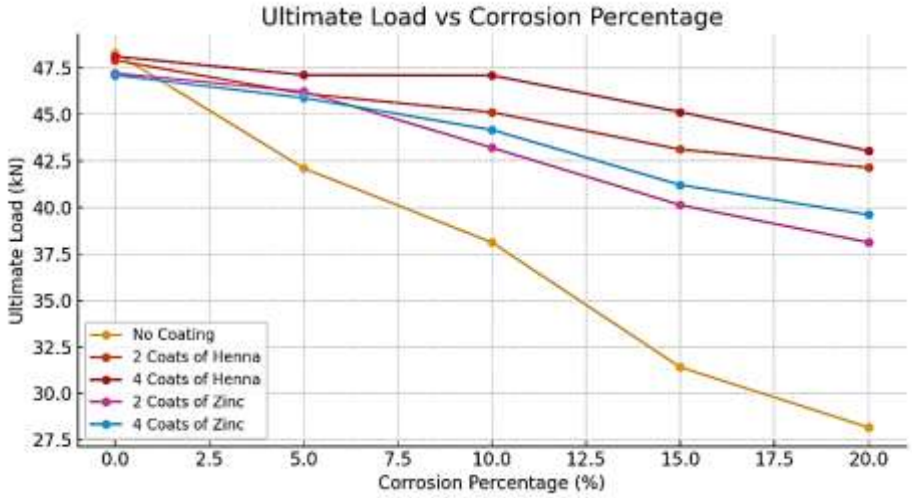


Fig. 9: Ultimate Load vs. Corrosion Percentage

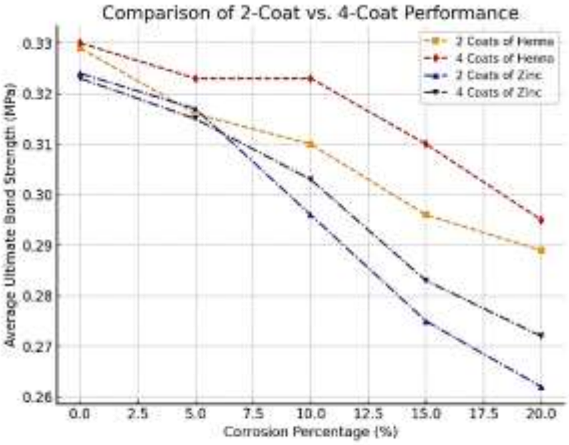


Fig. 10: 2 coat vs. 4 coat performance

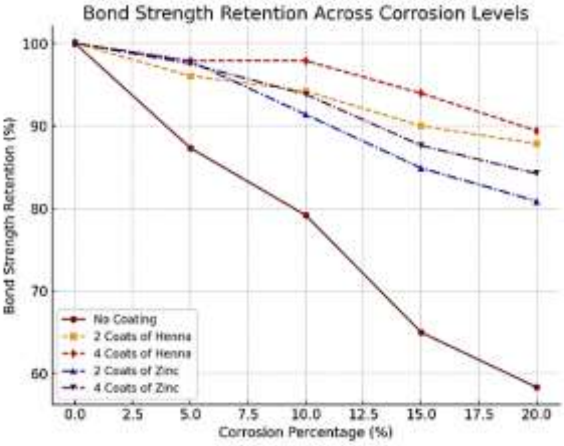


Fig. 11: Bond Strength Retention

As evident from Fig.10 and 11, henna coatings maintain higher bond strength than Zinc coatings at all corrosion levels. Uncoated bars show a steep decline, reaching ~58% retention at 20% corrosion. Henna-coated bars retain the highest bond strength, with 4 coats of Henna maintaining ~90% retention at 20% corrosion. Zinc coatings also improve retention, with 4 coats of Zinc holding ~84% at 20% corrosion. More coating layers significantly slow degradation, reinforcing the protective benefits of both organic and inorganic inhibitors.

