

ANALYSIS OF HISTORIC (80+) CONCRETE STRUCTURE EXPOSED TO WEATHERING

*Petr Lukáš¹, David Hes¹, Jiří Pazderka¹, Pavel Reiterman², Martin Jiránek¹
and Martina Záleská³*

1. *Czech Technical University in Prague, Faculty of Civil Engineering, Department of Architectural Engineering, 166 29 Prague, Thákurova 7, Czech Republic; petr.lukas@fsv.cvut.cz, david.hes@fsv.cvut.cz, jiri.pazderka@fsv.cvut.cz, jiranek@fsv.cvut.cz*
2. *Czech Technical University in Prague, Faculty of Civil Engineering, Experimental Centre, 166 29 Prague, Thákurova 7, Czech Republic; pavel.reiterman@fsv.cvut.cz*
3. *Czech Technical University in Prague, Faculty of Civil Engineering, Department of Materials Engineering and Chemistry, 166 29 Prague, Thákurova 7, Czech Republic; martina.zaleska@fsv.cvut.cz*

Received: 08.02.2025

Received in revised form: 24.07.2025

Accepted: 30.08.2025

ABSTRACT

The aim of the study was to analyze historic concrete structures from the 1930s and then to analyze the failures caused by water action on the structures. As part of the study, long-term moisture measurements were taken on a selected structure along with boundary conditions (temperature and relative humidity). By taking measurements at multiple locations on the structure using depth brush probes, it was confirmed that massive historic concrete structures exposed to external boundary conditions contain relatively high amounts of water (typically around 4%). This is mainly due to the large voids and porosity of the old concrete structure. The action of water in historic concrete structures leads to chemical reactions. Their products are chemical leachates which penetrate the surface of the structure. The analysis revealed that calcium is the dominant element, with measured values ranging from 92.42 % to 95.32 %. Although the structure studied is located in an agricultural area subjected to fertilization, the nitrate content was measured at only 0.031 %. Microscopic analysis confirmed potential calcium compounds recrystallization, which could jeopardize the durability of the remediation. This factor should therefore be carefully considered in the remediation design. Samples of historic concrete were produced according to the original 1930s recipe. These samples were subjected to diffusion permeability measurements. The average diffusion coefficient $D = 8,4 \cdot 10^{-9}$ (m²/s) was measured. Such diffusion permeability corresponds to poor quality concrete, even for the newly formed samples. Thus, the structure had these properties at the time of construction 80 years ago and subsequent degradation has had little effect.

KEYWORDS

Historical concrete structures, Structure moisture, Chemical leachates, Remediation of concrete structures

INTRODUCTION

In the 1930s, concrete was considered a relatively new material whose potential had not yet been fully exploited. As World War II approached and progressed, concrete began to be used extensively, including for military purposes [1]. Many buildings have survived that have been exposed to weather conditions for decades without any maintenance [2]. Since then, the properties and behavior of concrete (depending on the concrete mix composition, environment, production technology, processing, protection etc.) have been analyzed worldwide and today it is one of the most used building materials in construction industry [3, 4].

Historical concrete structures are very specific not only in terms of material properties but also in terms of causes of failure [5-9]. Thanks to the preserved structures located in different types of environments around the world, it is now possible to analyze the quality of 85-year-old concrete structures with respect to the different boundary conditions that have significantly changed the original parameters of these structures. Some of the basic boundary conditions affecting the quality of concrete include air temperature, relative humidity, location (which influences airflow velocity and the presence of biological degradation factors) and, of course, the maintenance of the structure [10-12].

The requirement for these concrete structures was to achieve a high durability, ensured by their dimensions, the strength of the concrete and the appropriate design of the steel reinforcement. Although production process was simpler compared to today's, the compressive strength of concrete reached least 450 kg/cm² (approximately 44,1 MPa). The original recipe was progressively developed and finally was composed of the following components:

- Aggregate – different types and quantities, depending on the location
- Cement – Portland cement with a higher content of gypsum (up to 4%) and silicon dioxide
- Water – with a very low water-cement (w/c) ratio

Concrete compositions based on the type of aggregate are shown in Table 1 [13].

Tab. 1 - Concrete recipe from 1930s depending on the type of aggregate

Composition	River aggregate	River and crushed aggregate
Sand 0-10	390 l	440 l
River gravel 20-40	300 l	300 l
River gravel 40-60	300 l	300 l
Cement (type A)	400 kg	400 kg
Water	100 l	100 l

Typical types of structures that have been exposed to weathering for long periods without any maintenance are reinforced concrete fortresses built in the 1930s across Europe (France, Germany, Czechoslovakia, Italy, UK, Switzerland, Yugoslavia, Belgium, Poland and other countries). In this study, objects of light fortifications Model 37, built between 1937 and 1938, were used to analyze the properties and behavior of historic concrete. One of these objects can be seen in Figure 1. Although these are fortification objects located in the territory of former Czechoslovakia, the research results can serve as a solid basis for further studies and remediations in other locations.

