Assessment of Reasons behind and Level of Destruction of Aquatic Supports in a Hydraulic Ash Removal Bridge

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Abstract. *The presented article describes a case of damage to concrete in the aquatic supports of a hydraulic ash removal bridge in a power plant. Carrying out an assessment of the causes of concrete damage, as well as determining the possibility of the occurrence of corrosive phenomena within it, and thus, consequently, predicting the durability of the building structure and selecting, on its basis, a proper repair-renovation procedure, required a series of essential studies and analyses to be carried out. Therefore, in the analyzed case, a complex study was carried out on the structure as well as tests on samples of concrete cut out, in the form of core drillings, from the damaged structure (among others: macroscopic, microscopic SEM, XRD, DTA, chemical analyses). Based on these studies, the types of corrosion responsible for the analyzed damage were determined.*

Keywords: *RC Aquatic Supports, Durability, Destruction, SEM, XRD, DTA, Chemical Analyses.*

1 Introduction

For years now, not much attention has been given to industrial reinforced concrete structures. Unfortunately, the consequences of this are progressing phenomena of various types of corrosion, especially when the structures are under conditions posing a risk of corrosion. It is known that the corrosion of materials which buildings are made from is of fundamental importance to their durability (*Błaszczyński et al., 2008*). The reasons behind the corrosion of concrete, and therefore reinforced concrete, can be manifold. Such corrosion usually takes place under the influence of external effects. In the recent years, a frequent phenomenon in building practice is the occurrence of cracking of reinforced concrete structures across their entire width as early as at the stage of their realization. The reason behind such a state of things, as proven in works (*Błaszczyński et al., 2008, Łowińska-Kluge et al., 2012*), is internal corrosion in concrete. Concrete, as a structural material, is subjected to the corrosive effects of the outside environment. One type of corrosion that this material undergoes, frequently neglected by designers, is biological corrosion – a specific case of chemical corrosion. It ought to be pointed out that numerous physical and chemical transformations taking place in concrete are the result of the activity of metabolic organisms, i.e. bacteria, fungi or algae. The destruction of material caused by these living organisms takes place, among others, under the influence of biogeophysical processes, such as the changes in the porosity of material as a result of the development of a biological membrane on the surface of the concrete (*Horbik et al., 2013, Łowińska-Kluge et al., 2016, Mejíaa et al., 2019*).

2 Short Description of Analyzed Structure

Aquatic supports of a hydraulic ash-removal bridge are found in the area of a power plant, or,

more precisely, over the waters of a lake surrounding the actual plant. The lake serves to naturally cool off turbines. The supports are monolithic reinforced concrete structures in the form of reinforced concrete footings, found on a steel grated structure supporting structure, the construction of which is based mainly on channels or I sections.

After many years of service, the supports of the hydraulic ash-removal bridge are in a bad technical condition. Corroded and spalling concrete can be seen, as well as the progressing corrosion of reinforcing steel (Fig. 1, 2).
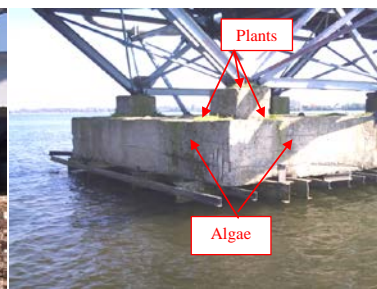

Figure 1, 2. Damages to pillars in the form of spalling corroded concrete and corroded reinforcing steel.

Centres of biological corrosion are also visible (Fig. 3 and 4).
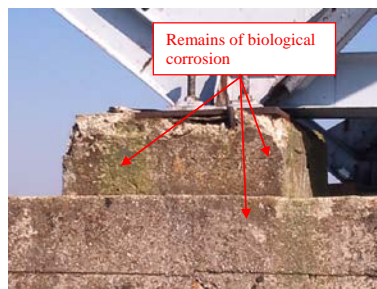
Figure 3. Reinforced concrete support with corrosion Centres.