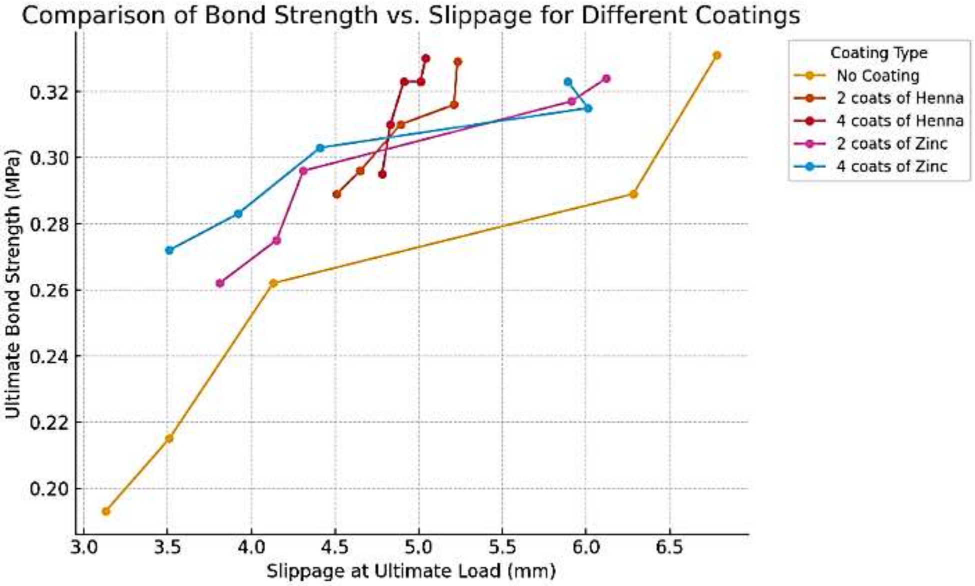


Fig. 12: Bond Strength vs. Slippage

As evident from the above Fig. 12, bond strength decreases as slippage increases, indicating that higher slippage leads to weaker bond performance. Samples with coatings (Henna or Zinc) exhibit slightly higher bond strength than uncoated samples, likely due to better adhesion and reduced corrosion effects. As corrosion percentage increases, both bond strength and slippage decrease. This is due to corrosion-induced damage weakening the bond between concrete and reinforcement. Henna-coated bars generally show slightly higher bond strength than zinc-coated bars at similar corrosion levels, suggesting better adherence properties. The superior bond strength retention observed in henna-coated reinforcement bars is due multiple factors. First, the surface texture of the dried henna coating—particularly when mixed with used engine oil—results in a micro-rough, slightly porous finish. This rough texture enhances mechanical interlock between the steel and surrounding concrete, unlike epoxy-based coatings which may create a smooth barrier. Second, the polyphenolic compounds in henna, such as lawsone, are known to chemically adsorb onto steel surfaces via coordinate bonding with iron atoms. This creates a stable passive layer that not only reduces corrosion but also inhibits rust expansion, which is a major contributor to bond degradation in corroded rebars. Additionally, this passive layer limits moisture ingress and chloride diffusion, reducing micro-cracking and concrete-rebar de-bonding typically associated with corrosion. These combined effects result in enhanced long-term bond performance even at high corrosion levels. Although zinc is a well-established sacrificial coating in corrosion protection, its comparatively lower performance in this study may be due to the that zinc coating primarily protects through anodic dissolution (sacrificial action), but once consumed or disrupted, it may no longer prevent localized corrosion.

4.3. Cost Analysis: Henna vs Zinc Coatings

The cost analysis highlights significant differences between henna and zinc coatings in terms of material price, coverage efficiency, and environmental impact. In terms of material cost, henna powder is more economical, ranging from ₹70 to ₹250 per kg, whereas zinc coatings are comparatively expensive, costing between ₹450 to ₹1400 per kg as per various online retailers (Amazon and IndiaMart). Despite zinc's higher material cost, its coverage efficiency is superior, achieving approximately 14 m^2 per kg per coat, whereas henna covers around 7 m^2 per kg per coat. When comparing the cost per square meter for a single coat, henna proves to be a more cost-effective option, costing approximately ₹10 to ₹36 per m^2, while zinc coatings range between ₹32 to ₹100 per m^2. From an application standpoint, henna offers a simpler, manual application process that requires minimal equipment, making it accessible for on-site applications with limited resources. In contrast, zinc coatings often demand specialized equipment, such as hot-dip galvanization setups, which adds to the overall labor and installation costs. In terms of environmental impact, henna holds a clear advantage as it is eco-friendly and biodegradable, posing minimal environmental risks. Conversely, zinc coatings require careful disposal procedures due to potential environmental concerns associated with heavy metal residues. Overall, henna offers a cost-effective, environmentally friendly, and easier-to-apply alternative, making it a promising choice for corrosion protection in certain structural applications. Combining both systems as a hybrid coating approach could provide an optimal balance between cost, performance, and environmental sustainability as shown in Table 4.

