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Selected corrosion problems of hydrotechnical structures

Wybrane problemy korozyjne dotyczące konstrukcji hydrotechnicznych

The article describes the influence of the environment on the corrosion of hydrotechnical structures. The mechanical, biological and chemical interactions on steel, concrete and reinforcing steel elements in concrete are discussed. Examples of destruction focused on the structures – in the marine environment and in the conditions of freshwater impact are shown.

Keywords: *hydrotechnical structures, corrosion, environmental impacts, chloride ions*

W artykule opisano wpływ środowiska na korozję budowli hydrotechnicznych. Omówiono mechaniczne, biologiczne i chemiczne oddziaływania na elementy stalowe, betonowe i na stal zbrojeniową w betonie. Pokazano przykłady zniszczeń konstrukcji – w środowisku morskim i w warunkach oddziaływania wody słodkiej.

Słowa kluczowe: *konstrukcje hydrotechniczne, korozja, oddziaływania środowiskowe, jony chlorkowe*

1. Introduction

Hydrotechnical structures operating in the marine environment, such as piers, wharves, breakwaters, or port infrastructure, play a key role in coastal protection, supporting maritime transportation and providing infrastructures for tourism, shipping, transhipment and fishing. These are structures that, because of their function, must be able to withstand very extreme environmental conditions.

Hydrotechnical structures operating in freshwater environments, such as dams, locks, canals, offshore power plants and dams, play a key role in managing water resources. However, constant contact with water, often with high velocity and varying flow dynamics, exposes these facilities to erosion and cavitation phenomena.

At the 25th Structural Failures Conference in 2011, the authors of the article [1] presented an analysis of the safety status of hydrotechnical facilities (dams, weirs, barrages) in Poland at the end of 2009, noting the varying conditions of their operation and the need for systematic assessment and modernization of their key elements. As far as corrosion problems are concerned, this work highlights the importance of regular monitoring and maintenance of structures exposed to aggressive water environments, including submerged areas and zones of fluctuating water levels, where corrosion and erosion processes accelerate material degradation. Fig. 1 shows statistics on the service life of hydrotechnical structures that continuously dam water. As such, the various structures that form the foundation of modern hydrotechnical structures, of which there are a huge number, are subject to a variety of degradation factors that affect their durability, safety and operating costs [2].

2. Types of environmental impacts on hydrotechnical structures

Environmental impacts affecting the durability of hydrotechnical structures [3–8] can be divided into the following groups:

– mechanical, including: the force of waves (height, length and intensity), as well as currents and their impact on foundation stability and erosion;
– biological, such as biofouling, which is characterized by the settlement of marine organisms on the surface of the structure, causing biological corrosion;
– chemical and electrochemical which include: the influence of chloride ions coming from seawater or roads desalination operations, or sulfate ions, e.g., at transhipment sites;
– physical, such as the effects of high humidity, cyclic freezing and thawing, ice, wind.

Areas particularly vulnerable are fluctuating water level zones. In these parts of the structure, chemical and physical processes are intensified, which accelerates the degradation of concrete and steel. Frequent immersion and drying promotes leaching of fine fractions and the formation of cracks in the concrete, through which chloride ions attack either concrete or reinforcement and penetrate more easily.

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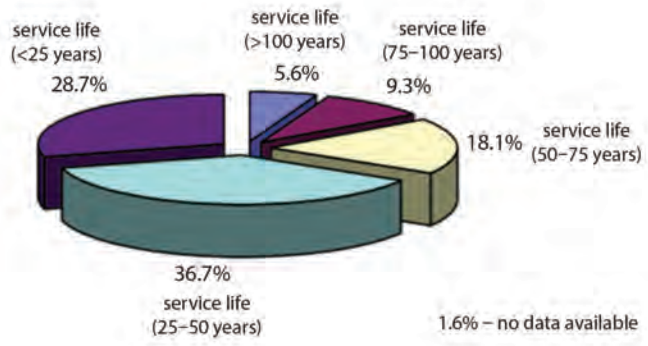

Fig. 1. Hydrotechnical structures classes I, III, IV and unclassified structures, permanently damming water – as of 31.12.2009, the actual service of the structure life was given

Source: [1, p. 287].

Rys. 1. Budowle hydrotechniczne klas I, III, IV i pozaklasowe stale piętrzące wodę – stan na 31.12.2009, podano faktyczny okres eksploatacji obiektów

Źródło: [1, s. 287].

3. Exposure classes and environmental corrosivity categories

3.1. Reinforced concrete structures – exposure classes

Structures are impacted by varying environmental conditions that influence their durability depending on the structural element affected [9]. For reinforced concrete structures, exposure classes are defined as described in PN-EN 206 [10], while steel structures have defined corrosivity categories, which are described in PN-EN ISO 12944-2 [11].

Exposure class is a classification of chemical and physical environmental conditions to which a reinforced concrete structure may be exposed [9, 12, 13]. The division of exposure classes depending on the interacting environment for concrete is shown in Table 1 [13], while an example of exposure class combinations for a given element of reinforced concrete structure exposed to a marine environment is shown in Fig. 2 and 3 [12].

