

BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

UDC [625.42:624.012.45]-044.74

O. O. OVCHYNNIKOV^{1*}, YE. A. PROKAZA², V. V. TERTYCHNYI³

^{1*}Department of Railway Track and Transport Structures, Ukrainian State University of Railway Transport, Oboronnyi Val Square 7, Kharkiv, Ukraine, 61050, tel. +38 (050) 780 63 39, email ovchinnicov_77@ukr.net, ORCID 0000-0002-6941-2076

²Department of Railway Track and Transport Structures, Ukrainian State University of Railway Transport, Oboronnyi Val Square 7, Kharkiv, Ukraine, 61050, tel. +38 (095) 166 51 10, email prokazaevgeniya@gmail.com, ORCID 0009-0000-7345-2145

³Department of Railway Track and Transport Structures, Ukrainian State University of Railway Transport, Oboronnyi Val Square 7, Kharkiv, Ukraine, 61050, tel. +38 (057) 730 10 60, email ppx_xiit@kart.edu.ua, ORCID 0009-0002-9025-6546

ANALYSIS OF EXISTING PROBLEMS AND APPROACHES TO EXTENDING THE SERVICE LIFE OF REINFORCED CONCRETE TRACK STRUCTURES AND METRO FACILITIES (A REVIEW)

Purpose. The article presents a comprehensive analysis of existing problems related to the durability and service life of reinforced concrete track structures and subway facilities operating under conditions of intensive loading and exposure to aggressive environmental factors. **Methodology.** Particular attention is paid to the specific operational features of metro infrastructure, including cyclic and dynamic loads, moisture penetration, temperature fluctuations, stray currents, and chemically aggressive environments, all of which significantly accelerate the degradation of reinforced concrete elements. **Findings.** The main deterioration mechanisms of concrete and reinforced concrete structures are examined, including reinforcement corrosion, physicochemical degradation of the cement matrix, fatigue damage accumulation, cracking development, and the influence of subgrade instability on the structural performance of track systems. These processes are shown to have a cumulative effect, leading to a reduction in load-bearing capacity, serviceability, and overall operational reliability of subway structures. **Originality.** The paper provides a scientific review of modern approaches to extending the service life of reinforced concrete structures, encompassing materials-based solutions, structural and design improvements, advanced calculation methods, and operational measures. Special emphasis is placed on protective strategies against aggressive impacts, such as the use of high-performance concretes, corrosion-resistant reinforcement, protective coatings, and repair systems. In addition, service life modelling techniques that account for corrosion kinetics and environmental exposure conditions are analyzed. **Practical value.** The study also highlights the growing role of digital technologies, including structural health monitoring systems, non-destructive testing methods, and data-driven predictive maintenance models, in ensuring the long-term reliability of metro infrastructure. It is demonstrated that an integrated application of protective, rehabilitative, and predictive measures enables a significant increase in the durability, safety, and operational efficiency of reinforced concrete track structures and metro facilities.

Keywords: subway; reinforced concrete structures; tracks; durability; reinforcement corrosion; service life extension; service life modelling

Introduction

Reinforced concrete structures of railway tracks and subway facilities are critical elements of transportation infrastructure, operating under conditions of increased mechanical loads, humidity, ground-water effects, and chemically aggressive environments.

The relevance of the issue of premature degradation and loss of operational suitability of reinforced concrete elements is due to the high intensity of metro operations and the limited possibilities for complete replacement of the structures.

Most modern structures are designed without a clear determination of their service life, and they do not take into account contemporary models of concrete degradation and reinforcement corrosion. Due to these circumstances, in recent years, there have been cases of significant reductions in load-bearing capacity after only 20–30 years of operation, accompanied by increased repair and maintenance costs, as well as risks to traffic safety.

In today's conditions, extending the service life of reinforced concrete structures is seen as a technical task and a component of sustainable devel-

opment for transportation infrastructure. This fact necessitates a shift from fragmented repair measures to a comprehensive engineering approach, which combines materials science solutions, structural reinforcement, service life modeling, monitoring systems, and digital technologies for operation management.

Purpose

To analyze the existing issues in the operation of reinforced concrete railway track and metro facility structures, and to summarize contemporary scientific and technical approaches to extending their service life under aggressive operational environments.

To achieve the set objective, the following tasks are outlined in the work:

- to analyze the main mechanisms of degradation of reinforced concrete structures in the subway under the influence of mechanical, physical, and chemical factors;
- to assess the role of reinforcement corrosion as the dominant factor in reducing the durability and load-bearing capacity of structures;
- to summarize modern materials science and structural solutions aimed at increasing the durability of concrete and reinforced concrete elements;
- to analyze practical methods of protecting reinforced concrete from aggressive impacts as a tool for extending the service life of existing structures.

Review of Sources on the Research Topic

Studies conducted at the Kharkiv Metro (Плугін, А. М., Плугін, А. А., Скорик, et al., 2003; Плугін, 2004) have established the destructive, including aggressive, impacts that lead to the deterioration of the reinforced concrete tunnel linings much earlier than the established service life. These impacts include the combination of water saturation of the structures and surrounding soils with leakage currents from the running rails, chemical and biological aggressiveness of groundwater and soils, saturation of unstable surrounding soils, and increased loads due to changes in urban planning conditions. Of these factors, water saturation can be considered the most influential (Плугін, А. Н., Плугін, А. А., Калинин, et al., 2006).