Table 4: Cost Analysis: Comparative

Parameter	Henna	Zinc
Cost	70 – 250 per kg	450 – 1400 per kg
Coverage Efficiency	7m^2 per kg per coat	14m^2 per kg per coat
Cost per m^2 (1-coat)	Rs. 10 – Rs. 36	Rs. 32 – Rs. 100
Application Process	Simple; can be applied manually	Requires specialized equipment (e.g., hot-dip galvanization)
Environmental Impact	Eco-friendly, biodegradable	Requires proper disposal procedures

6. ENVIRONMENTAL SUSTAINABILITY AND PRACTICAL IMPLICATIONS

Use of Zinc as an inhibitor coating presents significant environmental challenges as shown in Fig. 13. The galvanization process is highly energy-intensive, operating at temperatures around 450°C and involving flux chemicals like ammonium chloride or zinc ammonium chloride, which contribute to greenhouse gas emissions and toxic waste generation (Kumar et al. 2019). Moreover, during the service life of zinc-coated steel, zinc ions can leach into the environment, especially in wet, acidic, or coastal conditions. Studies have shown that zinc runoff from galvanized surfaces can contaminate surrounding soils and aquatic systems, potentially impacting microbial activity, plant growth, and aquatic organisms ((Kumar et al. 2024). Further, the accumulation of zinc in water bodies has been linked to bioaccumulation in aquatic life, with potential long-term ecological consequences. Due to these risks, many regulatory frameworks require controlled disposal or treatment of zinc waste and by-products, adding to the environmental management burden (Kumar et al. 2025). While zinc remains an effective corrosion barrier, its environmental footprint—including energy consumption, emissions, and potential ecotoxicity—limits its suitability in sustainable infrastructure development, especially when greener alternatives like biodegradable plant-based inhibitors are available.

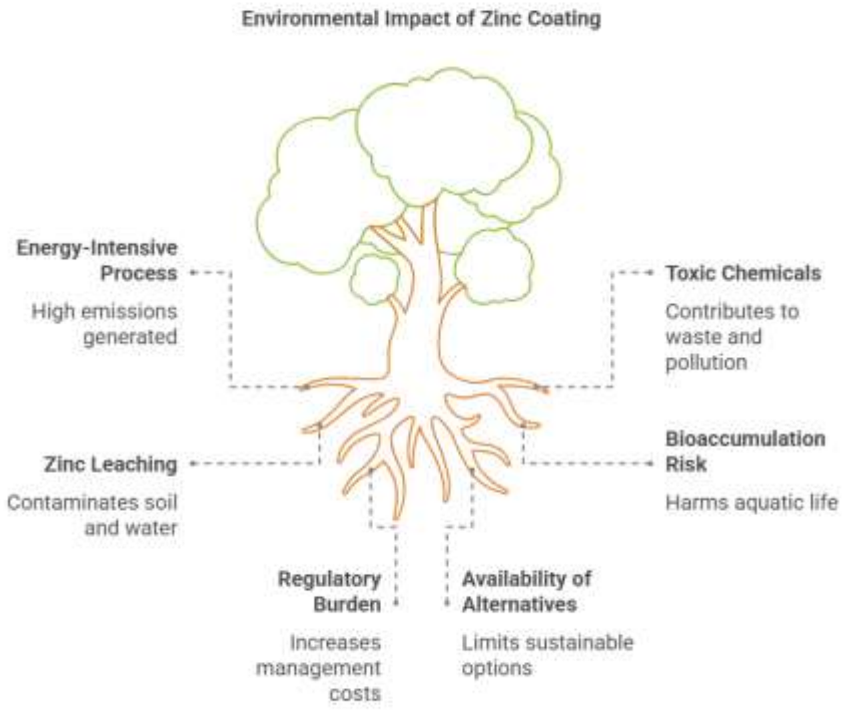


Fig. 13: Environmental Impact of Zinc Coating

The use of henna as a corrosion inhibitor presents a significant advancement toward sustainable construction practices as shown in Fig. 14. Unlike synthetic inhibitors, henna is a biodegradable, plant-based material with a low environmental footprint. Its effectiveness in reducing reinforcement corrosion directly translates to a reduction in steel deterioration and replacement over the structure’s lifecycle. This, in turn, minimizes the need for frequent maintenance, conserves natural resources, and reduces the energy and emissions associated with steel production and repair activities. By enhancing the longevity of reinforced concrete structures, the approach contributes to the goals of green infrastructure and sustainable urban development.