The long-term degradation processes to which concrete structures have been subjected must be considered in any remediation. The aim of this study is to assess the current state of 85-year-old structures in terms of possible sustainable remediation [14-18].

The most common failures of historic concrete structures are:

- Excessive moisture in the structure followed by the degradation of the cement paste (freezing, biodegradation, etc.)
- Effects of water flow within the structure, resulting in chemical degradation (leaching of chemicals, etc.)
- Loss of adhesion of the covering layer
- Insufficient surface integrity – cracks, etc.

- Partial mechanical destruction of the structure



Fig. 1 – Object of light fortifications Model 37 in Czechia

Today, the remediation of historic concrete structures dating back to the 1930s is a significant topic for professionals and the public. Experts are trying to develop a functional and sustainable remediation system that is universal for all types of historic concrete structures (with possible modifications based on the boundary conditions of the environment where the structure is located). It is believed that a functional remediation system for these structures can be achieved using new technologies and materials [19-23]. In the process of development, most emphasis is placed on research into the effect of crystallization mixtures applied to remediated structures [24-28].

METHODS

For this study, the object of light fortification Model 37 (built in 1937) near the village of Mradice in the Czechia was selected (see Figure 2). This object was intentionally chosen because the structures have not been maintained since 1938 (Munich Agreement). In addition, these objects were not seriously damaged (e.g. a broken machine-gun column, a missing part of the covering ear, etc.), thus the object has been preserved in its original state.

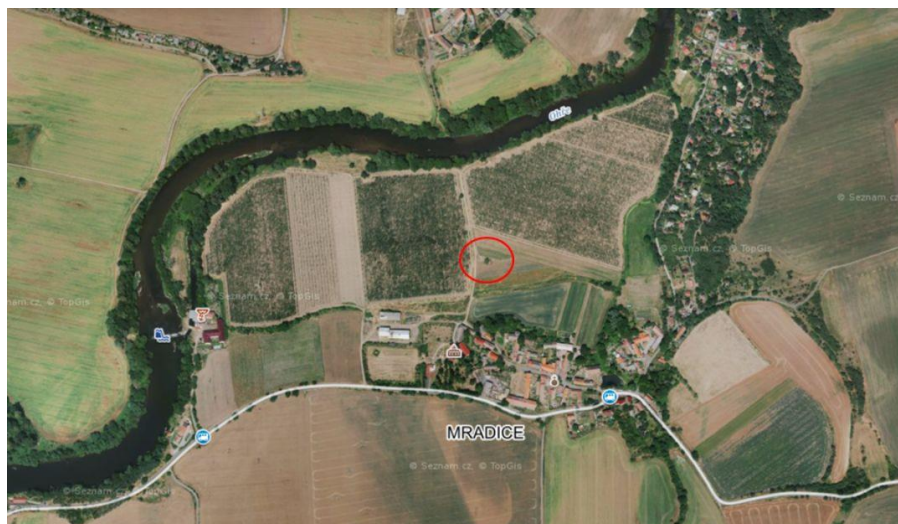


Fig. 2 – Overview map of the location of the object (Source: www.mapy.cz)

Research layout

As part of the analysis, the measurement of moisture in concrete structures was conducted using a resistance moisture meter to observe the behavior of structures based on the environmental boundary conditions.

Additionally, lime leachate samples were extracted from the structure and subjected to laboratory tests. The tests performed included the following:

- Chemical analysis of lime leachates using calorimetry
- ED-XDR spectroscopy
- Microscopic analysis

Moisture measurements of the structure

The aim of the in-situ measurements was, on the one hand, to determine the environmental boundary conditions in which the concrete structures are located in the long term and, on the other hand, to determine the behavior of moisture in relation to these conditions or to identify the main source of moisture.

For the resistance moisture meter measurements, it was first necessary to drill holes in the interior of the structure into which brush probes were inserted. Figure 3 shows the location of four points in the building plan that were selected for these holes. At these points, holes were drilled at three height levels (0.1 m, 0.7 m and 1.3 m above the floor) to obtain the moisture profile of the structure at the measured point. Given the technological procedure, pairs of holes were drilled, each with a diameter of 8 mm, approximately 300 mm long and spaced 80-100 mm apart depending on the location of the reinforcement.

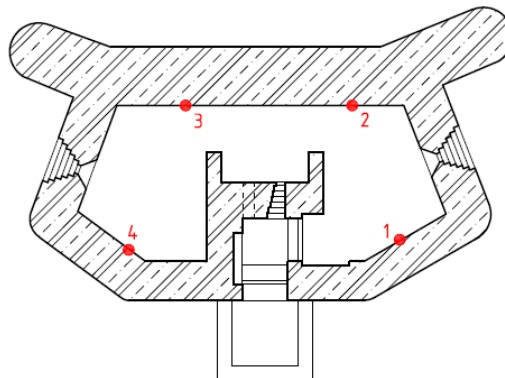


Fig. 3 – Diagram of moisture profile locations measured with resistance moisture meter

From October 25, 2019, to June 3, 2021, resistance moisture measurements in the structures were conducted at approximately weekly intervals to monitor the moisture behavior of the vertical structures over time (see Figure 4).