3.2. Steel structures – classification of environments

EN ISO 12944-2 [11] is concerned with the protection of steel structures against corrosion by means of coating systems. Within this standard, six atmospheric corrosivity categories are defined:

– C1: very low corrosivity;
– C2: low corrosivity;
– C3: medium corrosivity;
– C4: high corrosivity;
– C5: very high corrosivity;
– CX: extreme corrosivity; one of these types of environments is the offshore operating environment included in PN-EN ISO 12944-9 [14].

EN ISO 12944-2 also distinguishes between corrosivity categories in situations where structures or components are permanently immersed in liquid or placed in the ground. These categories include:

– Im1: immersion in fresh water,
– Im2: immersion in seawater or brackish water,
– Im3: soil,
– Im4: extreme environments such as seawater with high salinity or marine environments with intense wave and current influences (mainly applies to offshore structures),

Table 1. Division of exposure classes in relation to the interacting environment
Tabela 1. Podział klas ekspozycji w zależności od oddziałującego środowiska

Class designation	Description of the environment
1. No risk of corrosion or environmental aggression	
X0	For concretes that do not contain reinforcement and other metal elements: all environmental impacts except in cases of freeze/thaw, abrasion or chemical aggression. For reinforced concrete or concrete containing other metal elements: very dry
ENVIRONMENTAL IMPACTS ON REINFORCEMENT	
2. Corrosion due to carbonation	
If concrete containing reinforcement or other metal elements is exposed to air and moisture, the exposure should be classified as follows:	
XC1	Dry or permanently wet
XC2	Wet, rarely dry
XC3	Moderate humidity
XC4	Cyclic wet and dry
3. Corrosion due to chlorides not originating from seawater (inland zone)	
If concrete containing reinforcement or other metal elements is exposed to water containing chlorides, including de-icing salts, from sources other than seawater, the exposure should be classified as follows:	
XD1	Moderate humidity
XD2	Wet, rarely dry
XD3	Cyclic wet and dry
4. Corrosion due to chlorides from seawater (marine zone)	
If concrete containing reinforcement or other metal elements is exposed to chlorides from seawater, or those found in water or in the air, the exposure should be classified as follows:	
XS1	Exposed to airborne sale but not in direct contact with sea water
XS2	Permanently submerged
XS3	Tidal, splash and spray zones
ENVIRONMENTAL IMPACTS ON CONCRETE	
5. Freeze/thaw attack with or without de-icing agents	
When wet concrete is exposed to a strong cyclic freeze/thaw attack, the exposure should be classified as follows:	
XF1	Moderate level of water saturation without deicing agents
XF2	Moderate level of water saturation with de-icing agents
XF3	High level of water saturation without de-icing agents
XF4	High level of water saturation with de-icing agents or seawater
6. Chemical aggression	
When concrete is exposed to chemical aggression of natural soils or ground water, the exposure should be classified as follows:	
XA1	Chemically low-aggressive environment
XA2	Chemically moderately aggressive environment
XA3	Chemically highly aggressive environment
7. Abrasion-induced aggression	
When concrete is exposed to chemical aggression of natural soils or ground water, the exposure should be classified as follows:	
XM1	Moderate abrasion
XM2	Heavyy abrasion
XM3	Extreme abrasion

Source: [13, p. 17–18].
Źródło: [13, s. 17–18].

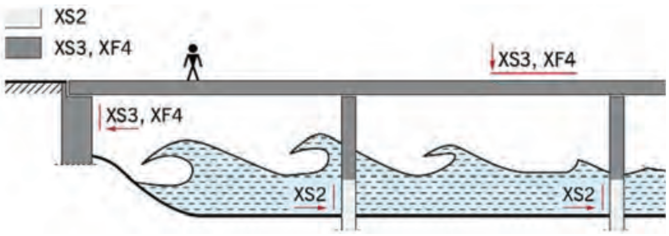

Fig. 2. Exposure classes of structures in the marine environment

Source: [12, p. 12].

Rys. 2. Klasy ekspozycji budowli w środowisku morskim
Źródło: [12, s. 12].

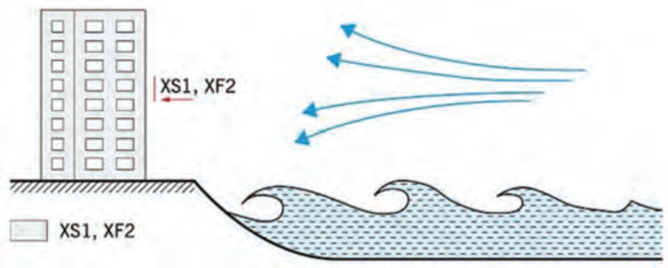

Fig. 3. Exposure classes of structures in the coastal zone

Source: [12, p. 12].

