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Enhanced Corrosion Resistance of Reinforced Concrete Using Inhibitor-Based Admixtures: An Experimental Study

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Abstract

Corrosion of embedded steel can have serious impacts on the durability of reinforced concrete structures, particularly when they are in harsh environments, such as marine and industrial environments. Mitigating this degradation is critical to long-lasting structural behavior. The concrete samples were chemically prepared by adding a variety of corrosion-inhibiting admixtures in different proportions and compared with normal concrete. Compressive strength testing, accelerated corrosion exposure, half-cell potential, and chloride penetration were performed to quantify the strength and corrosion resistance. Results revealed that the inclusion of the corrosion inhibitors effectively retarded the corrosion in steel reinforcement. The reinforced concrete, as well, proved to possess lower chloride penetration, and with satisfactory strength properties. Compared with the traditional mixes, these specimens had better resistance. Results clearly provide for the need for corrosion-reducing admixtures which serve as a useful and efficient medium to prolong the useful life of reinforced concrete. Such applications can safeguard buildings in hostile conditions and minimize over time maintenance requirements.

Keywords: Reinforced concrete, Corrosion inhibitors, Steel corrosion, Durability, Chloride penetration, Admixtures, Service life.

1.Introduction

Reinforced concrete is among high strength, durable, economical, and cost-efficient building materials used in today's civil engineering applications and is one of the most popular building materials. It is widely used in building, highways, bridges, and marine systems. Reinforced concrete functions under various loads and environmental conditions in good condition, whereas corrosion of embedded steel reinforcement continues to be one of the most serious durability issues of its kind, hindering its long-term performance. The corrosion of reinforcement occurs at the onset of such a physical process when certain sources such as chloride ions, carbon dioxide, oxygen, and moisture pass through the concrete and reach the steel. Chloride attack is one of the most important causes of corrosion among them, particularly in seas and marine areas. When corrosion begins, the steel reinforcement reacts with oxygen and moisture to form rust. These corrosion products take up more volume than the steel in the original position and cause pressure inside the concrete material. This interior expansion causes cracking, delamination, and, ultimately, spalling of the concrete cover. Consequently, the structural integrity of concrete is adversely impacted, along with service life. Apart from the issues related to safety, corrosion-related damage is also costlier due to maintenance, repair, and rehabilitation. There are different methods that are developed in order to mitigate reinforcement corrosion in concrete structures. These include protective coatings for steel bars, cathodic protection systems, surface sealants, and corrosion inhibitor admixtures. Of these, corrosion inhibitor admixtures have been considered as efficient methods of intervention that are readily added during concrete mixing and therefore can easily be added to cement concrete during mixing and do not require complex installation. Corrosion inhibitors are chemical agents that prevent corrosion of steel reinforcement by interfering with the electrochemical reactions taking place at the surface of the steel. As such, these inhibitors form a thin protective layer surrounding the reinforcement, which blocks the interaction between steel and hostile ions found in the environment. Inhibitors could, in some cases, even enhance the density of the concrete matrix to prevent its permeability and penetration of harmful agents. Recently the application of inhibitor-based admixtures has been recognised as an effective way to strengthen the durability of reinforced concrete structures in hostile environmental conditions to a certain extent. However, the performance of such inhibitors would be influenced by a wide range of factors including dosage, concrete composition, and environmental exposure. For that reason, experimental work is needed to verify the efficacy of corrosion inhibitor admixtures in reinforced concrete. The objective of this study is to study the effects of inhibitor-based admixtures on corrosion resistance performance and durability performance of reinforced concrete. The experimental approach involves testing for compressive strength, accelerated corrosion, half-cell potential, and chloride penetration, which are part of the experimental series. Hence, the findings from this study inform valuable research on the influence of corrosion inhibitors in enhancing the durability and service life of reinforced concrete structures.

