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Review of Corrosion Mitigation Techniques in Reinforced Concrete Using Migrating Corrosion Inhibitors

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Abstract: Corrosion of steel reinforcement is one of the major causes of deterioration in reinforced concrete structures exposed to aggressive environmental conditions. Chloride attack, moisture penetration, carbonation, and cyclic wetting–drying conditions accelerate the corrosion process and reduce structural durability. Various corrosion mitigation techniques have been developed to improve the service life of reinforced concrete structures, among which migrating corrosion inhibitors (MCIs) have gained significant attention due to their ability to penetrate hardened concrete and protect embedded reinforcement. This review paper presents a detailed study of corrosion mechanisms, deterioration of reinforced concrete under chloride exposure, corrosion protection techniques, and the effectiveness of migrating corrosion inhibitors based on recent research studies. The paper also reviews recent developments related to corrosion resistance, durability enhancement, and cyclic exposure behavior reported by different researchers. Finally, the proposed study on corrosion mitigation in reinforced concrete beams using migrating corrosion inhibitors under cyclic chloride exposure is presented.
Keywords: Reinforced concrete, corrosion mitigation, migrating corrosion inhibitor, chloride attack, durability, wetting–drying cycles, half-cell potential.

I. INTRODUCTION

Reinforced concrete is one of the most widely used construction materials due to its high compressive strength, durability, economy, and adaptability for various structural applications. Reinforced concrete structures are extensively used in bridges, buildings, marine structures, industrial facilities, and transportation infrastructure. However, the long-term durability of reinforced concrete structures is significantly affected by corrosion of embedded steel reinforcement.

Corrosion of steel reinforcement mainly occurs due to chloride ion penetration and carbonation in concrete. In coastal and marine environments, chloride ions penetrate through the concrete cover and destroy the passive oxide layer surrounding the reinforcement surface. Once the passive layer breaks down, electrochemical corrosion begins.

The corrosion products formed during this process occupy a larger volume than the original steel, generating internal stresses in concrete. These stresses result in cracking, delamination, spalling, reduction in bond strength, and deterioration of structural integrity.

The maintenance and rehabilitation costs associated with reinforcement corrosion are extremely high worldwide. Therefore, researchers have focused on developing various corrosion mitigation techniques to improve the durability and service life of reinforced concrete structures.

Among the available methods, migrating corrosion inhibitors are considered one of the most promising solutions because of their ability to penetrate hardened concrete and form protective layers around reinforcement.

A. Corrosion Mechanism in Reinforced Concrete

Steel reinforcement embedded in concrete remains protected under normal conditions because concrete provides a highly alkaline environment with pH values generally between 12.5 and 13.5. This alkaline environment forms a passive oxide layer around reinforcement surfaces.

However, aggressive environmental conditions gradually destroy the passive layer. Chloride ions from seawater, de-icing salts, and industrial exposure penetrate concrete through pores and cracks. When chloride concentration reaches a threshold level near the reinforcement surface, depassivation occurs and corrosion initiates.

The corrosion process is electrochemical in nature and involves anodic and cathodic reactions.

Anodic Reaction

$$Fe \rightarrow Fe^{2+} + 2e^-$$

Cathodic Reaction

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

The resulting corrosion products expand and exert tensile stresses on the surrounding concrete. This leads to:

- Cracking of concrete cover
- Delamination and spalling
- Loss of bond strength
- Reduction in reinforcement cross-section
- Decrease in structural durability

B. *Corrosion Mitigation Techniques*

Several techniques are used to reduce reinforcement corrosion and improve structural durability.

- Surface Coatings: Surface coatings reduce moisture and chloride penetration into concrete. However, coatings may deteriorate under long-term environmental exposure.
- Cathodic Protection: Cathodic protection systems apply external current to reinforcement and reduce corrosion activity. Although highly effective, the method is expensive and requires continuous monitoring.
- Corrosion Resistant Reinforcement: Epoxy-coated reinforcement and stainless steel bars are used in aggressive environments. However, these systems significantly increase construction cost.
- Corrosion Inhibitors: Corrosion inhibitors are chemical compounds used to reduce electrochemical reactions responsible for reinforcement corrosion. These inhibitors may be mixed with concrete or applied externally.

Migrating corrosion inhibitors have gained considerable attention because they diffuse through hardened concrete and protect reinforcement internally.

C. *Migrating Corrosion Inhibitors*

Migrating corrosion inhibitors are chemical compounds capable of penetrating hardened concrete through diffusion and capillary action. These inhibitors migrate toward embedded reinforcement and form a protective molecular film around the steel surface.

