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КОРРОЗИОННАЯ ДЕГРАДАЦИЯ АРМАТУРЫ В ЖЕЛЕЗОБЕТОНЕ: ОЦЕНКА, ПРОГНОЗИРОВАНИЕ, АНАЛИЗ И ЗАЩИТА

ТЕМІРБЕТОНДАҒЫ АРМАТУРАНЫҢ КОРРОЗИЯЛЫҚ ДЕГРАДАЦИЯСЫ: БАҒАЛАУ, БОЛЖАУ, ТАЛДАУ ЖӘНЕ ҚОРҒАУ

CORROSION-INDUCED DEGRADATION OF REINFORCING BARS IN REINFORCED CONCRETE: ASSESSMENT, PREDICTION, ANALYSIS, AND PROTECTION

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keywords:

corrosion wear, corrosion processes, reinforced concrete structures, structural inspection, protection, durability, economic losses, anti-corrosion measures, construction standards, structural safety.

ABSTRACT

The article examines the main aspects of corrosion impact on reinforced concrete structures of buildings, including the mechanisms of corrosion damage, factors contributing to this process, and the consequences for the strength and durability of construction objects. Various types of corrosion are analyzed, such as uniform, localized, and electrochemical corrosion, as well as methods for diagnosing and assessing the condition of reinforced concrete structures. Particular attention is given to modern corrosion protection technologies, including anti-corrosion coatings and cathodic protection. In conclusion, the importance of regular monitoring and preventive measures is emphasized to ensure the safety and reliability of buildings under the influence of aggressive environmental factors. The article will be useful for engineers, architects, and construction specialists, as well as for students of related fields.

Түйінді сөздер:

коррозиялықтозу, коррозиялық процестер, темірбетон конструкциялар, құрылыс конструкцияларын зерттеу, қорғау, ұзақ мерзімділік, экономикалық шығындар, антикоррозиялық шаралар, құрылыс нормалары, конструкциялардың қауіпсіздігі.

ТҮЙІНДЕМЕ

Мақалада ғимараттардың темірбетон конструкцияларына коррозияның әсер етуінің негізгі аспектілері қарастырылады. Онда коррозиялық бұзылу механизмдері, осы үдерісті күшейтетін факторлар және құрылыс нысандарының беріктігі мен ұзақ қызмет ету мерзіміне тигізетін салдары сипатталады. Коррозияның түрлі түрлері — біркелкі, жергілікті және электрохимиялық түрлері талданады, сондай-ақ темірбетон конструкциялардың жағдайын диагностикалау мен бағалау әдістері қарастырылады. Ерекше назар коррозиядан қорғаудың заманауи технологияларына, соның ішінде антикоррозиялық жабындарға және катодтық қорғауға аударылады.





Қорытынды бөлімде ғимараттардың қауіпсіздігі мен сенімділігін қамтамасыз ету үшін жүйелі мониторинг пен алдын алу шараларының маңыздылығы атап өтіледі. Мақала инженерлерге, сәулетшілерге, құрылыс саласының мамандарына және осы бағыттағы студенттерге пайдалы болмақ.

Ключевые слова:

коррозионный износ, коррозионные процессы, железобетонные конструкции, обследование строительных конструкций, защита, долговечность, экономические потери, антикоррозийные мероприятия, строительные нормы, безопасность конструкций.

АННОТАЦИЯ

В статье рассматриваются основные аспекты воздействия коррозии на железобетонные конструкции зданий, включая механизмы коррозионного разрушения, факторы, способствующие этому процессу, и последствия для прочности и долговечности строительных объектов. Анализируются различные виды коррозии, такие как равномерная, местная и электрохимическая, а также методы диагностики и оценки состояния железобетонных конструкций. Особое внимание уделяется современным технологиям защиты от коррозии, включая антикоррозионные покрытия и катодную защиту. В заключение подчеркивается важность регулярного мониторинга и профилактических мероприятий для обеспечения безопасности и надежности зданий в условиях воздействия агрессивных внешних факторов. Статья будет полезна инженерам, архитекторам и специалистам в области строительства, а также студентам профильных направлений.

INTRODUCTION

Reinforced concrete structures are key elements of modern building infrastructure, whose durability and load-bearing capacity depend on maintaining the integrity of steel reinforcement. One of the main factors leading to premature failure of such structures is corrosion of reinforcement initiated by exposure to aggressive environments (chlorides, carbon dioxide, moisture). This problem is global in scale, due to the widespread use of reinforced concrete, and leads to significant economic losses associated with repairs and risks to the safety of structures.

Scientific literature has studied individual corrosion mechanisms (uniform, electrochemical, pitting) in considerable detail and developed a wide range of protection methods, from passive (coatings, inhibitors) to active (cathodic protection). However, existing approaches are often fragmented. There is a shortage of integrated systems that would combine predictive diagnostics based on monitoring key parameters, mathematical modelling of corrosion rates, and adaptive planning of protective measures throughout the entire life cycle of a structure. This integrative gap limits the possibilities for timely and cost-effective management of corrosion risks.

The research hypothesis is that the development and implementation of a comprehensive methodology for assessing and predicting the corrosion condition of reinforced concrete structures, based on systematic monitoring of physicochemical, electrochemical and mechanical parameters, will significantly improve the accuracy of diagnostics, optimise the timing and methods of protective interventions and, as a result, increase the residual life and overall reliability of structures.

The aim of this study is to systematise current knowledge about the mechanisms of reinforcement corrosion in reinforced concrete structures, analyse existing diagnostic and protection methods, and develop proposals for a comprehensive assessment of the corrosion condition of structures based on the integration of non-destructive testing technologies, mathematical modelling and monitoring of key parameters. The study aims to structure the information necessary to move from local damage assessment to a comprehensive forecast of residual life, which is a pressing issue in the field of ensuring the reliability and safety of

construction projects. To achieve this goal, it is necessary to solve problems that will enable a transition from reactive measures to eliminate the consequences of corrosion to a proactive system for managing the corrosion safety of reinforced concrete structures at all stages of their life cycle.

1. Conduct a systematic analysis of current knowledge about the mechanisms and factors that initiate and intensify corrosion of steel reinforcement in concrete.