2. Literature Review

Research focusing on corrosion in reinforced concrete, especially in aggressive environmental exposure conditions (marine environments; for example, in an industrial setting) has been a significant area of research. This section summarizes main studies by discussing their methodology, findings, strengths, and limitations. Early studies tried to determine the main causes of corrosion. Some of the investigators used electrochemical methods of determination (including half-cell potential and linear polarization resistance) to prove that the leading triggers of corrosion are chloride ingress and carbonation. Their findings revealed that chloride ions break down the passive oxide coating of steel in the steel reinforcement and carbonation lowers the alkalinity of concrete. These investigations have laid a solid theoretical groundwork for research, but they were frequently confined to controlled laboratory settings and, thus, lacked field validation. Later research has studied the mechanical effects of corrosion. When conducting accelerated corrosion by means of the impressed current methods (e.g., impressed methods), the team showed that the amount of corrosion products occupies a larger volume than the original steel, and as a result, internal tensile stresses, cracks and spalling of concrete are introduced inside the concrete. Although these findings yielded good measurements of damage progression, the rapidity results of these studies sometimes resulted in the overestimation of the field degradation rate. Advances in material science shifted the focus to prevent any corrosion and specifically on inhibitor based admixtures. Comparative experimental methods were employed in comparing the concrete mixes with and without inhibitors for the same experiments. Both inorganic (nitrite-based) and organic (amine-based) inhibitors were reported. Results showed consistently that this admixture can reduce the corrosion current density through formation of a protective film on the steel. The strength of these studies is their practical application in construction, but some studies described variability in corrosion effect for environmental exposures and dosage application levels. This approach has also been studied in the context of chloride penetration resistance (RCPT, Diffusion Coefficient Analysis). Inhibitors were found to reduce chloride permeability and improve the durability. Microstructural analysis such as SEM and XRD in small scale confirmed better matrix densification. While these approaches provided significant details, they necessitated high-level apparatus and were not commonly practical for normal use. Studies made on new methodology (2022–2025) have combined state-in-the-field technologies and hybrid techniques. Combining corrosion inhibitors with auxiliary cementitious materials which consisted fly ash, silica fume and slag was implemented. The approach included multi-parameter optimization, such as durability indices, mechanical strengths, and long-term exposure studies. The results revealed the synergistic effects, where inhibitors reduced corrosion and pozzolanic compounds improved microstructure. Nevertheless, these systems can escalate complexity in mix design and require thorough quality control.

An alternative perspective has emerged with the use of green/eco-friendly inhibitors, obtained from plant extracts/industrial by-products. Weight loss, electrochemical impedance spectroscopy, and surface characterization are commonly performed in experimental procedures. These works showed good corrosion resistance with reduced environmental impact. But there are restrictions such as the variability in

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composition and the absence of prolonged durability data. Other field-based studies have validated laboratory results. They studied reinforced concrete structures in real-world marine environments for long time frames.

The findings also indicated that inhibitor-treated concrete displays lower rates of corrosion and a delayed crack development. The big benefit of these studies, however, is their real-world relevance but they are time-consuming and expensive. Moreover, corrosion behavior has been defined based on numerical modelling and simulation. These models include diffusion mechanisms, electrochemical kinetics, and environmental influences. Although they offer useful predictive capacity, their accuracy relies on what parameters, and assumptions are included in the data as inputs to predict the outcome.

In addition, numerical modeling and simulation studies have been carried out to predict corrosion behavior. These models incorporate diffusion mechanisms, electrochemical kinetics, and environmental factors. While they provide valuable predictive capability, their accuracy depends heavily on input parameters and assumptions.

2. Materials and Methods

2.1 Materials

2.1.1 Cement : Binding material for concrete specimens was ordinary Portland Cement (OPC). Since it is widely used in construction, cement provides reliable strength and durability. The cement reacts with water and forms a hardened paste that holds the aggregates together during the hydration phase, which creates its structural strength.

2.1.2 Fine Aggregate : Fine aggregate of the concrete mix was natural river sand. The sand was clean and devoid of impurities like clay, silt and organic matter. Fine aggregate provides the gap between coarse aggregates and enhances workability and uniformity in the concrete mix.

2.1.3 Coarse Aggregate : Crushed stone aggregates of the required size were applied as coarse aggregates. These aggregates serve as the primary framework for the concrete and make a major contribution to its strength and stability. The aggregates used were clean, strong, and free from dust or any harmful material which could influence the performance of concrete.

2.1.4 Water : Mixing and curing of concrete specimens was conducted in clean potable water. No oils, salts or chemicals were found in the water, thus preventing interference with cement hydration and reinforcement damage. To avoid poor strength development and durability of concrete, the water must be of proper quality to maintain good strength and durability.

2.1.5 Corrosion Inhibitor Admixture : Corrosion inhibitor admixtures were added in the concrete mix as a means to reduce corrosion of embedded steel reinforcement. This chemical additive works to slow down the electrochemical reactions which can create rust on steel. The inhibitor helps protect the reinforcement and enhance the durability of reinforced concrete, particularly in aggressive environments.