Furthermore, the affordability and availability of henna make it particularly suitable for application in developing regions, where cost-effective and eco-friendly engineering solutions are essential for large-scale infrastructure resilience.

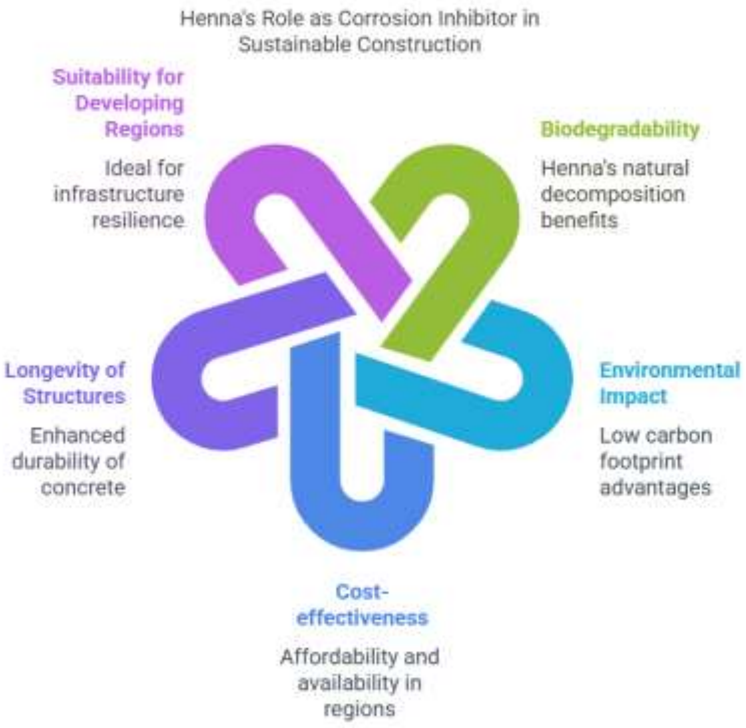


Fig. 14: Henna’s role in Sustainable Construction

Recent studies conducted discusses the Life Cycle Assessment (LCA) methodologies on the commercially available coating methods to prevent corrosion in steel, particularly in marine environments. Two most common methods used are Alkyd-Based Sol–Gel Coatings and Commercial Antifouling Coatings. A study conducted in 2024 analyzed the LCA of uncoated steel versus steel coated with an alkyd-based sol–gel system in marine settings. The findings revealed a significant 46% reduction in overall environmental impact for the coated system compared to the uncoated one. However, the study also identified that components like 3-glycidyloxypropyltrimethoxysilane and n-propanol contributed notably to environmental burdens, suggesting a need for bio-based alternatives to develop greener solutions (Borgaonkar & McNamara 2025, Song & Feng 2020). Another investigation focused on two commercial antifouling coatings—one based on Copper Oxide and the other on Zinc Oxide. Through a cradle-to-grave LCA, it was determined that the production phase had the highest environmental impact, primarily due to the use of chemical compounds. Laboratory tests further indicated strong bio-toxicity and contaminant diffusion in marine environments for both coatings, highlighting the necessity to replace toxic components with more environmentally friendly alternatives (Rossini et al. 2019, Suer et al. 2022, Detty et al. 2014). Furthermore, the use of used engine oil as a binder improved the hydrophobic characteristics and ease of application of the henna coating, it is important to recognize potential environmental and health concerns associated with its use. Used engine oil may contain residual heavy metals, combustion by-products, and other contaminants that could pose ecological risks if not managed properly. Although the oil in this study was used solely for laboratory-scale coating and was applied in small quantities, its large-scale or open-environment application would necessitate stringent containment and disposal practices to prevent leaching or contamination of soil and water systems. Future work should consider exploring environmentally safer binder alternatives—such as natural resins or plant-based oils—that provide similar adhesion and moisture resistance while aligning better with green construction practices.