2. Classify and evaluate the effectiveness of existing methods for diagnosing corrosion (visual, non-destructive testing, electrochemical) and protecting structures (passive and active).

3. Determine key parameters for a comprehensive corrosion index that reflects the degree of reinforcement wear, the condition of the protective concrete layer, and the aggressiveness of the environment.

4. Develop a conceptual model for predicting corrosion rates that integrates monitoring data and takes into account the influence of variable operating conditions.

5. Formulate practical recommendations for the application of an integrative approach to planning repair measures and justifying inter-repair intervals within the framework of regulatory and technical regulation.

The relevance and formulation of the research problem are determined by the following factors:

1. Technical and economic significance - reinforced concrete is the dominant material in global construction. Corrosion of reinforcement is the main cause of a reduction in its load-bearing capacity and durability, leading to enormous direct costs for repair and restoration, as well as indirect losses from facility downtime and risks to human life. Improving the effectiveness of corrosion control is of strategic importance for the sustainable development of infrastructure.

2. Despite extensive research into individual aspects of corrosion (mechanisms, protective materials), there is a lack of systematic solutions in practice, i.e. there is a gap between science and practice. Existing methods are often applied in isolation, without linking diagnostic data to predictive models to justify optimal timing and protection methods. This leads either to belated, emergency interventions or to unjustified costs for premature repairs.

3. The increasing aggressiveness of the environment and the dynamic nature of external factors (due to the use of de-icing agents, atmospheric pollution, extreme climatic phenomena) and the increase in the design life of critical infrastructure (bridges, nuclear power plants, high-rise buildings) require a transition from empirical approaches to scientifically based methods of structural resource management.

The study aims to overcome the fragmentation of existing knowledge and practices by synthesising diagnostics, forecasting and protection into a comprehensive system, which is a necessary step towards smart infrastructure asset management. Key current trends in research:

- a shift from passive protection (barrier coatings) to active and preventive protection (cathodic protection, inhibitors, self-compacting concrete);

- integration of non-destructive testing methods (ultrasound, thermography, radio wave methods) and electrochemical diagnostics (potential measurement, impedance spectroscopy) to assess the condition of reinforcement through concrete thickness;

- active development of digital modelling and the application of artificial intelligence to predict corrosion rates based on big data on materials and operating conditions;

- development of new composite materials (based on carbon fibres, nanomodified additives) both for strengthening structures and for performing protective functions;

The central problem addressed by this study is the lack of a unified methodological platform that would allow for quantitative assessment of the current corrosion state of a structure based on an agreed set of parameters (comprehensive corrosion index); reliably predict

the remaining service life based on mathematical models verified by monitoring data; optimise decision-making on the choice of protection method, timing and scope of repair work, minimising the life cycle of the structure.

MAIN PART

The authors in the article examined the main aspects of the impact of corrosion on steel structures, its causes, consequences, and protection methods. The durability characteristics of the samples are verified through regular monitoring of the time of corrosion initiation, the ratio of corrosion area, corrosion depth, and the amount of steel mass loss.

Corrosion is a natural process of material degradation that occurs as a result of chemical or electrochemical reactions with the surrounding environment. Steel structures used in the construction of buildings and facilities are subject to corrosion, which can lead to serious consequences, including a decrease in the strength, stability, and durability of the structures.

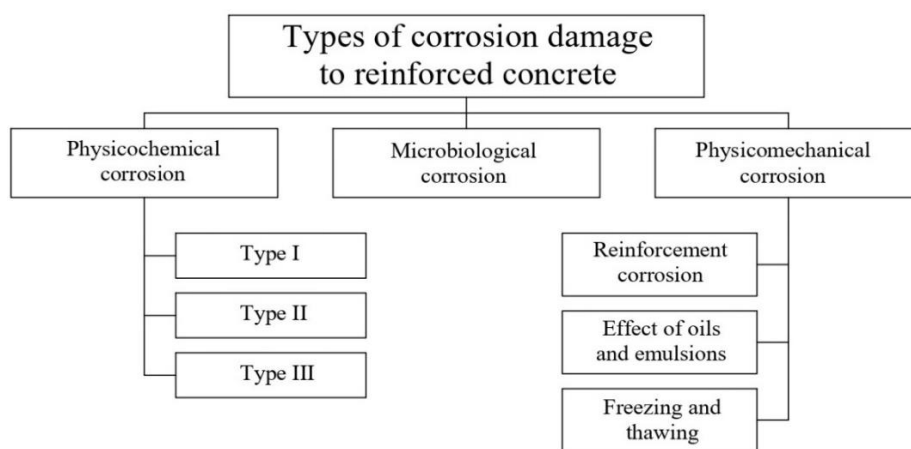


Figure 1. Types of corrosion in reinforced concrete structures (author's work)

Note – compiled by the authors

Corrosion of steel reinforcement in concrete is one of the key problems affecting the service life and durability of reinforced concrete structures (fig. 1). The main cause of corrosion is considered to be the penetration of chloride ions and carbon dioxide into the concrete. Chloride ions can cause local destruction of the protective film on the steel reinforcement, leading to localized corrosion. At the same time, carbon dioxide reduces the pH level of the concrete, which in turn promotes the formation of corrosion areas on the reinforcement. Corrosion significantly weakens concrete, especially when exposed to aggressive environments. Penetrating through the concrete protection, chlorides and carbon dioxide destroy the steel surface, accelerating the deterioration of structures (Qiu, Feng & Wu, 2025).

Corrosion of steel reinforcement in concrete structures raises increasing concern due to its impact on economic costs, safety, and operational performance. Corrosion processes (Fig. 2) lead to the formation of spalling, cracks, and a reduction in the diameter of the reinforcement, which can negatively affect the structural integrity of the structures (Hameed et al., 2023).