2.1.6 Steel Reinforcement Bars : To test the corrosion behavior in concrete specimens, steel reinforcement bars were inserted. The bars represent the reinforcement used in real reinforced concrete structures. Before casting, steel bars were cleaned to remove dirt or rust so that accurate corrosion readings could be taken during testing.

2.2 Mix Proportion

Table 1: Concrete Mix Proportion

Material	**Quantity (kg/m³)**
Cement	400
Fine Aggregate	650
Coarse Aggregate	1200
Water	180
Water-Cement Ratio	0.45
Corrosion Inhibitor (0%)	Control Mix
Corrosion Inhibitor (1%)	Mix A
Corrosion Inhibitor (2%)	Mix B

Concrete mix was designed according to standard guidelines. Different percentages of corrosion inhibitor admixtures (0%, 1%, and 2% by weight of cement) were incorporated into the concrete mixtures.

2.3 Preparation of Specimens : Concrete samples were cast in standard moulds and cured under controlled conditions for 7, 14, and 28 days. The specimens contained central reinforcement bars for corrosion analysis.

3. Experimental Tests :The mechanical strength and corrosion resistance performance of reinforced concrete specimens were evaluated through the following tests.

3.1 Compressive Strength Test : A compressive strength test was conducted to determine the load-carrying capacity of the concrete. Concrete cubes were cured under different curing period conditions with the help of a Compression Testing Machine (CTM). The maximum load applied before failure was recorded and was used for determination of the compressive strength of the concrete.

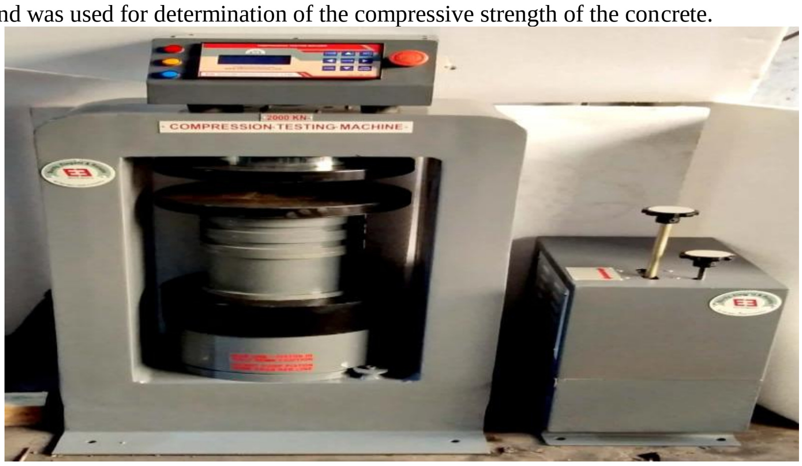

Fig1: Compression Testing Machine used for strength evaluation

3.2 Accelerated Corrosion Test

To simulate corrosion of reinforcement steel in a short time, an accelerated corrosion test was executed. Concrete samples were placed in a sodium chloride (NaCl) solution and an electric current was introduced to enhance the corrosion activity. Corrosion rate and damage evolution were observed and recorded.

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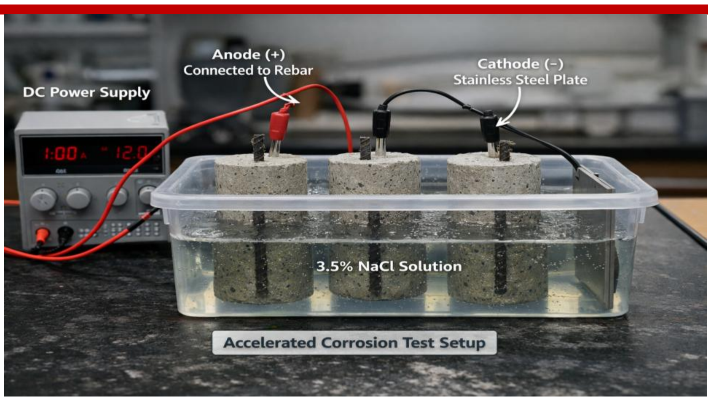

Fig2:Accelerated corrosion test setup with embedded reinforcement

3.3 Half-Cell Potential Measurement: The half-cell potential test is a non-destructive method of assessing the risk of corrosion of the reinforcement. A reference electrode, typically copper–copper sulfate, was positioned on the surface of the concrete and electrical potential differences between the electrode and the reinforcement steel were measured by a voltmeter. The measured potential values represent the probability of corrosion in the reinforcement.

