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Durability of Concrete Structures – Inspection of Lock Chambers

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Abstract: *In current codes the durability of concrete structures is usually guaranteed by describing mix design parameters, particularly the maximum water to cement ratio and the minimum cement content and by specifying the minimum concrete cover in dependency of the exposure conditions. European and German standards specify relevant requirements. However, the performance-based approach, which specifies the material's resistance against environmental impact, is getting more and more prominent. Hence, a research project was initiated to assess the reliability of structures planned and built according to current descriptive concept in German standards. Three types of structures were investigated: bridges, regular structures and hydraulic structures. This article covers the hydraulic structures. The structures investigated were four lock chambers in service for 10 to 13 years. The aim of the inspections was to come up with information about material performance and execution quality. Material tests were carried out in situ and in the laboratory. The in-situ investigations included the visual inspection of concrete surfaces, the measurement of concrete cover, the measurement of scaling and of carbonation depth. The laboratory tests were carried out on concrete cores taken during the inspections to determine the performance of the concretes used. The laboratory testing included compressive strength, carbonation depth, air void system in hardened concrete and freeze-thaw-tests. Based on the in-situ investigations and laboratory tests an evaluation of the structures is carried out regarding their durability for the target service life of 100 years.*

Keywords: *concrete, material, durability, hydraulic structures, sustainability*

1. Introduction

The durability of concrete structures is currently ensured by the descriptive concept given in European and German standards, e. g. DIN-EN 206-1 (DIN, 2001) and DIN 1045-2 (DIN, 2008). The descriptive concept prescribes certain parameters of concrete such as water to cement ratio, cement content and concrete cover depending upon the exposition of the structure. If these rules were properly applied regular reinforced concrete structures should last for at least 50 years. Hydraulic structures however are designed to reach a service life of at least 100 years.

Currently, there is work ongoing in European standardization committees to replace the descriptive concept with a performance-based concept. Such a performance concept is based on three base pillars: (1) mathematical models to predict the durability of the structure, (2) test methods to measure the material properties of the concrete and (3) a safety concept on a probabilistic basis. Therefore, the question of how do structures perform when built according to the current codes is of great importance. Comprehensive research with focus on concrete performance has been done in Europe and elsewhere. In the French PERFDUB-project (Dierkens, 2019) reinforced concrete structures have been investigated with respect to concrete performance. One aim of the PERFDUB-project was to come up with performance thresholds for durable structures. The performance-based concept was also addressed in RILEM TC 230-PSC providing durability indicators and their application in performance-based specifications (RILEM, 2015). The RILEM work evaluated the principles, merits and limitations of test methods for concrete performance. One conclusion was that suitable tests and devices for testing the performance of concrete cover exist.

It is well known that both the selected material and the construction quality (workmanship) of a structure, as well as the real exposure conditions affect its durability. Within a joint research program (DAfStb, 2020) (see Figure 1) the topic of structure assessment was addressed in one project. Three types of structures were evaluated within the project: (1) hydraulic engineering structures, (2) highway bridges and (3) regular building construction. This article deals with the investigation of hydraulic engineering structures.