Rys. 3. Klasy ekspozycji budowli w strefie brzegowej
Źródło: [12, s. 12].

which allows for the selection of appropriate corrosion protection systems tailored to the specific environment.

In addition, the PN-EN ISO 12944 standard distinguishes a number of exposure zones for structures exposed to water, which allows for a more precise selection of corrosion protection systems. These zones take into account different operating conditions, the intensity of contact with water and the corrosive intensities. They include:

– Atmospheric zone above the waterline – the structure is above the water level and is mainly exposed to humid marine or industrial air (categories C1–CX according to PN-EN ISO 12944-2). Corrosion occurs here under the influence of the atmosphere, without permanent immersion.
– Splash zone, which includes the area immediately adjacent to the water level, where structural elements are frequently and rapidly wetted by waves, splashes and sea breezes. This zone is particularly corrosively aggressive due to frequent and alternating wetting and drying, as well as the accumulation of salt and other contaminants.
– Tidal zone (variable immersion zone, where water and atmosphere interact alternately) – the structure is periodically submerged and surfaced in relation to tides or other changes in water level (such as river level or fluctuations in reservoirs), and repeated wet and dry cycles promote the intensification of corrosion processes.
– Submerged zone – elements of the structure remain permanently underwater.

The distinction of the above zones (atmospheric, splash, tidal and submerged Im1–Im4) allows a more accurate analysis of the operating conditions of the structure and the selection of appropriate coating systems, adapted to the specific environment and the degree of exposure to water. Table 2 presents a breakdown of the corrosivity categories of environments with examples of conditions and locations, while Table 3 presents a breakdown of categories by type of immersion.

3.3. Mechanical interactions

3.3.1. Waves

Waves are characterized by cyclic loads that can lead to fatigue of materials [15]. The height of the wave affects the magnitude of the dynamic force hitting the structure. Higher waves generate greater hydrodynamic pressure on the surface of the structure, which can lead to local damage to the concrete, such as surface spalling or cracking. Wave length determines the zone of force – longer waves affect a larger portion of the structure, which can lead to more extensive damage, especially in foundation zones and lower-lying portions of the structure.

3.3.2. Water currents

Water currents have a significant impact on erosion processes [15]. Strong coastal water currents cause the movement of sediment, sand and small stones, which hit the surface of concrete and steel elements and lead to their gradual degradation, which also had an impact on the case described in section 4.1. This phenomenon is called abrasive deterioration of materials. In addition to this, currents can also cause washouts of foundations, which leads to destabilization of the entire structure.

In addition, prolonged exposure to waves and currents leads to microcracks in the material, which can grow larger over time. In concrete exposed to seawater, microcracks become sites of chloride ion penetration, which initiates corrosion processes in reinforcing steel.

3.3.3. Erosion

Erosion is a mechanical process [4, 15], whereby structural materials degrade due to hydrodynamic forces and abrasion by waterborne particles. The effects of erosion include a reduction in the thickness of structural components, the formation of cavities and a weakening of structural integrity. In the long term, this leads to an increased risk of failure and increased maintenance costs.

3.3.4. Cavitation

Cavitation is a process involving the formation and implosion of gas bubbles in a liquid as a result of local pressure drops below the saturated vapor pressure of the liquid. In hydraulic engineering, cavitation [16] is most common in high flow velocity zones such as water culverts, overflows and water turbines.

The implosion of cavitation bubbles generates local shock waves of very high pressure (up to 1,000 MPa), which causes: micro-cracks in materials, loss of surface through material loss, and formation of stress concentration areas, which increases susceptibility to further damage. Erosion and cavitation often co-occur, amplifying their destructive effects. Cavitation phenomena can accelerate hydraulic and abrasive erosion through local damage to the material, which become that are more easily susceptible to further degradation. In turn, erosion can increase susceptibility to cavitation by creating surface irregularities that promote local flow turbulence and pressure drops.

Table 2. Division of environmental corrosivity categories with examples of conditions and places where they occur
Tabela 2. Podział kategorii korozyjności środowisk wraz z przykładowymi warunkami i miejscami ich występowania

Category	Scope of application (type of atmosphere)	Examples of occurrence
C1: very low	Climate-controlled interiors, dry atmosphere	Interiors of heated buildings with clean atmospheres, such as office buildings, museums, art galleries, living spaces with constant temperature and low humidity
C2: low	Low-pollution atmosphere	Interiors of unheated buildings, rooms with periodic condensation, rural areas with clean air
C3: moderate	Urban and industrial atmosphere with medium SO_2 pollution, coastal areas with low salinity	Cities with low emissions, suburban zones, production sites with high humidity and somewhat polluted air; for example: the production of foodstuffs, breweries, laundries, dairies
C4: high	Industrial and coastal atmosphere with moderately high salinity	Industrial areas with moderate emissions, seaports, coastal zones with high salinity exposed to offshore winds
C5: very high	Industrial atmosphere with high pollution and high humidity or coastal areas with high salinity levels	Structures near coastal areas with intense sea salt exposure with almost continuous moisture condensation and high air pollution
CX: extreme	Extreme aggressive industrial and marine environments. Areas on the high seas with high salinity and industrial areas with extreme humidity and aggressive atmospheres, as well as subtropical and tropical atmospheres	Offshore oil rigs, industrial installations in extreme conditions, areas with very high concentrations of chemical contaminants