In (Otieno et al., 2016), the author emphasizes that corrosion of steel components in concrete leads to cracking, a decrease in bond strength, a reduction in the cross-sectional area of the steel, and loss of serviceability. Reinforced concrete affected by corrosion not only loses its quality but also its structural integrity. Although modern technologies make it possible to successfully address corrosion issues (Waqas et al., 2023), the problem of corrosion remains relevant. The main mechanisms of corrosion in reinforced concrete are associated with the

interaction between concrete, reinforcement, and the surrounding environment, i.e., the thermodynamic instability of a system consisting of metal and environmental components ($\Delta_rG < 0$), which can be expressed by the following reactions:

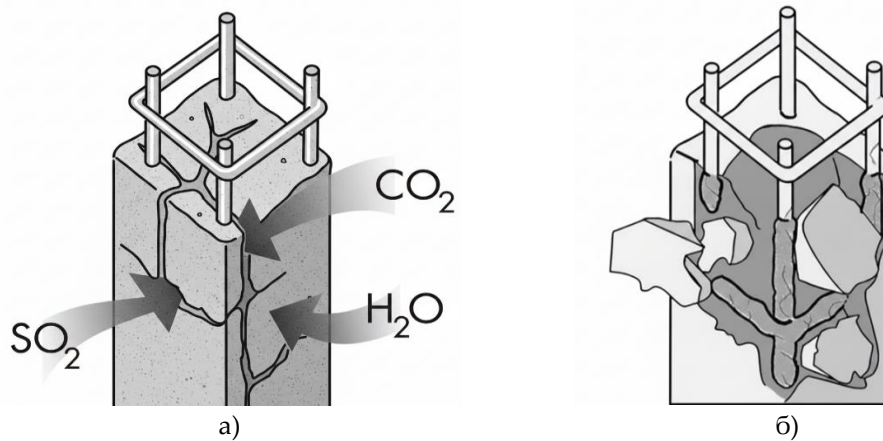
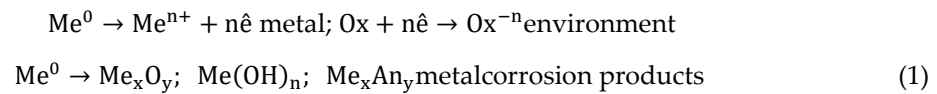


Figure 2. Concrete degradation under the influence of atmospheric and chemical factors: a) exposure to aggressive chemical components; b) reinforcement corrosion and concrete destruction (catalogue “Germann Instruments”, 2025)

Note – compiled by the authors

As is known, as a result of corrosion, the thickness of the metal (the diameter of the plate) decreases, i.e., the metal loses mass. From this, we can determine the rate of mass loss:

$$K = \frac{\Delta m}{S \cdot \tau}, \left[\frac{\text{g}}{\text{m}^2 \cdot \text{day}} \right] \quad (2)$$

and the rate of corrosion penetration into the metal, the depth indicator:

$$\Pi = \frac{h}{\tau}, \left[\frac{\text{mm}}{\text{year}} \right] \quad (3)$$

Let us consider this process in more detail. Penetration of the aggressive environment.

Corrosion of reinforcement in reinforced concrete begins with the penetration of aggressive substances (water, acids, chlorides, carbon dioxide, etc.) into the concrete. This may occur through microcracks in the concrete; pores and capillaries formed due to insufficient concrete density; or surface damage caused by mechanical effects or environmental exposure.

Degradation of the protective layer.

Under normal conditions, concrete provides protection for reinforcement due to its alkaline environment (pH around 12–13), which prevents corrosion. However, when aggressive substances penetrate the concrete, carbonation and chloride-induced corrosion occur. In the first case, carbon dioxide from the air dissolves in water and forms carbonic acid, which lowers the pH of the concrete, leading to the loss of the protective layer. In the second case, chlorides — for example, from seawater or de-icing agents — can cause corrosion of the reinforcement by breaking down the protective layer.

Reinforcement corrosion.

When the protective layer is damaged, the reinforcement begins to corrode. The corrosion process involves the oxidation of iron, resulting in the formation of iron oxides and hydroxides that expand in volume and create internal stresses. The corrosion products can cause further cracking in the concrete and deterioration of its strength properties.

Concrete destruction.

The increase in the volume of corrosion products leads to:

- the destruction of concrete around the reinforcement;
- the formation of cracks and delaminations, which reduce the strength and stability of the structure;
- increased permeability of the concrete, creating a self-sustaining cycle that promotes further penetration of aggressive substances (fig. 3).

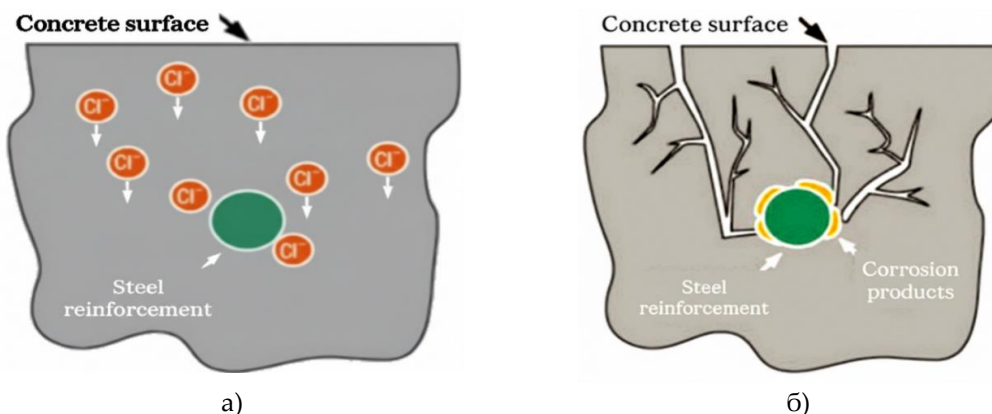


Figure 3. Concrete degradation due to reinforcement corrosion:

a) penetration of chloride ions into concrete; b) concrete destruction caused by the reinforcement corrosion process (catalogue "Germeticus", 2025)

Note – compiled by the authors

The corrosion mechanism occurs as a result of an electrochemical reaction caused by the potential difference between the reinforcement and the surrounding concrete (fig. 4). As a result of this reaction, anodic and cathodic zones are formed, leading to the complete loss of the reinforcement's designed properties (fig. 5).