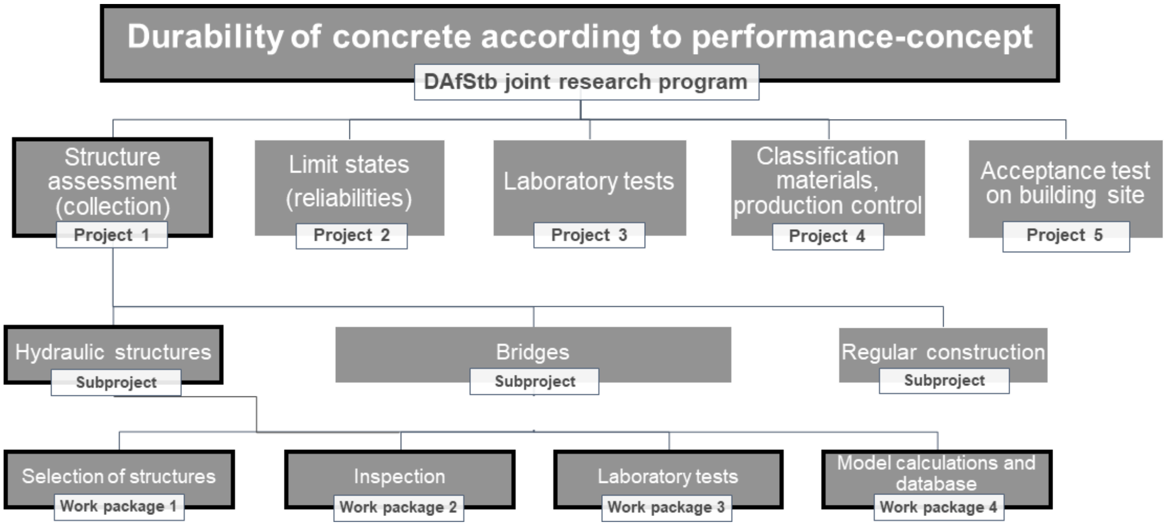

Figure 1. Joint research program (DAfStb, 2020).

2. Structure Investigations

2.1. Selection of Structures

The hydraulic structures were the first structures selected and investigated during the research project. Hydraulic structures are not as numerous as bridges or regular structures. Hence, the German Federal Waterways Engineering and Research Institute (BAW) in Karlsruhe supported the project and suggested relevant structures. The stock of hydraulic structures in Germany was searched for structures "planned and built according to DIN 1045:2001 / ZTV-W LB 215" (Bundesministerium für Verkehr, 2012) and "older than 10 years". Four structures (see Table 1) were identified which met these criteria.

Table 1. Hydraulic structures investigated.

Characteristics	Structures			
Structure ID	lock 1	lock 2	lock 3	lock 4
Location	river Mosel	Stichkanal Hildesheim	Mittelland Canal	river Mosel
In service	10 years	9 years	13 years	11 years
Type of cement	CEM III/A 32,5	CEM III/A 32,5	CEM III/A 32,5	CEM III/A 32,5
Cement content	280 kg/m³ + 40 kg/m³ basalt powder	290 kg/m³	330 kg/m³	280 kg/m³ + 40 kg/m³ basalt powder
water to cement ratio	0,54	0,48	0,48	0,54
Admixtures	air entrainer and plasticizer	air entrainer and plasticizer	air entrainer and plasticizer	air entrainer and plasticizer
Exposition classes	XC4, XF3, XM1	XC4, XF3, XM1	XC4, XF3, XM1	XC4, XF3, XM1
Strength class	C 25/30	C 25/30	C 25/30	C 25/30
Remarks				treated with curing agent after demolding

Two structures were located in the Western part of Germany along the river Mosel. Two other structures were located in the Northern part of Germany along the Mittelland Canal and Stichkanal Hildesheim. All four structures are lock chambers along German inland shipping lanes.

2.2. Safety during Inspection

Each structure was investigated for 2 to 3 days. During this period the lock chambers were closed for inland shipping traffic. The inspections were carried out from work boats. Safety was of great importance during the inspections. The German Federal Waterways Engineering and Research Institute and local operational staff carried out safety instructions and measures.

2.3. In-situ Tests

During the inspection, material tests were carried out on the structure such as visual inspection of concrete surfaces, measurement of concrete cover and carbonation depth. Concrete cores were taken from the structure for further laboratory testing. The inspections and assessment were carried out in accordance with fib-bulletin 59 (fib, 2011).

2.3.1. Visual Inspection of Concrete Surfaces

The visual inspection of concrete surfaces was conducted to spot and document apparent damages. The visual inspection of the surfaces focused on:

- bumps, voids and large pores on the surface,
- spalling of concrete over reinforcement,
- scaling due to freeze-thaw-attack or other exposures and
- crack formations (orientation and width of cracks).