Later, during inspections of subway tunnels, the authors of this article confirmed these conclusions. It was shown that water saturation manifests as infiltration of groundwater, even active flows through joints between the reinforced concrete blocks of the lining, technological openings in them, and even through the concrete body of the blocks (Figure 1). Filtration through the concrete leads to its leaching, with signs such as efflorescence (Figure 2), resulting in the loss of the concrete's protective properties against reinforcement and a reduction in its strength. The saturation of unstable surrounding soils and increased loads due to changes in urban planning conditions lead to the formation of cracks in the reinforced concrete blocks (Figure 3).



Figure 1. Infiltration through the reinforced concrete lining of the subway tunnel (photo taken by the authors)



Figure 2. Efflorescence of calcite (CaCO_3) – the product of leaching and carbonation of $\text{Ca}(\text{OH})_2$ from the concrete (photo taken by the authors)



Figure 3. Cracks in the reinforced concrete blocks of the tunnel linings (photo taken by the authors)

Additionally, in (Плугин, Калинин, Шумик, et al., 2001), it was recommended as an accessible and effective measure for restoring the impermeability and load-bearing capacity of reinforced concrete linings to inject hardening compositions based on cement or polymers through drilled holes in the lining.

Currently, to increase the effectiveness of restoration, injection is even carried out through perforated injectors, which are immersed in the holes to a depth of more than 2 meters (Figure 4).

In the work (Craeye, Renne, Audenaert, & Buyle, 2025), a comprehensive approach to extending the service life of existing concrete and reinforced concrete structures is discussed, taking into account technical, economic, and environmental factors throughout the entire life cycle of the

structure. The authors emphasize that the aging of concrete structures is one of the key issues of modern infrastructure, which leads to an increased demand for maintenance, repair, strengthening, or complete replacement of structures.

Particular attention in the study is given to reinforcement corrosion as the dominant mechanism of damage to reinforced concrete structures. According to the data presented by the authors, over 70 % of defects in reinforced concrete structures are related to corrosion processes, which directly affect both the durability of the structure and its residual load-bearing capacity. In this context, the need for a thorough diagnosis is highlighted, which includes identifying the mechanisms and causes of damage, assessing their intensity, and spatial spread.



Fig. 4. Restoration of impermeability and load-bearing capacity of reinforced concrete linings through injection using immersed perforated injectors (photo taken by the authors)

The authors propose a step-by-step approach to extending the life of structures, which includes: determining the actual load-bearing capacity, predicting technical durability, and estimating the remaining service life, as well as selecting the optimal repair or maintenance strategy. It is emphasized that both preventive (proactive) and restorative (reactive) measures should be applied depending on the condition of the structure and the conditions of its operation.

The practical value of the research is confirmed by the results of analysis conducted on real-world objects with varying functional characteristics, ages, and causes of damage. The work emphasizes the importance of applying a holistic, system-based approach to extending the service life of reinforced concrete structures, which is especially relevant for infrastructure objects with a long service life, particularly transportation facilities and metro elements.

In the work (Whitmore, 2022), modern approaches to extending the service life of concrete and reinforced concrete structures are presented, using the concepts of durable design outlined in the SHRP2 R19A documents and the Model Code for Service Life Design (FIB Bulletin 34). The authors emphasize that a significant portion of existing infrastructure objects were built without a clearly defined design service life. However, applying long-term operational principles allows for a sub-

stantial increase in their reliability and remaining service life.

The article mainly focuses on the corrosion of reinforcement as a key factor in the degradation of reinforced concrete structures. It is noted that implementing specialized protection and corrosion control measures can reduce the corrosion intensity of embedded reinforcement by more than 80%, which directly affects the extension of the service life of the structures. This approach is considered the most effective tool for enhancing the durability of structures without the need for their complete replacement.

The research justifies the feasibility of considering the extension of the service life of reinforced concrete structures as one of the key areas of sustainable infrastructure development, which is particularly relevant for transportation and engineering structures with a long service life.

In the article (Alexander, & Beushausen, 2019), an analysis of modern approaches to predicting the durability and modeling the service life of reinforced concrete structures is presented. The authors emphasize the growing attention of the scientific community to the issues of concrete structure degradation, driven by the need to ensure their reliable and long-term operation under conditions of intensive loads and aggressive environmental influences.

The main concepts of durability design are dis-

cussed, including the philosophy of limit states and damage development models, which are partially integrated into modern regulations, particularly the Model Code of the International Federation for Concrete (FIB) and ISO 13823 standards. It is noted that the implementation of such approaches has contributed to the shift from empirical solutions to engineering-based design for the durability of reinforced concrete structures.

A significant part of the work focuses on the analysis of service life prediction models, including models of concrete carbonation, chloride penetration, and reinforcement corrosion. Additionally, a critical evaluation of common assumptions used in service-life modeling is conducted, as well as the limitations of applying different approaches in the practice of design and assessment of the remaining resource of structures.

The study (Alexander & Beushausen, 2019) provides important theoretical groundwork for research aimed at evaluating the remaining service life and extending the service life of reinforced concrete structures, and can serve as a methodological basis for analyzing the durability issues of infrastructure objects, particularly transportation and underground structures.

