Review

Reinforced concrete corrosion: mechanism, challenges, prospective and future roadmap

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Abstract

One of the significant durability challenges is the corrosion of reinforced concrete, which significantly reduces its service life. Due to the ever-growing requirement for extended service periods of infrastructure, its cost-intensive maintenance procedures, substantial economic losses, and adverse environmental effects, developing state-of-the-art methods for repairing corrosion failures in concrete structures is essential. In general, traditional and electrochemical methods are two broad categories for fixing corrosion-induced damages in concrete structures. Nonetheless, because each of these solutions has its own restrictions along with its benefits, an integration of these mitigation strategies is suggested to reach the maximum threshold in preventing corrosion damage. In this critical review paper, the mechanism and mitigation strategies of corrosion in reinforced concrete are thoroughly discussed. Moreover, special emphasis was given to the challenges and future trends in reinforced concrete corrosion. The results of this paper demonstrate that further research is needed to develop solutions that can prevent the negative effects of reinforced concrete corrosion in a manner that is maximally sustainable, durable, environmentally benign, and economically feasible.

Keywords
Concrete degradation; steel rebar corrosion; corrosion mitigation; corrosion inhibitors; coatings

Introduction

Due to the durability properties, strength, and economics of steel-reinforced concrete, it is the most extensively utilized structural material globally. These structures have various durability-related problems, including steel reinforcement corrosion, sulfate attacks, and alkali-silica reactions [1]. In the contemporary world, one of the challenges is durability associated with concrete

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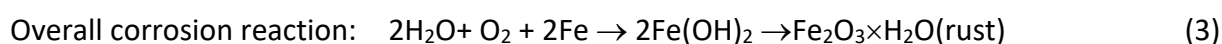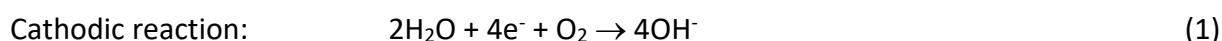Reinforced concrete corrosion

structures. In this context, steel reinforcement corrosion is highly problematic, as it causes several adverse effects, including delamination and degradation of structures, spalling, cracking, and rust formation [2,3]. Additionally, the corrosion of reinforcing steel bars in concrete can cause damage to parking structures, buildings, and highways, as well as the failure of parts of highways and the collapse of bridges [1]. These problems are regarded as a significant element in the damage to bridges and other civil infrastructures. The efficiency and aesthetic aspects of concrete structures can be considerably impacted by cracking, stress corrosion, galvanic corrosion, and atmospheric corrosion. Accordingly, it significantly threatens social safety and requires considerable repair costs. This is why it is worth noting that, from both protection and economic standpoints, steel reinforcement corrosion poses a severe challenge that can directly impact the sustainability of infrastructure [1]. As a result, extensive research is highly valuable for developing efficacious solutions or substances to prevent this type of corrosion [3].

Although considerable research has been conducted globally to extend the service life of steel-reinforced concrete constructions, their various dimensions have not yet been adequately explored. Thus, it is crucial to combine present scientific knowledge into a practical field. In this way, this review paper briefly addresses the mechanism and several mitigation measures, such as surface treatment of steel, admixtures in concrete, corrosion preventers, and other methods, which are thoroughly explored. Also, future perspectives on reinforced concrete corrosion. It is worth noting that a major novelty of this review paper lies in its greater emphasis on future perspectives and challenges in this critical and valuable field of study.

Mechanism of steel corrosion in concrete

Generally, when metals react electrochemically, chemically, or biochemically with their environment, surface loss happens, which causes their conversion to carbonates, hydroxides, or oxides. The corrosion converts an unstable metal to its stable thermodynamic state [4,5].

Lengthwise, the surface of an incorporated steel bar with a variation in electrical charge, the concrete performs as an electrochemical material with cathodic and anodic reactions on the steel, and the permeable water in the tough cement paste performs as an electrolyte [6]. Then, a current flows throughout the process, whereas the cathode remains undamaged, resulting in an aggressive invasion of the metal by a more negatively charged electrode at the anode [7]. Hence, corrosion of the rebar started. With the initiation of the hydration of steel, cement in concrete generates a passive defensive sheet on its surface, which has γ-Fe_2O_3 close to steel. The activity of ions between the surrounding concrete and the steel is obstructed by this passive protective layer, resulting in a reduction of corrosion and preventing steel damage [8,9]. Due to the occurrence of corrosion, this layer must collapse, which happens in the presence of water and oxygen, as well as in low-quality concrete, chloride, or carbonation ions [10]. Figure 1 presents the schematic of the corrosion mechanism in concrete. Also, the corrosion process can be expressed by Equations (1) to (3) [5,11]:

Cathodic reaction: $2H_2O + 4e^- + O_2 \rightarrow 4OH^-$ (1)

Anodic reaction: $Fe \rightarrow Fe^{2+} + 2e$ (2)

Overall corrosion reaction: $2H_2O + O_2 + 2Fe \rightarrow 2Fe(OH)_2 \rightarrow Fe_2O_3 \times H_2O (rust)$ (3)