Table 3. Division of categories by type of immersion
Tabela 3. Podział kategorii ze względu na rodzaj zanurzenia

Category	Type of immersion/soil environment	Examples of occurrence
Im1	Freshwater immersion	Hydrotechnical structures in rivers, lakes, freshwater reservoirs
Im2	Immersion in seawater or brackish water (slightly saline)	Port wharves, structural piles in the sea, foundations of sea bridges, coastal structures, locks, gates, piers, etc. without cathodic protection
Im3	Sinking/placement in the ground	Underground pipelines, steel foundations in the ground, pile structures in the ground, underground tanks
Im4	Immersion in seawater or brackish water (slightly saline)	Immersed structures (structures in the open sea) – with cathodic protection

3.4. Biological interactions

Despite the fact that reinforced concrete structures have high mechanical strength and durability, biofouling [17] has a significant impact on reinforced concrete hydrotechnical structures. The mechanisms of biofouling on reinforced concrete results from several key processes, such as the changing of surface characteristics, accelerating corrosion of reinforcement and increasing hydrodynamic loads. The first major effect of biofouling is a change in the surface roughness of the structure. Concrete, being a porous material, already in its natural form promotes the adhesion of marine organisms. The biofouling layer, consisting of a biofilm of microorganisms and sedimented macroscopic organisms such as clams and barnacles, significantly increases the hydrodynamic resistance of the structure. In the case of breakwaters, jetties or reinforced concrete foundations of offshore wind farms, the greater resistance to water flow can lead to an increase in the forces acting on the structure, which consequently increases the risk of mechanical damage, especially under extreme wave and current conditions.

Biofouling also affects the weight and stability of structures. Organisms such as clams or barnacles can form layers several centimetres thick, which significantly increase the weight of reinforced concrete elements. In the case of structures founded on a muddy marine substrate, such as bottom sediments, the additional load can lead to foundation settlement or destabilization. For example, in tropical areas where biological productivity is particularly high, the weight of biofouling can reach values of several hundred kilograms per square meter, which poses an additional problem for structures designed with little bearing capacity.

Another important aspect is the effect of biofouling on the corrosion process of reinforced concrete. Organisms inhabiting concrete surfaces can produce chemically aggressive substances. A major role in this process is played by sulphate-reducing bacteria (SRB), which convert sulphates present in seawater into hydrogen sulphide. The resulting hydrogen sulphide reacts with the reinforcing steel, leading to the formation of iron sulphides and accelerating corrosion. In addition, the biological activity of organisms can disrupt the natural pH of concrete, which weakens the passive layer on the surface of the reinforcement, making the steel more susceptible to corrosion.

Microbiologically influenced corrosion (MIC) can also develop in fresh water [18], which poses a significant challenge to the durability and reliability of hydraulic structures such as dams, weirs, culverts, canals, or locks. Microbial corrosion results from the metabolic activity of microorganisms – bacteria, algae, fungi, or lichens – which form biofilms on the surfaces of structures. Under the influence of microorganism metabolism, microfoci of corrosion are formed with locally altered pH and potential. In areas of biofilm formation, due to local differences in potential and availability of oxygen and ions, intense and spot corrosion (pitting) can occur. In the long term, this leads to a weakening of the structure, the formation of cavities and changes in the cross-section of the elements, while the increase in surface roughness due to local corrosion can further accelerate the build-up of further layers of biofilm and intensify the degradation process.

3.5. Ice and floe

Ice has a significant impact on hydrotechnical structures, both in terms of their design and operation. The impact of ice generates significant mechanical loads, resulting from its pressure on the various elements of the structure. The force of ice pressure can cause deformation and, in extreme cases, even damage to the structure. In addition, ice floes have a mechanical effect on protruding underwater elements, leading to their erosion or damage to protective anti-corrosion coatings, which increases the risk of corrosion.

The dynamic effects of ice, such as the oscillation of structures caused by regular impacts of ice floes or waving ice blocks, can weaken the structure in the long term. Cyclic stress changes caused by the freezing and thawing of ice can further contribute to material fatigue. Thermal influence, especially repeated transitions from negative to positive temperatures, is another important factor – temperature changes lead to the contraction and expansion of ice, which can generate high stresses in a confined space. In addition, low temperatures reduce the elasticity of materials, increasing their susceptibility to cracking.

The presence of ice in the water also changes the dynamics of flows around structures. This increases hydrodynamic drag, which can affect sediment settlement or depth changes around structures.