Figure 4. Reinforced concrete support of a road bridge on K. Satpayev Street (Astana) affected by corrosion (author's work)

Note – compiled by the authors

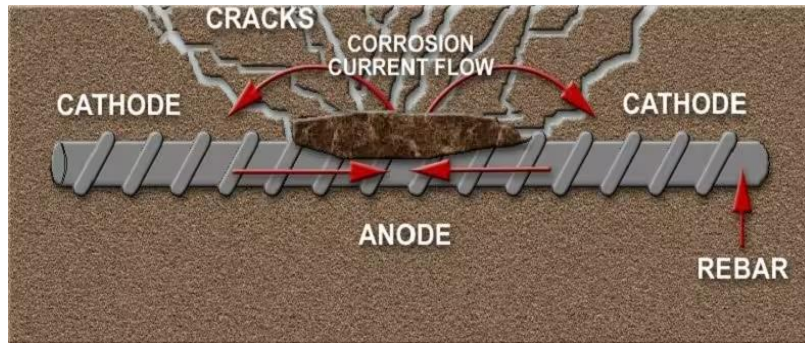
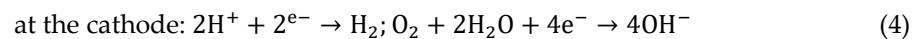
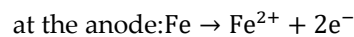


Figure 5. Formation of anode and cathode zones as a result of electrochemical corrosion (catalogue “John P. Broomfield”,2020)

Note – compiled by the authors

Reinforced concrete supports located in moist soil or directly in water—such as bridge piers or platform supports in marine environments—are subject to aggressive electrochemical corrosion. For this type of support, the process occurs as galvanic corrosion (fig. 6).

The formulas representing galvanic corrosion of steel include the following reactions:



The authors of (François et al., 2018) examined the relationship between the corrosion of steel reinforcement and its effects on the mechanical behavior of reinforced concrete structures. The researchers considered specific theoretical foundations of steel corrosion in concrete and its interaction with structural elements, including service cracks and concrete placement defects. Studies of the degradation mechanisms of the mechanical properties of steel bars and reinforced concrete revealed a decrease in ductility, a reduction in load-bearing capacity, redistribution of internal forces due to the formation of plastic hinges, and an increase in beam deflection during operation. Research conducted in (Natino et al., 2021) shows that, as a result of corrosion processes in steel elements within reinforced concrete structures, the cross-section of the reinforcement decreases by 25% for a single bar and by 20% for all bars in the structure.

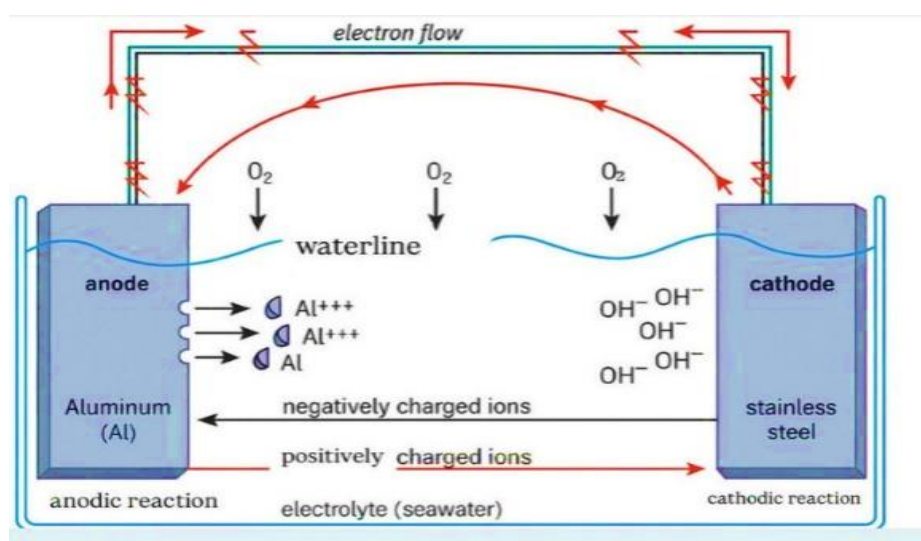


Figure 6. Diagram of the galvanic corrosion process (catalogue“Barque”,2025)

Note – compiled by the authors



LITERARY REVIEW

A number of authors in their studies examine the effect of anti-corrosion coatings on the strength of reinforcement using polymer coatings based on cement, as well as the application of epoxy coatings to reinforcement directly during construction before concreting (Kamde& Pillai, 2022; Vanama&Ramakrishnan, 2024; Zheng et al., 2025). In particular, the effectiveness of using different types of coatings is studied depending on the operating conditions of the structures, such as aggressive environments, high humidity, or exposure to mechanical loads. Special attention is paid to the durability of protective layers and their ability to maintain their protective properties over a long period. Research shows that the use of polymer and epoxy coatings can significantly increase the service life of reinforced concrete structures by minimizing the risk of reinforcement corrosion and providing additional protection for concrete against external influences.

Al-Dulaijan (2023) describes the performance characteristics of two types of coatings for steel: high-zinc epoxy and cement-based epoxy. Scientists evaluated these coatings through laboratory and field experiments. In field tests, concrete samples were exposed to seawater for more than five years. Salt spray and accelerated reinforcement corrosion tests showed that cement-based epoxy coatings perform better than zinc coatings. However, no visible differences in performance between the coatings were found on reinforced concrete slabs in field conditions. Based on their data, the scientists recommend using cement-based epoxy coatings as primers for steel.

Work (Tweek&Abdulsada, 2023) aims to demonstrate and review the positive impact of green inhibitors and organic inhibitors on chloride-induced corrosion.

Scientists studied the latest developments in the use of corrosion inhibitors in reinforced concrete (Yuvaraj et al., 2022) and conducted research in laboratory and field conditions. They once again proved that inhibitors are chemicals that are added to concrete in low concentrations to stop or delay corrosion in reinforced concrete structures. In their review study, the scientists examined various forms of inhibitors for concrete treatment and methods of their application. They compared the effectiveness of mixed and migrating inhibitors based on existing research.