Due to the occurrence of these reactions, rust is generated, which is significantly porous compared with steel, resulting in spalling and cracking [12]. Oxygen reduction happens at the cathode, and the iron is reduced at the anode *via* Equations (2) and (4) [3,4]:

$$Fe + OH^- \rightarrow [Fe(OH)]_{ads} + e^- + H^+ + Fe(OH)^+ \tag{4}$$

The availability of OH^- ions determines the generation of Fe $(OH)^+$. To maintain electro-neutrality, hydroxide ions migrate from the bulk to the surface as ferrous ions are produced. At higher pH values, Equation (4) is more probable on the iron surface. Maintaining $Fe(OH)^+$ ions, the electrode charge changes in an anodic direction and at the steel surface, the amount of $Fe(OH)^+$ increases, and then oxidizes to ferric oxide, described by Equation (5) [3,4]. Thus, a protective oxide layer is formed, which is the corrosion-resistant passive layer of steel. If the pH is decreased or the passive layer is penetrated by an acidic environment or aggressive species, such as chloride ions, then corrosion phenomena will start again [3].
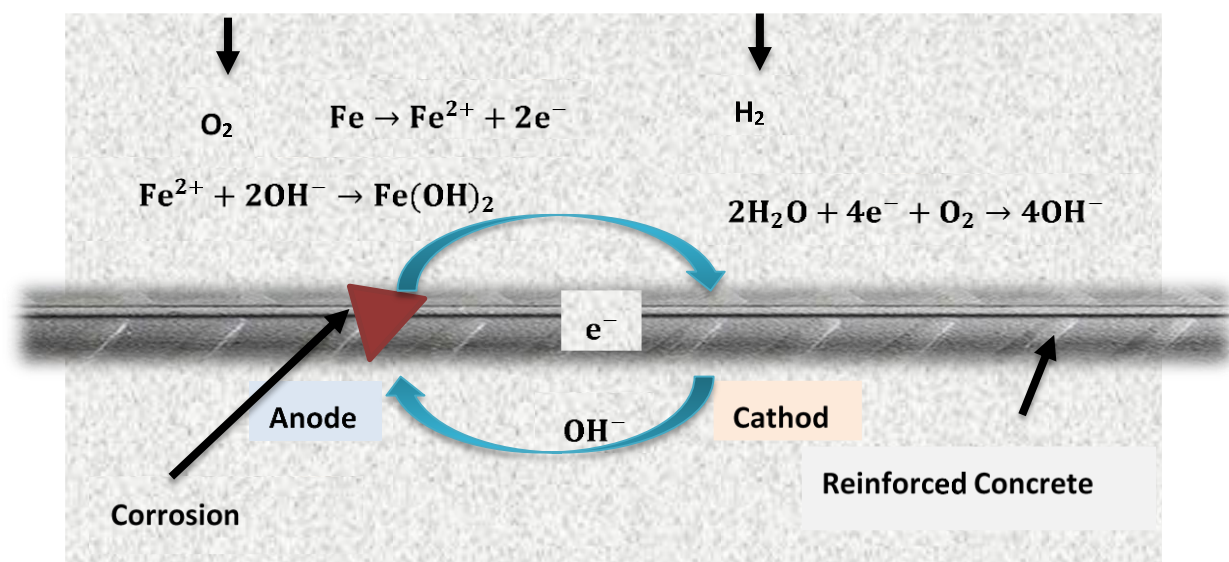
$$Fe(OH)^+ + H_2O \rightarrow 2e^- + 4H^+ + Fe_2O_3 \tag{5}$$

Figure 1. *Graphic design of corrosion mechanisms in concrete*

Also, corrosion initiation, onset, and propagation are three stages of steel bar corrosion in concrete, which is clearly demonstrated in Figure 2.
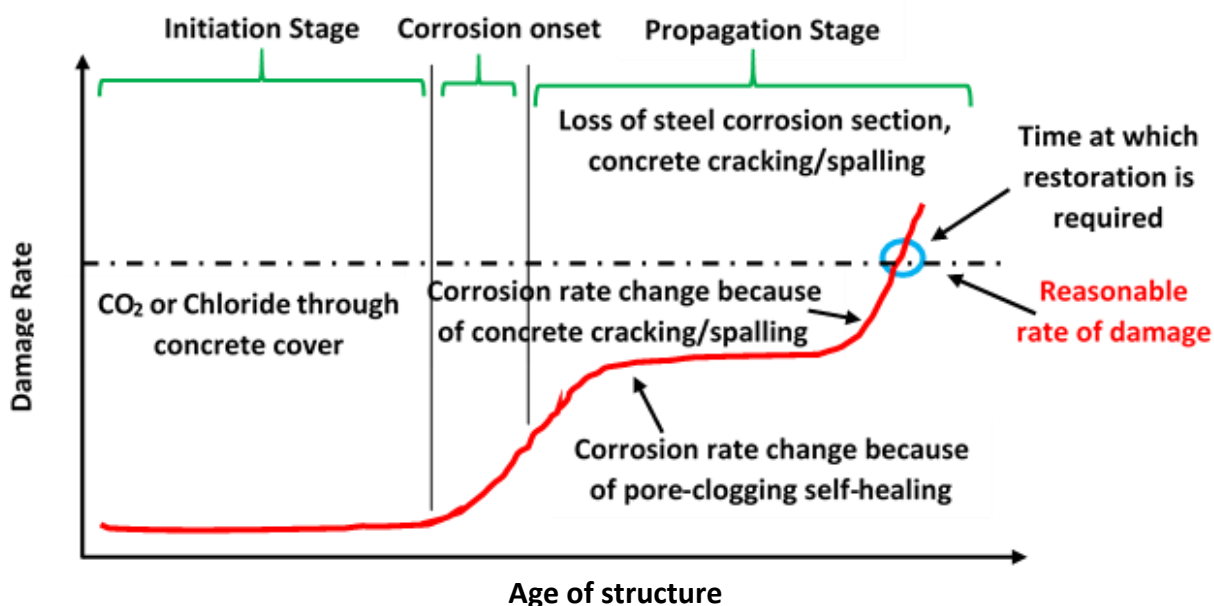

