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RESEARCH ARTICLE

ANALYSIS OF DEGRADATION MECHANISMS AND JUSTIFICATION OF REPAIR TECHNOLOGIES FOR CONCRETE HYDRAULIC STRUCTURES

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Abstract. *This study analyzes the mechanisms of damage and patterns of degradation in concrete hydraulic structures exposed to operational and environmental factors. A comprehensive analysis was conducted using literature data, field inspection results, and regulatory documents covering the period from 2015 to 2025. Structural–mechanical analysis and comparative evaluation of repair technologies were applied to systematize the findings and assess the efficiency and durability of different materials and methods. The main damage mechanisms were identified as cavitation, leaching of cement paste, reinforcement corrosion, and thermal fatigue. The use of ultra-high-performance fiber-reinforced concrete (UHPFRC) was found to reduce cavitation wear by 3-4 times, while bioconcrete enables partial self-healing of microcracks and increases the service life of structures by 25-40%. A classification of defects based on their type and depth of deterioration was developed, allowing for a rational selection of repair technology depending on operating conditions and damage characteristics. The scientific novelty of this research lies in the proposed systematic approach to assessing concrete degradation and in the justification of composite material applications for extending the service life of hydraulic structures.*

Keywords: *concrete structures, hydraulic structures, cracks, erosion, cavitation, corrosion, repair, injection technologies, fiber concrete, life cycle.*

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ҒЫЛЫМИ МАҚАЛА

ГИДРОТЕХНИКАЛЫҚ ҒИМАРАТТАРЫНЫҢ БЕТОН ҚҰРЫЛЫМДАРЫН ЗАҚЫМДАНУ МЕХАНИЗМДЕРІН ТАЛДАУ ЖӘНЕ ҚАЛПЫНА КЕЛТІРУ ТЕХНОЛОГИЯЛАРЫН НЕГІЗДЕУ

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Аңдатпа. *Бетоннан жасалған гидротехникалық ғимараттарының құрылымдарына өндірістік және табиғи факторлардың әсерінен туындайтын зақымдану механизмдері мен деградация заңдылықтары зерттелді. 2015–2025 жылдар аралығындағы ғылыми әдебиеттер, далалық зерттеу нәтижелері және нормативтік құжаттар кешенді түрде талданды. Алынған нәтижелерді жүйелеу үшін құрылымдық-механикалық талдау әдістері және технологиялық шешімдердің тиімділігі мен ұзақмерзімділігін салыстыру тәсілдері қолданылды. Негізгі зақымдану механизмдері ретінде кавитация, цемент тасының шайылуы, арматураның коррозиясы және температуралық шаршау анықталды. Ультраберік талшықты бетонды (UHPFRC) қолдану кавитациялық тозу қарқындылығын 3-4 есеге дейін төмендететіні, ал биобетондарды пайдалану микрожарықтардың ішінара өздігінен бітелуін және құрылымдардың ұзақмерзімділігін 25-40 % арттыратыны дәлелденді. Зақым түрі мен тереңдігіне қарай ақаулардың жіктелуі жасалды, бұл пайдалану жағдайлары мен бұзылу сипатына сәйкес қалпына келтіру технологиясын негізді таңдауға мүмкіндік береді. Зерттеудің ғылыми жаңалығы бетонның деградациясын бағалаудың жүйелік тәсілін ұсыну мен гидротехникалық ғимараттардың қызмет ету мерзімін ұзартуға бағытталған композиттік материалдарды қолдану бағыттарын негіздеуде көрініс табады.*

Түйін сөздер: *бетон құрылымдары, су шаруашылығы ғимараттары, жарықшақтар, эрозия, кавитация, коррозия, жөндеу, инъекциялық технологиялар, талшықты бетон, өмірлік цикл.*

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НАУЧНАЯ СТАТЬЯ

АНАЛИЗ МЕХАНИЗМОВ РАЗРУШЕНИЯ И ОБОСНОВАНИЕ ТЕХНОЛОГИЙ ВОССТАНОВЛЕНИЯ БЕТОННЫХ КОНСТРУКЦИЙ ГИДРОТЕХНИЧЕСКИХ СООРУЖЕНИЙ

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Аннотация. *Исследованы механизмы разрушения и закономерности деградации бетонных конструкций гидротехнических сооружений под воздействием эксплуатационных и природных факторов. Проведён комплексный анализ литературных данных, результатов полевых обследований и нормативных документов за период 2015–2025 гг. Для систематизации результатов применены методы структурно-механического анализа и сопоставления технологических решений по эффективности и долговечности. Установлено, что основными механизмами разрушения бетона являются кавитация, выщелачивание цементного камня, коррозия арматуры и термическая усталость. Применение ультравысокопрочных волокнистых бетонов (UHPFRC) снижает интенсивность кавитационного износа в 3-4 раза, тогда как использование biобетонов обеспечивает частичное самозалечивание микротрещин и повышение долговечности конструкций на 25-40 %. Разработана классификация дефектов по типу и глубине повреждения, что позволяет обоснованно выбирать технологию восстановления в зависимости от условий эксплуатации и характера разрушений. Научная новизна заключается в предложении системного подхода к оценке деградации бетона и обосновании направлений применения композитных материалов для продления ресурса гидротехнических сооружений.*

Ключевые слова: *бетонные конструкции, гидротехнические сооружения, трещины, эрозия, кавитация, коррозия, ремонт, инъекционные технологии, фибробетон, жизненный цикл.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС/ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігінің Ғылым комитетінің қаржылық қолдауымен № AP23487624 ғылыми жоба аясында орындалды.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование выполнено при финансовой поддержке Комитета науки Министерства науки и высшего образования Республики Казахстан в рамках научного проекта № AP23487624.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

The reliability and durability of hydraulic structures largely depend on the technical condition of their concrete components, which are continuously exposed to aggressive factors such as cyclic freezing and thawing, mechanical abrasion caused by water flow, cavitation, chemical degradation, and reinforcement corrosion.

Operational experience of hydraulic engineering structures shows that the most common defects include cracking, spalling and destruction of the concrete protective layer, cavitation damage, and corrosion processes that compromise the integrity of the structures. The presence of such defects not only reduces performance characteristics but also leads to significant maintenance and repair costs.

Methods for the rehabilitation of concrete structures, actively developed during the period 2015–2025, include both traditional approaches (such as the use of cement-based and polymer materials) and innovative technologies based on ultra-high-performance fiber-reinforced concrete (UHPFRC), injection mixtures, bio-concrete, and integrated protective systems **(Lampropoulos et al., 2023)**. The analysis of published studies revealed the absence of a systematic framework that links the mechanisms of concrete degradation with the selection of appropriate repair technologies depending on the nature of the damage **(Rakhimov et al., 2025)**.