Figure 4. Reinforced concrete support along with the covering vegetation and algae.

3 Performed Laboratory Tests

Laboratory tests were carried out on the collected samples from the objects, which covered: concrete core drillings of $\varnothing$ 4.5 mm, defined as Concrete A (Fig. 5) as well as concrete piece samples from areas near reinforcing bars and labelled as Concrete B (Fig. 6).

**Figure 5.** View of collected samples in the form of core drillings.

Figure 6. View of collected pieces.

3.1 Macroscopic Studies

Based on macroscopic observations, the occurrence of natural aggregate of a similar

granulation as well as certain amounts of carbonate aggregate was determined in the analyzed types of concrete. Concrete samples are characterized by a porous structure and varying dimensions of pores, with the remains of corroded reinforcement bars (Fig. 7a) and carbonate aggregate (Fig. 7b) determined on the majority of the samples.).

The presence of biotic factors in the form of algae and mosses, which can cause biological corrosion, is confirmed on the outer side of samples A and B (Fig. 8).
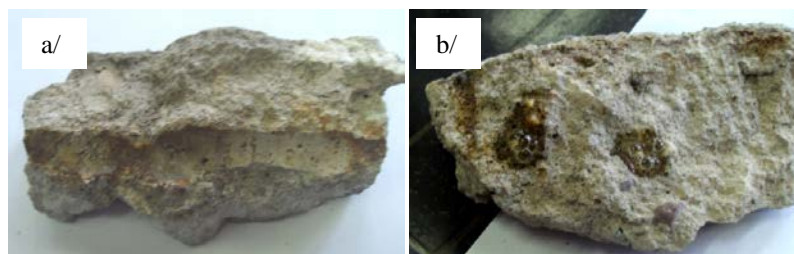
Figure 7. Piece samples of concrete: a/ porous structure and remains of corroded reinforcement bars, b/carbonate aggregate reacting with 10% HCl.

Figure 8. Concrete samples with visible biotic factors.

In order to assess the estimated course of carbonization in the analyzed concretes, the cross sections of concrete samples were sprayed with 1% phenolphthalein solution. Piece samples (Concrete B) are completely carbonized (Fig. 9), whereas in the samples from the core drillings (Concrete A), the carbonized layer is 1-3 cm in thickness (Fig. 10). Carbonization is not noted deeper within.

Figure 9. Pieces of Concrete B; completely carbonized concrete (all the way to the reinforcement bars) with visible remains of corroded reinforcement (pH>9).

Figure 10. Pieces of Concrete A; visible layer into concrete with an alkaline pH, carbonized 1-3 cm in thickness.

3.2 Determining Absorbability

Determining the absorbability of the collected concrete (serving the function of a cement

finish) was carried out using the desiccators - gravimetric method. The moisture content was determined in [%] from Formula (1):

$$n = (m-m_s)/m_s \cdot 100 \qquad [\%] \tag{1}$$

where:

n – absorbability [%],
m – mass of sample saturated with water to a constant mass [g],
m_s – mass of sample dried to a constant mass [g].

The results obtained for the analyzed concrete are given in Table 1.

Table 1. Absorbability of tested concretes.

Concrete type	Concrete A	Concrete B
absorbability [%]	6.77	7.84

The results presented in the above table are the average from three indications for each type of concrete.

All determined absorbability values exceed 5%. In accordance with p. 5.2 of the PH-88/B-06250 standard: absorbability of concrete should not be higher than 5% in the case of concrete directly exposed to the effects of atmospheric factors, as was the case in the concretes analyzed here.

3.3 Determining the pH Value of Concrete

The pH of aqueous extracts of ground concrete samples taken from different locations was measured. The measurements were carried out using a N5170E Ph-meter. A combined glass electrode was used for the studies. Each of the results is the average from three readings

Table 2. pH value of analyzed concretes.