Figure 2. *Corrosion stages of steel rebar. Adapted from [13]*

Mitigation of corrosion

Due to the ever-increasing requirement for extended service lives of infrastructure and the considerable expenses incurred for their construction and maintenance, the treatment of design and corrosion faults in concrete structures has become increasingly essential [14]. The protection of concrete should be performed from physical, electrochemical, and chemical points of view. The fixing and protective approaches for concrete are based on the principle that corrosion is an electrochemical phenomenon, and its major components are electrolyte, cathode, and anode. Exactly for this reason, the lack of any of the aforementioned elements can limit corrosion [3].

In general, traditional and electrochemical methods are two broad categories for fixing corrosion-induced damage in concrete structures. Traditional mitigation approaches include the elimination of delaminated/spalled concrete and replacing it with new bare concrete or encasement and overlays, membranes and barriers, sealers, coatings, patching, impregnation, and the application of corrosion preventers [15]. Such methods are transient for corrosion inhibition, which can accelerate corrosion in nearby treated regions [16].

However, in cases of severe structural damage, traditional methods are expensive and less efficient compared to electrochemical ones [17,18]. Electrochemical chloride elimination, electrochemical realkalization, cathodic prevention, and cathodic protection are major electrochemical methods for corrosion prevention [19]. In these methods, the chemical interactions and current movements due to corrosion are overcome by using an external DC source, using a transient or perpetual anode. From the synthetic anode, the applied current is directed to the reinforced steel to be protected. The current conveys a flow of ions throughout the permeable water in the concrete to the reinforcement [20]. The benefit of these methods is that only fractured concrete needs to be eliminated and fixed [21]. Here, major innovative methods for corrosion mitigation and prevention are thoroughly discussed [3].
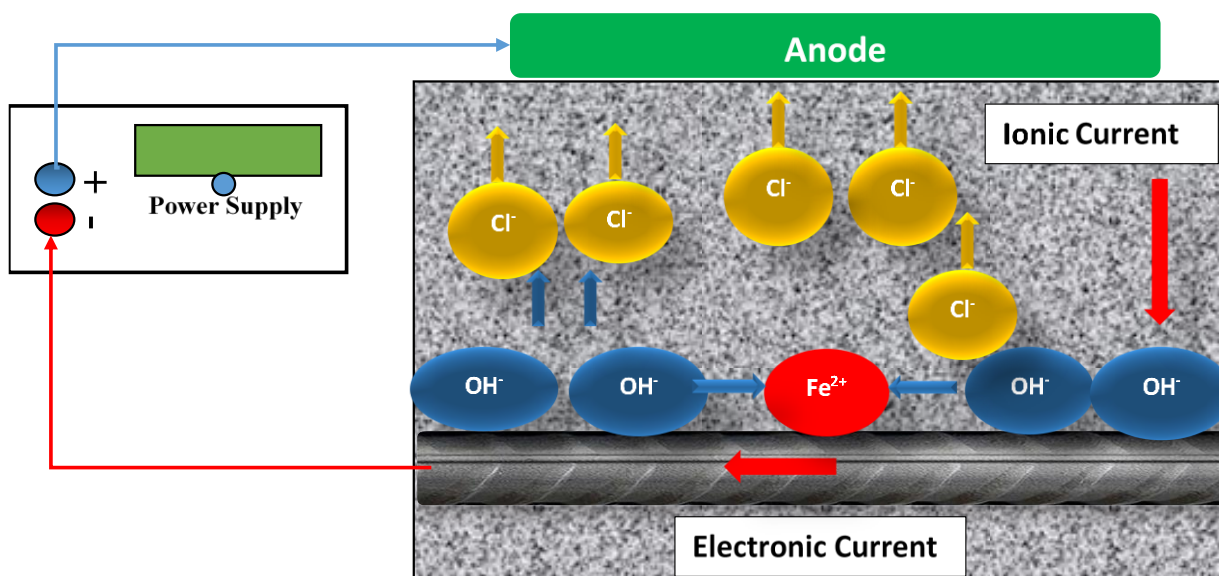
Cathodic protection or cathodic prevention

To avoid corrosion occurrence in reinforced concrete constructions that are exposed to chloride penetration, several electrochemical methods were utilized [22]. Additionally, cathodic protection [23] can be employed, which requires approximately 10 % of the cathodic protection energy. As a result, in comparison with concrete reinforcement fixing and improved cathodic protection, cathodic protection is more eco-friendly, requires lower materials due to lower current demand, and yields lower installation and operating costs [3]. Moreover, compared to traditional solutions, cathodic protection is a low-cost, simple, and effective method that can fix a greater region at the same time, and does not result in incipient anode issues. Hence, in chloride-driven corrosion structures, this method is the most appropriate fixing method [24]. Generally, cathodic protection is utilized as overwhelmed current cathodic protection (motivated by an external power supply), sacrificial anode and cathodic protection (passive system), and hybrid system (integration of both methods) [3]. Figure 3 illustrates the schematic representation of the sacrificial anodic and cathodic protection mechanisms.