The object of the research is the concrete structures of hydraulic engineering facilities, while the subject is the processes of their degradation and restoration using modern materials and technologies **(Sennikov et al., 2014)**.

The aim of the study is to develop an analytical framework for selecting and substantiating effective rehabilitation methods for concrete structures, ensuring improved durability and operational reliability.

2 LITERATURE REVIEW

The durability of concrete structures in hydraulic engineering facilities has been the subject of intensive research due to their operation under harsh environmental conditions, which necessitates the development of advanced repair strategies.

A bibliometric analysis for the period 2015-2025 revealed that scientific studies on concrete used in hydraulic structures are concentrated around five major thematic areas. The most actively developing topics are related to improving the strength and crack resistance of concrete, reflecting a sustained interest in issues of mechanical degradation and cavitation erosion. At the same time, there has been a noticeable increase in research focused on self-healing concretes and biotechnological approaches, which form a new direction in the study of material durability.

In parallel, integration with ultra-high-performance composite (UHPFRC) technologies – used for the repair and strengthening of hydraulic structures – has been intensifying. Numerical modeling of degradation processes and service-life prediction under fluctuating moisture and temperature conditions remain less developed areas, defining the prospects for further research. Thus, the results of bibliometric mapping confirm a gradual shift in research focus from the identification of damage to the development of adaptive and self-healing materials aimed at extending the service life of hydraulic engineering structures.

The results of the bibliometric analysis presented in **Figure 1** made it possible to identify the main directions of research development in the field of repair and protection of concrete structures in hydraulic engineering facilities for the period 2015–2025. The visualization revealed that the largest publication clusters are associated with improving the strength and crack resistance of concrete, the development of high-performance composites (UHPFRC), and biotechnological approaches to self-healing concrete. In addition, there is a consistent interest in topics related to electrochemical protection of reinforcement and modeling of degradation processes.

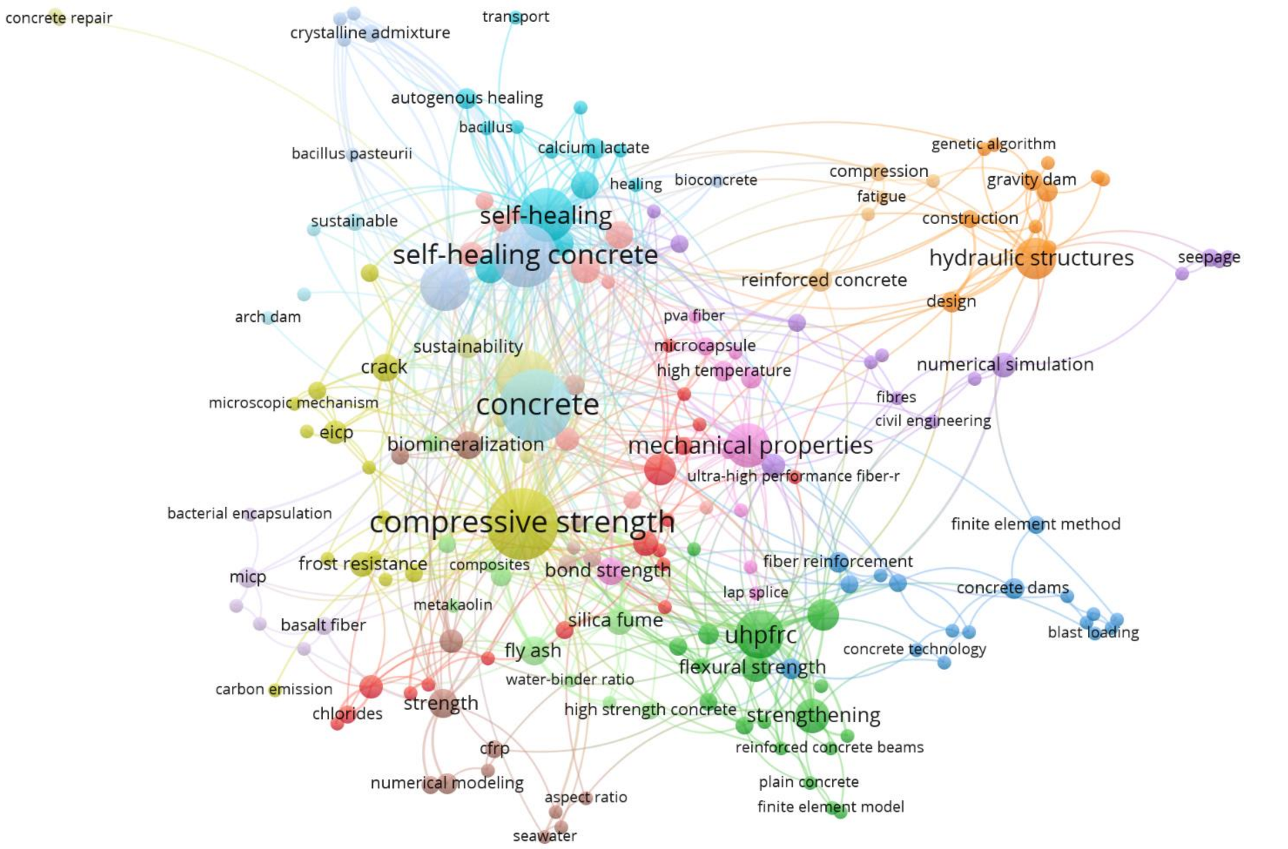

Figure 1 – Visualization of research topics on concretes for hydraulic structures (constructed in VOSviewer based on Lens.org data for 2015–2025). (author's material)

Thus, the results of the mapping served as the basis for identifying four key research areas presented below, each reflecting the current vector of scientific inquiry and practical solutions aimed at extending the service life and improving the protection of concrete structures in hydraulic engineering facilities.

1. *Application of high-performance composites.* One of the most effective materials for repairing areas exposed to intensive abrasive wear and high mechanical loads is ultra-high-performance fiber-reinforced concrete (UHPFRC). According to the study by **Yoo & Banthia (2022)**, the mechanical properties of UHPFRC are determined by the combination of curing conditions and fiber reinforcement parameters. Heat treatment accelerates hydration processes and promotes the formation of a dense cement matrix, while the use of deformed or elongated steel fibers enhances crack resistance and fracture energy. The selection of such technological parameters during mix design allows UHPFRC to be adapted to the specific operating conditions characteristic of hydraulic engineering structures.