2.3.2. Measurement of Concrete Cover

The measurement of the concrete cover was carried out using the electromagnetic method (device: Proceq Profometer 650AI). The testing area was measured by five parallel line-scans each having a length of 1m. The size of each testing area was approximately 1 m². Roughly 20 to 40 single rebars were detected in each testing area depending upon the degree of reinforcement. The concrete cover measured by the device was verified with concrete cover measurements on concrete cores containing rebars.

2.3.3. Core Drilling

After reinforcement bars had been localized by using the electromagnetic method, concrete cores with a diameter of 100 mm were drilled out of the chamber walls of the locks. The cores were taken by wet drilling process.

2.3.4. Carbonation Depth and Evaluation of the Durability

After core extraction, the carbonation depth was measured in four quadrants of the drilling hole. Therefore, freshly broken concrete surfaces were produced with a jack-hammer along the edge of the drilling hole. The carbonation depth was measured according to RILEM CPC 18 (RILEM, 1988) with a testing solution of 1 % phenolphthalein in 70 % ethyl alcohol. The measurements above the maximum water level were used to assess the risk of depassivation of the steel reinforcement. The calculations were carried out using the fib carbonation model (fib, 2006), the inspection data (concrete cover and carbonation depth) and the Bayes theorem, following the approach given in Greve-Dierfeld (2015). The fib model (see Eq. (1)) can be expressed as given (fib, 2006) :

$$x(t) = \sqrt{2 \cdot k_e \cdot k_c \cdot \left(k_t \cdot R_{ACC,0}^{-1} + \varepsilon_t\right) \cdot \Delta C_S \cdot t} \cdot \left(\frac{t_0}{t}\right)^{(0.5 \cdot p_{SR} \cdot ToW)^{b_w}} \tag{1}$$

Where: $x(t)$ is the carbonation depth at time t; k_e is a transfer parameter for the environmental conditions; k_c is a transfer parameter for the curing duration; k_t and ε_t are transfer parameters between accelerated and natural test conditions;

$R_{ACC,0}^{-1}$ is the inverse effective Carbonation resistance of the concrete under determined accelerated conditions [$mm^2/a/kgCO_2/m^3$]; ΔC_S is the CO_2 concentration in [$kgCO_2/m^3$]; t is the exposure time [s]; t_0 the reference time corresponding to 28 days; p_{SR} is the probability of driving rain [-]; ToW is the time of wetness, related to the number of days with a precipitation bigger than 2,5 mm [-]; and b_w is a regression parameter [-].

Considering the depassivation as a limit state, a limit state equation (LSE) can be defined using the concrete cover (d_c, in mm) as the resisting parameter. As soon as the carbonation front reaches the reinforcement, it is considered as depassivated. The LSE can be written as Eq. (2) (Gehlen, 2000) (fib, 2006):

$$LSE = d_c - x(t) \tag{2}$$

Therefore, using a full-probabilistic approach, the probability of depassivation can be calculated and expressed in terms of the reliability index, β, using the FORM or SORM algorithms (Gehlen, 2000). Furthermore, the carbonation depths measured at the structure can be used to update the initial calculation using Bayesian methods. The reader is directed to Gehlen (2000), fib (2006) and Greve-Dierfeld (2015) for further details on the model and the update methods. DAfStb (2008) states that a maximum depassivation probability of around 7 %, i.e. $\beta \geq 1.5$, is adequate for the exposure class XC4.

2.3.5. Refilling of Boreholes

The boreholes were closed with a concrete repair system. First, a cementitious bonding adhesive was applied on the inner surface of the core drill. Thereafter a concrete repair system was filled into the core holes and consolidated with a compaction rod. The concrete repair system had a very dry consistency comparable to earth-moist or highway concrete. Then the outer surface of the filled core hole was finished with a masonry board and trowel. Finally, metal plates were bolted over the filled holes for a few days to ensure that the concrete repair system would not be washed out during operation of the locks (fast rising/falling water level).

2.4. Laboratory Tests

Laboratory tests were carried out on concrete cores taken from the chamber walls. Structural and durability parameters were determined on sections of those cores (see Figure 2). The first section (1) had a length of 70 mm and was used to determine the freeze-thaw resistance or alternatively the splitting tensile strength. The second section (2) often contained steel rebars and could not be used for testing. If no steel was present this core section could be used for additional testing. The third section (3) had a length of 60 mm and was used for the assessment of the air-void system in hardened concrete. The fourth section (4) had a length of 100 mm and was taken for the compressive strength test. This article covers only the investigation of air-void system in hardened concrete.