In impressing current cathodic protection, the DC energy source is supplied from a permanent anode by the concrete electrolyte to steel bars (see Figure 4). To convey protective current to steel reinforcement, it utilizes an enduring, external energy resource, like a rectifier energized from fuel cells, batteries, solar cells, main supply, or other sources [25]. The current passed must be adequate to prevent the cathodic and anodic interactions that can occur at the steel surface, generating OH-, which will increase the basicity and re-passivate the steel bar, thereby reinforcing the passive layer [23].
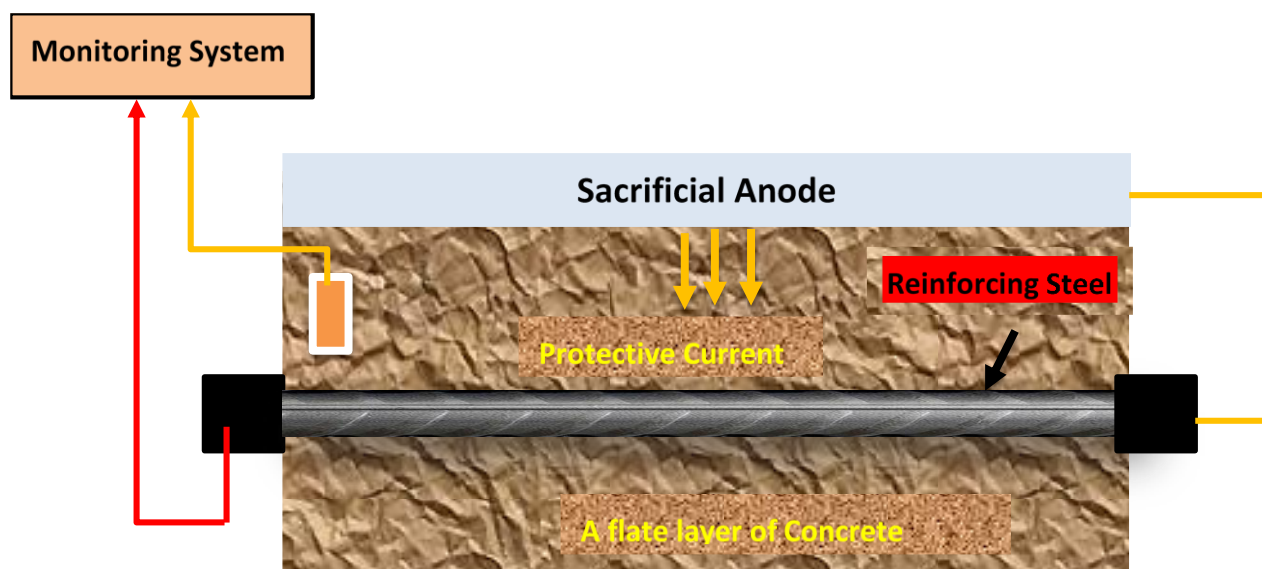
Figure 3. *Schematic illustration of sacrificial anodic cathodic protection mechanism*

Figure 4. *Schematic illustration of impressed current cathodic protection of reinforced steel in concrete*

Compared with sacrificial anode cathodic protection, increased current cathodic protection can effectively resolve considerable corrosion problems in large structures with extended service life. It is much more frequently applied in reinforced concrete [22]. The elimination of aggressive chloride ions through ionic migration, the generation of more negative reinforcement potential, the increase in the number of OH- ions at the steel reinforcement, and the overcoming of all locally produced corrosion cells are major benefits of these systems [3,20,26].

The failures in impressed current cathodic protection mainly comprise the connection waste at the frontier of concrete and conductive coating because of dehydration of concrete once water enters junction boxes and electro-osmosis happens, localized high current, and utilization of the anode, de-bonding of the overlay on metal mixed oxide (MMO)/Ti mesh, volatility of reference electrodes because of the solution leaches out, and failures of reference electrodes generally because of the absence of connection to the concrete which stems from grout shrinkage). Nevertheless, anode collapse does not result in rapid removal of protection, and the steel will remain in a passive condition for several years [27]. The application of pseudo-reference electrodes (stainless steel, graphite, or MMO/Ti) with precise reference electrodes provides alternative

observation tools with longer life and less precision. Also, other life expectancy challenges, such as the client's inability to repay the electricity bill, are present, which causes an interruption in the monitoring and operation process. Therefore, considering a maintenance contract is crucial [3].

Usually, to protect submerged structures and underground pipelines, sacrificial cathodic protection is utilized [28,29]. In this method, due to the potential variation between the sacrificed metal (anode) and the steel to be protected (cathode), DC current is produced [22,30]. Accessibility of a broad range of different anodes, low cost of observation and maintenance, and simplicity are among the major benefits of this method [30]. The small driving voltage, which may be insufficient to provide complete cathodic protection in all conditions, low control over the system, and the need for periodic alternation of anodic metal due to its dissolution are among the major drawbacks of this method [30]. Sacrificial anode cathodic protection is typically restricted to small-scale applications with short service life [31]. Based on Byrne *et al*. [22], the lower risk of hydrogen embrittlement makes sacrificial anode cathodic protection a more suitable solution for pre-stressed structures.