The study (Wei et al., 2021) considers the possibility of using carbon fiber waste to reduce steel corrosion in reinforced concrete structures. To the authors' knowledge, this research is the first attempt to investigate the corrosion resistance of carbon fiber waste in reinforced concrete under harsh conditions with constant loading. First, carbon fiber waste was treated with epoxy resin to ensure uniform dispersion of soft carbon fiber in the cement mixture, as the hydrophobic surface of carbon fiber and the galvanic connection between carbon fiber and steel bars in concrete had to be prevented. Second, to accelerate the corrosion process, reinforced concrete samples were subjected to an aggressive environment with high temperature (50 °C) and a 6-hour "wet-dry" cycle in a 3.5 wt% NaCl solution, along with continuous loading. Third, the corrosion properties of the RC specimens were monitored for 360 days using electrochemical methods such as linear polarization resistance and electrochemical impedance spectroscopy.

The work (Byrne et al., 2016) investigated electrochemical corrosion protection and presented protection methods. The authors proposed cathodic protection using an impressed current for protecting metal structures in concrete, and as a second method, the use of a more active sacrificial anode to generate excitation current.

Anodic coating, in this case with zinc, protects the base metal by means of a more active metal and demonstrates the following electrochemical corrosion process, Table 1:

Table 1. Electrochemicalcorrosion

Electrochemical corrosion of zinc-coated iron		
$\varphi_{\text{Fe} \text{Fe}^{2+}}^0 = -0,44\text{В}$	>	$\varphi_{\text{Zn} \text{Zn}^{2+}}^0 = -0,76\text{В}$
Oxidizingagent		Reducingagent
<i>Note – compiled by the authors</i>		

here: anodic process(-) $\text{Zn} \rightarrow \text{Zn}^{2+} + 2\text{e}$

cathodic process (+) $\text{O}_2(\text{g}) + 4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2\text{O}$ (5)

In case of coating damage, a galvanic cell is formed, and zinc acts as the anode, as a result of which it corrodes, while the steel reinforcement itself remains intact (fig. 7):

(-)A[Zn]: $\text{Zn}^0 - 2\text{e}^- \rightarrow \text{Zn}^{2+}; \quad \text{Zn}^{2+} + 2\text{OH}^- \rightarrow \text{Zn}(\text{OH})_2$ (6)

(+)K[Fe]: $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\text{O}$ (pH < 7) or $\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^-$ (pH = 7) (7)

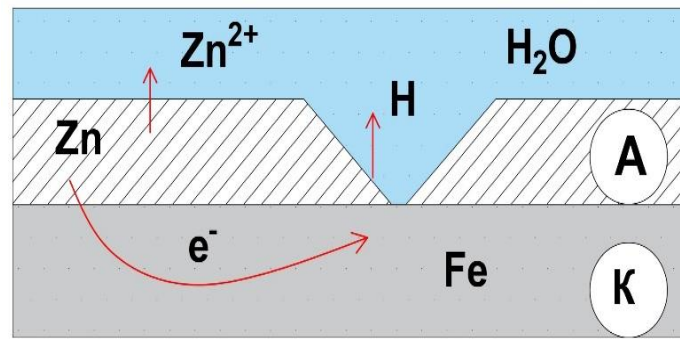


Figure 7. Diagram of electrochemical corrosion (catalogue “Stephen Lower”,2022)

Note – compiled by the authors

MATERIALS AND METHODS

To prevent corrosion in reinforced concrete structures, the following methods are used:

- use of corrosion-resistant reinforcement (for example, coated steel);
- addition of admixtures to concrete that improve its impermeability and resistance to aggressive environments;
- regular monitoring of the condition of structures and performing repair works at the first signs of corrosion.

As noted in (Sohail et al., 2021), the traditional methods of protecting steel structures include “passive” and “active” protection methods. In passive protection, metal products, parts, and structures are placed above ground and protected with special primer layers and enamel coatings, with possible use of bituminous mastic. In active protection, the difference in electrical potential between the anode and cathode is used, where the “anode” part is intentionally corroded to ensure the safety of the “cathode.”

Modern protection technologies increasingly rely on advanced approaches. Researchers (Mihashi et al., 2011) presented the results of corrosion tests on fiber-reinforced cement composites containing only polyethylene (PE) plus hybrid steel cords (SC), and PE fibers. In this study, the metal was subjected to accelerated corrosion by applying an external potential between a steel rod anode and a cathode made of steel wire mesh placed outside the concrete. The results showed that hybrid fiber-reinforced cement composites (HFRCC) containing hybrid SC and PE fibers demonstrated superior performance compared to mortar and fiber-reinforced cement composites (FRCC) containing only PE fibers.



Scientists (Gharieb et al., 2024; Jiang et al., 2014; Khatri et al., 2025; Mihashi et al., 2011; Ming et al., 2023; Wang et al., 2019) proposed adding polymer composite materials to concrete to densify and strengthen it, thereby preventing aggressive environments from reaching the metallic parts of reinforced concrete structures. Other researchers (Cheng et al., 2022; Kamde et al., 2021) suggested protecting the metallic components directly by applying a protective layer in the form of an anode – that is, a metal that corrodes more readily to protect the main reinforcement – and using inhibitors (Asaad, 2021; Palanisamy et al., 2016; Valdez-Salas et al., 2021; Venkatesh et al., 2019).

Understanding corrosion processes and modeling the rate of corrosion are key aspects for ensuring the durability and reliability of structures (Cheng & Maruyama, 2023; Ji & Ye, 2023; Lollini&Redaelli, 2021). Modeling involves the use of various mathematical and numerical methods. Simulating corrosion propagation rates in concrete reinforcement helps assess the condition of a structure and predict when and where corrosion may occur, aiding in maintenance and repair planning. Information about corrosion rates can also be used to select more durable materials and technologies, increasing the lifespan of structures. Modeling assists in developing effective corrosion protection methods such as the use of corrosion-resistant alloys or special coatings. Modern technologies like machine learning and artificial intelligence open new horizons for corrosion prediction (Chou et al., 2017). These methods make it possible to process large datasets obtained from experiments and field studies, reveal hidden patterns, and improve prediction accuracy. Reliable estimates of the degree of corrosion and the time to reach safety limits (Yadeta, Siriwardane& Mohammed, 2023) are critical for analysing the reliability of reinforced concrete structures. Engineers and decision-makers can use this data to plan inspections and maintenance.