2. *Crack repair and sealing.* The restoration of the integrity of concrete structures requires the use of materials capable not only of effectively filling cracks but also of ensuring long-term sealing performance, particularly under conditions of high humidity and chemical aggression. A study **(Li et al. 2022)** showed that the introduction of microcapsules containing an epoxy resin curing agent into the cement composition contributes to the restoration of strength and sealing of cracks, especially when exposed to various curing conditions. Biocementation, as one of the methods of microbial sealing, also shows high efficiency in restoring the waterproofing of concrete structures **(Cardoso et al. 2024)**. The presence of moisture on the concrete surface significantly reduces the adhesion strength with epoxy resins, which emphasises the need for thorough preparation of the substrate and the selection of moisture-resistant compounds when repairing structures in a humid environment **(Szewczak and Lagod 2022)**.

3. *Long-term corrosion protection.* Reinforcement corrosion remains the primary mechanism of reinforced concrete deterioration. For the protection of already damaged structures, the review by **Hu et al. 2022; Javeed et al. 2024** discusses electrochemical methods, particularly cathodic protection (CP) and electrochemical chloride extraction (ECE), as effective therapeutic solutions. CP systems, including configurations using carbon fiber-reinforced polymer (CFRP) as an anode, are capable of significantly slowing down corrosion progression.

4. *Self-healing ("smart") materials in construction.* One of the most actively developing areas of materials science is the creation of concretes capable of autonomous crack repair, thereby reducing maintenance costs and improving structural longevity.

The most thoroughly studied and experimentally validated mechanism of concrete self-healing is the biotechnological approach, which involves incorporating spores of *Bacillus* bacteria into the cement matrix **(Javeed et al. 2024)**. Upon contact of water with a crack, the microorganisms become active and initiate the process of bio-induced calcium carbonate ($CaCO_3$) precipitation, which restores the integrity of the concrete structure. This bio-induced self-healing mechanism transforms concrete from a passive structural material into an active, self-regulating system capable of autonomously responding to damage and extending the service life of hydraulic engineering structures. The use of bio-concretes offers promising prospects for the development of infrastructure with enhanced durability and reduced maintenance requirements.

3 MATERIALS AND METHODS

This study employed methods of systematic analysis and comparative evaluation of data on the mechanisms of degradation and repair technologies for concrete structures of hydraulic engineering facilities.

3.1. Data collection and analysis

The information base of the study was formed through an analysis of scientific publications, regulatory and technical documentation, and reports on the practical application of repair technologies.

The search for relevant sources was conducted in international and Russian scientometric databases – *Scopus*, *Web of Science*, *eLibrary*, and *Google Scholar* – covering the period from 2015 to 2024. The key search queries included: "repair of hydraulic concrete structures," "concrete durability," "reinforcement corrosion," "crack injection," "ultra-high-performance fiber-reinforced concrete (UHPFRC)," "electrochemical protection of concrete," and "bio-concrete." Additionally, current regulatory standards (GOST, SP) and real-world case studies of hydraulic structure repairs – including those implemented in the Republic of Kazakhstan – were analyzed.

3.2. Development of the classification framework

To systematize and further analyze the collected data, a two-level analytical framework was developed and applied.

1. Classification of degradation mechanisms **(Golewski, 2023)**. All defects were grouped into four main categories according to their origin and nature:

- Physico-mechanical degradation;
- Chemical degradation;
- Corrosion of reinforcement;
- Biogenic and microbiological degradation.

2. Systematization of repair methods.

Repair technologies were categorized in accordance with the above classification of damages they are intended to address. The main groups of methods include injection techniques, repair mortars (including polymer-cement compositions), protective systems based on UHPFRC, multilayer chemical-resistant coatings, electrochemical protection methods, and biotechnological approaches.

3.3. Evaluation criteria

The comparative analysis of the effectiveness of repair technologies was carried out based on three key criteria identified from the literature review:

1. Technical efficiency: The ability of the method to eliminate defects and restore the operational characteristics of the structure (e.g., strength and water tightness).
2. Durability: The predicted service life of the repaired area until the recurrence of damage, estimated from accelerated tests and practical field data.
3. Economic feasibility: The life-cycle cost evaluation of repair technologies using the *Lifecycle Cost Index (LCCI)*, which accounts for initial expenses as well as the frequency and cost of subsequent repair cycles.

The results obtained from the application of these methods – including the detailed analysis of degradation mechanisms, descriptions of repair technologies, and their comparative performance – are presented in the following section.

4 RESULTS AND DISCUSSION

4.1. Classification and Characteristics of the Main Types of Degradation

Based on the analysis of published research and practical case studies, a classification of the principal degradation mechanisms of concrete structures in hydraulic engineering facilities was developed. Grouping the damage types according to their nature and origin allows for a systematic approach to diagnostics and represents the first step in selecting an appropriate repair strategy **(Figure 2)**. The main categories include.

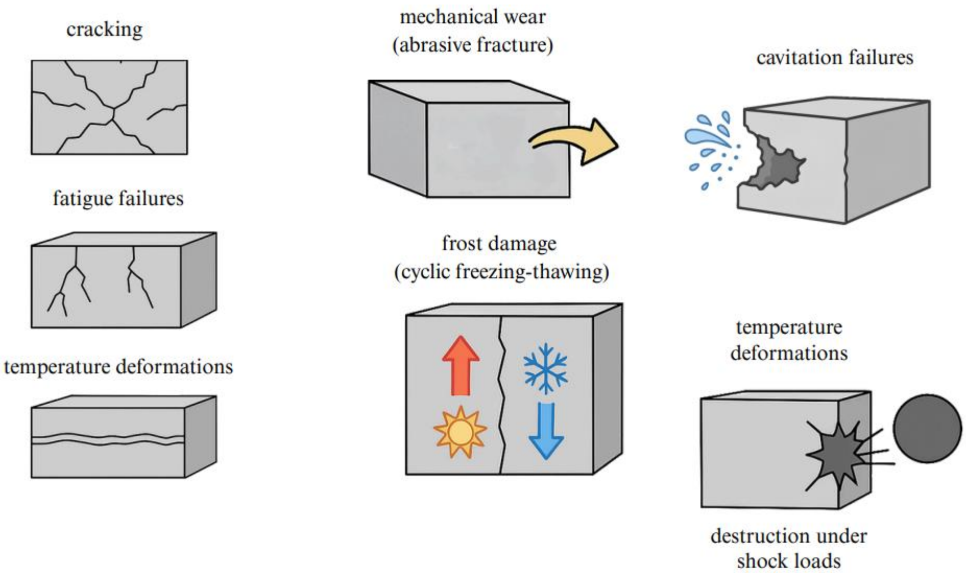

Figure 2 – Visualization of the types of physico-mechanical degradation of concrete structures (author's material)

4.1.1. Physico-mechanical degradation

This group comprises damage caused by external mechanical and climatic effects. The main types are as follows:

- Crack formation resulting from thermal shrinkage and deformation, leading to the loss of monolithic integrity of the structure.
- Cavitation damage occurring in zones of high-velocity water flow, where the collapse of vapor bubbles generates impact loads and localized surface destruction.
- Abrasive wear in areas where concrete is exposed to contact with solid particles carried by water (sediments) or with ice.