In a hybrid cathodic protection system, to maintain and restore alkalinity, a transient impressed current is coupled with a low-maintenance galvanic structure. Usually, the system includes providing a significant current for a week and operating the arrangement galvanically. The realkalization of acidic sites offers significant potential, providing a high pH and thus enhancing steel passivity [3]. However, this method of corrosion protection is rather new and has not yet been thoroughly investigated. According to Glass *et al*. [32], this remediation method is capable of significantly reducing corrosion failures and also requires a lower maintenance process.

Electrochemical chloride extraction

For the treatment of high chloride-driven corrosion in corroded structures, the electrochemical chloride extraction method is suitable due to its low cost, transient nature, and non-destructive nature [19]. Through the utilization of an electrical field for a short time, the outside deposited anode encompassed by a solution of alkaline electrolyte and the steel bar, the negatively charged chloride ions available at the steel surface will be eliminated [33]. Such ions move towards the external layer of the anode, thereby decreasing the likelihood of corrosion occurrence [34,35. Additionally, OH- ions are generated by the reduction of O_2 and H_2O at the steel surface, supplying alkalinity to the concrete in the vicinity of the rebar [3]. Compared to cathodic protection, this method of corrosion inhibition also requires a higher applied current and cost [15,20,36]. Because of the possibility of hydrogen embrittlement and, similarly, a danger of reaction of alkali-silica because of elevated OH⁻ dosage in the proximity of the steel surface, it is not suggested to utilize this method with pre-stressing wires [21,37,38].

Because of the initiation of the electric potential difference variation of the steel (cathode) and the external anode, the resulting reactions (Equations (6) to (9)) happen in the electrochemical extraction remediation [1,39].

At the cathode (steel):

$$2H_2O_{(l)} + 4e^- + O_{2(g)} \rightarrow 4OH^-_{(aq)} \tag{6}$$

$$2e^- + H_2O_{(l)} \rightarrow H_{2(g)} + 2OH^-_{(aq)} \tag{7}$$

at the anode:

$$2H_2O_{(l)} \rightarrow 3e^- + 4H^+_{(aq)} + O_{2(g)} \tag{8}$$

$$2Cl^-_{(aq)} \rightarrow 2e^- + Cl_{2(g)} \tag{9}$$

Equation (7) presents the evolution of H_2 gas at the steel reinforcement because of the less cathodic potential, which is motivated by the significant amounts of applied current. Additionally, a higher applied current can generate cracks in the concrete due to the increased chloride extraction rate. Hence, the applied current has been applied between 1-5 A m^{-2} in different research [40]. To prevent the reaction (9), the pH of the electrolyte must be appropriate. Moreover, extreme alkaline conditions in electrolytes offset the hydrogen ions generated *via* the reaction (8) and defend the surface of concrete against acidification [1]. Hence, solutions of sodium hydroxide, calcium hydroxide, and remediated water are frequently utilized as exterior electrolytes [41]. Nevertheless, the chloride ions migrate more readily in the concrete due to the existence of saltwater, leading to increased corrosion [18].

Electrochemical realkalization

To protect steel in carbonated concrete effectively and for a long time, the electrochemical realkalization method is utilized. In this method, between a temporary external anode, an alkaline electrolyte solution including hydroxyl ions or carbonate and steel in concrete, for a short time, a low electrical field is utilized [3,37,42]. In this case, compared with cathodic protection, the electrical charge is greater than 50 times, thus requiring higher costs. Then, in steel, the oxygen is reduced and hydrogen can be produced if highly negative potentials are obtained [21]. With the help of these reactions, OH$^-$ on the steel surface will be produced, which can assist the steel in reaching passivity. The basicity of carbonated concrete is increased and the pH value is kept higher than 10.5 to maintain and supply a passive protective layer coating the reinforcing steel, which is known as electrochemical realkalization [34,43]. The solutions of potassium, lithium and sodium as an electrolyte may be utilized. Considerable applied current can generate several side effects, like anodic acidification, bond degradation, the possibility of alkali-aggregate reaction, and, in the case of high-strength, the feasibility of hydrogen embrittlement pre-stressing steel once the potential converts further negative than -1000 mV [12,20,37].

Concrete coatings

By the utilization of surface coatings and remediation on the surface of reinforced concrete, simple and low-cost protection can be achieved. The primary purpose of surface coating is to provide an obstacle between the environment and the concrete surface, thereby rendering it less permeable to moisture and less susceptible to the attack of aggressive materials, while also augmenting the concrete's resistivity. The concrete coating would be highly advantageous if corrosion is caused by carbonation. However, chloride-motivated corrosion failure absorbs higher amounts of moisture, making surface treatment inadequate to halt the corrosion. Cementitious coatings, hydrophobic impregnation, and organic coatings are the main categories of concrete corrosion [3,21].

Cementitious coatings have sufficient resistance against chloride penetration and carbonation. However, its long-term bond is the main challenge. In order to generate restraint to concrete that is in danger of delamination, epoxy-coated glass scrim is integrated with cementitious coatings [46]. The type of application methods, substrate properties, bond strength, and air permeability are the main factors that heavily influence the surface treatment phenomena. Practically, to reach the maximum bond, grit blasting has been demonstrated to be the perfect solution for preparation [3].

