Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

Study of Concrete Degradation during the LTO in NPPs due to Boric Acid

Filip Sedlák[1], Michaela Joanidisová[2], Marek Postler[3]

[1] Corrosion Specialist, UJV Rez, Czech Republic (filip.sedlak@ujv.cz)
[2] Chemistry Specialist, UJV Rez, Czech Republic (michaela.joanidisova@ujv.cz)
[3] Material Specialist, UJV Rez, Czech Republic (marek.postler@ujv.cz)

ABSTRACT

This paper describes a long-term exposure experiment that investigates the behaviour of structural and heavy concrete used in nuclear power plants. The concrete specimens were exposed to a boric acid solution to simulate the "aggressive" environment that may occur in nuclear facilities. Several key properties were measured during the experiment, including compressive strength, bulk density, and the depth of corrosion, neutralization, and carbonation. The aim of the study is to evaluate the durability and degradation mechanisms of concrete under prolonged exposure to corrosive media and to provide valuable insights into the long-term behaviour of concrete in nuclear environments. The results highlight the effects of the boric acid solution on the physical and mechanical properties of the concrete and offer critical data for the design, maintenance, and safety of concrete structures in nuclear power plants.

INTRODUCTION

Under operating conditions of the primary circuit of nuclear power plants (NPPs), contact of the primary medium containing boric acid (H_3BO_3) with structural metal or construction materials cannot be ruled out.

The aim of the long-term experimental work is to evaluate the effect of boric acid solution from the spent fuel pool (SFP) on the mechanical properties of the structural concrete and heavy concrete in the case of long-term contact. Long-term exposure tests monitor the course of degradation of concretes used in the load-bearing structures of the containment building of a nuclear power plant. The obtained data are continuously evaluated, and the effects of these processes are quantified.

In order to determine and evaluate the effect of long-term contact of structural concrete (SC) with the SFP solution (aqueous solution of boric acid with concentration 15 g/kg), test samples of concrete were produced according to the recipe corresponding to the materials used in the construction of SFP. The results from the evaluation of the effect of boric acid on the properties of concrete will be used as input data in case of recorded leaks for the evaluation of the effect on the long-term safe operation of the SFP throughout the lifetime of the NPP (LTO).

SAMPLES

The first batch for long-term exposure tests contained the following sample types:

- Concrete B20: Structural concrete B20 including biological protection concrete, with a bulk density of up to 2350 kg/m³ (protection of the personnel or external environment).
- Concrete B28: Heavy concrete B28 (walls of the spent fuel storage pools).

Structural concrete B20

The structural concrete samples were made based on the original concrete composition recipe (confidential information), i.e. of the provided technical specification for the composition of the structural concrete used during the construction of NPP. Based on the provided data, structural concrete with the following mix composition in kg per 1 m³ of fresh concrete was prepared (Table 1).

Table 1: Ingredients of construction concrete B20

Item - ingredient
Cement
Heavy aggregate
Crushed aggregate (fraction 1)
Crushed aggregate (fraction 2)
Plasticizer
Water

All components used in the preparation of the specimens comply with the relevant European standards and can be considered completely identical to the components used in the construction of the NPP.

Heavy concrete B28

The heavy concrete samples were made based on the original concrete composition recipe (confidential information), i.e. of the provided technical specification for the composition of the heavy concrete used in the construction of NPP. Based on the provided data, heavy concrete with the following mix composition in kg per 1 m³ of fresh concrete was prepared (Table 2).

Table 2: Ingredients of heavy concrete B28

Item - ingredient
Cement
Iron flakes
Magnetite (fraction 1)
Magnetite (fraction 2)
Plasticizer
Water

All components used in the preparation of the specimens comply with the relevant European standards and can be considered completely identical to the components used in the construction of the NPP.

SAMPLE PREPARATION

The test specimens (cubes) were produced according to the standard ČSN 12 390-1. The doses of the individual ingredients were weighed:

- for additives with an accuracy of 0.1 g,
- for cement and aggregates (bulk material) with an accuracy of 1 g.

A forced circulation mixer was used for the mass mixing. After moistening the mixing space, water with a plasticizing additive was added, followed by cement and subsequently by aggregates.