Enhancement of the abrasion resistance of concrete can be achieved through modification of its structure using surface-active agents, which promote a more uniform distribution of the cement matrix and reduce material porosity. Experimental data by **Moldamuratov et al. (2023)** confirm that the combined use of such additives with controlled water-to-cement ratios significantly improves the wear resistance of hydraulic concretes under turbulent water flow conditions.

4.1.2. Chemical degradation

This category encompasses the deterioration processes of the cement matrix caused by exposure to aggressive chemical agents, leading to a loss of strength and structural integrity **(Figure 3)**. The main types include:

- Leaching: Dissolution and removal of calcium hydroxide $Ca(OH)_2$ by soft water, which increases porosity and decreases the density of concrete.
- Acid corrosion: Destruction of cement matrix components upon contact with acids (e.g., H_2SO_4) formed as a result of industrial emissions or biogenic processes.
- Corrosion caused by aggressive gases: The impact of atmospheric gases (CO_2, SO_2, HCl), which dissolve in water to form acids that chemically attack the concrete.
- Sulfate attack: Interaction of sulfate ions (SO_4^{2-}) from groundwater or industrial environments with the aluminate phases of cement, resulting in the formation of expansive products (ettringite) and the development of internal stresses.

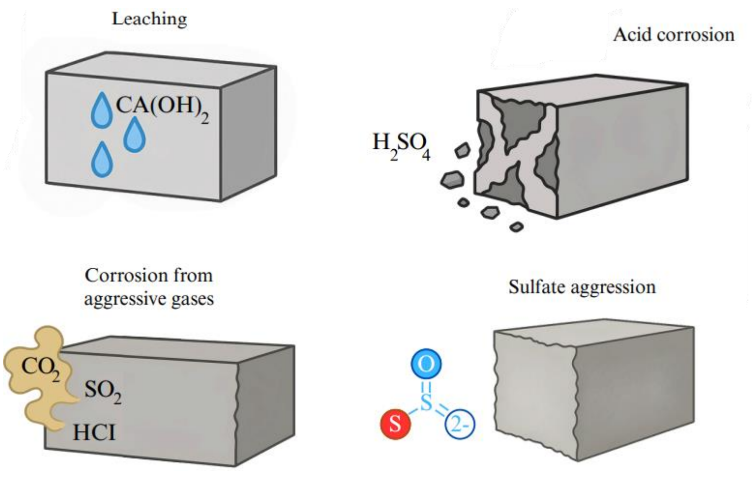

Figure 3 – Types of chemical degradation in concrete structures (author's material)

4.1.3. Corrosion-Induced Damage of Reinforcement

Reinforcement corrosion is one of the most critical types of deterioration in reinforced concrete structures, as it directly affects the structural load-bearing framework. The process is initiated by the ingress of moisture, CO_2, and chlorides into the concrete, which destroy the passive oxide film on the steel surface **(Figure 4)**.

- Carbonation corrosion: Caused by the penetration of carbon dioxide, which lowers the pH of the concrete to a level at which the passive protective film on the reinforcement becomes unstable and breaks down.
- Chloride-induced corrosion: Localized breakdown of the passive film due to chloride ions, leading to severe pitting corrosion even under high pH conditions.
- Delamination of the protective layer: Corrosion products (rust) have a volume 2-6 times greater than that of the original metal. The resulting internal pressure causes cracking and delamination of the concrete cover.

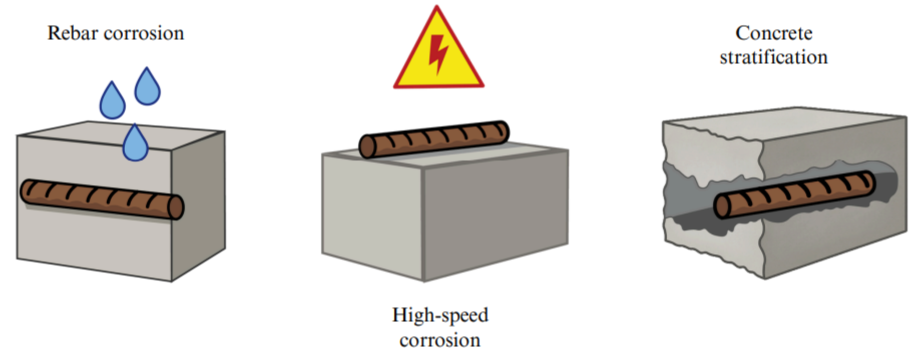

Figure 4 – Visualization of corrosion mechanisms affecting reinforcement in concrete structures (author's material)

4.1.4. Biogenic and Microbiological Deterioration

These are complex degradation processes caused by the activity of microorganisms such as algae, fungi, bacteria, and lichens. Biogenic agents not only induce local pH changes and moisture accumulation but also produce aggressive organic and inorganic acids. In particular, sulfur-oxidizing bacteria are capable of converting elemental sulfur into sulfuric acid (H_2SO_4), which accelerates the corrosion of the cement matrix **(Figure 5)**.

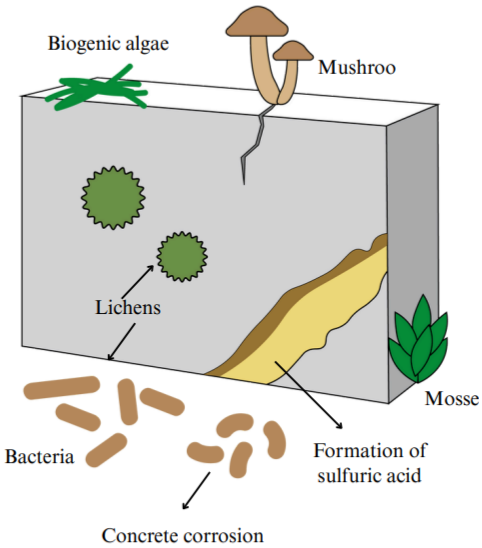

Figure 5 – Biogenic and microbiological impact on a concrete structure (author's material)

The presented classification indicates that concrete damage rarely occurs due to a single cause. A synergistic effect of multiple mechanisms is often observed – for example, cracks resulting from thermal deformation (a physical factor) can facilitate the ingress of sulfates (a chemical factor) and chlorides to the reinforcement (a corrosion factor). Therefore, an effective repair strategy should aim not only to eliminate the visible defect but also to mitigate the primary and accompanying mechanisms of deterioration **(Sun et al., 2022; Hu et al., 2024)**.