Fig3:Half-cell potential measurement using copper–copper sulfate electrode

3.4 Chloride Penetration Test : The chloride penetration test was conducted to see if concrete can resist the ingress of chloride. Concrete samples were placed in chloride solutions, then the depth of penetration of chloride ions was measured. An assessment of the durability of concrete in harsh environments like marine environments is performed for this test.

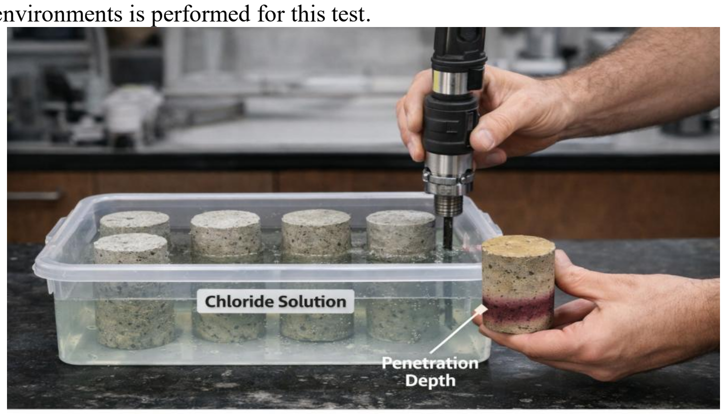

Fig4:Chloride penetration testing of concrete specimens

3.5 Visual Crack Observation: During the corrosion process, cracks were visually observed on the concrete surface. The extent, pattern, and distribution of crack width were observed in order to evaluate deterioration of reinforced concrete specimens.

4. Results and Discussion

The performance of reinforced concrete utilizing corrosion inhibitor admixtures was monitored by means of compressive strength testing, half-cell potential tests, chloride penetration testing, accelerated corrosion testing, and visual crack analysis. These experimental results illustrate the performance improvement properties of inhibitor-based admixtures on reinforced concrete by enhancing the mechanical and durability properties

.4.1 Compressive Strength Results

Table 2: Compressive Strength Results

Mix Type	**7 Days (MPa)**	**14 Days (MPa)**	**28 Days (MPa)**
Control Concrete	24	30	36
1% Inhibitor Concrete	25	32	38
2% Inhibitor Concrete	26	33	40

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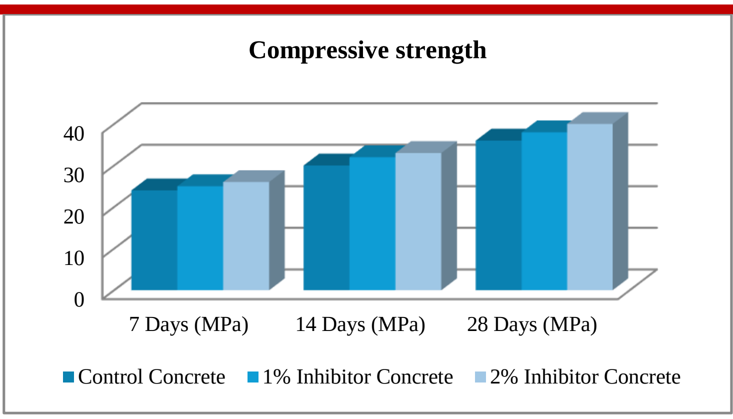

Fig5: Compressive strength results

The compressive strength results also show that with a slightly increased proportion of corrosion inhibitor admixtures the mechanical strength of concrete improved. At 7 days of curing the compressive strength of the control concrete reached 24 MPa, 1% inhibitor concrete 25 MPa, 2% inhibitor mix 26 MPa. The effectiveness is ascribed to improved hydration and microstructural densification in a cement matrix by chemical admixtures. 14 days later, the compressive strength of the control mixture increased to 30 MPa, 32 MPa for the 1% inhibitor mix, and 33 MPa for the 2% inhibitor mix. The strength increase correspondingly indicated improved bonding between cement paste and aggregates. The compressive strength of the control concrete improved up to 36 MPa after 28 days of curing whereas, 1% and 2% inhibitor mixes achieved 38 MPa and 40 MPa respectively. The strength after finishing a 2% inhibitor mix was approximately 11% higher than that of control specimen. This indicates that the inhibitor admixture not only safeguards reinforcement but also increases concrete matrix density and strength development.