The concrete mixture was placed in plastic molds in two layers and compacted by piercing. After laying the last layer, the filled molds were compacted by tapping exactly 20 blows against the base. The specimens were not vibrated due to the consistency of the concrete mixture, which in all recipes was at the lower limit of the S3 class.

On the second or third day, the specimens were removed from the molds and marked with the date of manufacture. The specimens were stored on wooden pallets in an outdoor environment and intensively misted (sprinkled) with water during the first seven days.

A slump test was conducted for the fresh concrete mixture, which in all cases ranged between 100 and 120 mm. At the same time, empty molds and molds filled with fresh concrete mixture were weighed. Then, the bulk density in the fresh state was determined for all specimens. The average values of the bulk density for the individual recipes in the fresh state were as follows:

- Structural concrete B20: 2362 kg/m³
- Heavy concrete B28: 3554 kg/m³

At the same time, at the age of 28 days, or slightly older, compressive strength tests were performed on the concrete according to ČSN EN 12504-3. The test was always performed on one set (three cubes).

TESTING EQUIPMENT

Two exposure tanks with a storage capacity of 40 samples were made for the exposure of test specimens.

The tank for exposure in an environment with continuous regeneration of the corrosive medium (boric acid solution) is equipped with a heating section in a separate circulation circuit and a regeneration circuit with ion-exchange columns (modelling the penetration into the interspace of the drainage section of double-lined pools with a large crack). The tank for exposure of specimens in a static corrosive medium is not heated, and the medium is replaced periodically once a year (modelling dead volumes in the interspace of the drainage sections of double-lined pools).

The volume of the corrosive medium in both tanks is 450 litres of boric acid solution with a concentration of 15 g/l. The tanks have internal dimensions of 120 x 70 x 75 cm. The test specimens were placed in three layers within a 5 x 3 matrix. The total initial weight of the test specimens in the tank exceeded 400 kg, and the weight of the boric acid solution at a water level of 70 cm is approximately 450 kg. The exposure tanks are thermally insulated and equipped with a lid that prevents excessive water evaporation and contamination from the surroundings. The basic schematic of the exposure tank (the type with regeneration of the corrosive medium) is shown in Figure 1.

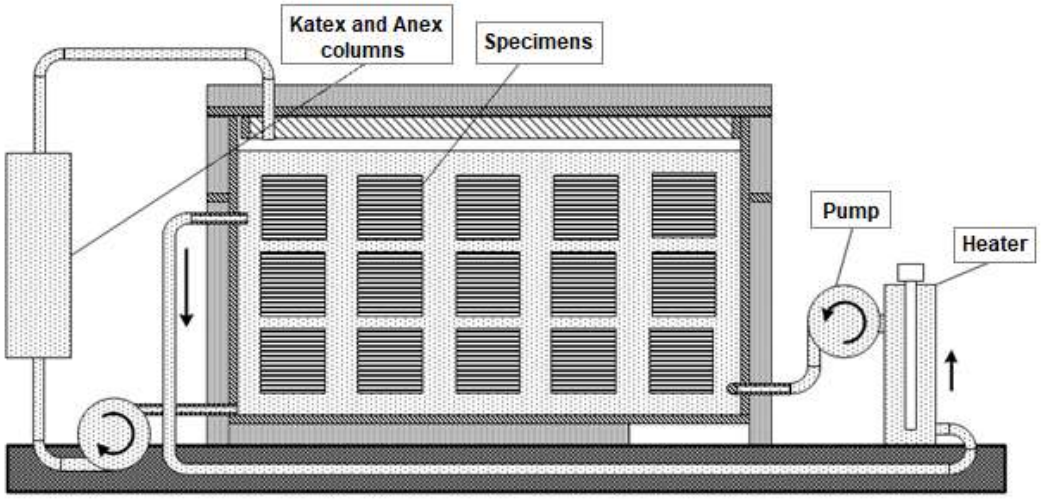

Figure 1: Diagram of exposure tank with medium regeneration.

In addition to the sets of prepared specimens exposed in the two different test conditions described here above, the sets of reference specimens were also prepared, placed in boxes with an environment of 100% relative humidity (specimens placed in plastic boxes above the water level and at laboratory temperature).