4.2. Systematization of Damage Mechanisms and Selection of Appropriate Repair Technologies

The analysis made it possible to generalize and structure the available data on concrete degradation in hydraulic structures, identifying four main groups of damage: physical–mechanical, chemical, corrosion-related, and biogenic. The results demonstrate that for each damage type, there exists a hierarchy of repair technologies with proven effectiveness. As shown in the following sections, the choice of an optimal solution depends not only on the nature of the defect but also on its scale and the required service life of the repaired structure.

4.3. Comparative Analysis of Restoration Technologies

4.3.1. Repair of Physical–Mechanical Damage: From Injection to UHPFRC

For the restoration of cracks, the most versatile method is injection grouting **(Tanyildizi et al., 2022) (Figure 6)**.

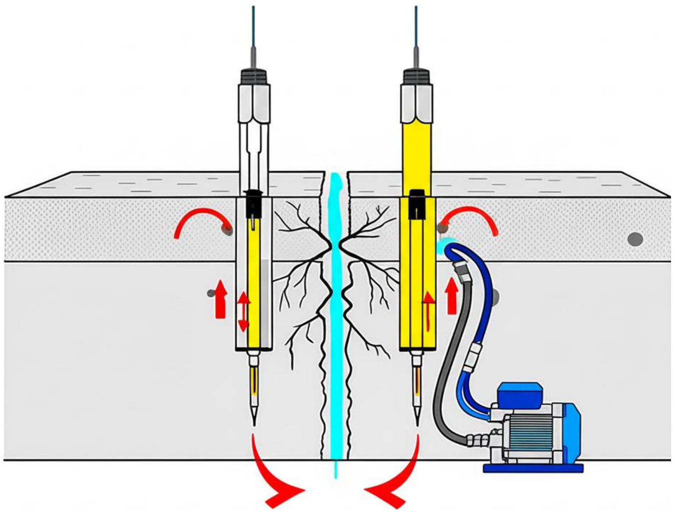

Figure 6 – Schematic representation of the crack injection technology (author's material).

The analysis revealed that the choice between epoxy and polyurethane resins depends on the intended purpose: epoxy resins provide structural bonding and restoration of load-bearing capacity, while hydroactive polyurethanes are indispensable for sealing active and water-leaking cracks due to their elasticity and expansive properties **(Chen et al., 2024) (Figure 7)**.

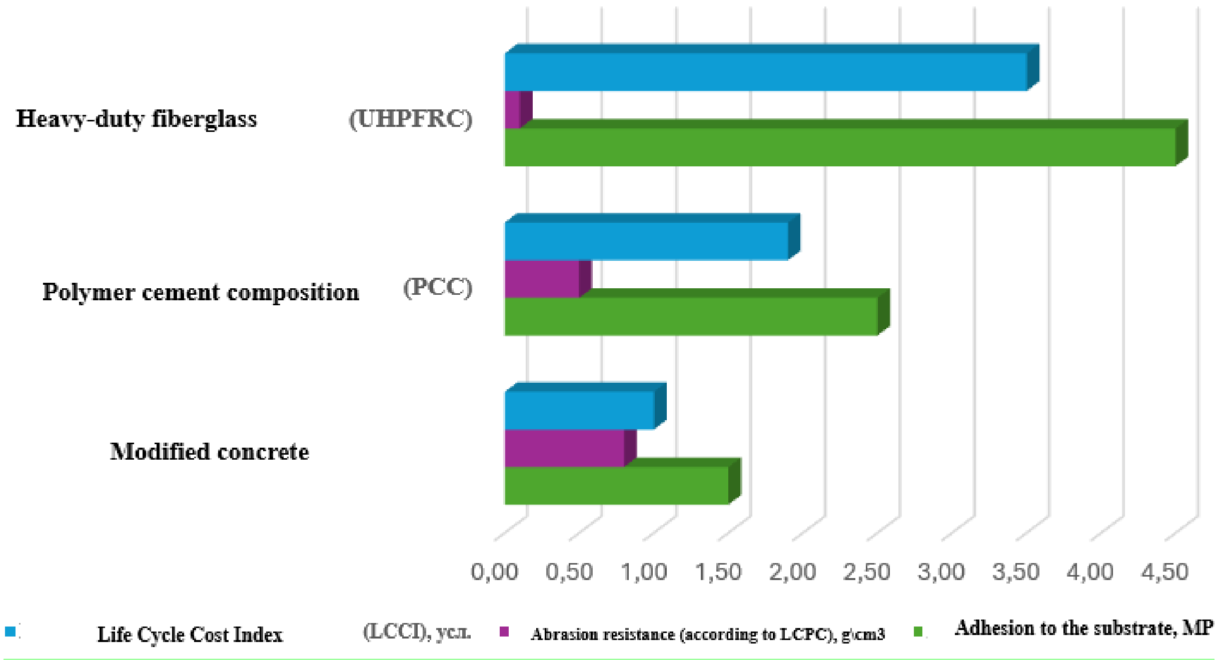

Figure 7 – Comparison of repair materials for concrete based on durability, adhesion, and cost efficiency indicators (author's material)

Ultra-high-performance fiber-reinforced concrete (UHPFRC) significantly surpasses both materials in all evaluated parameters **(Huang et al., 2022)**. Its compressive strength reaches 150–200

MPa, adhesion exceeds 4.0 MPa, and abrasion loss is less than 0.2 g/cm². The combination of high mechanical strength, superior adhesion, and extremely low wear ensures exceptional durability and operational reliability, even under the harsh conditions typical of hydraulic structures **(Zhakipbayev et al., 2025)**. The use of UHPFRC represents a technically sound solution for highly loaded areas that require maximum abrasion resistance and structural integrity.

Experimental data **(Moldamuratov et al., 2023)** confirm that the wear resistance of hydraulic concretes depends strongly on the regulation of the water-to-cement ratio and the type of surface-active agent (surfactant) used, which is consistent with the results presented in **Table 1**.