The protective layer reduces anodic and cathodic corrosion reactions and delays corrosion initiation.

1) Working Mechanism of MCIs

- The mechanism of migrating corrosion inhibitors involves:
- Penetration through concrete pore structure
- Migration toward reinforcement surface
- Adsorption on steel reinforcement
- Formation of protective molecular film
- Reduction in electrochemical corrosion reactions

2) Types of Corrosion Inhibitors

- Organic Inhibitors
- Organic inhibitors mainly include amino alcohol-based compounds.
- Inorganic Inhibitors
- These include nitrites and phosphates that modify electrochemical reactions.
- Mixed Inhibitors
- Mixed inhibitors influence both anodic and cathodic reactions.
- Encapsulated and Smart Inhibitors
- Advanced inhibitors are encapsulated within microcapsules and released under aggressive conditions.

3) Advantages of MCIs
- Easy application
- Ability to penetrate hardened concrete
- Suitable for repair applications
- Reduced maintenance cost
- Improved durability
- Long-term corrosion protection

4) Limitations of MCIs
- Performance depends on concrete permeability
- Limited long-term field studies
- Variation in diffusion characteristics
- Environmental dependency

II. LITERATURE REVIEW

Corrosion of steel reinforcement is one of the major causes of deterioration in reinforced concrete structures, especially in marine and chloride-rich environments. The penetration of chloride ions through concrete leads to depassivation of reinforcement steel, initiating electrochemical corrosion. Corrosion products occupy a larger volume than the original steel, resulting in cracking, spalling of concrete cover, reduction in bond strength, and loss of structural integrity. Researchers have identified permeability, porosity, and crack development as the primary factors influencing chloride penetration and corrosion activity in reinforced concrete structures.

Yongqi Liu et al. [1] studied the corrosion of steel reinforcement is a critical durability issue plaguing reinforced concrete (RC) structures worldwide, leading to immense financial burdens from maintenance and repair. Kuijiao Li et al. [2] focused on the corrosion of steel reinforcement is a major cause of degradation in reinforced concrete structures. V´aclav Koˇcí et al. [3] performed the experiments on the rise of basalt fibres as a promising alternative to steel reinforcement in concrete, but emphasizes their primary weakness: their susceptibility to degradation in the highly alkaline environment of concrete.

Henggen Zhang et al. [4] have investigated the use of basalt fibres (BF) to improve the durability of solidified shield waste mud (ZSWM) obtained from Zhanjiang City, China.. Ma et al. [5] worked on the effectiveness of rare-earth metal (REM) carboxylate inhibitors in mitigating corrosion is significantly impacted by the condition of the steel surface. Zhou et al. [6] focused on the corrosion of basalt-polypropylene hybrid fibres concrete (BPHFC) in marine environments is a complex process driven by the combined effects of compound salts and drying-wetting cycles. Yoo et al. [7] studied the corrosion poses a significant threat to metallic infrastructure, prompting a growing demand for effective mitigation strategies. Qibin Xu. [8] explored the use of basalt fibres (BFs) as a core component in a new composite material engineered for superior environmental corrosion resistance.

Although considerable research has been conducted on the mechanical and durability properties of basalt fiber reinforced concrete, limited studies are available on the corrosion mitigation performance of basalt fiber reinforced concrete beams under chloride exposure conditions. Therefore, the present study focuses on evaluating the effectiveness of basalt fibers in reducing corrosion activity in reinforced concrete beams exposed to aggressive chloride environments using half-cell potential testing.

III. METHODOLOGY

The methodology adopted in the present study involves the experimental investigation of corrosion mitigation in Basalt Fiber Reinforced Concrete (BFRC) beams exposed to chloride-rich environments. The experimental program was designed to evaluate the influence of basalt fibers on the corrosion resistance and durability performance of reinforced concrete beams subjected to accelerated corrosion conditions. The methodology includes material selection, concrete mix design, preparation of specimens, curing, exposure to chloride attack, corrosion monitoring, and analysis of results. The key phases of the research are as follows:

A. Chloride Exposure and Wetting–Drying Cycles

Reinforced concrete structures located in marine and coastal environments are continuously exposed to chloride-rich conditions. Chloride ions enter concrete through pores, capillary channels, and microcracks.

The major mechanisms responsible for chloride transport include:
- Diffusion
- Capillary absorption
- Permeation
- Cracking

Wetting–drying cycles accelerate chloride penetration and corrosion activity. During wetting cycles, chloride-containing solution penetrates concrete pores, while drying cycles increase chloride concentration due to moisture evaporation.