In the work (Alexander, 2018), a comprehensive overview of modern approaches to the design and modeling of the service life of concrete and reinforced concrete structures is presented. It is shown that the growing demands for durability, operational reliability, and sustainability of infrastructure objects cannot be realized without the application of forecasting and modeling methods for degradation processes in concrete. The author justifies the need to shift from traditional regulatory-prescriptive design approaches to models focused on operational characteristics, which are based on evaluating the material's actual behavior over time.

Premature failure of concrete structures is a common phenomenon and is caused by insufficient understanding of degradation mechanisms, imperfect criteria for concrete acceptance at construction sites, as well as changes in the properties of cements and construction technologies. The main factors contributing to reduced durability include external aggressive influences (sulfate corrosion, freeze-thaw cycles), internal material incompatibilities (alkali-aggregate reaction), and the action of aggressive environments. The most dangerous factor for reinforced concrete structures remains reinforcement corrosion, which leads to cracking, de-

lamination, and destruction of the concrete's protective layer, as well as a reduction in load-bearing capacity and operational suitability of the structures. The article critically evaluates the current durability design practices, which are mainly based on prescriptive standards and the use of compressive strength as an indirect indicator of durability. The author emphasizes that the same strength values can be achieved through different methods, which significantly differ in the ability of concrete to resist the penetration of aggressive environments. Moreover, laboratory tests of samples do not reflect the true quality of concrete in the structure, especially in the protective layer zone.

The author analyzes international experience in the use of service life models and operational specifications in Europe, North America, Scandinavian countries, Canada, and Australia. It is shown that the most advanced approaches are based on probabilistic analysis and experimental determination of the parameters of aggressive substance diffusion in concrete, which allows for a reasoned prediction of the onset of reinforcement corrosion.

It is emphasized that ensuring the durability of reinforced concrete structures is impossible without transitioning from formal compliance with regulatory requirements to integrated design based on service life models and operational criteria. This approach helps reduce the risk of premature damage, optimize infrastructure maintenance costs, and ensure its sustainable operation throughout the specified service period.

The review article (Rusnak, 2025) summarizes modern approaches to the preservation and strengthening of reinforced concrete infrastructure objects under conditions of aging, increasing operational loads, and stricter environmental requirements. It is noted that a significant portion of reinforced concrete structures worldwide is approaching the end of their design service life, which necessitates the development of sustainable and long-lasting strategies for their preservation and modernization.

The work analyzes the impact of the main degradation factors of concrete infrastructure, particularly the aggressive effects of the environment, aging changes in materials, and increased loads during operation. It is noted that traditional repair approaches often do not provide the necessary level of durability and economic efficiency, which highlights the need for the implementation of innovative materials and technologies.

The article focuses on modern material solu-

tions aimed at increasing durability and reducing the environmental footprint of concrete structures. These solutions include low-carbon binders, the use of mineral additives, geopolymer concretes, and self-healing materials. The application of these technologies not only extends the service life of structures but also reduces greenhouse gas emissions throughout the life cycle of the structures.

In general, the work (Rusnak, 2025) presents the author's modern view on the sustainable development of reinforced concrete infrastructure objects and emphasizes the need to transition to operationally-oriented and life-cycle approaches in the design, repair, and extension of the service life of reinforced concrete structures.

In the scientific work (Redaelli, Bertolini, & Lollini, 2011), a study is conducted on the features of reinforcement corrosion as one of the main causes of the degradation of reinforced concrete structures. The authors emphasize the need for using models that describe the initiation and subsequent development of corrosion processes for designing structures with a specified service life.

Among the main directions, the importance of applying the probabilistic approach of FIB, which is oriented towards service-life-oriented design, is emphasized. At the same time, it is noted that this approach requires long-term validation, as its practical reliability remains insufficiently confirmed.

To assess the adequacy of the model, the authors applied the FIB procedure to real structures built in the past and compared the predicted results with data from actual inspections. Significant discrepancies were found between the model estimates and the actual condition of the structures.

In the scientific article (Лучко, Назаревич, & Кравець, 2016), the problem of reduced load-bearing capacity of reinforced concrete beams in transportation infrastructure due to corrosion damage is analyzed. The research was conducted on the example of structures in a railway unloading hub, which has direct practical value for railway and metro infrastructure objects. As part of the study, the authors analyzed modern repair and restoration technologies, including injection methods and materials that allow restoring the design strength and reliability of monolithic reinforced concrete elements. The results of the study confirmed the feasibility of using modern composite systems to extend the service life of reinforced concrete structures in transport facilities, which is especially relevant for objects with long service lives and limited possibilities for complete re-

placement of structures.

In the study (Коваленко, В. В., Заяць, Пшiнько, & Коваленко, С. В., 2016), the impact of complex modifying additives on the process of concrete structure formation in foundation slabs was analyzed. The work shows that the microstructure of cement stone and the physicochemical characteristics of concrete significantly depend on the composition of modifiers and the technological parameters of curing. The use of the polycarboxylate additive PLKP contributes to the formation of a nanostructured, more homogeneous, and dense cement stone structure, which positively affects the strength and durability of concrete. The authors established that eliminating or reducing the intensity of steam curing reduces negative structural changes associated with the growth of ettringite crystals. The results obtained are important for justifying materials science approaches to improving the service life of reinforced concrete foundations in transport facilities, including metro objects and railway infrastructure.