Ice accumulation in narrow channels can lead to the formation of ice dams, raising the water level and increasing the load on structures. In the face of these challenges, it is necessary to consider the impact of ice in the design of such structures. Structures must be made of materials that can withstand low temperatures and be designed to withstand the forces generated by ice. Only a comprehensive approach to these issues can ensure the safety and durability of hydrotechnical structures in harsh marine environments.

3.6. Corrosion due to aggression of chloride ions from seawater

The marine environment is particularly conducive to chloride corrosion [4, 19], due to the high concentration of chlorides and the presence of salt aerosol, which is deposited on the surface of the structure. In addition, the wet-dry cycles that occur in tidal zones intensify the corrosion process by increasing the transport of chlorides deep into the concrete. Humidity and temperature also play a key role – higher temperatures accelerate chemical reactions and diffusion processes, while high humidity promotes ion migration in the concrete pore solution. The influence of these factors makes chloride corrosion in the marine environment a phenomenon that is particularly difficult to control and represents one of the greatest challenges of modern structural engineering, especially in terms of the durability of hydrotechnical structures. Reinforced concrete structures such as bridges, breakwaters and wharves are exposed to continuous exposure to aggressive environmental conditions.

The phenomenon of chloride corrosion leads to the gradual deterioration of reinforcing steel and a reduction in the load-bearing capacity of the structure, and is a complex process that depends on many factors, such as the properties of the concrete, environmental conditions and the build quality.

The mechanism of chloride corrosion can be divided into several stages. The first is the penetration of chloride ions through concrete, which, despite its apparent impermeability, is characterized by a porous structure. Chloride ions migrate into the concrete, and the rate of this process depends on the quality of the concrete, especially its porosity and water-cement ratio (*w/c*). Concrete with a higher w/c ratio is more permeable, which facilitates the penetration of chloride ions, which affect both the concrete matrix and reinforcement. With the concrete components, they form Friedel salts and Kuzel salts. When the concentration of chloride ions on the surface of reinforcing steel reaches a critical level, depassivation of the protective oxide layer, which naturally forms on the steel surface under alkaline conditions, occurs. This depassivation leads to the initiation of point corrosion known as pitting corrosion. This is a particularly dangerous form of corrosion, as it causes a local weakening of the steel cross-section, which can lead to a sudden and uncontrolled failure or a structural catastrophe.

4. Examples of structural damage

4.1. Case 1

4.1.1. Destruction of steel hydrotechnical structure

Due to continuous exposure to a variety of often aggressive environmental factors or financial savings, hydrotechnical structures require intensive repair work such as that described in articles [7, 20–24] to extend their service life. Below, two cases of problems with hydrotechnical structures (a weir and a wharf) examined in Road and Bridge Research Institute are described. Both cases are examined within a very short period of time after being put into service.

A hydraulic structure such as a weir, damming up water in a river, leads to the formation of two hydraulic zones. In front of the structure, the water velocity decreases as the water surface rises. This causes sedimentation and accumulation of solid materials transported by the water. At the same time, the stream has a uniform character. At the overflow, a significant change in the nature of the flow to fast and rapidly varying can be observed. A hydraulic jump is formed, in which the internal energy of the stream increases. Below the weir, there is increased turbulence and increased flow velocities in the riverbed area. This type of water flow causes a variety of damage to the structure described below.

4.1.2. Description of the structure

The subject of the assessment was the steel structure of the weir. The documentation showed that the elements had been protected with a three-coat epoxy coating system on a less well-prepared substrate (primer, interlayer, topcoat). Previously, pitting was levelled using a two-component thixotropic epoxy-metal composite. It was not stated whether summer or winter curing agents were used, which has an impact on the curing times of the coatings.

4.1.3. Damage assessment

During the site visit, the elements were viewed from the upper water side and the lower water side (from the top of the weir). The inner part was inaccessible. The following damage was found:

– unevenness of the coatings in the form of streaks in the vertical axis; in many places, especially on the upper water side along these

areas of unevenness, there was damage due to friction/wearing of successive layers, local corrosion and pitting corrosion (Photo 1);
– local detachment of coatings from the pitting levelling compound (Photo 2);
– leaky connection of the seal with the wall surface allowing the accumulation of stones (Photos 3, 4).

4.1.4. Tests

The following tests were performed:
– Tests during the site visit: adhesion of coatings – the adhesion of coatings to the steel substrate was measured using the cross--cut method in accordance with PN-EN ISO 16276 -2. The test was performed outside the areas directly adjacent to the places of local detachment. The degree of adhesion was determined to be 0–1, which is correct.
– Laboratory tests:
  - Identification of the coatings used – in order to confirm the compatibility of the products used on the structure, an identification test was performed in accordance with PN-EN 1767. Identification was performed by comparing the FTiR spectra of the samples taken with the standards. The test was performed using a Nicolet iS10 infrared spectrophotometer. The spectrum was performed using the reflectance method (ATR) at a resolution of 4 cm^{-1}. Crystal used: diamond. The tests confirmed the compatibility of the products used.
  - Scanning microscope and optical microscope tests – tests were performed on a JOEL 6010 LV scanning electron microscope with an EDX attachment and on an Olympus GX-41 metallographic microscope. The tests made it possible to identify the number of coatings (Photos 5, 7), their thickness (Photo 5) and see their structure (Photos 6, 8). Four coatings were located (Photos 5, 7) and their thicknesses were determined (Photo 5): primer (40–53 µm), interlayer (222 µm) and topcoat (178 µm).