To form a comprehensive corrosion index, the authors suggest including key parameters that reflect the level and dynamics of damage to reinforced concrete structures under the influence of corrosion, which is important for predicting the remaining service life and planning repair measures:

- Degree of reinforcement corrosion – residual metal thickness (% loss relative to the original thickness) and presence of corrosion damage (rust thickness, mass loss);
- Reinforcement corrosion potential – measurement of the electrochemical potential of reinforcement relative to a standard electrode, identifying active corrosion zones and their intensity;
- Condition of protective concrete – thickness and integrity of the concrete cover, presence of cracks and spalling, and indicators of water impermeability and permeability;
- Chemical parameters of concrete – pH value, degree of carbonation, and chloride content, which increase environmental aggressiveness and accelerate reinforcement corrosion;
- Visual signs of damage – characteristic crack patterns, concrete spalling, and presence of corrosion stains on the surface;
- Temperature and humidity conditions during operation – influence of climate and microclimate, which can accelerate or slow down corrosion processes.

These parameters can be used in the development of regulatory and technical documentation for determining maintenance intervals for reinforced concrete structures affected by corrosion.

RESULTS AND DISCUSSION

In accordance with the stated objective, the following results were obtained:

1. A systematic analysis of current knowledge has established that the dominant factor limiting the durability of reinforced concrete is electrochemical corrosion of reinforcement induced by chlorides and carbonation of concrete. A critical gap has been identified between the in-depth study of individual mechanisms and their fragmentary consideration in practical diagnostic and predictive methods.

2. Based on the results of the classification of diagnostic and protection methods, a taxonomy has been developed that divides methods into reactive (inspection and repair after damage detection) and predictive-proactive (monitoring + modeling). It has been proven that the greatest potential for improving reliability and economic efficiency lies in the combination of non-destructive electrochemical control (linear polarization, impedance spectroscopy) with active long-term protection methods (cathodic, inhibitors).

3. As part of the development of a comprehensive approach to assessment, a structure for a comprehensive corrosion index (CCI) has been proposed as an integral quantitative indicator of the condition of a structure. The principle of hierarchical aggregation of data from direct measurements to generalized indicators and an integral index has been defined, requiring the assignment of weighting coefficients depending on the type of structure. The CCI aggregates several key parameters:

- degree of corrosion wear of reinforcement (loss of cross-section, mass);
- electrochemical potential and corrosion rate;
- thickness and integrity of the protective concrete layer;
- depth of carbonation and chloride concentration near the reinforcement;
- nature and width of cracks;
- aggressiveness of the environment (temperature and humidity conditions).

4. In terms of forecasting, a concept for a hybrid forecasting model has been formulated, which will enable a transition from conservative estimates to dynamic forecasting of residual resources and will combine:

- a deterministic component (physico-chemical laws of agent diffusion, kinetics of electrochemical reactions);
- a stochastic/adaptive component based on machine learning methods, which adjusts the forecast as new monitoring data becomes available (CCM);

5. As a practical conclusion, a generalized scheme of a predictive corrosion safety management system has been developed, representing a closed cycle (Fig. 8):

It is necessary to include the stages of predictive modeling and calculation of CCI in the regulatory and technical framework to justify the intervals between repairs and select an operation strategy.

It follows that overcoming the current problems in reinforced concrete protection lies not in the creation of a new insulating material or method, but in the systematic integration of existing diagnostic, modeling, and protection technologies based on quantitative integral criteria (QIC) and adaptive predictive models.

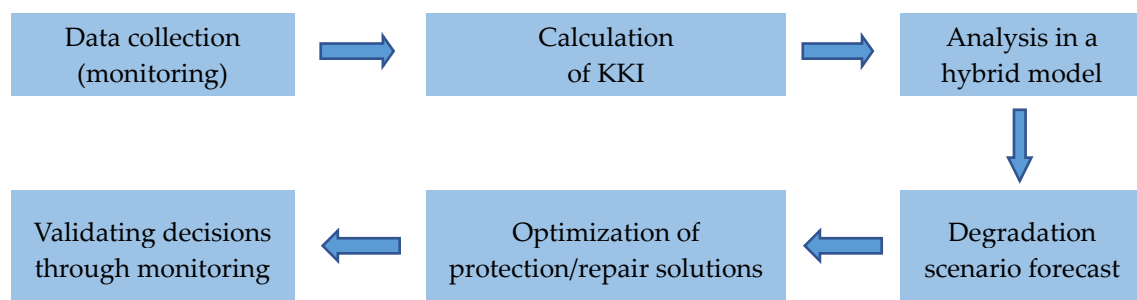


Figure 8. Diagram of a predictive corrosion safety management system (author's work)
Note – compiled by the authors

CONCLUSIONS

Reinforcement corrosion in reinforced concrete structures is one of the main causes of their deterioration. It reduces the strength and durability of structures, which can have serious



implications for the safety of buildings and facilities. The primary factors contributing to corrosion are aggressive chemical environments, high humidity, temperature fluctuations, and insufficient reinforcement protection.

Various methods exist for diagnosing the condition of reinforced concrete structures, including visual inspection, ultrasonic testing, and electrochemical techniques, which allow timely detection of corrosion processes.

Effective corrosion protection methods include the use of corrosion-resistant materials, application of protective coatings, cathodic protection, and various concrete additives that modify its physical properties, directly influencing the condition of reinforcement in concrete, along with regular maintenance.

To prevent corrosion in concrete reinforcement, regular inspections and monitoring of reinforced concrete structures are necessary for early detection of corrosion processes. In the design and construction of new structures, corrosion-resistant reinforcement materials and additives that enhance concrete resistance to aggressive environments should be used, and protective coatings should be applied to reinforced concrete surfaces to minimize the effects of external factors promoting corrosion. Mathematical modeling of corrosion propagation rates should be applied in the specific context of the construction process.