While the short-term performance of henna-based coatings in an accelerated corrosion environment has demonstrated promising results, the long-term stability of these organic coatings under real-world exposure conditions remains a critical aspect for future validation. Organic compounds like lawsone and tannins present in henna may be susceptible to degradation when subjected to prolonged moisture exposure, fluctuating pH conditions (e.g., carbonation), or elevated temperatures commonly experienced in tropical or marine climates. Such environmental variability could affect the durability and adhesion of the coating over time. Although the hydrophobicity imparted by the used engine oil binder may initially reduce moisture ingress, its performance over extended periods under cyclic wet-dry or freeze-thaw conditions is not established. Therefore, future studies should focus on evaluating the stability and protective capacity of henna coatings under varied environmental conditions.

5. CONCLUSIONS AND FUTURE SCOPE

Using corrosion inhibitors to delay the rate of corrosion in concrete is a well-established and efficient method. However, the importance lies in understanding the location of corrosion in concrete. The corrosion in concrete occurs at the surface of the reinforcement bars which is embedded inside the concrete. Once these bars starts to corrode, rust is formed on the surface of the reinforcement bars which imparts stresses on the surrounding concrete, resulting in formation of cracks and ultimately leads to spalling of concrete. So there lies a need to use innovative methods to control the corrosion on the surface of the reinforcement bar. As proven from the research conducted the use of corrosion inhibitors coated on the surface of the reinforcement bar provides good protection against corrosion. The coatings of corrosion inhibitors delay the decay of the protective film over the surface of the reinforcement bars, which occurs due to change in pH of the concrete due to ingress of chlorides, sulphates and other harmful chemicals. As evident from the above research coatings of Henna powder and zinc powder were effective in delaying the rate of corrosion by almost 100% and 40% respectively. 4 coats of henna delayed corrosion progression to the 20% level by up to 14,525 minutes (~10 days), compared to 6,132 minutes (~5 days) for uncoated samples—representing a 137% improvement in time to critical corrosion level. This is due to the presence of organic tannins and antioxidants in henna, which form a protective barrier that slows the electrochemical reactions responsible for corrosion. However, another parameter to study was how does the provision of coatings effect the bond strength of concrete. Upon investigating it was observed that Henna coatings maintain higher bond strength than Zinc coatings at all corrosion levels at almost 90% retention levels of the bond strength at 20% corrosion levels. Uncoated bars experienced a 42% reduction in bond strength at 20% corrosion levels, demonstrating significantly lower protection. Further the cost analysis concluded that providing Henna coating on the steel surface was cost-effective at ₹10 – ₹36 per m^2, with a simple manual application process. This is due to the fact that the surface texture of the henna coating prepared was rough which further aided and enhanced the bond strength of concrete. This signifies that rather relying of epoxy-based coatings method on the reinforcement surface to control the corrosion which is a costlier method, materials like henna powder can be efficiently used as coatings on the surface of the reinforcement bars to control the corrosion along with minimal change in the bond strength of concrete resulting in more durable and long lasting concrete. This novel approach differentiates itself from epoxy-based and admixture-based techniques by targeting corrosion precisely at the source—on the steel surface—while maintaining bond strength. The results demonstrate that henna coatings can deliver dual benefits of corrosion inhibition and bond preservation, offering a low-cost, environmentally sustainable alternative to conventional protective systems.

An aspect that requires further investigation is the long-term durability of organic coatings. Since these coatings are organic in nature, they are susceptible to degradation over time. Exploring the sustained effectiveness of these organic inhibitor coatings in providing corrosion protection over extended periods presents a valuable area for future research. Once studied, this will further strengthen the effectiveness of the organic inhibitors in mitigating corrosion and reduce the dependency on the industrial based coatings for corrosion protection of the reinforcement steel in concrete and can further reduce the overall cost in repairs of structures. The use of natural inhibitors such as henna offers a promising pathway toward sustainable construction, combining durability enhancement with environmental responsibility. Although this study focused on individual performance of zinc and henna coatings, combining both in a hybrid coating system could be explored in future studies to achieve a balance between the sacrificial protection of zinc and the passive barrier action of henna. This concept is speculative at this stage and was not part of the current experimental scope.