4.1.5. Discussion

1. Correct coatings were used to protect the structure, as determined by infrared spectroscopy.
2. Damage to the coatings was observed (partial loss of all layers), up to the complete disappearance of all layers and the occurrence of corrosion processes and pitting. Greater destruction was observed on the upper water side.
3. Along the vertical axis of the structure, unevenness of the coatings (referred to as "streaks") was observed, and coating damage is similarly arranged, with the largest occurring at the bottom of the wall and the smallest at the top of the wall, which explains the different water flows in the top and bottom layers.
4. Poor adhesion of the lower seal was found, resulting in dirt falling behind it. Damage to the coatings indicates mechanical damage, rather than leaching of the coatings, which was most likely caused by the impact of stones and other solid elements present in the water. The genesis of the damage is as follows: the formation of minor damage, followed by continuous and systematic waterlogging by flowing water and expansion of the damage, which was facilitated by the weakened adhesion of coatings in places.

Photo 1. Unevenness and damage of coatings and pitting corrosion

Fot. 1. Nierówności i zniszczenia powłok oraz wżery korozyjne

Photo 2. Local detachment of coatings

Fot. 2. Miejscowe odspojenie powłok

Photo 3. Leaky connection of the seal with the wall

Fot. 3. Nieszczelne połączenie uszczelki ze ścianą

Photo 4. A crevice filled with stones

Fot. 4. Szczelina wypełniona kamieniami

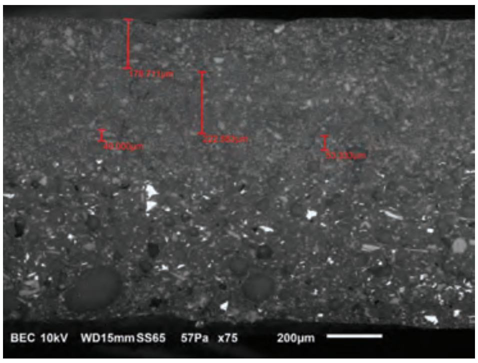

Photo 5. Cross-section of the coatings, where the four coatings are visible, and their thicknesses marked – photo taken with a scanning microscope

Fot. 5. Przekrój powłok: cztery powłoki z oznaczeniem grubości – zdjęcie wykonane z użyciem mikroskopu skaningowego

5. The samples showed the presence of sand embedded in the coating, which may indicate improper vacuuming of the surface or dusting by wind during application, which negatively affects the durability of the protection.
6. An analysis of the data shows that the anti-corrosion work was carried out in the autumn, without shielding or air conditioning, which, given the weather conditions at the time, posed great risks to the proper acclimation of the coatings. In many cases, the coatings were insufficiently cured before applying the next

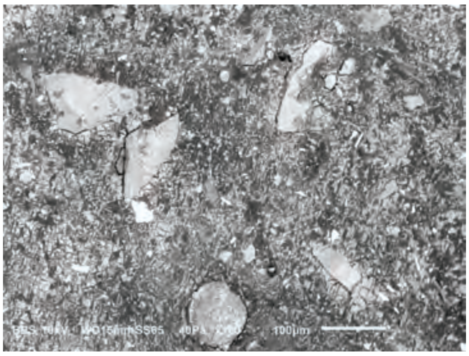

Photo 6. Structure of the bottom side of the removed coatings: sand particles embedded in the coating are identified – photo taken using a scanning microscope

Fot. 6. Struktura spodniej powierzchni zdjętej powłoki: wmalowane w powłokę cząsteczki piasku – zdjęcie wykonane z użyciem mikroskopu skaningowego

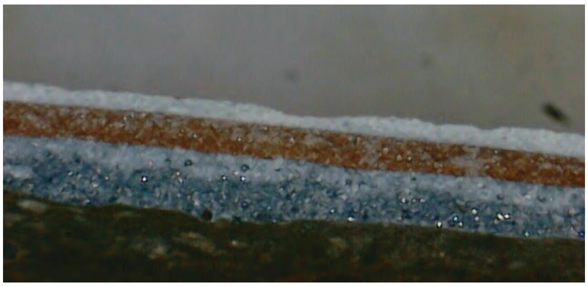

Photo 7. Cross-section of the coatings, where four coatings are visible – photo taken with a metallographic microscope

Fot. 7. Przekrój z widocznymi czterema powłokami – zdjęcie wykonane z użyciem mikroskopu metalograficznego