4.2 Half-Cell Potential Measurement

Table 3: Half-Cell Potential Results

Mix Type	Potential (mV)	Corrosion Probability
Control Concrete	-420	High
1% Inhibitor	-320	Moderate
2% Inhibitor	-250	Low

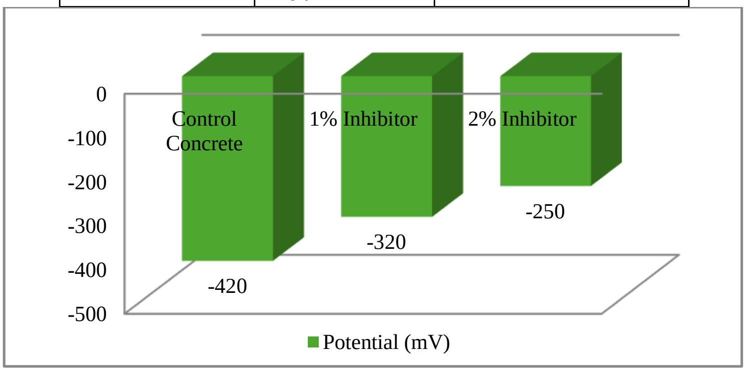

Fig6:Half-Cell Potential Results

The half-cell potential experiments were carried out to measure the probability and nature of corrosion of the embedded reinforcement. It is generally recommended that potential values more negative than -350 mV indicate a high risk of corrosion, according to the most common corrosion probability criteria. The potential of action of the control concrete sample was -420 mV suggesting a high probability of active corrosion of the reinforcing steel. This finding verifies that concrete without corrosion inhibitors is more prone to electrochemical corrosion mechanisms. Potential value of the 1% inhibitor mixture improved to about -320 mV which means there is a moderate chance of corrosion. The decrea se in negative potential implies that corrosion inhibitor decreases electrochemical processes on the steel surface. At low likelihood for corrosion, the 2% inhibitor mixture had the lowest negative potential value of -250 mV. This finding shows that higher inhibitor dosage is associated with a good corrosion resistance of the reinforcement steel, as a protective layer is formed around the steel surface.

4.3 Chloride Penetration Test

Table 4: Chloride Penetration Results

Mix Type	Chloride Penetration Depth (mm)
Control Concrete	18
1% Inhibitor Concrete	12
2% Inhibitor Concrete	8

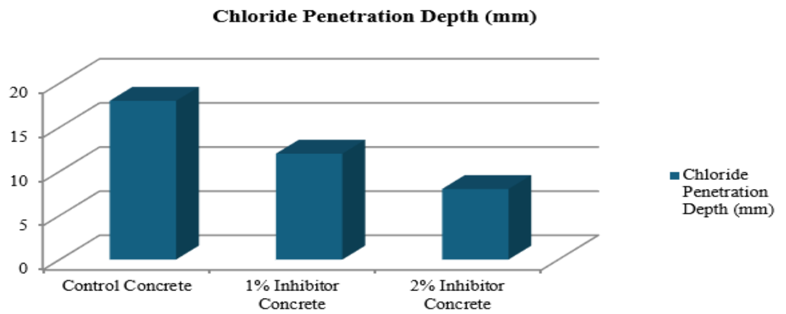

Fig7:Chloride Penetration Results

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The penetration test of chloride determines the resistance of concrete to intrusion of chloride ions; this is a significant contributor to reinforcement corrosion in marine and coastal environments. The control concrete specimen showed a chloride penetration depth of 18 mm, indicating relatively greater permeability. This enables chloride ions to penetrate the reinforcement and trigger corrosion mechanisms.

The 1% inhibitor concrete led to a penetration depth of 12 mm, which is 33% lower than the control mix. The improvement indicates that the inhibitor admixture improves the compactness of the microstructure of the concrete.

The 2% inhibitor had the lowest chloride penetration, 8 mm, accounting for almost 55% decrease with respect to control concrete. The lower permeability suggests that inhibitor-based admixture effectively halts the diffusion of chloride ions and increases the durability of concrete in aggressive environments.

4.4 Accelerated Corrosion Test Analysis: With the effect of corrosion occurring over a extended period, accelerated corrosion tests were performed. For the steel testing, the reinforced concrete cases were exposed to a solution of sodium chloride by an applied external electrical current, which would speed the process of corrosion. The control specimens showed earlier crack formation and rust stains visible on the concrete surface indicating active corrosion of the reinforcement steel. Conversely, results of corrosion inhibitor mixture showed delayed crack development and lower corrosion current values, indicating increased corrosion resistance.