Depending on the protection mechanism, corrosion protection methods are divided into passive and active. Passive methods include high-performance fiber-reinforced cement mortar coatings, anti-corrosion coatings, and corrosion inhibitors. Active protection involves cathodic protection and electrochemical chloride extraction.

Among these methods, fiber-reinforced cement mortar stands out for its effectiveness in preventing corrosion due to its high strength, although it is mainly used for structural strengthening because of its superior mechanical properties. Carbon fiber-reinforced polymer can serve dual functions: as a strengthening material and as an anode in cathodic protection and electrochemical chloride extraction. This unique material capability makes it highly promising for protecting corrosion-damaged reinforced concrete structures.

Corrosion in reinforced concrete structures is a multi-stage process that requires attention and preventive measures to ensure the durability and safety of buildings and facilities.

A systematic analysis has shown that, despite in-depth research into individual corrosion mechanisms and the availability of a wide range of protective technologies, the key obstacle to improving the durability of structures remains the gap between diagnosis, prediction, and decision-making. Existing approaches are often reactive in nature, and the methods used are studied in isolation, without taking into account their synergy or long-term behavior in real operating conditions.

The central result of the work is the proposed concept of a Comprehensive Corrosion Index (CCI), designed to become a universal quantitative tool for the integrated assessment of structural condition. The CCI aggregates key physicochemical, electrochemical, and mechanical parameters, enabling the transition from qualitative descriptions to controllable quantitative criteria. To implement the predictive function, the need to develop hybrid mathematical models combining deterministic corrosion laws with adaptive machine learning algorithms that correct the forecast based on continuous monitoring data is justified.

Based on these elements, a generalized scheme of a predictive decision support system has been developed, forming a closed cycle of “monitoring – assessment (KKI) – forecast – protective intervention – validation.” The implementation of this approach will optimize the timing and scope of repair work, minimize life cycle costs, and shift from a strategy of planned preventive maintenance to management based on actual condition and predicted risk.

Prospects for further research are related to empirical validation and calibration of the proposed methodology on real-world objects, development of standardized data collection

protocols for model training, and in-depth study of the long-term effectiveness and compatibility of combined protection methods. The implementation of these areas will contribute to the formation of a new paradigm in the operation of construction facilities, based on data, forecasts, and intelligent resource management, which is a necessary condition for ensuring the long-term safety and sustainability of critical infrastructure.

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REFERENCES

- Al-Dulajjan, S. U. (2023). A Laboratory and Field Assessment of the Performance of Rebar Coatings. *Materials (Basel, Switzerland)*, 16(12), 4270. <https://doi.org/10.3390/ma16124270>
- Asaad, M. A. (2021). Commercial and Green Corrosion Inhibitors for Reinforced Concrete Structures: A Review. *International Journal of Current Science Research and Review*, 04(02). <https://doi.org/10.47191/ijcsrr/v4-i2-04>
- Byrne, A., Norton, B., & Holmes, N. (2016). State-of-the-art review of cathodic protection for reinforced concrete structures. *Magazine of Concrete Research*, 68(13), 664–677. <https://doi.org/10.1680/jmacr.15.00083>
- Cheng, L., & Maruyama, I. (2023). A Prediction Method for the Corrosion Rate of Steel Rebar in Carbonated Mortar under Variable Environmental Conditions. *Journal of Advanced Concrete Technology*, 21(8), 611–630. <https://doi.org/10.3151/jact.21.611>
- Cheng, X., Xia, J., Wu, R. J., Jin, W. L., & Pan, C. G. (2022). Optimisation of sacrificial anode cathodic protection system in chloride-contaminated reinforced concrete structure. *Journal of Building Engineering*, 45. <https://doi.org/10.1016/j.jobee.2021.103515>
- Chou, J. S., Ngo, N. T., & Chong, W. K. (2017). The use of artificial intelligence combiners for modeling steel pitting risk and corrosion rate. *Engineering Applications of Artificial Intelligence*, 65, 471–483. <https://doi.org/10.1016/j.engappai.2016.09.008>
- François, R., Laurens, S., & Deby, F. (2018). Corrosion and its Consequences for Reinforced Concrete Structures. Elsevier. <https://doi.org/10.1016/B978-1-78548-234-2.50009-3>
- Gharieb, M., Aboutaleb, S.A., Dokaila, A.M., & El-Attar, M. (2024). Impact of combined organic chemical inhibitor on mechanical properties of cement pastes and steel reinforcement corrosion in concrete upon exposure to aggressive environment. *Construction and Building Materials*, 420, 135567. <https://doi.org/10.1016/j.conbuildmat.2024.135567>
- Hameed, A., Afzal, M. F. U. D., Javed, A., Rasool, A. M., Qureshi, M. U., Mehrabi, A. B., & Ashraf, I. (2023). Behavior and Performance of Reinforced Concrete Columns Subjected to Accelerated Corrosion. *Metals*, 13(5), 930. <https://doi.org/10.3390/met13050930>