During the exposure of the test specimens, the following parameters are monitored:

- Water level in the exposure tanks – once a day, during the experiment,
- Temperature in the regeneration tank – once a day + online recording with data collection.
- pH of the solution in the regeneration tank – once a day, during the experiment, the frequency of checks was reduced.
- Conductivity of the solution in the regeneration tank – once a day.
- Boric acid concentration – as needed, typically once a month.

EVALUATION METHODOLOGY

Determination of compressive strength

Compression strength tests were conducted on unreinforced specimens according to ČSN EN 12 390-3

Determination of the density of concrete

Tests to determine the bulk density are conducted according to ČSN EN 12 390-7. The determinations are carried out on specimens intended for compression strength testing.

Determination of the depth of damage

The dedicated part of specimens after exposure in the corrosive environment were dried and the depth of concrete corrosion (H_{cor}) was determined on the cross-section of the fragment (by cutting off the side wall with the dimensions of the fragment - 150 x 150 x 30 mm) as the depth of the change in the colour tone of the cement paste from the exposed surface by direct measurement according to ČSN EN 14 630, Article 4.3. The determination was carried out only on the exposed specimens.

Determination of the depth of neutralization

After drying and fracturing the fragment of the exposed specimen and applying an acid-base indicator, the depth of concrete neutralization (H_{ntr}) was determined on the cross-section of the fragment as the depth of the colour tone change from the exposed surface, following the procedure according to ČSN EN 14 630.

Determination of carbonation depth

After drying and fracturing the fragment of the reference specimen and applying a phenolphthalein solution, the depth of concrete carbonation (H_{car}) was determined on the cross-section of the fragment as the depth of the colour tone change from the exposed surface, following the procedure according to ČSN EN 14 630.

EXPERIMENT SCHEDULE

The exposure time for specimens of both types of concrete was chosen to be 3, 5, 7, 10, and 15 years. Schedule is as follows:

- 17.1.2017 - Start of specimen exposure
- 16.1.2020 - Removal of 24 concrete samples after 3 years of exposure
- 17.1.2022 - Removal of 24 concrete samples after 5 years of exposure
- 17.1.2024 - Removal of 24 concrete samples after 7 years of exposure
- 17.1.2027 - Removal of 24 concrete samples after 10 years of exposure
- 17.1.2032 - Removal of 24 concrete samples after 15 years of exposure

EXPOSURE PARAMETER VALUES

Due to the installed system for adjusting the exposure solution (a bypass on the tank equipped with a cation-exchange column and an anion-exchange column saturated with borate anion), it was not necessary to collect samples for chemical analysis. The chemistry of the environment was monitored through the periodic measurements of the conductivity and pH of the solution at locations - after the cation-exchange column, after the anion-exchange column, and in the tank.

Samples were taken only randomly to determine the boric acid content in the corrosive solution.

The course of pH values and conductivity values of the exposure solution over the monitored period is shown in the graph, Figure 2.