Silicate-dependent substances, siloxanes, and silanes are the hydrophobic impregnation materials that defuse away from the surface of concrete and on the permeable walls, a water-resistant lining is produced, thus avoiding the permeation of chloride ions and other destructive species into concrete [21]. On the erect surfaces where the water can run away, hydrophobic

impregnation materials are the most appropriate solution as they are not efficacious against standing water [44]. However, there is still inadequate research work on the application of silanes as a component of polymer concrete [3].

Organic coatings, by creating a constant polymeric film on the concrete surface, block the entry of chloride ions and CO_2. Vapor-permeable coatings or dense coatings are two types of organic coatings. Vapor-permeable coatings enable the concrete to dehydrate, decreasing the chance of destruction or blistering from trapped moisture. However, in highly polluted concrete, the generation of salt crystals can cause the coating to fail. However, dense coatings do not allow moisture to enter the concrete when used, which may result in adhesion degradation and coating failure [3,21].

Alternative reinforcements

The application of reinforcement material fabricated by anti-corrosion materials like fiber-reinforced plastic or stainless steel is a practical approach to avoid reinforced concrete corrosion. Fiber-reinforced plastics possess significant tensile strength, are lightweight, and have good corrosion resistance properties [45]. Basalt fiber, carbon fiber (highly resistant to alkaline/acidic conditions), glass fiber (degrades with time when exposed to alkaline/acidic conditions), and aramid fiber (sensitive to environmental degradation) are major forms of this material. Although concrete is open to marine ecology compared with glass fiber and aramid fiber, carbon fiber offers higher corrosion resistance. However, it is expensive. Glass fiber can be a good corrosion-resistant and economical alternative to carbon fiber [46]. Also, in comparison with other fibers, basalt fiber presents greater thermal stability and can offer adequate resistance against fire. Nonetheless, little research has been conducted about it. Practically, an integrated utilization of carbon fiber and cathodic protection is suggested [3].

The only type of corrosion that can happen in stainless steel is pitting corrosion. Other types of corrosion, such as crevice corrosion, stress corrosion, or intergranular corrosion, require highly aggressive conditions, like those found in seawater desalination, and have a very low chance of occurrence. Due to the greater stability of the passive film of carbon or mild steel, the corrosion prevention of stainless steel is essential [21]. In a review paper conducted by Shokri and Sanavi Fard [11], the corrosion prevention of various degrees of copper, stainless steel, nickel, aluminum and titanium alloys was thoroughly explored. Nevertheless, the application of stainless steel as an alternative to mild steel reinforcement is cost-prohibitive [47]. Although its application can be prioritized by an external layer of stainless steel and when they are integrated with carbon steel, leaving the remaining as carbon steel, the danger of carbon steel galvanic corrosion is increased [21,47]. Nonetheless, corrosion is reduced when carbon steel is combined with stainless steel compared to when it is combined with passive carbon steel [47,48]. It must be noted that the chance of hydrogen embrittlement must be evaluated individually by ascertaining the safe potential of the specific form of stainless steel utilized in the infrastructure [3].

Corrosion inhibitors

Corrosion inhibitors like ferrous salts, stannous salts, phosphates, benzoates, nitrites, and chromates are chemical compounds that decrease the amount of corrosion without remarkably altering the quantity of any other corrosion species [4,49]. Based on the standard operating life model, corrosion preventers may have the capability to extend both the initiation and propagation times. In comparison with other corrosion protection methods, corrosion inhibitors are cost-effective and simple. They can be classified as anodic, cathodic, or integrated preventers based on their mode of action. For instance, sodium hydroxide as a cathodic inhibitor for corrosion in concrete

can neutralize the reaction of cathodic corrosion, perform the reaction of oxygen and decrease the corrosion by diminishing the steel corrosion potential. Calcium nitrite, as the most extensively applied anodic inhibitor for concrete, can neutralize the reaction of anodic corrosion, thus decreasing corrosion by elevating the steel corrosion potential [3]. The integrated corrosion preventers neutralize both anodic and cathodic reactions and decrease the amount of corrosion without altering the corrosion potential by superficial adsorption on steel bars and therefore generating a protective layer [50]. Nevertheless, anodic inhibitors have a considerable impact [51]. The overall category of corrosion preventers is depicted in Figure 5.
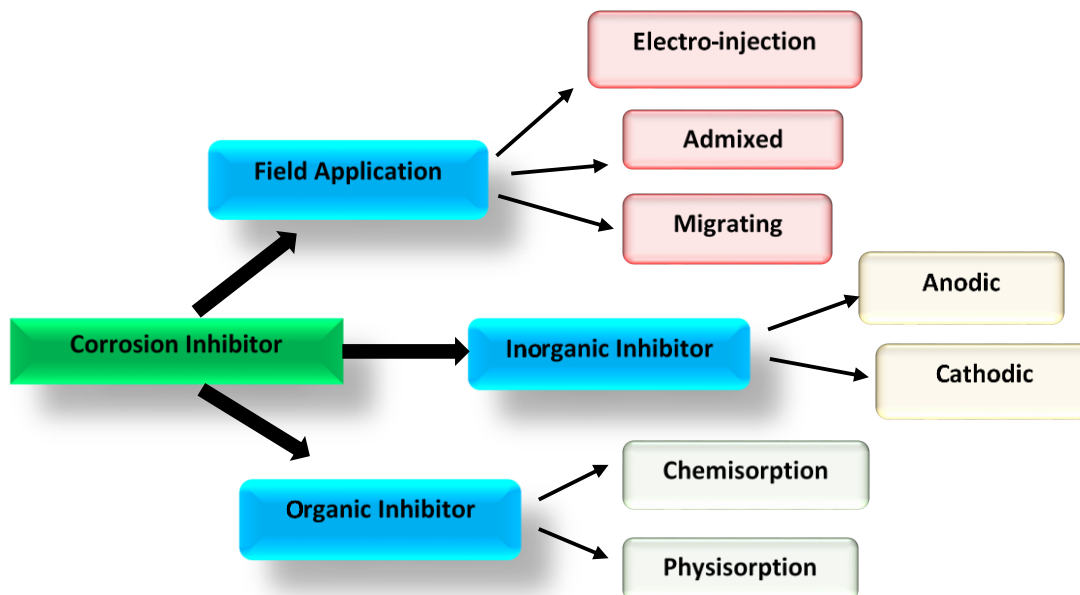
Figure 5. *The overall category of corrosion inhibitors*