Fig. 4 – In-situ moisture measurement using electrical resistive hygrometer

To obtain accurate results, due to the imperfections of the analyzed structure, calibration was performed by gravimetric laboratory examination of the collected damaged samples. Based on the values from in-situ moisture measurements and gravimetric laboratory examination, the calibration coefficient $K [-]$ was determined, which in this case has a value of 1.557. Moisture damage, as well as visible cavities and reinforcement corrosion in the concrete structure, can be seen in Figure 5 and Figure 6.



Fig. 5 – Moisture damage and visible cavities in the concrete structure



Fig. 6 – Visible cavities and reinforcement corrosion in the concrete structure

Analysis of chemical efflorescence

A laboratory measurement of the chemical content of the lime leachate sample (salinity measurement) was carried out. For salinity testing, the sample marked in Figure 7 was taken from fortification Model 37 (from 1937) number C-27/52a/A-140Z, located near the village of Mradice.

During the laboratory testing, the pH value of the sample (acidity/alkalinity) was examined and the presence of the following chemicals in addition to calcium was detected:

- Chlorides
- Nitrates
- Sulphates
- Ammonia

The tested sample was crushed to a finer fraction and 2 g of the sample was measured out for further testing. The sample was then placed in an Erlenmeyer flask and 100 ml of water was

added. This flask containing the sample was then sealed and subjected to ultrasound to ensure thorough mixing and dissolution of chemicals in the water. After ten minutes, the flask was removed from ultrasound and heated to a temperature of 100 °C. Once the boiling point was reached, the flask was removed and left to allow the sample to settle until the following day. The next day, the prepared solution, free of solid particles, was decanted using a pipette into a clean bottle. Approximately 30 ml of the solution was collected. This purified solution was then used to measure the pH and to test the content of water-soluble chemicals. Testing of the samples was first carried out by qualitative analysis and later by quantitative analysis (see below).



Fig. 7 – Location of leachate sample taken away from the object C27/56a/A-140Z near to Mradice

Qualitative (calorimetric) analysis

Qualitative analysis was used to preliminarily determine both the presence and approximate concentration of specific chemicals in the sample (mg/l). During the analysis, the test strips were immersed in the prepared solution, resulting in a change of their color (see Figure 8). These colors were compared with a calorimetric scale, which indicates the approximate concentration of salt in the sample. Using qualitative analysis, the solution was tested for the presence of nitrates. There was no color change after immersing the test strip in the solution. This indicates that there are no nitrates in the sample. This finding was later confirmed by quantitative analysis.



Fig. 8 – Calorimetric measurement of pH

Quantitative (photometric) analysis

For quantitative analysis, a Spectroquant® Pharo300 UV-VIS photometric device was used. The device measures the absorption of light rays passing through the modified solution (sample). It is necessary to modify the solution by adding chemical substances that cause a color change. The choice of these substances depends on the type of chemical being analyzed, and the absorption depends on the concentration of the solution. If a high concentration is found or if the photometer is unable to determine the exact chemical content, the sample must be diluted with distilled water in a ratio of 1:10 or 1:100. A cuvette containing the mixed solution is then inserted into the apparatus. Immediately thereafter, the instrument begins to emit light beams of different wavelengths in the visible light spectrum. It is therefore important to close the device quickly to prevent the entry of external light which could affect the measured values. Part of the spectrum passes through the sample while another part is absorbed. The device measures the absorption and then calculates the concentration of the substance in the sample.

The output of the spectrometer measurement is the concentration of the measured substance in the sample (mg/l). For salinity classification in Table 2, it is necessary to recalculate the concentration to mg/g using the sample density.

Tab. 2 - Classification of masonry salinity due to ČSN P 73 0610

The degree of salinity of the masonry	Salt amount (mg/g) of a sample as a percentage of weight					
	Chlorides		Nitrates		Sulphates	
	mg/g	% weight	mg/g	% weight	mg/g	% weight
Low	< 0,75	< 0,075	< 1,0	< 0,1	< 5,0	< 0,5
Increased	0,75 - 2,0	0,075 - 0,20	1,0 - 2,5	0,1 - 0,25	5,0 - 20	0,5 - 2,0
High	2,0 - 5,0	0,20 - 0,50	2,5 - 5,0	0,25 - 0,50	20 - 50	2,0 - 5,0
Very high	> 5,0	> 0,50	> 5,0	> 0,50	> 50	> 5,0

ED-XRF Spectroscopy

ED-XRF spectroscopy is a suitable and reliable method to determine the chemical composition of lime leachate samples. This method performs a rapid, non-destructive, multi-element analysis of the sample. The analysis can measure substances ranging from fluoride (F) to uranium (U) across a wide range of concentrations, from tenths of ppm to one hundred percent. Using ED-XRF, it is possible to analyze homogeneous low-viscosity materials, solid samples, slags, powders, plastics, and thin layers. For this measurement, the original leachate sample from the object in Mradice was used (S1).