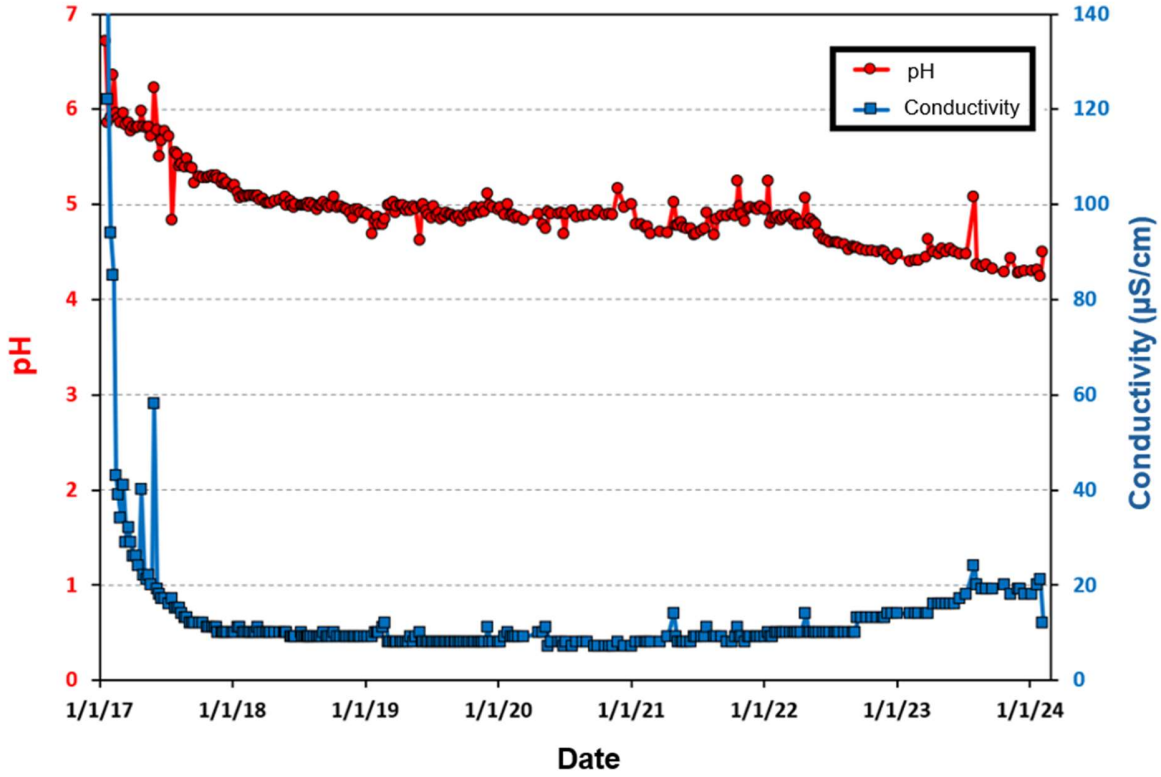

Figure 2: pH and conductivity values of the corrosive environment over time.

Throughout the monitored period, the values of the observed parameters of the corrosive environment were reasonably stable, and the regeneration interval for the ion-exchange columns was extended to more than 3 months for the cation-exchange column. For the anion-exchange column, the operating time between regenerations was around one year. The temperature of the corrosive medium remained constant at 40 ± 0.1°C during the monitored period, with the exception of three drops lasting several hours caused by power outages. The temperature drop during a heating failure did not exceed 20 hours, and the medium temperature dropped to a maximum of 25°C.

COMPRESSIVE STRENGHT DETERMINATION RESULTS

The tests were conducted according to the standard ČSN EN 12 390-3. The results are presented in Table 3 and the graph is shown in Figure 3.

Table 3: Results of determination of compressive strength of test specimens.

	Start of exposure		After 3 years		After 5 years		After 7	
	p (MPa)	Average	p (MPa)	Average	p (MPa)	Average	p (MPa)	Average
Reference samples B20	45,5	46,6	59,9	58,9	57,4	59,9	55,1	55,7
	47,8		58,2		60,4		54	
	46,5		58,7		61,9		58,1	
Regen. B20	-	-	31,1	31,5	31,7	30,4	32,7	32,9
	-		31,0		28,1		33,8	
	-		32,3		31,5		32,0	
Static B20	-	-	56,4	53,2	55,4	54,1	56,1	52,8
	-		49,9		55,4		50,2	
	-		53,3		51,5		52,0	
Reference samples B28	52,3	50,0	62,4	62,9	58,6	60,1	58,9	59,2
	50,7		67,8		58,3		59,1	
	47,1		58,6		63,3		59,5	
Regen. B28	-	-	26,6	28,8	29,8	29,5	24,1	24,8
	-		26,8		28,6		27,2	
	-		33,0		30,0		23,1	
Static B28	-	-	52,1	53,0	59,0	56,7	57,4	53,7
	-		49,5		54,6		51,6	
	-		57,5		56,6		52,1	