Concrete type	Concrete A	Concrete B
pH value	10.28	7.29

A typical pH for normal concretes is a pH = 12.3 to 12.7. A pH value = 11.8 is the limiting value at which the C-S-H (tobermorite) and aluminosilicate phases in the cement rock are stable. Concrete at a PH < 11.8 ceases provide protection for steel. All collected samples were characterized by a pH < 11.8, which confirms the corrosion processes of steel taking place within the concretes. The pH of Concrete B points to extensive processes of corrosion.

3.4 Determining Concrete Strength

Studies on the compressive strength were carried out on a universal durometer for static samples. The machine has a electrohydraulic drive with a hydraulic control system. In accordance with the calibration certificate and with p. 4.2.2 of PN-EN 12390-4:2001: *Concrete tests. Part 4: Compressive strength. Requirements for durometers,* the machines ought to be categorized in Class 0.5. The maximum load of the machine was 300 kN.

The tests were carried out in accordance with the PN-EN 12390-3:2002: *Concrete tests. Part 3: Compressive strength of samples for testing.* Compressive strength tests were carried out on samples cut out from the provided drillings. In connection with the small diameters of the boreholes, only samples with a surface of < 225000 mm^2 were obtained, and thus all results should be lowered by a value of 10 to 15%. The carried out tests provided results of compressive strength with values ranging from 11.81 MPa to 27.19 MPa. The obtained average strengths, with a large range of values, allow only for qualifying the analyzed concretes in classes from 10 to 20 MPa, depending on the level of damage.

# 4 Selected Structural-Chemical Tests

The collected samples were also subjected to necessary structural-chemical tests, such as:
- microscopic examinations,
- necessary chemical analyses.

4.1 Microscopic Tests

In order to determine the structure and type of created compounds, as well as to assess the possibilities as well as directions of further reactions in the analyzed Concretes A and B, microscopic examinations were carried out.

Microscopic examinations were also to serve the purpose of assessing the potential possibilities and directions of further reactions taking place in the analyzed concrete (*Łowińska-Kluge et al., 2006*). The studies were carried out in accordance with the assumed guidelines of microscopic analyses, using a type VEGA TS 5135 MM scanning microscope, at a low vacuum in electrons reflected on non-sputter-coated samples. Over the course of the tests, photographs of characteristic areas of the analyzed samples were taken. Example result has been shown in Fig. 11.
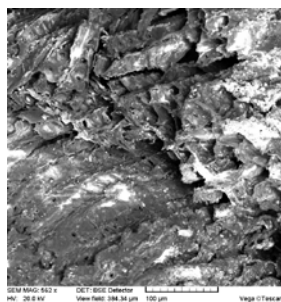
Figure 11. Microscopic SEM image of Concrete B surfaces contaminated with biotical factors (mosses, algae, fungi); very porous structure of cement matrix; visible "fibrous etchings" caused by the activity of biotic factors present in the gel phase.

Non-model microanalyses of EDS using an x-ray microanalysis system of characteristic products of reactions observed in the concrete of the finish and on eave sheet metals were also carried out.

The presence of carbon, calcium, oxygen, silicone, phosphorus, iron, sulphur, small amounts of nitrogen as well as trace amounts of potassium, zinc and aluminium is confirmed on the surface of the carried out non-model EDS x-ray microanalysis of the surface of

Concrete B contaminated with biotic factors (Fig. 11). Calcium silicates and aluminates had probably already undergone decomposition.

4.2 Necessary Chemical Analyses

In an effort to precisely specify the amount of compounds which can influence the properties of the analyzed concretes, chemical analyses of samples of these concretes were carried out.

Chemical analyses were carried out on adequately-sized samples of ground concretes A and B in accordance with the standards (*PN-EN 196-2:1996, PN-EN 196-21:1997, PN-EN 197-1:2002*) as well as the method of classical chemical analysis. The obtained results [%] have been presented in Tables 3 and 4.

Table 3. Determined $SO_{3\,total.}$, MgO, CaO, Na_2O, K_2O and Na_2Oeq contents in the entire concrete.