Methodology

The research was carried out through an independent analytical review of literature sources on the selected topic, with in-depth analysis. The search for sources was conducted using publicly available technologies.

Findings

Railway infrastructure includes track structures, metro facilities, viaducts, bridges, tunnels, and other constructions. All of these function under conditions of high humidity, groundwater influence, aggressive environments, and technogenic factors, and are constructed using reinforced concrete and metal elements. Given the significant volume of capital investment and the strategic role of rail transport in national logistics, these structures are subject to increased requirements for reliability, durability, and operational safety.

During the implementation of effective maintenance and servicing programs, the quality of construction is improved, and a stable level of operational readiness is maintained over time. At the same time, to achieve the designated service life, it is critically important to conduct preliminary studies on potential damage and degradation mechanisms that may develop in the structures during operation. In this context, special attention must be

given to the losses associated with disruptions or restrictions in train movement, reduced capacity, or temporary withdrawal of objects from service due to structural defects or premature failure.

Concrete structures (dry or weakly moisture-saturated) are resistant to most physicochemical degradation processes, including alkali-aggregate reaction, sulfate corrosion, freeze-thaw cycles, as well as electrochemical processes such as reinforcement corrosion caused by chlorides or carbonation. However, railway infrastructure objects, especially subway tunnels, underground track sections, bridge structures, and water-carrying constructions, are often in constant or periodic contact with water-saturated soils, drainage waters, or anti-icing reagents. Under these conditions, physicochemical and electrochemical degradation processes lead to internal expansion and destruction of cement hydration products, which, combined with steel reinforcement corrosion, result in the loss of the load-bearing capacity of the structures.

During operation, irreversible damage accumulates in the cement stone and reinforcement, which is why the key task is the design and selection of appropriate materials and technological solutions that allow for the maximum delay in the penetration of aggressive substances and ensure the operability of the structures within the specified service life. Over the last few decades, design methods that account for durability have been improved, primarily through the development of computational models, but in practice, even modern approaches do not always guarantee achieving sustainable durability of structures.

Numerous examples of transport bridges and viaducts in Europe are telling, where, despite a design service life of 100 years, significant damage occurs after only 20-25 years of operation, primarily due to premature chloride corrosion of reinforcement. These cases testify to the ineffectiveness of traditional design approaches, material selection, construction technologies, and the lack of proper quality control. Insufficient consideration of physical, chemical, and electrochemical degradation processes during the design phase is a primary cause of this situation.

A long service life for structures operating in aggressive and complex operational conditions can only be achieved through coordinated efforts from all participants in the process – clients, designers, material manufacturers, contractors, and control and operational services.

The technical maintenance of railway tracks is

an integral part of the production activities of enterprises and structural units in the railway industry, ensuring the functioning of one of the key systems of rail transport. This activity aims to maintain the track and related engineering structures in proper technical condition, in compliance with established regulatory requirements. The main goal of technical maintenance is to ensure the continuous and safe movement of trains at permissible speeds for specific sections, which is the basic condition for the reliable operation of the railway network.

The achievement of this goal is ensured through a set of interconnected measures, which include both scheduled repair work and daily maintenance of the tracks. An important role is played by the systematic monitoring of the technical condition of the upper track structure, regular inspections of tracks and structures, timely detection of defects, and prevention of malfunctions. The elimination of failure causes is based on the analysis of technical control results, as well as the implementation of measures for the modernization and reconstruction of railway lines, engineering structures, and embankments. All elements of the track must ensure the stable and uninterrupted movement of trains at the design speeds specified for the corresponding section.

The track infrastructure of metro systems represents a multifunctional infrastructure complex, the main purpose of which is to perform preventive work, as well as current and capital repairs of railway tracks and structures, in order to maintain the required level of safety and operational reliability. The central element of this complex is the railway track, which consists of technical constructions and devices ensuring train movement at designated speed parameters. It includes elements of the upper track structure, rail base with fastenings and ballast layer, embankment, drainage systems, anti-deformation protection, reinforcing and protective structures, as well as ballastless track structures. The track infrastructure accounts for more than half of the infrastructure's fixed assets, and the costs of its maintenance represent a significant portion of overall operational expenses. In the current conditions of infrastructure development, the priority task of the track complex is the optimization of production costs while ensuring the uninterrupted and safe movement of trains.

In modern operating conditions, metro systems are subjected to high loads on the infrastructure, accelerating the physical and chemical aging of the

reinforced concrete structures of tracks and facilities. The combined impact of mechanical, physical, and chemical degradation factors is systemic, leading to the accelerated reduction of load-bearing capacity and durability of structures. The main problems of reinforced concrete track and subway facility structures include:

Mechanical loads and material fatigue. During cyclical loading from rolling stock, wear occurs on the rails, ties, and ballast layer. Defects related to **rolling contact fatigue (RCF)** arise, manifesting as surface cracks on the rails and damage to the fastenings.

Over time, under the influence of these loads, structural fatigue of reinforced concrete (joint nodes or welds) occurs, which can lead to cracking and failure due to residual stresses.

The process of accumulating fatigue damage in reinforced concrete elements during cyclical loading, coupled with the influence of aggressive factors, is nonlinear in nature and significantly depends on the operating conditions.

Chemical and physical degradation. The impact of external aggressive factors (moisture, aggressive salts, and freeze-thaw cycles) leads to reinforcement corrosion, gradually destroying the concrete, resulting in carbonation, reinforcement corrosion, and reduced durability of the structures.