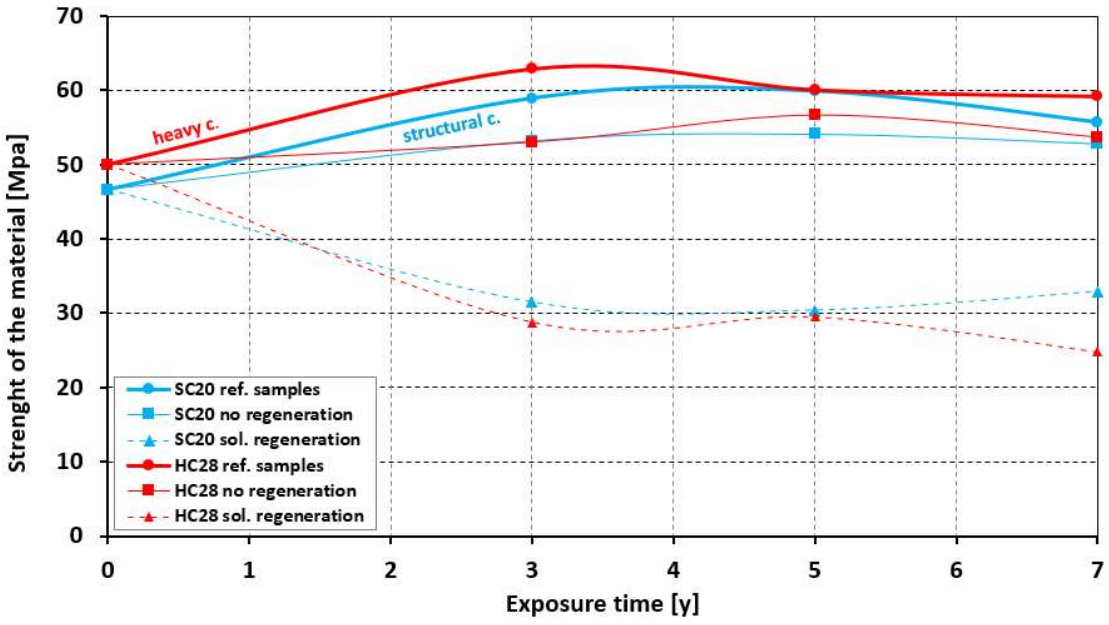

Figure 3: Course of compressive strength values of exposed concrete samples for WWER NPP.

VOLUME WEIGHT DETERMINATION RESULTS

The tests were conducted according to the standard ČSN EN 12 390-7. The results are presented in Table 4.

Table 4: Results of the determination of the bulk density of the test specimens.

	Start of exposure		After 3 years		After 5 years		After 7	
	(kg/m^3)	Average	(kg/m^3)	Average	(kg/m^3)	Average	(kg/m^3)	Average
Reference samples B20	2307	2317,3	2330	2313	2340	2340	2340	2340
	2327		2290		2330		2310	
	2318		2320		2340		2350	
Regen. B20	-	-	2270	2283	2280	2280	2309	2250
	-		2270		2280		2300	
	-		2310		2270		2135	
Static B20	-	-	2340	2333	2340	2330	2380	2360
	-		2300		2340		2340	
	-		2360		2320		2360	
Reference samples B28	3512	3515,7	3520	3497	3510	3520	3526	3520
	3480		3490		3510		3528	
	3555		3480		3530		3501	
Regen. B28	-	-	3530	3500	3460	3470	3410	3460
	-		3480		3480		3470	
	-		3490		3470		3500	
Static B28	-	-	3510	3497	3520	3540	3520	3560
	-		3490		3520		3530	
	-		3490		3590		3580	

RESULTS OF DETERMINATION OF THE DEPTH OF NEUTRALIZATION, CARBONATARION AND CORROSION

The tests were conducted according to the standard ČSN EN 14 630. The results are presented in

Table 5.

Table 5: Results of the determination of the depth of neutralization, carbonation, and corrosion.

	Unit	After 3 years			After 5 years			After 7		
		H_{ntr}	H_{car}	H_{cor}	H_{ntr}	H_{car}	H_{cor}	H_{ntr}	H_{car}	H_{cor}
Reference samples B20	d_x mean (mm)	-	1	-	-	2	-	-	2	-
	d_x max (mm)	-	1	-	-	4	-	-	3	-
Regeneration samples B20	d_x mean (mm)	5	-	3	12	-	3	10	-	4
	d_x max (mm)	7	-	4	15	-	4	12	-	5
Static samples B20	d_x mean (mm)	3	-	3	3	-	3	3	-	3
	d_x max (mm)	4	-	4	4	-	4	4	-	4
Reference samples B28	d_x mean (mm)	-	1	-	-	1	-	-	2	-
	d_x max (mm)	-	1	-	-	1	-	-	3	-
Regeneration samples B28	d_x mean (mm)	6	-	3	9	-	3	9	-	3
	d_x max (mm)	7	-	4	10	-	4	10	-	5
Static samples B28	d_x mean (mm)	3	-	4	2	-	2	2	-	2
	d_x max (mm)	4	-	6	3	-	4	4	-	3

H_{ntr} = Depth of neutralization. H_{car} = Depth of carbonatation. H_{cor} = Depth of corrosion

EVALUATION

Test Environment

The chosen exposure environment with continuous regeneration corresponds in composition and temperature to the potential leakage of solution from the spent fuel storage pools, specifically in the area of direct contact with the metal lining/cladding. This means that this exposure solution is relatively very aggressive from a corrosion point of view (lower pH and higher salinity of the solution). In terms of selection of test parameters, this is intentionally the most conservative choice of conditions that could be achieved in a real system.