Table 1
Comparative characteristics of modern repair materials for wear zones

Characteristic	Modified concrete (as per GOST requirements)	Polymer cement composition (PCC)	Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC)
Compressive strength, MPa	50 – 60	60 – 80	150 – 200
Adhesion to the substrate, MPa	1.5 – 2.0	2.5 – 3.5	> 4.0
Abrasion resistance (LCPC), g/cm2	0.8 – 1.0	0.4 – 0.7	< 0.2
Cavitation resistance (relative)	Loq	Medium	Super High
Lifecycle Cost Index (LCCI), a.u.*	1.0	1.8 – 2.5	3.0 – 4.5

Note: The Lifecycle Cost Index (LCCI) takes into account not only the initial material cost but also its durability, as well as the frequency and cost of maintenance and repair intervals. Despite the high initial cost of UHPFRC, its use can be economically justified in critical structural zones due to the substantial increase in service life.

When analyzing abrasive wear and cavitation, comparative data indicate the technological advantage of next-generation composite materials. Polymer-cement composites (PCC) demonstrate significantly higher adhesion and wear resistance compared to conventional concrete **(Zuhair Al-Jaberi et al., 2022) (Figure 8)**.

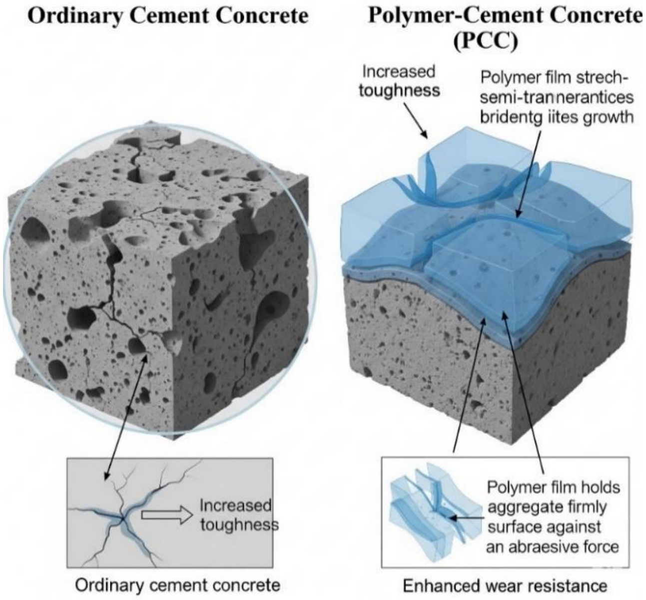

Figure 8 – Comparison of the microstructure of ordinary cement concrete and polymer-cement concrete (author's material).

However, a qualitative leap in performance is achieved through the use of ultra-high-performance fiber-reinforced concrete (UHPFRC). Its resistance to abrasion and cavitation –

exceeding that of conventional concretes by a factor of 8-12 – is attributed to the synergistic combination of an ultra-dense matrix and the micro-reinforcing effect of steel fibers, which prevent aggregate spalling under the impact of high-velocity water flow **(Bandara et al., 2023)**.

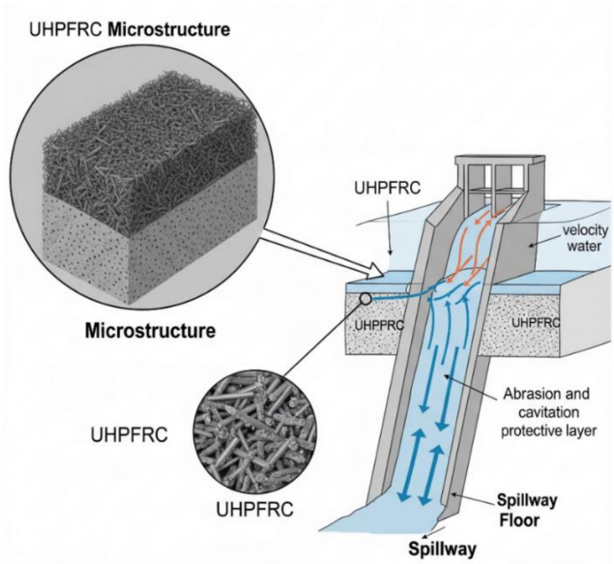

Figure 9 – Microstructure and application of ultra-high-performance fiber-reinforced concrete (UHPFRC) for the protection of hydraulic structures (author's material).

Microstructural analysis of cement composites **(Kabdushev et al., 2023)** confirms that the density and uniformity of the cement matrix are directly correlated with resistance to cavitation wear and crack formation, which aligns with the observed performance advantages of UHPFRC illustrated in **Figure 9**.

The high Lifecycle Cost Index (LCCI) of UHPFRC, presented in Table 1, often serves as a barrier to its widespread application. However, our analysis – supported by operational data from the *Three Gorges Dam* – demonstrates that for critical zones of hydraulic structures (such as stilling basins and spillway aprons), where the cost of repeated repairs and equipment downtime is extremely high, the initial investment in UHPFRC is economically justified due to a substantial extension of the maintenance interval (from 3-5 years to 15-20 years).

4.3.2. Protection against chemical and biogenic aggression

The analysis of protection methods against chemical corrosion confirms that the most reliable solution is the formation of a multi-layer barrier system **(Figure 10)**.

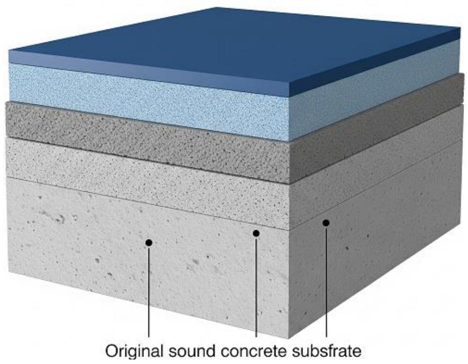

Figure 10 – System of concrete protection against chemical corrosion (author's material).

The use of specialized sulfate-resistant or calcium aluminate cements for repair, followed by the application of a final hybrid polymer coating, provides comprehensive protection against leaching, as well as acidic and sulfate attack **(Moldamuratov et al., 2022)**.

In the context of biogenic deterioration, alongside traditional rehabilitation methods, an actively developing approach involves the use of self-healing concrete, which ensures autogenous crack sealing and enhances the durability and service life of hydraulic concrete structures **(Osta & Mukhtar, 2024)**.