According to the results of the review paper from Lee *et al.* [55], greater research efforts are needed to determine the performance of mixed and organic inhibitors in long-term conditions and under various conditions, such as different types of cement and varying chloride content. Just those preventers that can extend the service life because of electrochemical or chemical reactions with the reinforcement can be regarded as corrosion inhibitors for concrete. Nevertheless, it has not been demonstrated that corrosion inhibitors are consistently effective, and they may only slow down corrosion. Additionally, they are water-soluble and may have the opportunity to leach out from concrete [51]. In addition, the widely employed inhibitors are naturally toxic and expensive [53]. Therefore, replacing such negative inhibitors with low-cost, eco-friendly, non-toxic alternatives is of prime concern. Based on the findings of Raja *et al*. 49], organic heterocycles, BTAH, mono and amino-alcohol-driven inhibitors, polycarboxylates, amino acids, alkanoamines, amines, and green products can be efficaciously applied as corrosion inhibitor substitutes for concrete corrosion. Hence, due to environmental considerations, green inhibitors must be investigated in-depth as a promising future for corrosion inhibitors.

Admixtures in concrete

To significantly improve the characteristics of the generated concrete, liquid or solid materials known as admixtures are added to the concrete mixture. Corrosion inhibitors are the main admixtures that are applied to advance the corrosion prevention of steel reinforcement, which primarily involves inorganic and organic chemicals. Nevertheless, admixtures that are predominantly utilized for improving the structural efficiency of concrete are highly appealing

because of their great performance, such as corrosion control, impermeability, bond strength, mechanical strengths, and improvement in workability. They are generally mineral substances like slag, silica fume, and fly ash [1].

Surface treatment of steel

Because of the cost-effective feature of steel, the reinforcing bars frequently utilized are mild steel. However, stainless steel offers good durability and mechanical characteristics; however, due to its considerable cost, it is not adequately suitable for applications in reinforced concrete [54]. A primary cause of deterioration in reinforced concrete constructions is their limited corrosion resistance. As a result, various remediation methods have been employed on a steel surface to enhance corrosion resistance. For example, by applying this method through epoxy coating, the corrosion of steel rebar is significantly diminished, as it acts as an obstacle to aggressive corrosion attacks. However, the impaired zones of epoxy-coated steel (at which pitting corrosion might have happened) and the feeble bonding between concrete and epoxy-coated steel are frequent issues with epoxy coating [1,55]. Also, galvanization (coating with zinc) considerably enhances the corrosion prevention of steel by performing as a sacrificial anode. It has been detected in numerous investigations that not only compared with epoxy-coated steel, galvanized steel generates enough bond to concrete, but also compared to epoxy coating, the zinc coating has a limited tendency to de-bond. Hence, along with the development of bond strength, surface remediation methods for steel, such as sandblasting, surface oxidation, and cement slurry coating, enhance the corrosion resistance of concrete [1].

Future trends and challenges

Exploring novel methods to substantially increase the operating life of reinforced concrete, which is often compromised by significant corrosion failure in these structures, is of prime concern. In this context, several future perspectives regarding chloride-induced or carbonation-based corrosion for extending the operating life of reinforced concrete are briefly examined in the following subsections [56].

Alternative binders

Developing new substitutes for Portland cement is highly appealing. Activated aluminosilicate (AA), calcium sulfoaluminate cement (CSA), magnesium-based cement, and calcium aluminate cement (CAC), and their combinations are mineral-dependent alternative binders. Some of them have strength gain and rapid setting, rendering them appealing for quick construction or repair. Some compositions are believed to participate significantly in sustainability by presenting features similar to Portland cement concrete; however, with reductions in calculations like embodied CO_2 or embodied energy [57]. Variations in alternative binder ingredients cause various reaction crops and microstructures that generate changes in the corrosion of embedded steel and their ability to resist fluid and ion penetration. For developing enduring reinforced concrete from such substances, realizing relationships between corrosion efficiency, structure, and composition in alternative binder systems is critical [56].

Because the pH value must be adequate to ensure the corrosion prevention of embedded steel due to passivation, carbonation in alternative binders is essential. Compared to ordinary concrete, even without carbonation, some alternative binders naturally exhibit a lower pH [58-60]. Moreover, the effect of carbonation on the infrastructure and ingredients of the binder is essential to ensure corrosion prevention. Especially, carbonation in CAC and CSA blends can cause considerable

disintegration of the main strength-giving phases, thus decreasing the resistance of cracks in the cover of concrete [61,62].