Microscopic analysis

A sample of crushed lime efflorescence, taken from the solution prepared for the quantitative analysis of sample S1, was used to examine the microscopic structure of the efflorescence.

The sample collected was applied to a microscope slide, which was then labelled according to the corresponding sample. The slide with the prepared sample was then placed under a microscope. Figure 9 shows its structure before crystallization was examined. In the next step, the sample was exposed to a constant temperature of 60 °C for 14 days, during which the sample crystallized due to water evaporation, as shown in Figure 10. From the figures, it is clear that the solution contained a significant amount of dissolved substances. These substances crystallized after the evaporation of the solution.

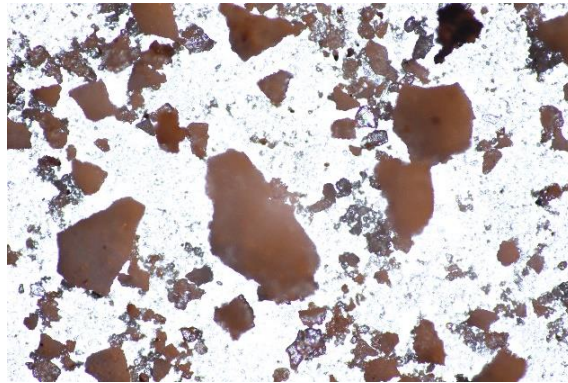


Fig. 9 – The lime efflorescence sample S1 (before crystallization)

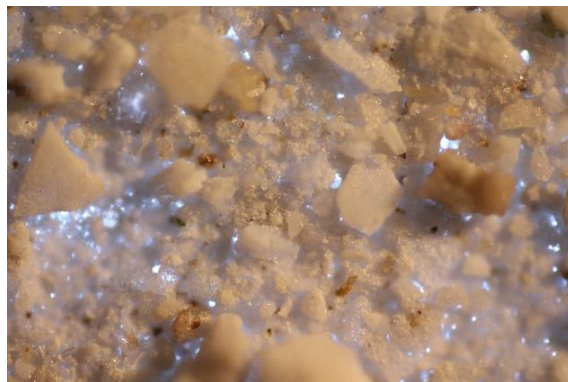


Fig. 10 – The lime efflorescence sample S1 (after crystallization)

Diffusion permeability

As part of the analysis, the diffusion permeability of high strength concrete used for development of fortifications in the 1937 – 1938 was determined.

Three test specimens were prepared based on extant concrete recipes from the 1930s. The production of the specimens aimed to replicate the properties of the original concrete as closely as possible. Due to the nature of the test and the size of the samples, it was necessary to adjust the gravel fraction used. Subsequently, measurements of all three samples were performed, and the results were recorded.

For laboratory purposes, three specimens were prepared (see Figure 11), with dimensions ranging from 37.0 mm to 39.3 mm. The effective area (the area through which radon diffuses into the accumulation chamber) of all specimens was $140 \cdot 10^{-4} \text{ m}^2$ (140 cm^2). A gravel fraction of 4/16 mm was used as aggregate.



Fig. 11 – Preparation of the samples for measurement

According to the test methodology A specified in ISO/TS 11665-13, samples of the tested material were placed between the source chamber and three accumulation chambers, as can be seen in Figure 12. Radon diffuses through the tested samples from the source chamber, which is connected to the RF 100 radon source, into the accumulation chambers. Radon concentrations on both sides of the samples are continuously measured by TSR-4 TERA detectors (in the accumulation chambers) and continuous ionization chambers (in the source chamber). The radon diffusion coefficient is determined from the time-dependent radon concentrations in the chambers, as shown in Figure 13. The calculation is based on an iterative numerical solution of the one-dimensional time-dependent radon diffusion equation. The final value of the radon diffusion coefficient is obtained when the solution has a minimal deviation from the measured radon concentration in the accumulation chamber [29, 30].