Repeated cycles increase oxygen availability and accelerate electrochemical corrosion reactions.

The rate of chloride penetration depends on:
- Water-cement ratio
- Concrete permeability
- Moisture content
- Exposure conditions
- Crack formation

B. *Corrosion Monitoring Techniques*

Different techniques are available for monitoring reinforcement corrosion in concrete structures.
- Half-Cell Potential Method: The half-cell potential method is one of the most commonly used non-destructive techniques for corrosion assessment. The method measures electrical potential difference between reinforcement and a reference electrode. ASTM C876 Criteria Half-cell Potential (mV) Corrosion Probability Greater than -200 90% probability of no corrosion -200 to -350 Uncertain corrosion condition Less than -350 90% probability of active corrosion The technique is simple, economical, and suitable for long-term monitoring.
- Electrochemical Impedance Spectroscopy: Electrochemical impedance spectroscopy evaluates corrosion behavior and protective characteristics of concrete systems.
- Linear Polarization Resistance: This method estimates corrosion current density and corrosion rate.
- Gravimetric Analysis: Weight loss measurements are used to determine actual reinforcement corrosion after exposure

C. *Accelerated corrosion exposure*

After completion of curing, the beam specimens were subjected to accelerated corrosion exposure using a 3.5% NaCl solution. The purpose of accelerated corrosion was to simulate aggressive marine environmental conditions within a shorter period.

The specimens were exposed to alternate wetting and drying cycles. Each cycle consisted of:
- Immersion of specimens in NaCl solution for a specified duration
- Drying under atmospheric conditions

A total of six wetting and drying cycles were conducted. The repeated cycles facilitated chloride penetration into concrete and accelerated corrosion activity in the embedded reinforcement.

D. *Half-cell potential test*

The corrosion behaviour of reinforcement steel was monitored using the Half-Cell Potential Test as per ASTM C876 guidelines.

This non-destructive test helps in determining the probability of corrosion activity in reinforced concrete.

A copper-copper sulphate electrode was used as reference electrode. The potential difference between reinforcement steel and reference electrode was measured using a voltmeter.

The observed readings indicate the probability of corrosion:
- More positive potential values indicate lower corrosion probability
- More negative values indicate higher corrosion activity

The readings obtained from different beam specimens were compared to evaluate the effectiveness of basalt fibers in corrosion mitigation.

IV. RESEARCH GAP

Previous research studies established that chloride-induced corrosion is one of the major durability issues affecting reinforced concrete structures. Several corrosion mitigation techniques have been developed to improve structural service life, among which migrating corrosion inhibitors demonstrated promising performance. Although many studies investigated corrosion inhibitors under laboratory conditions, limited experimental research is available on the use of embedded migrating corrosion inhibitor caplets in reinforced concrete beams exposed to cyclic chloride wetting–drying environments. Furthermore, long-term monitoring of corrosion progression using half-cell potential measurements under controlled exposure conditions remains insufficiently explored.

Therefore, a detailed experimental investigation is necessary to evaluate the effectiveness of migrating corrosion inhibitors in improving corrosion resistance and durability performance of reinforced concrete beams.

V. PROBLEM STATEMENT

Corrosion of steel reinforcement is one of the most critical factors affecting the durability, safety, and service life of reinforced concrete structures. In chloride-laden environments such as coastal regions or areas exposed to de-icing salts, chloride ions penetrate the concrete cover and initiate corrosion at the steel surface. The resulting corrosion products expand and generate internal stresses, leading to cracking, spalling, and loss of bond between concrete and steel. This ultimately compromises structural integrity and durability. Traditional corrosion mitigation methods such as surface coatings, increased concrete cover thickness, and conventional inhibitors often provide limited protection. Migrating corrosion inhibitors introduced through caplets offer a potential advantage because they diffuse through hardened concrete and provide in-situ protection to steel reinforcement.

Therefore, the present study focuses on evaluating the effectiveness of migrating corrosion inhibitor caplets in reinforced concrete beams subjected to cyclic wetting–drying chloride exposure conditions.

VI. PROPOSED STUDY

Study on corrosion mitigation in reinforced concrete beam using migrating corrosion inhibitors

VII. PROPOSED EXPERIMENTAL METHODOLOGY

1) Preparation of reinforced concrete beam specimens
2) Incorporation of migrating corrosion inhibitor caplets
3) Exposure to chloride wetting–drying cycles
4) Periodic half-cell potential measurements
5) Corrosion monitoring for six months

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