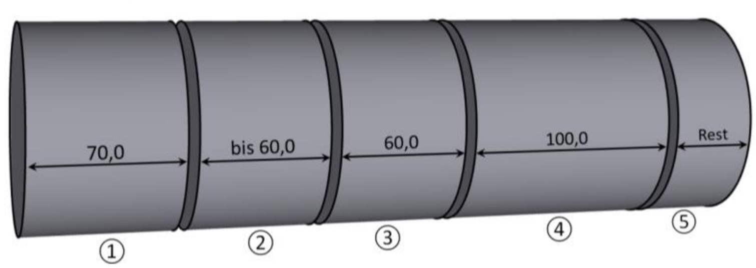

Figure 2. Schematic draft of a concrete core with test sections.

2.4.1. Air-void System in Hardened Concrete

The air-void system in hardened concrete was determined according to DIN EN 480-11 (DIN, 2005) on a section of the bulk concrete. Two concrete prisms (140 x 20 x 40mm) were cut from the core sections and polished before microscopical work began. The measuring lines were evenly distributed over the cross sections. The air-void system was scanned along the measuring lines by a high-resolution optical microscope. The freeze-thaw resistance of concrete is highly dependent upon the microstructure of the material. According to ZTV Beton StB 07 (ZTV, 2007) the freeze-thaw resistance of concrete can be determined by two parameters: (1) the amount of micro air voids A300 and (2) the spacing factor L. Both parameters are calculated after scanning the air-void system.

3. Results and Discussion

3.1. Visual Inspection

The visual inspection of the concrete surface of the chamber walls showed significant differences in concrete quality and freeze-thaw resistance. Locks 1 and 3 showed extensive damages due to freeze-thaw attack in the concrete surface subject to wet and dry cycles. Scaling depths of up to 10 mm (see Figure 3) and more could be observed with locks 1 and 3. With lock 3 the concrete surface subject to wet and dry cycles could partially be peeled off by hand (see Figure 4).

Figure 3. Measurement of scaling depth due to freeze-thaw attack at lock 3.

Figure 4. Concrete surface damaged by freeze-thaw attack at lock 3 can be peeled off by hand.

Lock 2 showed less extensive freeze-thaw damage than locks 1 and 3. The least damaged concrete surfaces due to freeze-thaw attack were observed in lock 4. Many surfaces of lock 4 still showed the formwork structure (see Figure 5) and looked as if the formwork had only recently been removed. The concrete surfaces of lock 4 were treated with a curing agent after demolding. Nevertheless, all locks showed vertical cracks, induced by constraint stress due to hydration heat development of cement, having a crack width in the toleration range of 0.1 to 0.3 mm, in a few cases up to 0.6 mm (see Figure 6).

Figure 5. After 11 years of service life lock 4 showed the least damaged concrete surfaces.

Figure 6. Vertical crack in wall of lock 1 with a crack width of up to 0.6 mm.

3.2. Concrete Cover

The concrete cover measurements on the four locks are shown in Figure 7. It can be seen that the minimum concrete cover and the nominal concrete cover are in good alignment with the technical specifications in the drawings (ZTV-W LB 215). The lowest standard deviation was observed with lock 4.