Fig. 12 – The samples ready for measurement

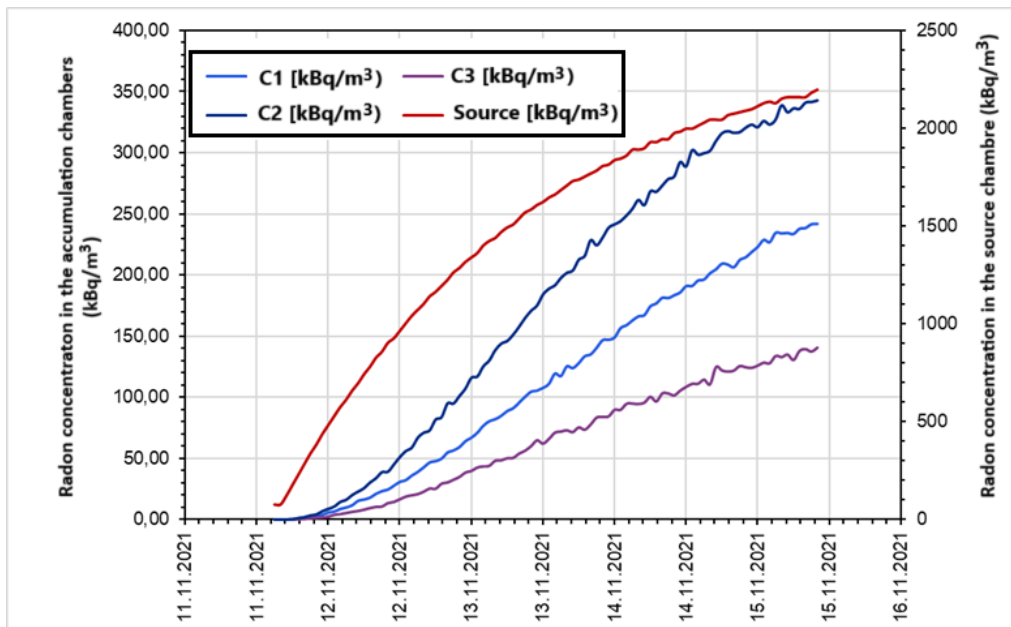


Fig. 13– The time course of radon concentration in the accumulation chambers and in the source chamber (output of the measuring system of radon concentration RM-2)

RESULTS

Structure moisture measurement

The long-term analysis was used to determine the moisture behavior of the concrete structure during the model year. The moisture measured from September 2, 2019 to July 23, 2021 depends on the position of the structure (whether it was exposed or covered by an earth mound) and the boundary conditions (weathering). Moisture ranged from 3.5% to 4.6% at Point 1, 1.7% to 3.0% at Point 2, 3.0% to 4.5% at Point 3, and 3.5% to 5.0% at Point 4. Values with an extreme deviation indicate the effect of boundary conditions. The lowest humidity values were measured in winter, indicating water freezing in the structure and drier air. Extremely high moisture values were measured during autumn when the structures were exposed to heavy rainfall and during winter due to snow melt. Higher moisture on the exposed side of the structure is likely due to the retention effect of the earth embankment, which was constructed using stone fill.

The analysis further revealed that moisture levels within the height profile of the structure vary significantly. This suggests that the dominant source of water in the structure is not rising groundwater, but weathering water. Another cause of variability in the measured values is the porous and voided structure of the concrete structures caused by manual compaction during construction.

Analysis of chemical leachates

A sample of lime leachate, taken from the fortification near Mradice, was subjected to chemical analysis using both qualitative and quantitative analysis. The analysis determined that the chemical content in the lime leachate was low. The sample was found to contain 0.0124 % chloride, 0.031 % nitrate and 0.209 % sulphate. No ammonia was detected in the sample, as shown in Figure 14.

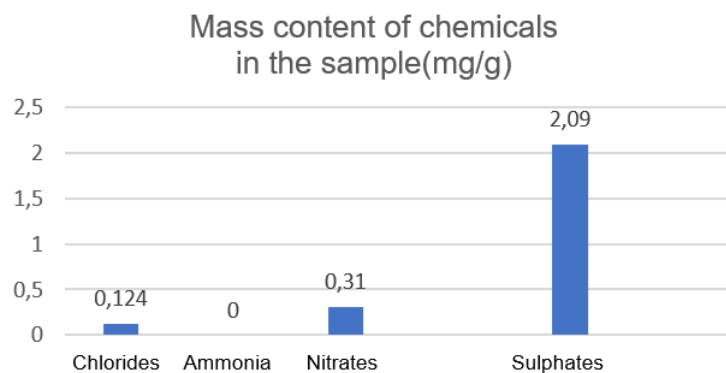


Fig. 14 – Photometric result of lime leachate of sample S1

Although the structure is situated in the middle of the field, the salinity classification of the measurements determined that the sample contained trace amounts of sulfate, nitrate, and chloride.

As a result of this finding, it is not necessary to include any chemical protection measures in the remediation. This conclusion applies only to the analyzed structure and cannot be generalized to all structures. In such cases, a new analysis should be carried out.

ED-XRF Spectroscopy

As part of the ED-XRF Spectroscopy analysis, the composition of the sample extract taken from the structure was analyzed. According to the measured results, presented in Table 2, ED-XRF Spectroscopy revealed that the calcium component accounted for 92.42% and 95.32% of the total composition of the samples. Other elements detected in the sample were aluminum, silicon, strontium, magnesium, barium, and iron; however, all were present only in trace amounts, confirming

the results of the analysis in previous chapter. Additionally, a very low presence of titanium, potassium, zinc, and manganese were detected in the composition.