Concrete	Content of compounds in mean concrete sample [%]*					
	SO_{3total}	CaO	MgO	Na_2O	K_2O	$Na_2Oeq.$
A	2.44	29.53	1.03	0.14	0.387	0.39
B	0.96	32.87	1.53	0.11	0.70	0.57

* The results are the means of three recordings.

In Concrete A, a significantly higher content of SO_3, higher content of Na_2O and lower contents of MgO, K_2O and CaO occur as compared to Concrete B.

Estimated calculations of the amount of indicated compounds for concretes in [kg] and a comparison of the obtained results for the cement only [%] have been presented in Table 4.

An experimentally determined amount of cement was assumed for calculations due to not being familiar with the actual amount of cement used to create the tested concretes. In doing so, 306 kg cement per m^3 were assumed for Concrete A m^3, and 302 kg cement per m^3 for Concrete B. Concrete A has a relative density of 2446 kg/m^3, whereas that of concrete B is 2391 kg/m^3.

Table 4. Estimated amounts of $SO_{3całk.}$, MgO, Na_2Oeq in concrete.

Concrete type	In relation to:	Amount of indicated compounds in concrete		
		SO_{3total}	MgO	Na_2Oeq
Concrete A: - relative density = 2446 kg/m^3, - cement = 306 kg/m^3,	Concrete mass [kg]	(2.44·2446/100) = 59.68 kg/m^3	(1.03·2446/100) = 25.19 kg/m^3	(0.39·2446/100) = 9.53 kg/m^3
	Cement mass [kg]	(59.68·100/306) = 19.50 %	(25.19·100/306) = 8.23 %	(9.53·100/306) = 3.11 %
Concrete B: - relative density = 2391 kg/m^3, - cement = 302 kg/m^3,	Concrete mass [kg]	(0.96·2391/100) = 22,95 kg/m^3	(1.53·2391/100) = 36.58 kg/m^3	(0.57·2391/100) = 13.63 kg/m^3
	Cement mass[kg]	(22.95·100/302) = 7.60 %	(36.58·100/302) = 12.11 %	(13.63·100/302) = 4.51 %

The indicated amounts of SO_{3total} for the analyzed concretes range between 19.50% (A) to 7.60% (B) in relation to the estimated cement mass. The obtained amounts do not fulfil the requirement from Table 3 of the standards (*PN-EN 197-1:2002*) for Portland cement and Portland cements with additives, which, according to the standard, cannot exceed the value of 3.5%.

The indicated amounts of MgO, *i.e.* 8.23% in Concrete A and 12.11% in Concrete B, in reference to cement mass, exceed (according to *Peukert, 2000*), the permissible value of 4%. Over many years, MgO content of 5% in cement was permitted in the standards of most countries. However, cases of the destruction of many structures in the USA and other countries, as well as results of long-term studies, showed that additional safety measures are necessary.

The indicated amounts of alkalis (Na_2Oeq), *i.e.* 3.11% (A) and 4.51% (B) in relation to the cement mass exceed, according to (*Peukert, 2000*), the permissible value of 0.6%.

Sulphur compounds recalculated for total sulphur, MgO and Na_2Oeq in the tested concretes may come from the applied aggregates and their contaminants, as well as from cement.

5 Analysis Along with Assessment

Based on the description of the existing state, carried out tests and earlier analyses, it can be stated that the observed phenomena are mainly caused by leaching, carbon and biotic corrosion. Signs of sulphuric corrosion were not noted, though the use carbon aggregate and small amounts of fly ashes were confirmed in the concrete.