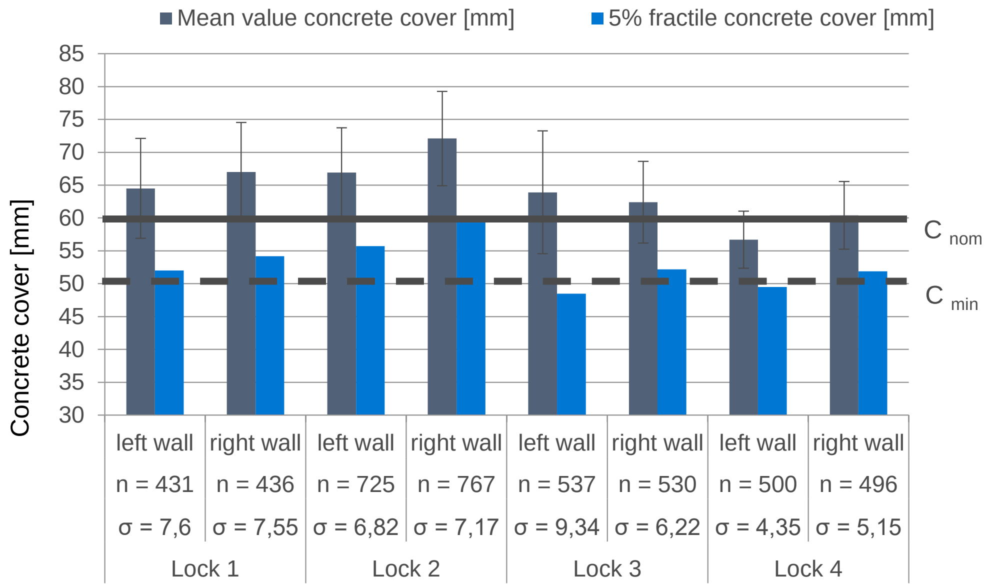

Figure 7. Concrete cover (mm) of locks investigated.

3.3. Carbonation Depth and Carbonation Rate

The carbonation depth was measured on freshly prepared concrete surfaces at the edges of bore holes. From these carbonation depths natural carbonation rates were calculated. The natural carbonation rates observed on the four locks are given in Figure 8. The highest carbonation rates were measured at lock 1 made with CEM III/A and basalt powder as binder at a water to cement ratio of 0.54. The lowest carbonation rates were observed at lock 4 with the same binder type and w/c-ratio. The only difference was the application of a curing agent on concrete surfaces of lock 4. From Figure 8 it can be seen that the concrete subject to wet and dry cycles (wet concrete in the tidal zone) showed lower carbonation rates than concrete not subject to wet and dry cycles (concrete above headwater level). The calculated carbonation rates were ranging from 1.2 to 4.3 mm/√a. The results indicate that the moisture in the concrete prevents the transportation of CO_2 into the concrete pores and hence reduces the carbonation rate, especially in the areas subject to wet and dry cycles. The observed carbonation depths are probably largely due to the time between the completion of the structural component and the start of water exposure.

The carbonation rates were also plotted as a function of orientation (North, East, South, West). It was found that the highest carbonation rates could be observed along the West-East axis (see Figure 9). In Germany the “weather side” is usually West, meaning the rain comes usually from the Western direction. Hence, carbonation rates should, theoretically, be lowest on concrete surfaces facing West. However, this could not be observed.