The results obtained from the ED-XRF analysis, together with the long-term study of these structures, indicate that the efflorescence is the result of the carbonation of Portlandite ($\text{Ca}(\text{OH})_2$) caused by its exposure to the air near structural cracks. The potential presence of chloride salts, such as calcium chloride, was considered but excluded due to the absence of plausible source. The other elements, particularly those present in trace amounts, depend mainly on the type of aggregate used in the concrete.

Tab. 3 - Composition of the sample according to the ED-XRF spectroscopy method

Sample	Locality	Composition	Chemical symbol	Content (%)
S1	Mradice	Calcium	Ca	92,42
		Aluminium	Al	2,45
		Silicon	Si	1,38
		Strontium	Sr	1,15
		Barium	Ba	0,982
		Iron	Fe	0,665
		Magnesium	Mg	0,606
		Titanium	Ti	0,149
		Potassium	K	0,097
		Zinc	Zn	0,0856
		Manganese	Mn	0,0062

Microscopic analysis

Microscopic analysis was performed on the samples intended for quantitative analysis. From the aforementioned procedure and figures, it is clear that the lime leachates can recrystallise, which has a significant impact on the remediation design, as lime leachates cannot be removed by dissolution. A suitable solution to eliminate the formation of lime leachate is likely to be the application of a crystalline waterproofing, which will create an impermeable zone in the structure at a depth of approximately 50 mm and prevent further spread of the calcite solution through the porous structure. Due to the structure of historical concrete structures, it is probably not possible to completely eliminate the formation of leachates throughout the structure, but it is possible to eliminate their presence on the surface. However, the question remains as to the effect of the leachates within the structure on the structure itself in terms of the pressures generated. This should be the subject of further study.

Permeability

As part of the analysis, the diffusion permeability of the concrete was measured on three specimens. The following parameters were determined: average diffusion coefficient $D = 8,4 \cdot 10^{-9}$ (m^2/s), diffusion length $l = 63,2 \cdot 10^{-3}$ m and average radon resistance $R_{Rn} = 5.1$ (Ms/m) with the mentioned tolerances in Table 3.

Since the diffusion coefficient D and the diffusion length l are material constants, the radon resistance depends on the thickness. Thus, for concrete 0,5 m thick, the radon resistance is approximately 10 212 Ms/m. This is of course only valid if there are no cracks in the concrete structure.

The measured values correspond to concrete of lower quality. This is probably due to the aggregate fraction used in the samples. In the case of a real structure from the 1930s, the measured results would likely be even worse due to large voids (imperfect compaction in 1938) and large aggregate fraction.

Tab. 3 - Average measured diffusion parameters of the samples

Material		Concrete
Diffusion coefficient D (m ² /s)	Average	$8,4 \cdot 10^{-9}$
	$\pm U$	$\pm 1,0 \cdot 10^{-9}$
Diffusion length l (m)	Average	$63,2 \cdot 10^{-3}$
	$\pm U$	$\pm 7,5 \cdot 10^{-3}$
Radon resistance R_{Rn} (Ms/m)	Average	5,1
	$\pm U$	$\pm 0,6$

RESULTING OPTIONS FOR REMEDIATION OF HISTORIC CONCRETE STRUCTURES

The study determined that the concrete structures from the 1930s have been exposed to long-term degradation due to high moisture within the structure. A dominant result of this moisture is the frequent and repeated formation of efflorescence on the surface of the structure, which is visually very noticeable.

For the design of durable and functional remediation measures, the formation of lime leachates is a major factor that must be systematically addressed to make the remediation as efficient as possible. It is also necessary to ensure that the surface layer has the same or similar thermal expansion as the concrete structure to prevent cracking and subsequent loss of adhesion.

The conclusions of the study confirmed the need for a complex approach to the remediation of the surface layers of historic concrete buildings. To eliminate all the negative effects analysed above, it is clearly necessary to design a multi-layered remediation system, the basis of which must be measures to prevent the penetration of calcite water on the surface and to ensure the durability of the surface layer, especially in terms of thermal expansion and cohesion with the original surface of the structure. Based on these findings, the authors of the paper have started the development of a 4-layer remediation system designed for the reconstruction of 80+ old concrete structures. The remediation system is based on a combination of the use of a crystallization coating with a crystallization mortar, using a reinforcement layer and a special final remediation plaster. This complex remediation system will be presented in the next publication.