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REFERENCES

1. Afandi, M.E., Yehia, S., Landolsi, T., Qaddoumi, N. and Elchalakani, M., 2023. Concrete-to-concrete bond Strength: A review. *Construction and Building Materials*, *363*, p.129820. 10.1016/j.conbuildmat.2022.129820.
2. Arslan, D., Özdemir, S.A., Cansever, N. and Sungur, E.I., 2024. Corrosion behavior of N80 tubing steel in the produced water. *Sigma Journal of Engineering and Natural Sciences*, *42*(2), pp.414-424. https://doi.org/10.14744/sigma.2024.00038 .
3. Asaad, M.A., Hussein, M.N., Alkadhimi, A.M. and Saleh, A.T., 2021. Commercial and green corrosion inhibitors for reinforced concrete structures: a review. *Int. J. Curr. Sci. Res. Rev*, *4*, pp.88-89. https://doi.org/10.47191/ijcsrr/v4-i2-04 .
4. ASTM G109-21: Standard Test Methods for Determining Effects of Chemical Admixtures on Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments.
5. ASTM C876-15: Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete.
6. Bajaj, D. and Khurpade, P.D., 2024. An Eco-friendly Mangifera indica Leaves Extract Corrosion Inhibitor for Stainless Steel in Acidic Medium. *Nature Environment and Pollution Technology*, *23*(1), pp.139-150. https://doi.org/10.46488/nept.2024.v23i01.010 .
7. Borgaonkar, A. and McNamara, G., 2024. Environmental Impact Assessment of Anti-Corrosion Coating Life Cycle Processes for Marine Applications. Sustainability, 16(13), p.5627. https://doi.org/10.3390/su16135627.
8. Cai, R., Tian, Z. and Ye, H., 2022. Durability characteristics and quantification of ultra-high strength alkali-activated concrete. *Cement and Concrete Composites*, *134*, p.104743. https://doi.org/10.1016/j.cemconcomp.2022.104743 .
9. Çöğürcü, M.T. and Uzun, M., 2022. Effects of accelerator type and dosage on the mechanical and durability properties of rapid-setting precast concrete. *Sigma Journal of Engineering and Natural Sciences*. https://doi.org/10.14744/sigma.2022.00084 .
10. Courard, L., Piotrowski, T. and Garbacz, A., 2014. Near-to-surface properties affecting bond strength in concrete repair. *Cement and Concrete Composites*, *46*, pp.73-80. https://doi.org/10.1016/j.cemconcomp.2013.11.005 .
11. Deliktaş, E.B., Uysal, M. and Güngör, N.D., 2024. Investigation of using cave bacteria in the production of self-healing mortars. *Sigma Journal of Engineering and Natural Sciences*, *42*(6), pp.1712-1728. https://doi.org/10.14744/sigma.2024.00054 .
12. Detty, M.R., Ciriminna, R., Bright, F.V. and Pagliaro, M., 2014. Environmentally benign sol–gel antifouling and foul-releasing coatings. Accounts of chemical research, 47(2), pp.678-687. 10.1021/ar400240n.
13. Dybeł, P. and Wałach, D., 2017, October. Evaluation of the development of bond strength between two concrete layers. In *IOP conference series: Materials science and engineering* (Vol. 245, No. 3, p. 032056). IOP Publishing. https://doi.org/10.1088/1757-899x/245/3/032056 .
14. El-Etre, A.Y., Abdallah, M. and El-Tantawy, Z.E., 2005. Corrosion inhibition of some metals using lawsonia extract. *Corrosion science*, *47*(2), pp.385-395. https://doi.org/10.1016/j.corsci.2004.06.006 .
15. Fernando, S., Gunasekara, C., Law, D.W., Nasvi, M.C.M., Setunge, S. and Dissanayake, R., 2023. Assessment of long term durability properties of blended fly ash-Rice husk ash alkali activated concrete. *Construction and Building Materials*, *369*, p.130449. https://doi.org/10.1016/j.conbuildmat.2023.130449 .
16. Bureau of Indian Standards (BIS). (1967). Methods of testing bond in reinforced concrete - Part 1: Pull-out test (IS 2770-1:1967).
17. Julio, E.N., Branco, F.A. and Silva, V.D., 2004. Concrete-to-concrete bond strength. Influence of the roughness of the substrate surface. *Construction and building materials*, *18*(9), pp.675-681. https://doi.org/10.1016/j.conbuildmat.2004.04.023 .
18. Kadhim, A., Al-Amiery, A.A., Alazawi, R., Al-Ghezi, M.K.S. and Abass, R.H., 2021. Corrosion inhibitors. A review. *International Journal of Corrosion and Scale Inhibition*, *10*(1), pp.54-67. 10.17675/2305-6894-2021-10-1-3.