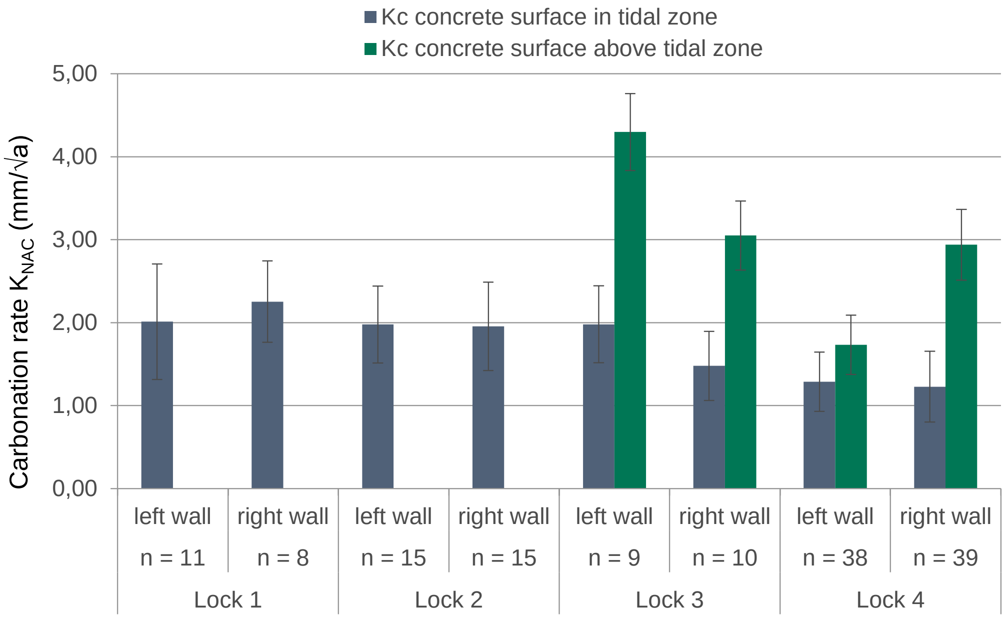

Figure 8. Natural carbonation rates (mm/√a) of locks investigated.

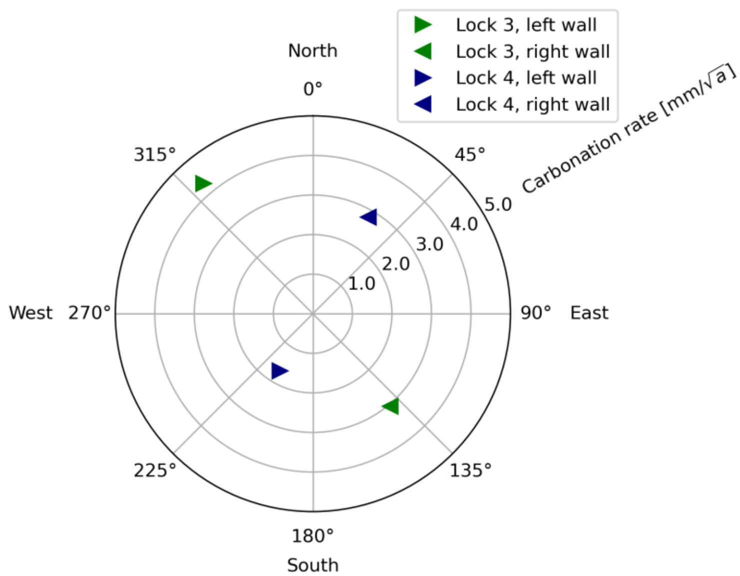

Figure 9. Natural carbonation rates (mm/√a) for locks 3 and 4 as a function of orientation, for concrete above headwater level.

3.4. Evaluation of the Durability against Carbonation-induced Corrosion

The concrete cover and carbonation depth measurements were used to estimate the remaining service life of the structure. The model variables were calculated following Gehlen (2000). Figure 10 shows the calculated (a-priori) and the measured carbonation depths at the time of inspection (11 years) for both chamber walls of lock 4. It can be seen, that the model prognosis and the inspection measurements are close to each other, though the right wall shows slightly higher carbonation depths as predicted. For this reason, both the a-priori calculated carbonation depths and the measurements were used to update the model calculation and estimate the probability of depassivation at a service life of 100 years.