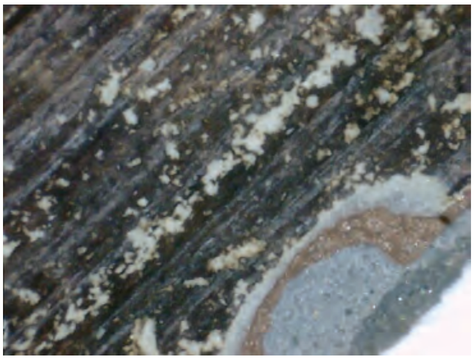

Photo 8. Damages and unevenness of coatings (from the top) in the vertical axis of the paintings – photo taken with a metallographic microscope

Fot. 8. Zniszczenia i nierówności powłok w osi pionowej wymalowań – zdjęcie powłok (od góry) wykonane z użyciem mikroskopu metalograficznego

layer and before flooding with water. They had not achieved full curing, which also meant full mechanical resistance to solid contaminants flowing with water, and the leaking seal behind which these contaminants accumulated and then scrubbed over the coatings exacerbated this phenomenon.

It was recommended that the coatings should be completely removed, the surface be cleaned to Sa 2.5, and the protection be reapplied.

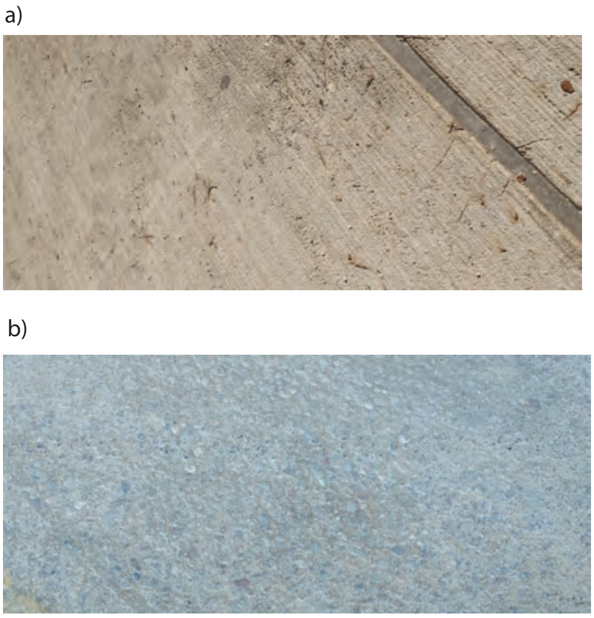

Photo 9. Effects of marine environment on elements of reinforced concrete hydrotechnical structures operating in a marine environment: a) exposure of diffuse reinforcement, b) exposure of the aggregate structure

Fot. 9. Wpływ działania środowiska morskiego na elementy żelbetowych konstrukcji hydrotechnicznych pracujących w środowisku morskim: a) odsłonięcie zbrojenia rozproszonego, b) odsłonięcie struktury kruszywa

4.2. Case 2

4.2.1. Site description

The subject of the evaluation was the reinforced concrete structure of a wharf. The documentation indicated that the designed concrete should be resistant to environmental aggressiveness in accordance with exposure classes XC4, XS3, XD3, XF4, XA2.

4.2.2. Damage assessment

During the site inspection, elements of the surface of the reinforced concrete structure were viewed and the following findings were made: exposure of diffuse reinforcement (Photo 9a) and exposure of the aggregate structure due to chloride ions (Photo 9b).

4.2.3. Tests

The following tests were performed:

– During the site visit:
  - Pull-off strength test – the test was performed in accordance with PN-EN 1542 [25] using a DYNA Z-8 device. 50 mm diameter punches were used for testing. Epoxy glue was used for bonding. Six measurements were made. An example of the type of punch breaking off from the substrate is shown in Photo 10.
  - Determination of the degree of carbonation of concrete – the determination was carried out on the pull-off sites. Rainbow test was used for the test, which, after reacting with the concrete substrate, stains to a specific colour assigned to the corresponding pH value. An example of the determination with the Rainbow test scale is shown in Photo 11, where it is indicated that at a depth of 5 mm the pH of the concrete is acidic.

Photo 10. View of a sample detachment during work on a concrete wharf

Fot. 10. Widok przykładowego zerwania w trakcie prowadzenia prac na nabrzeżu betonowym

Photo 11. One of the test locations used to determine the concrete reaction at the measurement site

Fot. 11. Przykładowe miejsce oznaczenia odczynu betonu

Photo 12. Cross-sectional view of the sample

Fot. 12. Przekrój poprzeczny próbki

- Samples were taken for laboratory testing – six of Φ100 mm cores were drilled from the entire cross-section of the wharf, from which samples were prepared (the lower part of all the cores was used to test compression resistance according to PN-EN 13791 [26], the upper part of three cores was used to test abrasion resistance according to PN-EN 13892-4 [27]), and another three cores were used to test structure and contamination by scanning microscopy.