19. Kamarska, K.V., 2024. Investigation of Rosemary Oil as Environmentally Friendly Corrosion Inhibitor of Aluminum Alloy. *Nature Environment and Pollution Technology*, *23*(3), pp.1723-1727. https://doi.org/10.46488/nept.2024.v23i03.044 .
20. Kumar, A., 2020. Introduction of Inhibitors, Mechanism and Application for Protection of Steel Reinforcement Corrosion in Concrete. In *Corrosion*. IntechOpen. https://doi.org/10.5772/intechopen.92374 .
21. Kumar, N., Chalisey, B., Saharan, S. and Gupta, M., 2019. Effect of Surface Applied Organic and Inorganic Corrosion Inhibitors on Reinforced Steel in Concrete. *International Journal of Engineering and Advanced Technology*, *9*(2), pp.3023-3031. https://doi.org/10.35940/ijeat.b4092.129219 .
22. Kumar, N., Noor, I.S.M., Yahya, M.Z.A. and Prakash, S., 2025. Botanical corrosion inhibitors in reinforced concrete: material sustainability assessment and analysis-a review. *Zastita Materijala*, *66*(1), pp.40-55. https://doi.org/10.62638/zasmat1092 .
23. Kumar, N., Prakash, S., Ghani, S., Gupta, M. and Saharan, S., 2024. Data-driven machine learning approaches for predicting permeability and corrosion risk in hybrid concrete incorporating blast furnace slag and fly ash. *Asian Journal of Civil Engineering*, *25*(4), pp.3263-3275. https://doi.org/10.1007/s42107-023-00977-8 .
24. Monticelli, C., Frignani, A. and Trabanelli, G., 2000. A study on corrosion inhibitors for concrete application. *Cement and concrete research*, *30*(4), pp.635-642. https://doi.org/10.1016/s0008-8846(00)00221-0 .
25. Rossini, P., Napolano, L. and Matteucci, G., 2019. Biotoxicity and life cycle assessment of two commercial antifouling coatings in marine systems. Chemosphere, 237, p.124475. 10.1016/j.chemosphere.2019.124475.
26. Shunmuga Vembu, P.R. and Ammasi, A.K., 2023. A comprehensive review on the factors affecting bond strength in concrete. *Buildings*, *13*(3), p.577. https://doi.org/10.3390/buildings13030577 .
27. Song, G.L. and Feng, Z., 2020. Modification, degradation and evaluation of a few organic coatings for some marine applications. Corrosion and Materials Degradation, 1(3). https://doi.org/10.3390/cmd1030019.
28. Söylev, T.A. and Richardson, M.G., 2008. Corrosion inhibitors for steel in concrete: State-of-the-art report. *Construction and building Materials*, *22*(4), pp.609-622. https://doi.org/10.1016/j.conbuildmat.2006.10.013 .
29. Suer, J., Traverso, M. and Jäger, N., 2022. Review of life cycle assessments for steel and environmental analysis of future steel production scenarios. Sustainability, 14(21), p.14131. https://doi.org/10.3390/su142114131.
30. Sugama, T. and Pyatina, T., 2017. Bond durability of carbon-microfiber-reinforced alkali-activated high-temperature cement adhering to carbon Steel. *Engineering*, *9*(02), p.142. https://doi.org/10.4236/eng.2017.92007 .
31. Yan, F., Lin, Z. and Yang, M., 2016. Bond mechanism and bond strength of GFRP bars to concrete: A review. *Composites Part B: Engineering*, *98*, pp.56-69. https://doi.org/10.1016/j.compositesb.2016.04.068 .
32. Ye, H., Cai, R. and Tian, Z., 2020. Natural carbonation-induced phase and molecular evolution of alkali-activated slag: Effect of activator composition and curing temperature. *Construction and Building Materials*, *248*, p.118726. https://doi.org/10.1016/j.conbuildmat.2020.118726 .
33. Zhao, L. and Luo, Q., 2024. Evaluating bonding strength in UHPC-NC composite: A comprehensive review of direct and indirect characterization methods. *Construction and Building Materials*, *443*, p.137701. https://doi.org/10.1016/j.conbuildmat.2024.137701 .