Under the influence of aggressive environmental factors, moisture penetration and the diffusion of carbon dioxide (CO₂) and chloride ions (Cl⁻) into the concrete occur, which subsequently leads to the development of a carbonation zone, a decrease in the alkalinity of the concrete matrix, and the initiation of reinforcement corrosion. Corrosion processes are accompanied by the formation of cracks and delamination of the concrete, which, in combination with increased dynamic loads and instability of the track foundation, accelerates the loss of load-bearing capacity and durability of the structures.

Instability of the ballast or bearing layer. Wear of the ballast layer and lack of stability lead to track settlement, curvature, and increased dynamic loads on the structures. Improper compaction, uneven load distribution, and local deformations reduce the durability of the track and increase repair costs.

Lack of quality maintenance. Traditional maintenance methods involve fixed and interval-based inspections/repairs, without considering the actual condition of the components. The absence of quality forecasting of the structures' resources pre-

vents proper planning of maintenance at the necessary level.

Thus, the outlined problems highlight the need for a comprehensive approach to extending the service life of reinforced concrete structures of tracks and metro facilities, which combines materials science, structural, and operational solutions.

Approaches to extending service life. The extension of the service life of reinforced concrete track structures and metro facilities is achieved through various classical and more modern scientific and technical approaches.

Materials science and structural solutions. Among the main structural solutions, the use of reinforced and pre-stressed reinforced concrete ties for load-bearing structures should be noted, as they provide increased resistance to fatigue and wear. In addition, the use of concrete with a low water-cement ratio and special additives to reduce permeability and increase the corrosion resistance of reinforcement is important.

Among the innovative materials that help improve the durability of concrete ties, the following should be highlighted: fiber reinforcement (FRP, SMA); additives to concrete mixtures (fibers, recycled materials); improvements in mechanical and durability characteristics.

Another approach to extending the service life of reinforced concrete track structures and metro facilities is service life modeling considering corrosion.

Modeling determines the service life of reinforced concrete with supplementary cementitious materials (SCM), showing how corrosion and carbonation degradation affect the behavior of concrete.

Corrosion resistance studies of concrete systems. In recent years, significant progress has been made in the study of the corrosion resistance of cement systems, leading to the development of highly effective concretes with enhanced durability.

Particular attention at this stage is given to sulfate corrosion, which is characterized by the formation of poorly soluble salts within the material's structure and the development of internal stresses. The increased corrosion resistance is explained by the formation of a fine crystalline microstructure in the cement stone with a predominance of C-S-H phases, which ensures effective pore clogging. This effect is achieved through the complex optimization of the physical packing density of particles, chemical interactions (hydration reactions,

pozzolanic reactions), and adhesive interactions between the cement stone and the aggregate. This results in an increase in compressive strength by 8 ... 12 %, bending strength by 3 ... 9 %, and corrosion resistance coefficient by up to 1.09 ... 1.1, confirming the high effectiveness of the modified systems.

Pozzolanic admixtures contribute to the binding of free $\text{Ca}(\text{OH})_2$ into calcium hydrosilicates, reducing the risk of reactions with chlorides, sulfates, and magnesium salts. This enhances the durability of concrete structures in aggressive environments.

The use of such cement systems allows the production of high-performance concrete of class C45/55 with a corrosion resistance coefficient of up to 1.1, promising for increasing the operational service life of structures (Kirakevych, Rusyn, & Bobetskyi, 2024).

Protection of reinforced concrete from aggressive impacts. Among the new, practically implemented methods for enhancing the durability of reinforced concrete structures in aggressive environments, a comprehensive protection of concrete and reinforcement from liquid and gas corrosion-active factors is applied, while simultaneously restoring the load-bearing capacity of damaged elements. This approach is aimed not only at slowing down degradation processes but also at extending the service life of structures without their complete replacement.

A detailed implementation of this method is presented in the study (Pohrybnyi, Dovzhenko, Kyrychenko, Mytrofanov, 2024), where the enhancement of the operational suitability of reinforced concrete structures is considered in the context of objects with an increased level of environmental hazard. Reinforced concrete is regarded as an engineering-based complex of structural, materials science, and calculation measures aimed at preserving the load-bearing capacity and limiting the development of corrosion damage over time.

As an example of the application of the method, the building of an acid and alkali wastewater neutralization station is considered, where the aggressive environment and high humidity caused intense physical aging of the structures. The identified damage included a 10 ... 20 % reduction in concrete strength, reinforcement corrosion up to 35 %, the development of cracks, and delamination of the protective layer. The loss of the protective function of the concrete shell significantly accelerated the corrosion processes of the reinforcement, which directly affected the operational suitability

and safety of the facility.

The key element of the method for protecting reinforced concrete from aggressive impacts is the assessment of the remaining load-bearing capacity of the structures, considering the actual condition of the concrete. For this purpose, an approach based on the use of extreme deformation characteristics of concrete and the variation method in plasticity theory was applied. The use of the concrete compression deformation diagram in the form of a fractional-rational function allows for considering the maximum deformation energy and correctly determining the parameters of dangerous normal cross-sections under bending, while strength in inclined sections is assessed using the truss and disc model methods, which have experimental confirmation.