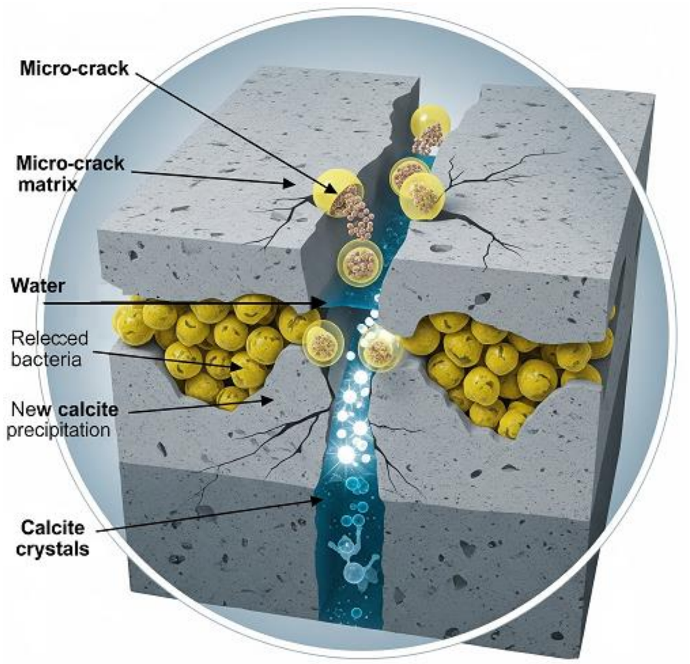

Figure 11 – Principle of bio-concrete operation (author's material).

The mechanism illustrated in **Figure 11**, where encapsulated bacteria are activated upon crack formation and produce calcium carbonate ($CaCO_3$), represents a transition from passive repair to an intelligent, autonomous system. According to recent studies, this technology is capable of sealing cracks up to 0.8 mm wide, marking a breakthrough in maintaining the watertightness of concrete structures **(Chaolin Fang & Varenyam Achal, 2023)**.

4.3.3. Long-Term Protection of Reinforcement Against Corrosion

The service life prediction of repair systems, presented in **Figure 12**, is one of the most illustrative results characterizing the behavior of reinforced concrete during restoration. The analysis of the graph indicates the low efficiency of localized repair strategies (Curve A). This behavior is explained by the incipient anode effect: after repairing a small area, a highly alkaline environment is created, turning it into a cathode, while the adjacent zones of old chloride-contaminated concrete become anodes, leading to accelerated corrosion. Complete removal of the contaminated concrete (Curve B) provides a longer, though still time-limited, improvement in durability **(Saqif et al., 2022)**.

Only the use of active protection systems, in particular embedded galvanic anodes (Curve C), ensures that the reinforcement remains in a passive state for a predicted period of 15–20 years **(Jakiyayev et al., 2021)**. The anode corrodes instead of the steel reinforcement, thereby providing cathodic protection **(Harahap et al., 2023)**.

The results of the service life analysis emphasize the need to reconsider existing repair approaches for reinforced concrete hydraulic structures. Instead of performing cyclic local repairs every 3–5 years, it is more rational to implement electrochemical cathodic protection systems, especially under aggressive environmental conditions.

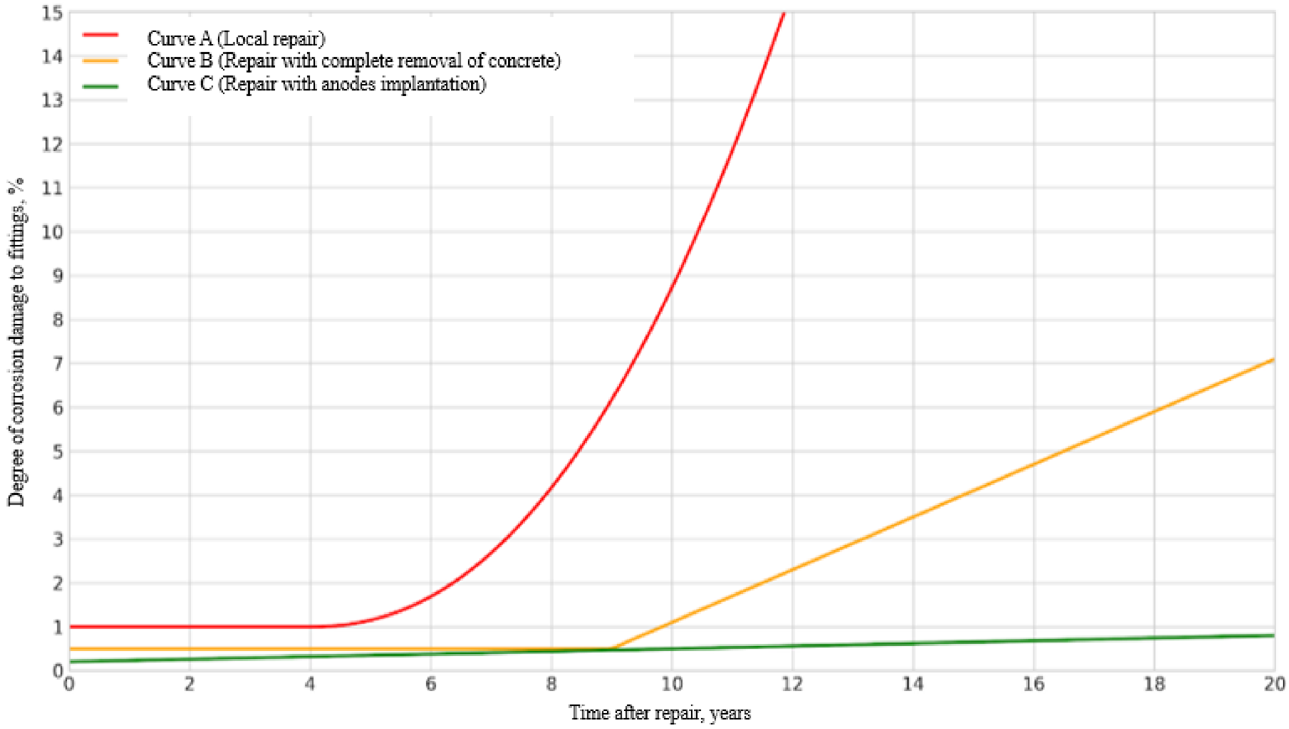

Figure 12 – Predicted service life of repairs under different reinforcement protection strategies(author's material)

4.4. Discussion in the Context of Kazakhstan's Conditions

The practical implementation of the discussed technologies at hydraulic facilities in Kazakhstan, such as the Kirov Reservoir and the Aktobe Hydraulic Complex – provides an opportunity to specify and validate the findings. The severely continental climate of Kazakhstan, characterized by large annual and diurnal temperature variations (freeze-thaw cycles), imposes increased requirements on the thermal compatibility and frost resistance of repair materials (F300 and above).