The boric acid solution is characterized by a low degree of dissociation, and therefore, upon contact with alkaline concrete mixture, there is a rapid decrease in acidity.

This variant corresponds to the static environment used, where relatively low corrosion aggressiveness is expected. The environment reflects the residual static volume in the interspace of the double-lining, which is in prolonged contact with the concrete. It takes also into account the influence of diffusion processes in cases where the lining is damaged only locally, and the corrosive environment is partially exchanged in the interspace of the double-lining.

Ongoing test results

Mechanical tests on the exposed specimens demonstrated the expected development of characteristics. In the case of specimens exposed in the environment with continuous regeneration, a clear decrease in compressive strength occurred (Figure 3). For specimens exposed in the static mode, the expected increase in strength occurred due to curing, while this increase was only slightly affected by degradation processes (reaction of the cement paste and aggregate with the boric acid solution), as indicated by comparison with the results obtained from reference specimens (Figure 3).

CONCLUSION

The ongoing results demonstrated the expected development of the monitored parameters.

For specimens exposed in the static mode (simulation of the corrosion process in the location of static exposure with minimal media replacement), after seven years of exposure, the compressive strength increased to 113% of the original strength (concrete B20) and 107% of the original strength (heavy concrete).

For the reference specimens, the compressive strength increased to 118% of the original strength for both types of concrete.

The results of samples exposed in a static environment show almost no difference from the reference samples. This is due to the fact, that boric acid is a weak acid, which leads to its rapid neutralization due to the high alkalinity of the concrete. This condition most likely reflects the reality at the NPP. Long-term exposure to unrenewed boric acid does not pose a problem for long-term operation.

For specimens exposed in the environment with continuous regeneration (simulation of the corrosion process directly at the location of media penetration through the double-lining – maximally conservative conditions), after seven years of exposure, the compressive strength decreased to 71% of the original strength (concrete B20) and 50% of the original strength (heavy concrete).

The dynamic experiment, which involves the regeneration of the boric acid, represents a very conservative scenario, where the concrete behind the second lining would be in constant contact with fresh boric acid from the spent fuel pools. In this case, a deterioration in properties was expected. However, the data so far suggest stabilization of the process, but this will be confirmed or disproven over time. The final samples will be analysed in 2032 (after 15 years of exposure).

The difference between structural and heavy concrete exposed under the same conditions is practically negligible based on the results obtained so far. This is very important finding from the point of view of ensuring safe long-term operation of the plant.

REFERENCES

Karnik, D., Sedlak, F. (2022). Exposure tests of concrete corrosion of the SF pool, Technical report no. 849, Nuclear Research Institute, Rez, CZ.

Karnik, D., Sedlak, F. (2022). Exposure tests of concrete corrosion of the SF pool, Technical report no. 850, Nuclear Research Institute, Rez, CZ.

Sedlak, F. (2022). Monitoring of the inflow and assessment of the condition of double-lined SF pools, Technical report no. 860, Nuclear Research Institute, Rez, CZ.

Sedlak, F. (2023). Monitoring of the inflow and assessment of the condition of double-lined SF pools, Technical report no. 988, Nuclear Research Institute, Rez, CZ.

Czech office fort standards, metrology and testing. (2021). ČSN EN 12390, Testing hardened concrete - Part 1: Shape, dimensions and other requirements for specimens and moulds.

Czech office fort standards, metrology and testing. (2008). ČSN EN 14630, Products and systems for the protection and repair of concrete structures - Test methods - Determination of carbonation depth in hardened concrete by the phenolphthalein method.

Czech office fort standards, metrology and testing. (2005). ČSN EN 12504, Testing concrete in structures - Part 3: Determination of pull out force.