In practical terms, the implementation of the method involves a combination of structural reinforcement and protective measures. For elements whose load-bearing capacity does not meet operational requirements, steel jackets and diagonal braces with mounting bolts are used. Protection from moisture and aggressive environments is ensured by the use of penetrating waterproofing materials, elastic two-component chemically-resistant polymer coatings, and acid-resistant ceramic tiles. Damaged areas of concrete are restored after cleaning from corrosion products, with the formation of an adhesion layer between the old and new material, while steel elements are protected by cold galvanizing and multi-layer polyurethane coatings.

Thus, the combination of reinforced concrete protection from aggressive impacts with calculated assessments of remaining load-bearing capacity and structural reinforcement represents a modern and effective method for improving the durability of reinforced concrete structures. When this approach is applied comprehensively, it stabilizes the technical condition of objects under challenging operating conditions and extends their service life by controlling and limiting degradation processes.

One of the supplementary, yet equally important, approaches to extending service life is regular preventive maintenance: rail grinding to remove surface defects, restore profiles, and reduce stress concentrations (reducing RCF); monitoring the condition of the ballast, further compaction, and replacement of worn sections to ensure track stability; and planned updating of fastenings and ties, taking into account actual wear.

Reliability and life cycle modeling (LCCA) involves the use of statistical models (Weibull distri-

bution, negative binomial distribution) to forecast the service life of rails, ties, and fastenings. Additionally, the use of digital models and BIM is planned for monitoring the condition of structures and real-time maintenance scheduling.

Originality and practical value

Structural monitoring systems involve the installation of displacement, vibration, stress, and corrosion sensors to monitor the condition of structures in real time. During such monitoring, areas with increased degradation are identified, and the risk of further failures is predicted. When using this data to create integrated TOD-track/station models, the interaction between superstructures and underground facilities is evaluated.

The use of innovative digital technologies (machine learning, deep learning for predicting component degradation and optimizing maintenance schedules, using data from sensors and maintenance history) allows for predicting wear, minimizing downtime, and ultimately enhancing the safety of further operation.

Thus, the modern approaches applied to extend the service life of reinforced concrete structures in metro systems primarily involve the integrated combination of materials science solutions, regular preventive maintenance, predictive reliability modeling, digital monitoring, and the use of machine data analysis. This integrated approach can ensure the extension of the service life of tracks and structures while simultaneously reducing operational costs and enhancing passenger safety.

Conclusions

The study has established that during operation, reinforced concrete structures of tracks and metro facilities undergo complex degradation due to the combined effects of mechanical loads, physical and physicochemical processes, as well as the impact of the aggressive operational environment. The combination of cyclical loads, increased humidity, temperature fluctuations, and chemical aggression leads to the accelerated reduction of the durability of concrete and reinforced concrete elements, confirming the systemic nature of degradation processes and the necessity of their comprehensive analysis.

The work demonstrates that reinforcement corrosion is the dominant mechanism for the loss of operational suitability of reinforced concrete structures in underground and humid operating conditions. Corrosion processes, especially in the pres-

ence of chlorides and under carbonation conditions, intensify, leading to a reduction in the effective cross-section of reinforcement, decreased load-bearing capacity of structures, and accelerated crack formation in the concrete's protective layer.

The analysis of modern materials science and structural solutions showed that ignoring the transition from local repair measures to comprehensive engineering methods, which combine material protection, structural reinforcement, and calculated assessment of remaining load-bearing capacity, significantly limits the potential for extending the service life of existing reinforced concrete structures. At the same time, the use of modern concrete, corrosion-resistant materials, and effective reinforcement schemes creates the prerequisites for stabilizing the technical condition of the structures.

It was established that the application of practical methods for protecting reinforced concrete from aggressive impacts, particularly penetrating waterproofing, chemically-resistant polymer systems, and structural reinforcement, is an effective tool for extending the service life of existing structures. Combining these measures with service life modeling considering corrosion processes and the use of digital monitoring technologies allows for a shift towards predictive durability management and optimizes infrastructure maintenance costs. Overall, the integrated approach that combines materials science, structural, operational, and digital solutions is the most promising direction for extending the service life of reinforced concrete structures in metro systems and track infrastructure.

REFERENCES

- Alexander, M. G. (2018). Service life design and modeling of concrete structures: Background, developments, and implementation. *Revista de la Asociación Latinoamericana de Control de Calidad, Patología y Recuperación de la Construcción*, 8(3), 251-265. DOI: <https://doi.org/10.21041/ra.v8i3.325>
- Alexander, M., & Beushausen, H. (2019). Durability, service life prediction, and modelling for reinforced concrete structures – review and critique. *Cement and Concrete Research*, 122, 17-29. DOI: <https://doi.org/10.1016/j.cemconres.2019.04.018>
- Craeye, B., Renne, N., Audenaert, A., & Buyle, M. (2025). Durable and sustainable service life extension of existing concrete structures: A holistic approach within a life cycle perspective. *MATEC Web of Conferences*, 409, 00001. DOI: <https://doi.org/10.1051/mateconf/202540900001>
- Kirakevych, I., Rusyn, B., & Bobetskyi, Y. (2024). Ce-