Unfortunately, the contractor refused to provide data on water and air contamination, making it much more difficult to search for reasons behind the occurrence of the present phenomena. The lack of adequate tightness of the surface layer caused constant dampening of the remaining layers of the analyzed concretes. Therefore, the moisture contained and persisting in the concrete led to the slow dissolvent of calcium compounds from the cement stone. This moisture, being the result of precipitation waters, that is soft waters with low carbonate hardness as well as water evaporating from the surrounding lake, leads to the emergence of leaching corrosion. Leaching is a diffusion process, the course of which is significantly influenced by water flow speed and pressure. The aggressiveness of soft water increases in lower temperatures. The leaching of calcium hydroxide begins in the surface layers. Over the course of time, $Ca(OH)_2$ from increasingly deeper layers is leached into the environment. First, $Ca(OH)_2$ (so-called free calcium) is dissolved, and along with the lowering of pH, also the calcium from hydrated silicates and calcium aluminates. These calcium compounds settled on the steel reinforcement bars and, in the presence of moisture, reacted with carbon dioxide (CO_2) that got through from the atmosphere. These gases, along with moisture, also entered the inside of the cement stone with the leaching of Ca compounds. The occurring reactions resulted in the formation of, among others, calcium carbonate and iron carbonate. These products are clearly identified during microscopic studies and over the course of EDS microanalysis. Steel reinforcement bars, in places of contact with concrete, were in a constantly moist environment.

Non-model EDS microanalysis revealed, above all, the presence of products from the cement matrix "interspersed" with products of rebar corrosion, as well as showing the

occurrence of products of the decomposition of the cement matrix and reinforcement bars (in the form of mainly calcium carbonates, iron and zinc). The probable distribution of calcium silicates and aluminates was determined on the basis of the carried out non-model x-ray EDS microanalysis of a zone of Concrete B surface contaminated with biotic factors. The lack of portlandite (significantly lower amount of C-S-H phases), very high amount of calcite (3.5 times higher) and decreased amount of quartz (twice lower), as compared to Concrete A, point to the extensive corrosion of the cement matrix in Concrete B. Sulphur compounds recalculated for total sulphur, MgO and Na_2Oeq content in the assessed concretes may come from the applied aggregates and their contaminants, as well as from cement.

As indicated by the results of the carried out laboratory studies and conducted analyses, the corroded surface layer of the concrete ought to be removed all the way to the reinforcement bars, with the uncovering and cleaning of the rebars. Next, new layers ought to be made in accordance with one of the systemic repair technologies.

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References

Błaszczyński T. and Łowińska-Kluge A. (2008). *Durability assessment of RC floors based on concrete properties*, 6th International Conference AMCM'2008, Łódź, Poland, 371-372 + CD.

Horbik D., Łowińska-Kluge A., Górski Z.*,* Stanisz E. and Zgoła-Grześkowiak A. (2013)*. Microwave-Assisted Extraction Combined with HPLC-MS/MS for Diagnosis of Fungal Contamination in Building Materials*, J. Braz. Chem. Soc., Vol. 24, No. 9, 1478-1486.

Łowińska-Kluge A. and Błaszczyński T. (2012). *The influence of internal corrosion on the durability of concrete*, Archives of Civil and Mechanical Engineering, vol. XII, No 2, 219-227.

Łowińska-Kluge D., Horbik D., Zgoła-Grześkowiak A., Stanisz E. and Górski Z. (2016). *A comprehensive study on the risk of biocorrosion of building materials,* Corrosion Engineering, Science and Technology, DOI: 10.1080/1478422X.2016.1174326.

Łowińska-Kluge A. and Jóźwiak K (2006). *A study of the resistance of concrete to corrosion using SEM and microanalysis*, Microscopy and Analysis, 20, 1, 2006, 19-21.

Mejíaa E., Tobónb J.T. and Osorioc W. (2019). *Urban structure degradation caused by growth of plants and microbial activity*, Materiales de Construcción, Vol. 69, Issue 333, January-March, DOI.10.3989/mc.2019.09517.

Peukert S. (2000). *Cementy powszechnego użytku i specjalne* (in Polish), Polski Cement, Kraków.

PN-EN 196-2:(1996). *Methods of cement investigations. The chemical analysis of cement*.

PN-EN 196-21:(1997). *Methods of cement investigations. Designation of chlorides, carbon dioxide and alkalies content in the cement.*

PN-EN 197-1:(2002). *Cement. Part 1. Composition, requirements and conformities criteria concerning of general use cements.*