- Hu, J. Y., Zhang, S. S., Chen, E., & Li, W. G. (2022). A review on corrosion detection and protection of existing reinforced concrete (RC) structures. *Construction and Building Materials*. <https://doi.org/10.1016/j.conbuildmat.2022.126718>
- Ji, H., & Ye, H. (2023). Machine learning prediction of corrosion rate of steel in carbonated cementitious mortars. *Cement and Concrete Composites*, 143. <https://doi.org/10.1016/j.cemconcomp.2023.105256>
- Jiang, C., Fan, K., Wu, F., & Chen, D. (2014). Experimental study on the mechanical properties and microstructure of chopped basalt fibre reinforced concrete. *Materials and Design*, 58, 187–193. <https://doi.org/10.1016/j.matdes.2014.01.056>
- Kamde, D. K., Manickam, K., Pillai, R. G., & Sergi, G. (2021). Long-term performance of galvanic anodes for the protection of steel reinforced concrete structures. *Journal of Building Engineering*, 42. <https://doi.org/10.1016/j.jobe.2021.103049>
- Kamde, D. K., & Pillai, R. G. (2022). Corrosion initiation and its effect on bond characteristics and service life of reinforced concrete systems with Cement-Polymer-Composite coated steel rebars. *Structures*, 44, 248-260. <https://doi.org/10.1016/j.istruc.2022.08.003>
- Khatri, W.A., Al Mehthel, M., Salazar, O., Baig, M., & Al Wohaibi, S. (2025). Use of Polymeric Materials in Construction to Improve Durability & Sustainability. *World Journal of Engineering and Technology*, 13(1). <https://doi.org/10.4236/wjet.2025.131002>
- Lollini, F., & Redaelli, E. (2021). Corrosion rate of carbon steel in carbonated concrete made with different supplementary cementitious materials. *Corrosion Engineering Science and Technology*, 56(5), 473–482. <https://doi.org/10.1080/1478422X.2021.1916236>
- Mihashi, H., Ahmed, S. F. U., & Kobayakawa, A. (2011). Corrosion of reinforcing steel in fiber reinforced cementitious composites. *Journal of Advanced Concrete Technology*, 9(2), 159–167. <https://doi.org/10.3151/jact.9.159>
- Ming, X., Liu, Q., Wang, M., Cai, Y., Chen, B., & Li, Z. (2023). Improved chloride binding capacity and corrosion protection of cement-based materials by incorporating alumina nano particles. *Cement and Concrete Composites*, 136. <https://doi.org/10.1016/j.cemconcomp.2022.104898>
- Natino, M. R. L., Yang, Y., Nakamura, H., & Miura, T. (2021). Experimental study on the effect of anti-corrosive coatings on bond behavior of corroded rebar. *Construction and Building Materials*, 274, 121716. <https://doi.org/10.1016/j.conbuildmat.2020.121716>
- Otieno, M., Beushausen, H., & Alexander, M. (2016). Chloride-induced corrosion of steel in cracked concrete—Part II: Corrosion rate prediction models. *Cement and Concrete Research*, 79, 386-394. <https://doi.org/10.1016/j.cemconres.2015.08.008>
- Palanisamy, S. P., Maheswaran, G., Kamal, C., & Venkatesh, G. (2016). *Prosopis juliflora* – A green corrosion inhibitor for reinforced steel in concrete. *Research on Chemical Intermediates*, 42(12), 7823–7840. <https://doi.org/10.1007/s11164-016-2564-1>
- Qiu, J.R., Feng, D.C., & Wu, G. (2025). A multi-physics dual-phase field model for chloride-induced localized corrosion process and cracking in reinforced concrete. *Computer Methods in Applied Mechanics and Engineering*, 434, 117578. <https://doi.org/10.1016/j.cma.2024.117578>
- Sohail, M.G., Laurens, S., Deby, F., Balyssac, J.P., & Al Nuaimi, N. (2021). Electrochemical corrosion parameters for active and passive reinforcing steel in carbonated and sound concrete. *Materials and Corrosion*, 72(12), 1854–1871. <https://doi.org/10.1002/maco.202112569>
- Tweek, M. K., & Abdulsada, S. A. (2023). Study title or description. *KOM – Corrosion and Material Protection Journal*, 67, 50-58. <https://doi.org/10.2478/kom-2023-0007>
- Valdez-Salas, B., Vazquez-Delgado, R., Salvador-Carlos, J., Beltran-Partida, E., Salinas-Martinez, R., Cheng, N., & Curiel-Alvarez, M. (2021). *Azadirachta indica* leaf extract as green corrosion inhibitor for reinforced concrete structures. *Materials*, 14(12). <https://doi.org/10.3390/ma14123326>

- Vanama, R. K., & Ramakrishnan, B. (2024). Experimental investigation on the bond-slip behavior of rebars coated with epoxy and polyurethane systems: A comparative study. *Journal of Building Engineering*, 94, 110066. <https://doi.org/10.1016/j.job.2024.110066>
- Venkatesh, C., Mohiddin, S. K., & Ruben, N. (2019). Corrosion inhibitors behaviour on reinforced concrete – A Review. In *Lecture Notes in Civil Engineering* (Vol. 25, pp. 127–134). Springer. https://doi.org/10.1007/978-981-13-3317-0_11
- Wang, D., Ju, Y., Shen, H., & Xu, L. (2019). Mechanical properties of high performance concrete reinforced with basalt fiber and polypropylene fiber. *Construction and Building Materials*, 197, 464–473. <https://doi.org/10.1016/j.conbuildmat.2018.11.181>
- Waqas, H. A., Bahrami, A., Sahil, M., Poshad Khan, A., Ejaz, A., Shafique, T., Tariq, Z., Ahmad, S., & Özkılıç, Y. O. (2023). Performance Prediction of Hybrid Bamboo-Reinforced Concrete Beams Using Gene Expression Programming for Sustainable Construction. *Materials* (Basel, Switzerland), 16(20), 6788. <https://doi.org/10.3390/ma16206788>
- Wei, A., Tan, M. Y., Koay, Y. C., Hu, X., & Al-Ameri, R. (2021). Effect of carbon fiber waste on steel corrosion of reinforced concrete structures exposed to the marine environment. *Journal of Cleaner Production*, 316, 128356. <https://doi.org/10.1016/j.jclepro.2021.128356>
- Yadeta, K.F., Siriwardane, S.C., & Mohammed, T. A. (2023). Service life prediction of reinforced concrete structures subjected to corrosion: a comparative study. *International Journal of Structural Integrity*, 14(3), 480–497. <https://doi.org/10.1108/IJSI-12-2022-0149>
- Yuvaraj, S., Nirmalkumar, K., Rajesh Kumar, V., Gayathri, R., Mukilan, K., & Shubikksha, S. (2022). Influence of corrosion inhibitors in reinforced concrete – A state of art of review. *Materials Today: Proceedings*, 68(6), 2406-2412. <https://doi.org/10.1016/j.matpr.2022.09.118>
- Zheng, S., Li, Y., Feng, Q., Liang, X., Wu, X., & Xu, R. (2025). Experimental investigation on bond-slip behavior of epoxy-coated rebars in steel fiber reinforced concrete. *Case Studies in Construction Materials*, 22, e04767. <https://doi.org/10.1016/j.cscm.2025.e04767>

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