CONCLUSION

The analyses carried out confirmed that one of the biggest problems in terms of damage to the surfaces of historical concrete structures is lime leaching, which is closely related to the mechanism of water transport in concrete. Although the concrete structure in this study is located in the field where fertilizers are commonly used, the analysis of lime leachate revealed that other chemicals (chlorides, nitrates, sulphates and ammonia) were present in the sample only in trace amounts. ED-XRF spectrometry performed on the lime leachate samples showed that the dominant element in the leachate was calcium as expected and the minor elements that were only present in trace amounts in the sample were aluminium, silicon, strontium, magnesium, barium and iron. Examination of the microscopic structure of both samples confirmed the ability of calcium compounds to recrystallize, which is quite important in the formation of leachates by flow through the pore system of the structures. To design a durable and functional remediation measure, it is essential to prevent the flow of calcium-rich water and the recrystallization of calcium compounds within the pore system and on the structure's surface. This can be effectively avoided by the surface

application of crystallisation coatings, which will prevent the penetration of liquid water into the structure, but at the same time keep the structure diffusely open.

In particular, the aim of the study was to obtain important data for the subsequent development of a special comprehensive remediation measure for 80+ year old concrete structures. This comprehensive remediation system will be presented in a future.

ACKNOWLEDGEMENTS

This work was supported by the project SGS22/138/OHK1/3T/11.

REFERENCES

- [1] Sutherland R.J.M., 1996. Understanding historical concrete. ICE Proceedings Structures and Buildings, vol. 116(3), p. 255-263. ISSN 0965-0911, <https://doi.org/10.1680/istbu.1996.28741>
- [2] Holcapek O., Reiterman P., Pazderka J., 2020. Properties of Czech WW2 Concrete Fortifications after 80 Years. In: XV International Conference on Durability of Building Materials and Components, edited by Serrat C., Casas J.R, Gibert V, <https://doi.org/10.23967/dbmc.2020.115>
- [3] Trtík T., Chyliik R., Fládr J., Vašková J., 2022. Analysis of the Migration Process of Concrete Layers during Compaction. Solid State Phenomena, vol. 336, p. 159-163, <https://doi.org/10.4028/p-79aoi5>
- [4] Pan X., Shi Z., Shi C., Ling T.C., Li, N., 2017. A Review on Surface Treatment for Concrete – Part 2: Performance. Construction and Building Materials, vol. 133, p. 81–90, ISSN 0950-0618, <https://doi.org/10.1016/j.conbuildmat.2016.11.128>
- [5] Lukáš P., Pazderka J., 2021. Analysis of moisture level in concrete structures of WW2 bunker no. 37 in Czechia. In: AIP Conference Proceedings 2322, 020039 (2021), <https://doi.org/10.1063/5.0042718>
- [6] Jedidi M., Benjeddou O., 2018. Chemical causes of concrete degradation. MOJ Civil Engineerig, vol. 4(1), p. 40-46.
- [7] Nývlt M., Pazderka J., 2019. ANALYSIS OF CORROSION PRODUCTS FROM WW2 CONCRETE BUNKERS IN CZECHIA. Acta Polytechnica CTU Proceedings, vol. 22, p. 77-82, ISSN 2336-5382, <https://doi.org/10.14311/APP.2019.22.0077>
- [8] Pazderka J.; Reiterman P., 2019. CZECH WW2 CONCRETE FORTIFICATIONS: CORROSION PROCESSES AND REMEDIATION METHOD BASED ON CRYSTALLIZING COATING, Acta Polytechnica, vol. 59(4), p. 359-371, ISSN 1210-2709, <https://doi.org/10.14311/AP.2019.59.0359>
- [9] Pazderka J., Purkrtová M., Reiterman P., 2016. Moisture-Related Problems of Historic Concrete Structure. Materials Science Forum , vol. 865, p. 219-223, <https://doi.org/10.4028/www.scientific.net/MSF.865.219>
- [10] Zatloukalová J., Pazderka J., Lukáš P., Reiterman P., 2021. Study on Permeability of Concrete Fortifications from WW2 Based on Mercury Intrusion Porosimetry. Solid State Phenomena, vol. 325, p. 162-167, <https://doi.org/10.4028/www.scientific.net/SSP.325.162>
- [11] Liang M.-T., Lin S.-M., 2003. Modeling the transport of multiple corrosive chemicals in concrete structures: Synergetic effect study. Cement and Concrete Research, vol. 33(12), p. 1917-1924, [https://doi.org/10.1016/S0008-8846\(03\)00081-4](https://doi.org/10.1016/S0008-8846(03)00081-4)
- [12] Bochen J., 2015. Weathering effects on physical–chemical properties of external plaster mortars exposed to different environments. Construction and Building Materials, vol. 79, p. 192–206, <https://doi.org/10.1016/j.conbuildmat.2014.12.079>
- [13] Pazderka J., Reiterman P., Ženíšek M. et al., 2022. Stavebně technické průzkumy pevností z 30. let 20. století a technická řešení jejich obnovy. Praha: CTU. Faculty of Civil Engineering, p. 9-12, ISBN 978-80-01-07070-3
- [14] Kim J., Kitagaki R., 2020. Chemical properties and mass transfer resistance of mortar surface modified with silicate-based surface impregnant. Construction and Building Materials, vol. 262, 120806, <https://doi.org/10.1016/j.conbuildmat.2020.120806>
- [15] Pavlů T., Fořtová K., Mariaková D., Řepka, J., Pazderka J., 2020. Improvement of the Durability of Recycled Masonry Aggregate Concrete. Materials, vol. 13(23), 5486, <https://doi.org/10.3390/ma13235486>
- [16] Nývlt M., Pazderka J., Reiterman P., 2021. Comparative Study of Different Types of Waterproofing Screeds with a Focus on Cohesion with Selected Building Materials after the Freeze-Thaw Exposure. Applied Sciences, vol. 11(23), 11256. <https://doi.org/10.3390/app112311256>