- mentitious systems for high-performance concretes with improved corrosion resistance. *Journal of Thermal and Building Physics*, 6(1), 109-122. DOI: <https://doi.org/10.23939/jtbp2024.01.109>
- Pohrybnyi, V. V., Dovzhenko, O. O., Kyrychenko, V. V., & Mytrofanov, P. V. (2024). Improving the operational suitability of reinforced concrete structures in aggressive environments. *AIP Conference Proceedings*, 2684, 030033. DOI: <https://doi.org/10.1063/5.0120475>
- Rusnak, C. R. (2025). Sustainable strategies for concrete infrastructure preservation: A comprehensive review and perspective. *Infrastructures*, 10(4), 99. DOI: <https://doi.org/10.3390/infrastructures10040099>
- Redaelli, E., Bertolini, L., & Lollini, F. (2011). Durability design of reinforced concrete structures. *Construction Materials*, 164(6), 273-282. DOI: <https://doi.org/10.1680/coma.1000040>
- Whitmore, D. (2022). Extending the service life of existing concrete structures to last beyond 100 years. *MATEC Web of Conferences*, 364, 04025. DOI: <https://doi.org/10.1051/mateconf/202236404025>
- Коваленко, В. В., Заяць, Ю. Л., Пшінько, П. О., & Коваленко, С. В. (2016). Структурування в бетонах підрейкових основ. *Наука та прогрес транспорту*, 2(62), 174-189. DOI: <https://doi.org/10.15802/stp2016/67353>
- Лучко, Й. Й., Назаревич, Б. Л., & Кравець, І. Б. (2016). Відновлення несучої здатності залізобетонних балок пошкоджених корозією розвантажувального вузла підїздного залізничного шляху. *Мости та тунелі: теорія, дослідження, практика*, 10, 61-69. DOI: <https://doi.org/10.15802/bttrp2016/96167>
- Плугін, А. А. (2004). Агресивні дії на залізобетонну обробку тунелів метрополітену. *Збірник наукових праць Української державної академії залізничного транспорту*, 63, 48-62.
- Плугін, А. М., Плугін, А. А., Скорик, О. О., et al. (2003). Електрокорозія бетону залізобетонних блоків обробки метрополітену. *Збірник наукових праць Української державної академії залізничного транспорту*, 56, 126-135.
- Плугін, А. Н., Плугін, А. А., Калинин, О. А., et al. (2006). Долговечность конструкций и сооружений из бетона, эксплуатируемых в условиях обводнения. *Автомобільні дороги і дорожнє будівництво*, 73, 248-253.
- Плугін, А. Н., Калинин, О. А., Шумик, Д. В., et al. (2001). Содержание и ремонт инженерных сооружений, работающих в сложных условия *Залізничний транспорт України*, 2(23), 49-53.
- О. О. ОВЧИННИКОВ^{1*}, Є. А. ПРОКАЗА², В. В. ТЕРТИЧНИЙ³

^{1*}Кафедра залізничної колії і транспортних споруд, Український державний університет залізничного транспорту, майдан Оборонний Вал 7, Харків, Україна, 61050, тел. +38 (050) 780 63 39, ел. пошта ovchinnikov_77@ukr.net, ORCID 0000-0002-6941-2076

²Кафедра залізничної колії і транспортних споруд, Український державний університет залізничного транспорту, майдан Оборонний Вал 7, Харків, Україна, 61050, тел. +38 (095) 166 51 10, ел. пошта prokazaevgeniya@gmail.com, ORCID 0009-0000-7345-2145

³Кафедра залізничної колії і транспортних споруд, Український державний університет залізничного транспорту, майдан Оборонний Вал 7, Харків, Україна, 61050, тел. +38 (057) 730 10 60, ел. пошта prx_xiit@kart.edu.ua, ORCID 0009-0002-9025-6546

АНАЛІЗ ІСНУЮЧИХ ПРОБЛЕМ ТА ПІДХОДІВ ДО ПОДОВЖЕННЯ РЕСУРСУ ЗАЛІЗОБЕТОННИХ КОНСТРУКЦІЙ КОЛІЇ І СПОРУД МЕТРОПОЛІТЕНУ (ОГЛЯД)

Мета. У статті представлено комплексний аналіз існуючих проблем, пов'язаних із довговічністю та строком служби залізобетонних колійних конструкцій і споруд метрополітену, що експлуатуються в умовах інтенсивних навантажень та впливу агресивних факторів навколишнього середовища. **Методологія.** Особливу увагу приділено специфічним експлуатаційним особливостям інфраструктури метрополітену, зокрема циклічним і динамічним навантаженням, проникненню вологи, температурним коливанням, блукаючим струмам та хімічно агресивним середовищам, які суттєво прискорюють деградацію залізобетонних елементів. **Результати.** Розглянуто основні механізми руйнування бетонних і залізобетонних конструкцій, зокрема корозію арматури, фізико-хімічну деградацію цементної матриці, накопичення втомних пошкоджень, розвиток тріщин та вплив нестабільності ґрунтової основи на конструктивну роботу колійних систем. Показано, що ці процеси мають кумулятивний характер і призводять до зниження несучої здатності, експлуатаційної придатності та загальної експлуатаційної надійності споруд метрополітену. **Наукова новизна.** У роботі наведено науковий огляд сучасних підходів до подовження строку служби залізобетонних конструкцій, що охоплюють матеріалознавчі рішення, конструктивні та проєктні удосконалення, сучасні методи розрахунку

та експлуатаційні заходи. Особливу увагу приділено захисним стратегіям від агресивних впливів, зокрема застосуванню високоміцних бетонів, корозійностійкої арматури, захисних покриттів і ремонтних систем. Крім того, проаналізовано методи моделювання строку служби, які враховують кінетику корозії та умови впливу навколишнього середовища. **Практична цінність.** У дослідженні також підкреслено зростаючу роль цифрових технологій, зокрема систем моніторингу технічного стану конструкцій, методів неруйнівного контролю та моделей прогнозного технічного обслуговування на основі даних, у забезпеченні довготривалої надійності інфраструктури метрополітену. Показано, що комплексне застосування захисних, відновлювальних і прогнозних заходів дозволяє суттєво підвищити довговічність, безпеку та експлуатаційну ефективність залізобетонних колійних конструкцій і споруд метрополітену.