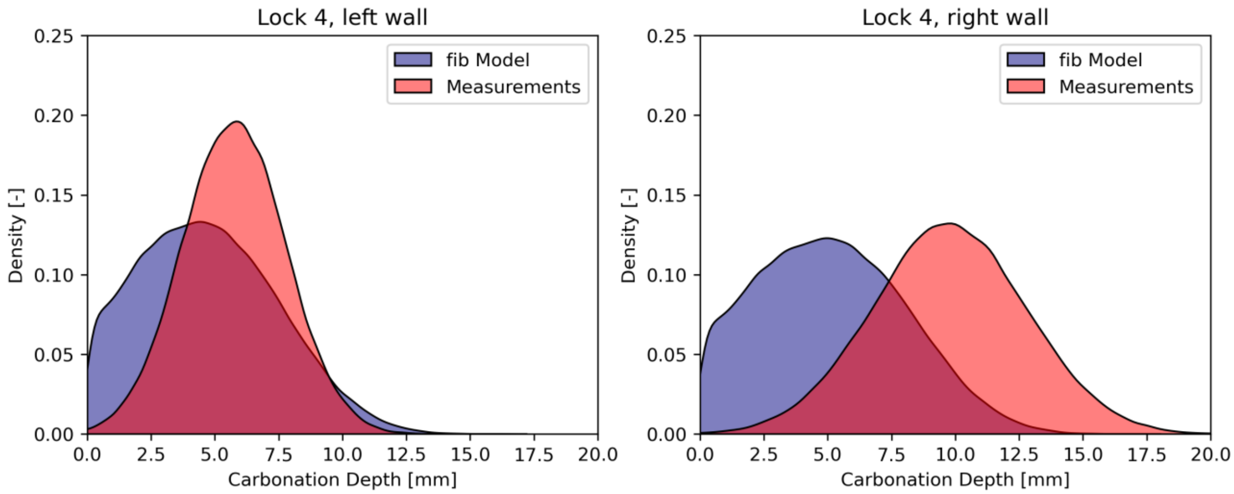

Figure 10. Predicted (fib Model) vs measured carbonation depths at lock 4 above headwater level, (t = 11 years).

Figure 11 shows the evolution of the reliability index (β) in time for the left and right chamber walls of the locks 3 and 4. Both chamber walls of the two analysed locks achieve a target reliability index at an age of 100 years higher than the minimum set by DAfStb (2008) of 1.5. The lowest reliability index (right wall of lock 4) has a value of 2.92, which corresponds to a probability of depassivation lower than 1 %, suggesting that for these elements, carbonation-induced corrosion is of secondary concern during their targeted service life.

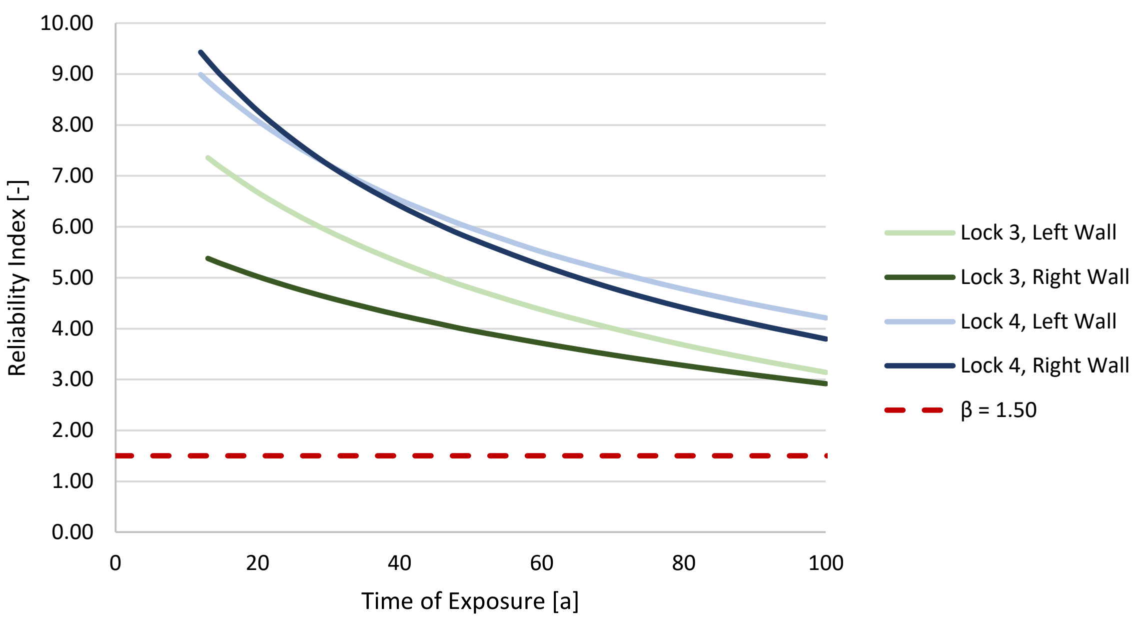

Figure 11. Reliability index as a function of exposure time for locks 3 and 4 (concrete above headwater level).