Most of the specimens showed the best performance with the 2% inhibitor mix exhibiting minimal surface cracking and lower corrosion activity. This confirms that inhibitors are very effective in corrosion resistance, slowing the corrosion process in reinforced concrete.

4.5 Visual Crack Observation: On the corrosion test basis, visual inspection of concrete specimens indicated a clear distinction of crack-formation mechanism between the control and inhibitor mixes. The wider cracks and surface degradation caused by the growth of corrosion products around the steel reinforcement was recorded within control specimens.

These cracks facilitate moisture and aggressive ions to penetrate the concrete, hastening structural decay. Additionally, specimens which had corrosion inhibitors demonstrated smaller crack widths and reduced surface damage. The inhibitor surrounding the steel reinforced layer acts as a barrier against corrosion expansion preventing early cracking of the concrete cover.

4.6 Overall Performance Evaluation: The combined results from compressive strength testing, half-cell potential measurements, chloride penetration tests, accelerated corrosion tests, and visual crack observations clearly demonstrate the effectiveness of corrosion inhibitor admixtures in reinforced concrete.

The 2% inhibitor mix consistently showed the best performance, including:

1) Higher compressive strength
2) Lower corrosion probability
3) Reduced chloride penetration
4) Delayed crack formation
5) Improved durability characteristics

These improvements confirm that corrosion inhibitor admixtures provide a reliable and cost-effective solution for protecting reinforcement steel and enhancing the service life of reinforced concrete structures exposed to aggressive environments.

5. Conclusion

The experimental study aimed to evaluate the efficiency of using corrosion inhibitor admixtures aimed to improve the corrosion resistance and durability of reinforced concrete.

The incorporation of corrosion inhibitors greatly increases reinforced concrete performance under aggressive environmental conditions. Inhibitor admixtures exhibited superior compressive strength in concrete specimens compared to conventional concrete as they exhibited increased microstructural properties and enhanced bonding characteristics.

Half-cell potential analysis shows that the chances of corrosion in reinforced steel decreases dramatically with increase in inhibitor concentration. Control concrete had a high corrosion probability, while 2% inhibitor concrete exhibited low corrosion activity.

Chloride penetration tests showed that the penetration depth of chloride ions was significantly reduced with nearly 55% lower penetration depth than control concrete (2% inhibitor blend). One reason for this improvement is the reduction in the permeability as well as the development of a protective film on the surface reinforcement.

Accelerated corrosion testing and visual crack observations both indicated that inhibitor-based admixtures can significantly postpone corrosion initiation and slow the crack development in reinforced concrete specimens.

The findings indicate that corrosion inhibitor admixtures is an economical and successful means of corrosion resistance of reinforcing steel and that, as a result, increasing the longevity of reinforced concrete materials. It is also possible to contribute to significantly increase the service life of these infrastructure exposed to marine, industrial and chloride-rich conditions, and minimize cost of maintenance and repair, by application of inhibitor-based admixtures.

Future study of corrosion inhibitors such as the one mentioned will also entail an investigation of performance in long-term field tests, dosage optimization, and a combination of corrosion inhibitors and other methods to improve durability of sustainable construction.

Future Work

Such investigation was done and verified that inhibitor-based additives can enhance rehabilitation performance on reinforced concrete. Yet more research is required to better understand and achieve application of these materials. We suggest future research on long-term performance of corrosion inhibitor admixtures, i.e., real environment condition-reactive concrete structures, including marine, coastal and industrial conditions.

And in addition, we also suggest to carry out more experiments in the use of the combination of corrosion inhibitors with other cementitious substances (fly ash, silica fume, and ground granulated blast furnace slag). Studying these combinations could aid improvement of strength and durability and therefore improve the environmentally-friendly properties of the concrete.

In future work, advanced monitoring techniques can also be applied. Electrochemical sensors, corrosion monitoring systems and data-driven prediction based models are some of the methods that can be used that can accurately assess the initiation and progression of corrosion of reinforced concrete structures. Moreover, it could also be looked at for eco-friendly corrosion inhibitors of natural or organic materials. These green inhibitors could yield excellent performance for the reinforcement steel and minimize their environmental damages.

Finally, practical field research should be conducted to assess the workability of corrosion inhibitor admixtures in practical construction works. This will help in the development of practical guidelines for the use of these approaches in long-term reinforced concrete structures.

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