Ключові слова: метрополітен; залізобетонні конструкції; колія; довговічність; корозія арматури; подовження ресурсу; моделювання терміну служби

REFERENCES

- Alexander, M. G. (2018). Service life design and modelling of concrete structures: Background, developments, and implementation. *Revista de la Asociación Latinoamericana de Control de Calidad, Patología y Recuperación de la Construcción*, 8(3), 251-265. DOI: <https://doi.org/10.21041/ra.v8i3.325> (in English)
- Alexander, M., & Beushausen, H. (2019). Durability, service life prediction, and modelling for reinforced concrete structures – review and critique. *Cement and Concrete Research*, 122, 17-29. DOI: <https://doi.org/10.1016/j.cemconres.2019.04.018> (in English)
- Craeye, B., Renne, N., Audenaert, A., & Buyle, M. (2025). Durable and sustainable service life extension of existing concrete structures: A holistic approach within a life cycle perspective. *MATEC Web of Conferences*, 409, 00001. DOI: <https://doi.org/10.1051/mateconf/202540900001> (in English)
- Kirakevych, I., Rusyn, B., & Bobetskyi, Y. (2024). Cementitious systems for high-performance concretes with improved corrosion resistance. *Journal of Thermal and Building Physics*, 6(1), 109-122. DOI: <https://doi.org/10.23939/jtbp2024.01.109> (in English)
- Pohrybnyi, V. V., Dovzhenko, O. O., Kyrychenko, V. V., & Mytrofanov, P. V. (2024). Improving the operational suitability of reinforced concrete structures in aggressive environments. *AIP Conference Proceedings*, 2684, 030033. DOI: <https://doi.org/10.1063/5.0120475> (in English)
- Rusnak, C. R. (2025). Sustainable strategies for concrete infrastructure preservation: A comprehensive review and perspective. *Infrastructures*, 10(4), 99. DOI: <https://doi.org/10.3390/infrastructures10040099> (in English)
- Redaelli, E., Bertolini, L., & Lollini, F. (2011). Durability design of reinforced concrete structures. *Construction Materials*, 164(6), 273-282. DOI: <https://doi.org/10.1680/coma.1000040> (in English)
- Whitmore, D. (2022). Extending the service life of existing concrete structures to last beyond 100 years. *MATEC Web of Conferences*, 364, 04025. DOI: <https://doi.org/10.1051/mateconf/202236404025> (in English)
- Kovalenko, V. V., Zaiats, Yu. L., Pshinko, P. O., & Kovalenko, S. V. (2016). Strukturoutvorennya v betonakh pidreikovykh osnov. *Nauka ta prohres transportu*, 2(62), 174-189. DOI: <https://doi.org/10.15802/stp2016/67353> (in Ukrainian)
- Luchko, Y. Y., Nazarevych, B. L., & Kravets, I. B. (2016). Vidnovlennia nesuchoi zdatnosti zalizobetonnykh balok poskodzhennykh korozieiu rozvantazhualnogo vuzla pidizdnogo zaliznychnoho shliakhu. *Mosty ta tuneli: teoriia, doslidzhennia, praktyka*, 10, 61-69. DOI: <https://doi.org/10.15802/bttrp2016/96167> (in Ukrainian)
- Pluhin, A. A. (2004). Ahresyvnii dii na zalizobetonnu obrobku tuneliv metropolitenu. *Zbirnyk naukovykh prats Ukrainiskoi derzhavnoi akademii zaliznychnoho transportu*, 63, 48-62. (in Ukrainian)
- Pluhin, A. M., Pluhin, A. A., Skoryk, O. O., et al. (2003). Elektrokoroziiia betonu zalizobetonnykh blokiv obrobky metropolitenu. *Zbirnyk naukovykh prats Ukrainiskoi derzhavnoi akademii zaliznychnoho transportu*, 56, 126-135. (in Ukrainian)
- Pluhyn, A. N., Pluhyn, A. A., Kalynyn, O. A., et al. (2006). Dolhovechnost konstruktsyi y sooruzhenyi yz be-tona, ekspluatyruemykh v usloviakh obvodnyeniya. *Avtomobilni dorohy i dorozhnie budyvnytstvo*, 73, 248-253. (in Ukrainian)
- Pluhyn, A. N., Kalynyn, O. A., Shumyk, D. V., et al. (2001). Soderzhanye y remont ynzhenernykh sooruzhenyi, robotaiushchykh v slozhnykh usloviya *Zaliznychnyi transport Ukrainy*, 2(23), 49-53. (in Ukrainian)

Article received: 18.02.2026.

Review date: 20.04.2026.

Publication date: 29.05.2026.