3.5. Air-void System of Hardened Concrete

The air-void system of concrete from the chamber walls of the locks is displayed in Figure 12. The parameters were obtained on sections of concrete cores 13 to 19 cm below the surface. From Figure 12 it can be seen that the mean value for air content A was between 3.7 and 7.1 Vol.-%. The content of micro air pores ranged from 2.4 to 3.9 Vol.-% while the spacing factor L was between 0.11 and 0.16 mm (not displayed). According to ZTV Beton StB 07 (ZTV, 2007) these values characterize a freeze-thaw resistant concrete.

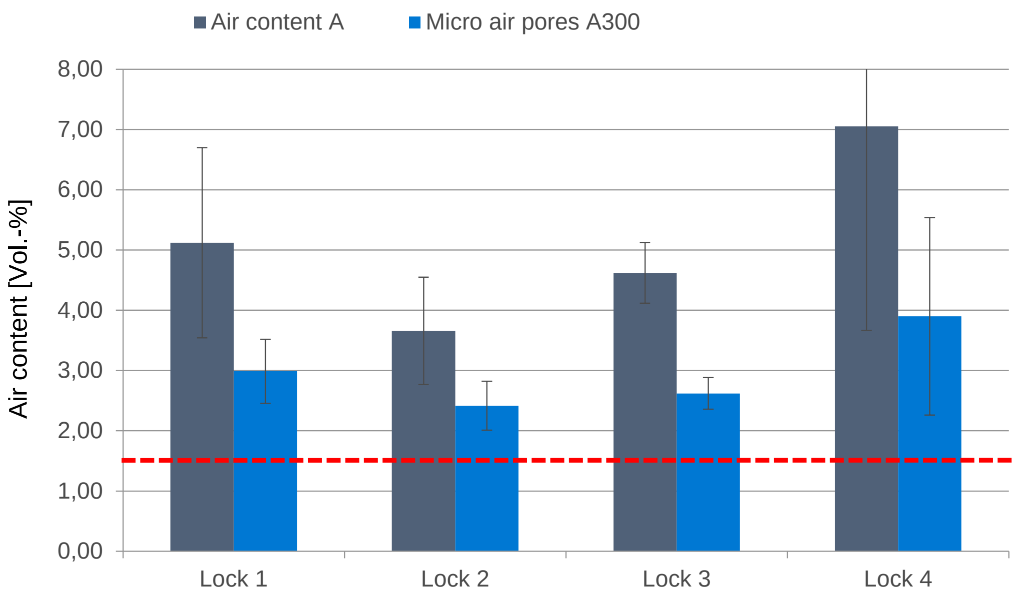

Figure 12. Air content A and content of micro air pores A300 (Vol.-%) of locks investigated.

4. Conclusions

Four hydraulic structures along German inland shipping lanes were investigated with respect to execution quality and material performance. The investigation scope included the chamber walls of reinforced concrete locks made with air-entrained concrete containing CEM III/A.

The in-situ tests showed that the minimum concrete cover and the nominal concrete cover were in good alignment with the technical specifications in the drawings. The cover measurements indicate a good quality of the executions. The calculated natural carbonation rates from the on-site measurements were between 1.2 and 4.3 mm/√a. Low carbonation rates were observed with moist concrete (in the tidal zone) while relatively high carbonation rates were found with dry concrete (above headwater level). For two locks, the natural carbonation rates were used to estimate the risk of corrosion within a service life of 100 years. For the structures investigated, the carbonation front will not reach the outer reinforcement layer within this period.

The analysis of the air void system of hardened concrete showed that all investigated structures were made with a concrete having sufficient freeze-thaw resistance. Air content A, the content of micro air pores A300 and spacing factor L are all in the range of freeze-thaw resistant concrete.

The visual inspection of the concrete surface showed huge differences in concrete quality and apparent freeze-thaw resistance. The concrete surfaces showing relatively low freeze-thaw damage (lock 4) were treated with a curing agent after demolding.

5. ACKNOWLEDGMENTS

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