Our analysis showed that the successful use of polyurethane injection resins at the Aktobe Hydraulic Complex for joint sealing confirms their effectiveness under active deformation conditions. At the same time, operational experience demonstrates that for the repair of abrasion zones in spillway structures, the most wear- and frost-resistant materials, such as UHPFRC, should be preferred – even despite their higher initial cost – since traditional concretes require repeated repairs every 5-7 seasons.

Thus, for the conditions of Kazakhstan, it is necessary to adapt international experience: the selection of technologies should be based not only on the type of defect, but also on a comprehensive analysis of climatic loads and long-term economic efficiency. Further research focused on the development and testing of repair mixtures optimized for the specific operating conditions of hydraulic structures in the region appears to be highly relevant.

Comparative analysis of the accumulated repair cost using traditional concrete and UHPFRC. The **Figure 13** demonstrates the break-even point (approximately 12 years), after which the high initial cost of UHPFRC is compensated by the elimination of frequent repair needs, typical for traditional materials under the climatic conditions of Kazakhstan.

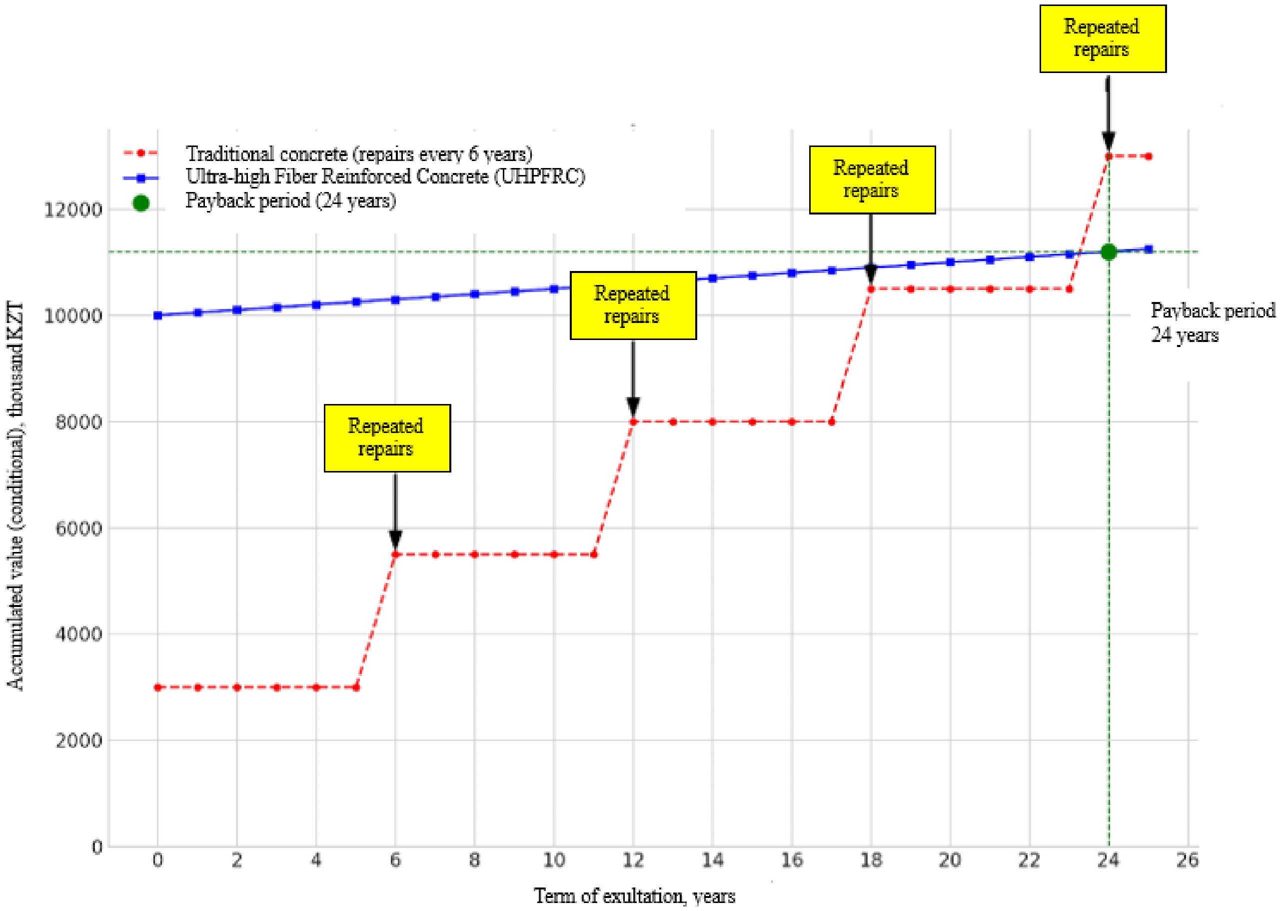

Figure 13 – Comparative analysis of repair technology efficiency (author's material).

5 CONCLUSIONS

The review and analysis conducted in this study made it possible to systematize the main mechanisms of concrete degradation in hydraulic structures and to identify modern technologies for their restoration. The key findings of the research are as follows:

1. It has been established that the degradation processes in hydraulic concrete structures are synergistic in nature: primary physico-mechanical damages (e.g., cracking) critically accelerate secondary chemical and corrosion mechanisms. This confirms the inefficiency of local repairs when the root cause is not addressed.

2. Comparative analysis revealed the absence of a universal repair solution and defined a clear hierarchy of applicable technologies. The optimal choice depends on the dominant degradation mechanism:

- UHPFRC for zones of intensive abrasion.
- Elastic polyurethane injection resins for sealing active leakages.
- Electrochemical methods for long-term reinforcement protection.

3. Evaluation based on the lifecycle cost index (LCCI) confirmed that, despite their higher initial cost, innovative materials (such as UHPFRC) and technologies (such as galvanic anodes) are economically justified for repairing critical and hard-to-access areas of hydraulic structures, due to their significantly extended maintenance intervals.

4. Active electrochemical protection systems are the only approach that not only halts ongoing reinforcement corrosion, but also prevents its initiation in adjacent zones (the "incipient anode" effect), thereby ensuring maximum repair durability.

5. For the Republic of Kazakhstan, the primary challenge lies not in the direct adoption of foreign technologies, but in the development of adapted rehabilitation strategies.

These strategies must take into account the harsh continental climate (increased requirements for frost resistance and thermal compatibility of materials) and the specifics of the national regulatory framework.

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