Also, threshold chloride fillings will be determined for the formulation of each alternative binder. Although appealing from an efficiency, cost, or sustainability viewpoint, a greater realization of structure, chemistry, and environmental interaction of these cementitious systems is required to ensure a highly desirable corrosion resistance when steel is reinforced [63].

Ultra-high-efficiency concrete

Usually, concrete with compressive strength over 150 MPa is defined as ultra-high-efficiency concrete, which is generally fabricated with a low amount of water, a large amount of silica fume, fly ash, cement, fine sand, and high-strength steel fibers. According to the findings of Graybeal [64], the permeability of chloride, as calculated by ASTM C 1202-12, was below 100 coulombs, a significantly low permeability. The physical rays cracked in flexure demonstrated the penetration of chloride into a 5-mm-wide crack of merely 5 mm, and because this small crack is usual in even greatly stressed ultra-high-efficiency concrete, its prevention of both carbonation and chloride penetration is considerable. Although it is compared with traditional concrete, it possesses considerable durability and offers significant protection for embedded steel reinforcement [56].

Self-healing concrete

The corrosion of cracked concrete frequently happens due to the elevated degrees of transport-tation of aggressive species at or in the proximity of the location of cracking, and the period of corrosion initiation is decreased in comparison with uncracked concrete in the same situations [65]. However, (a) swelling of the cement matrix and constant hydration, (b) particle sedimentation and (c) the generation of calcium hydroxide or calcium carbonate cracks in concrete can self-heal and decrease the chloride penetrability [56]. Based on Zhutovsky and Nayman [66], a liquid that will not cause a dissolution reaction or leaching, stability of the crack, and the presence of water as the main ecological situation must be provided to ensure that the self-healing process occurs. For corrosion mitigation, healing must occur before the concrete is exposed to chlorides [56].

Future trends in corrosion measurements, mitigation and control

- For a thorough, non-destructive assessment of corrosion on reinforced concrete infrastructures, higher advancements in the indirect polarization methods for calculating the polarization resistance are needed. It is demanded to expand observation instruments that can calculate the distribution of polarization resistance and concrete resistivity in the material. For the evaluation of the operating life of reinforced concrete infrastructures, the advancement of a single instrument with the ability to provide both factors by electrical tomography is essential.

- For the evaluation of the operating life of present reinforced concrete infrastructures, a standard methodology must be established. The purpose is to precisely measure the amount of annual corrosion based on the immediate corrosion rates. Models that regard regular changes in temperature and relative humidity with merely a few calculations must be expanded. The application of different kinds of embedded sensors can be anticipated for automatic measure-ments of the ecological parameters for new infrastructures.

- Development of non-corrosive reinforcements like high-strength grade non-corroding reinfor-cement, especially stainless-steel alloys, and advanced glass fiber-reinforced polymer composite rebars can greatly mitigate corrosion in reinforced concrete.

- To enhance the realization of corrosion mechanisms in wide-range and small-range structures, further explorations are still needed. Substitutes for producing reinforced concrete structures, such as 3D printing, may offer a better approach to reducing material heterogeneity. This approach can facilitate a better understanding of the corrosion mechanisms through trials of steel-concrete interface situations, reproducible pore size distributions, and the determination of an optimal concrete design.

- Because the equation of Stern-Geary, which was demarcated for uniform corrosion, is usually unreliable for natural corrosion in reinforced concrete infrastructures, further investigations are needed to relate the polarization resistance to corrosion rate. Also, even with the calculation of the polarization resistance, the amount of corrosion can be estimated with this conventional method.

- Despite numerous research works performed on sacrificial anode and cathodic protection, corrosion control in previously damaged concrete is still challenging. Although galvanic anodes are broadly utilized with patch fixing to avoid the incipient anode impact, their operating life is not extended adequately, and coating patch-repaired concrete with embeddable galvanic anodes for their protection must be considered. Based on the experiences, galvanic anodes are not recommended to be utilized in the tidal area unless protected with jackets [3].

- Although the hybrid cathodic protection system's novel corrosion protection method has great potential to be the future of cathodic protection systems, it still needs additional breakthroughs in terms of operation, installation, and anode type.

- Each technique of corrosion control for steel-reinforced concrete has definite pros and cons. Hence, higher research efforts are required to expand the eco-friendly, cost-effective, and enduring techniques for corrosion protection of embedded steel that do not negatively impact the structural efficiency of steel and concrete.

Conclusion

Reinforced concrete corrosion is regarded as a highly complex process due to the mechanical properties of reinforced concrete, the electrochemical reactions, the material characteristics of concrete, and the electrochemical nature of steel corrosion in concrete. Reinforcement in concrete corrosion is a significant challenge that needs to be considered in the design of concrete infrastructures open to aggressive conditions. In this review paper, the mechanism of corrosion in reinforced concrete was briefly discussed. Major mitigation strategies are thoroughly explored. Finally, different challenges associated with corrosion in reinforced concrete and future trends are comprehensively investigated. Realizing the corrosion mechanism and its alleviation methods is crucial for introducing a suitable protection methodology. Based on economic conditions, practicality, and value engineering, the appropriateness of any alleviation strategy is different from one structure to another. Hence, there is no unique and perfect strategy for every structure, and each one requires assessment based on its specific condition.

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