– In the laboratory:
- Testing the compressive strength of concrete according to EN 13791 [26]: Evaluation of the Compressive Strength of Concrete in Structures and Precast Concrete Products. A compressive strength test was performed to determine if it is consistent with the design. Test specimens were prepared in accordance with PN-EN 12504-1 [29] by cutting cylinders with a diameter of Φ100 mm and a height of 100 mm, the bases of the specimens were ground and aligned to the until they were flat and parallel.
- Abrasion resistance of concrete according to PN-EN 13892-3 [30]: Test Methods for Subfloor Materials – Part 3: Determination of Abrasion Resistance According to Bohme [30] and abrasion resistance according to PN-EN 14157 [31] (method B).
- Determination of chloride and other impurities in concrete. The test was performed to determine whether the chloride ions content found in the concrete cover is the main cause of the problems. The test used powdered concrete that was taken from a depth of up to 1 cm from the provided cores and the following reagents: silver nitrate (V) solution (0.02 mol/L), ammonium thiocyanate solution (0.1 mol/L), nitric acid (V) (5 mol/L), ammonium and iron (III) sulphate indicator solution, deionized water.
- Determination of pH values and verification of carbonation resistance according to PN-EN 13295: Products and Systems for the Protection and Repair of Concrete Structures – Test Methods – Determination of Carbonation Resistance [28]. Incisions were made on samples from the top surface and the pH value was determined at the fracture sites. Photo 12 shows a value of pH = 11 on a specimen cross-section as per the stain colour produced. The depth of carbonatization to about 6 mm was determined.

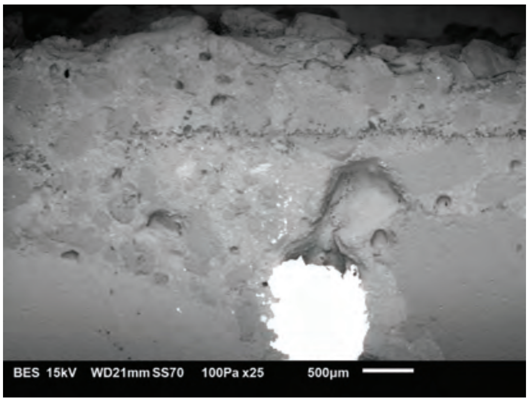

Photo 13. Cross section of sample R1

Fot. 13. Przekrój poprzeczny próbki R1

- Determination of the structure of concrete – the test was carried out using a JEOL JSM-6010LV scanning microscope in the backscattered electron composition (BEC) mode. Microscopic observations of concrete samples taken in the form of boreholes were carried out on the scanning microscope. The appearance of the cross-section of the sample is shown in Photo 13.

4.2.4. Test results

Based on the tests, it was found that the concrete used is characterized by:

– correct compressive strength parameters – these parameters did not deteriorate from those originally assumed in the design;

– scanning microscope analysis of cross sections of concrete samples clearly indicated that chloride ions are absent deep into the concrete structure, and only occur near the surface, which means that the concrete protects against chloride ions penetration, while determination of chloride content at 10 mm depth of the concrete matrix showed that their concentration is negligibly small;

– the cross-sectional examination of the top layer of concrete core samples showed that the concrete did not undergo carbonation, and its pH was correct and provided protection for the reinforcement;

– the cross-sectional examination showed that the concrete was only damaged near the surface.

Examination of the cross-section indicated that the concrete was not damaged in depth, confirming that the nature of the impact was only superficial for the time being and did not pose a risk to the bearing capacity of the structure.

5. Summary

The article presents key environmental hazards affecting durability of hydrotechnical structures, including both steel and reinforced concrete elements. In summary, corrosion of hydrotechnical structures, whether steel or reinforced concrete, is a complex phenomenon resulting from the characteristics of the aquatic and marine environment, as well as the mechanical and chemical loads. As such, it requires a multidisciplinary approach to be effectively controlled. The durability of structures operating in such extremely harsh conditions can only be achieved through the synergistic use of knowledge from chemistry, materials physics, and civil engineering. Although there are several standards for the anticorrosion protection of hydrotechnical metal and concrete structures, there seems to be a lack of comprehensive European guidelines that would fully cover the anticorrosion protection of such structures operating in difficult water conditions. Filling this normative gap would be crucial to ensure a uniform, effective and safe approach to corrosion protection, taking into account specific material, structural and environmental requirements.

An exception is the Norwegian NORSOK M-501 standard [32], which specifies requirements for the selection of coating materials, the various functions they are to perform, surface preparation, application procedures and inspection for protective coatings to be applied during the construction and installation of metal offshore and coastal facilities, as well as guidelines for subsequent maintenance work and detailed requirements for persons performing and supervising work in this area.

The introduction of appropriate design standards, the systematic monitoring of the technical condition of structures and the use of modern protection technologies form the basis for effectively combating corrosion and ensuring the safety of infrastructure. Early reactions of construction managers to emerging damage provide the greatest chance of stopping degradation processes.

CRediT authorship contribution statement

Urszula Paszek: Conceptualization, Funding acquisition, Investigation, Resources, Visualization, Writing – original draft, Writing – review & editing.

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