- [17] Pavlů T., Pazderka J., Fořtová K., Řepka J., Mariaková D., Vlach T., 2022. The Structural Use of Recycled Aggregate Concrete for Renovation of Massive External Walls of Czech Fortification. *Buildings*, 12(5), 671, <https://doi.org/10.3390/buildings12050671>
- [18] Chew M.Y.L., De Silva, N., 2003. Benchmarks to Minimize Water Leakages in Basements. *Structural Survey*, vol. 21(4), p. 131-145, <https://doi.org/10.1108/02630800310507140>
- [19] Song Z., Xue X., Li Y., Yang J., He Z. et al., 2016. Experimental exploration of the waterproofing mechanism of inorganic sodium silicate-based concrete sealers. *Construction and Building Materials*, vol. 104, p. 276-283, <https://doi.org/10.1016/j.conbuildmat.2015.12.069>
- [20] Bader T., Waldner B.J., Unterberger S.H., Lackner R., 2019. On the Performance of Film Formers Versus Penetrants as Water-repellent Treatment of High-performance Concrete (HPC) Surfaces. *Construction and Building Materials*, vol. 203, 481-490, <https://doi.org/10.1016/j.conbuildmat.2019.01.089>
- [21] Chang J., Li W.Z., Wang D., Zhang Y.Y., 2020. Effect of silicate modulus on tensile properties and microstructure of waterproof coating based on polymer and sodium silicate-activated GGBS. *Construction and Building Materials*, vol. 252, 119056, <https://doi.org/10.1016/j.conbuildmat.2020.119056>
- [22] Almusallam A., Khan F., Dulaijan S., Al-Amoudi O., 2003. Effectiveness of surface coatings in improving concrete durability. *Cement and Concrete Composites*, vol. 25(4-5), 473-481, [https://doi.org/10.1016/S0958-9465\(02\)00087-2](https://doi.org/10.1016/S0958-9465(02)00087-2)
- [23] Chang S.H., Kang T.H., Choi S.W., Lee C., Hwang G.S., Choi M.S., 2016. An Experimental Study on Fundamental Properties of A Sprayable Waterproofing Membrane. *Tunnel and Underground Space*, 26(3), <https://doi.org/10.7474/TUS.2016.26.3.220>
- [24] Žáková H., Pazderka J., Reiterman P., 2020. Textile Reinforced Concrete in Combination with Improved Self-Healing Ability Caused by Crystalline Admixture. *Materials*, vol. 13(24), 5787, <https://doi.org/10.3390/ma13245787>
- [25] Lim S., Kawashima S., 2019. Mechanisms Underlying Crystalline Waterproofing Through Microstructural and Phase Characterization. *Journal of Materials in Civil Engineering*, 31(9), [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.000275](https://doi.org/10.1061/(ASCE)MT.1943-5533.000275)
- [26] Rahman M., Chamberlain D., 2017. Performance of Crystalline Hydrophobic in Wet Concrete Protection. *Journal of Materials in Civil Engineering*, 29(6), [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.000177](https://doi.org/10.1061/(ASCE)MT.1943-5533.000177)
- [27] Scancelli R.J., 1996. Use of Xypex Admixture to Concrete as an Inhibitor to Reinforcement Steel Corrosion. *Materials for the New Millennium*, p. 1276-1280, ISBN: 0-7844-0210-8
- [28] Reiterman P., Davidová V., Pazderka J., Kubissa W., 2020. Reduction of Concrete Surface Permeability by Using Crystalline Treatment. *Romanian Journal of Materials*, vol. 50(1), p. 69-74
- [29] Jiránek M., Kačmaříková V., 2019. Radon diffusion coefficients and radon resistances of waterproofing materials available on the building market. *Journal of Environmental Radioactivity*, vol. 208-209, 106019, <https://doi.org/10.1016/j.jenvrad.2019.106019>
- [30] Rogers V.C., Nielson K.K., Holt R.B., Snoddy R., 1994. Radon Diffusion Coefficients for Residential Concretes. *Health Physics*, vol. 67(3), p. 261-265, <https://doi.org/10.1097/00004032-199409000-00006>