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Spörel, Frank

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Freeze-Thaw-Attack on Concrete Structures – Laboratory Tests, Monitoring, Practical Experience

Frank Spörel [a]

[a] Federal Waterways Engineering and Research Institute, Karlsruhe, Germany

Abstract:
Waterway structures like locks are exposed to severe freeze-thaw attack. Sufficient resistance of the concrete to this exposure has to be assured. In Germany the concrete used for federal waterway structures in exposure class XF3 has to undergo a CIF test in the laboratory in addition to meeting descriptive requirements. In the meantime, experience has been gained with this procedure and several structures based on it have been in operation for up to ten years. In order to establish the procedure, research was conducted concerning the transferability of laboratory tests to practical experience. One important aspect here was a service life study on the degree of water saturation of the concrete under practical conditions in combination with temperature exposure. Taking the example of a lock, this paper presents the results of laboratory tests as well as monitoring data for the degree of water saturation and temperature exposure and undertakes an assessment of the condition of the structural concrete after ten years in operation.

1 Introduction

Waterway structures are solid structures that place special requirements on concrete properties. A low heat of hydration of the concrete is necessary to minimize restraint. This results in certain limitations concerning cement properties and content. To achieve a sufficient freeze-thaw resistance and meet the requirements resulting from limitations on the heat of hydration, consideration must be given to the concrete technology when choosing the raw materials and mix design.

In addition to European and national standards [1, 2], requirements regarding concrete for the construction of waterway structures under the responsibility of the Federal Ministry of Transport and Digital Infrastructure (BMVI) have been regulated for more than 3 decades now in the “Supplementary Technical Contract Conditions – Hydraulic Engineering” [3]. Concerning freeze-thaw exposure in exposure class XF3, the concrete has to undergo CIF testing according to the BAW Code of Practice “Frost Resistance Tests for Concrete” [4]. The procedure is similar to that described in [5]. When testing slowly hardening concrete, the test starts at an age of 56 days. After casting, the specimens are stored for 14 days in water and subsequently for 42 days in a climate chamber at 20°C / 65% relative humidity.

One question which has been discussed ever since the CIF test became mandatory in 2004 is the transferability of the test results to the performance of the exposed concrete during operation of the structure. In particular, very little has been known until now about seasonal variations in the degree of water saturation as an important aspect of a freeze-thaw attack; information has also been lacking on additional water adsorption, which can be described by the micro-ice lens pump according to Setzer [6]. For this reason, a monitoring system was installed on several structures [7] to contribute to new findings concerning temperature exposure and the degree of water saturation by the concrete under different conditions. The data was evaluated to receive an impression of the intensity of freeze-thaw attack. This paper describes the results for a lock taking account of the actual condition of the structure.

2 Structure and Measuring System

2.1 General

To investigate freeze-thaw attack on concrete structures, a lock was equipped with sensors. Several measuring points were installed, so that observations were possible at parts of the structure with different moisture and temperature exposure. A data logger with a remote control allowed an immediate analysis of the data which was collected over a period of several years.

A non-destructive determination of the degree of saturation of concrete is only possible using indirect measurement methods. A continuous, depth-dependent measurement of the resistivity was transferred to the degree of saturation by means of a calibration in the laboratory. The resistivity measurement was conducted using a multiring electrode (MRE). The MRE is a sensor consisting of several rings of stainless steel, each with a thickness of 2.5 mm, with an insulating plastic ring between two steel rings. It enables AC resistance measurements of the concrete between two adjacent steel rings in eight steps at a frequency of 10.8 Hz and at a depth of 7 to 42 mm from the concrete surface. The measuring depth can be increased to 87 mm using two MREs and a distance piece [8]. A multitemperature probe (MTP) is installed near the MRE in order to monitor temperature exposure. The MTP is equipped with eight PT 1000 sensors to facilitate temperature measurements at eight different distances from the concrete surface.

The example in Figure 1 shows a sectional view of a lock with four measuring points installed inside the northern side wall of the northern lock chamber. The concrete surface is orientated in a southerly direction. Measuring point MP1 is permanently submerged whereas MP2 and MP3 are located between the head water and the tail water, and are thus in frequent contact with water (XF3). MP4 is unsheltered and exposed to rain and freezing (XF1).

The concrete with blast furnace slag cement and fly ash had an equivalent water-to-cement ratio of 0.47 (k=0.4) without an air entraining agent (Table 1). To demonstrate the typical effects in exposure classes XF3 and XF1, this paper will focus on MP3 and MP4.

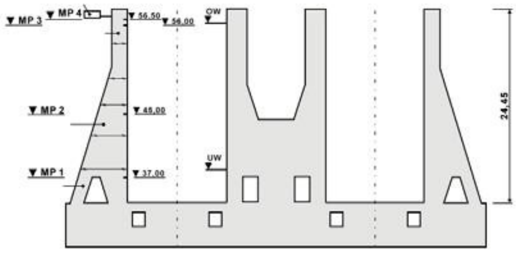

Fig. 1: Measuring points in the side wall of the lock

Table 1: Concrete mix design

Material	Content [kg/m^3]
CEM III/A 32.5 N LH	270
Fly ash	80
Water	140
Plasticizer	3
Aggregate	1876

The investigations were conducted by the Institute of Building Materials Research, RWTH Aachen University, by order of the Federal Waterways Engineering and Research Institute.

2.2 Calibration

To enable the resistivity to be converted to the degree of water saturation of concrete, a calibration provided a relation between these two parameters. This relation was determined by simultaneously measuring the degree of saturation and the resistivity using the two-electrode method (TEM) at a concrete temperature of 20°C. Different degrees of saturation were set in 28 concrete disks with a diameter of 80 mm and a height of 20 mm by capillary suction and drying at a temperature of 60°C. The disks were sealed and stored for two weeks prior to the resistivity measurements, to allow a uniform moisture distribution inside them. To minimize the influence of hydration on the resistivity, the calibration was started on concrete at least two years old. The water content is the most dominant parameter influencing the resistivity of concrete. However, besides the concrete-specific parameters like the w/c ratio, degree of hydration, cement type, content of additions or carbonation, resistivity is also influenced by environmental conditions such as temperature variations or the chloride content due to marine exposure or the use of de-icing agents [9]. Investigations aiming to determine the degree of saturation indirectly by means of resistivity measurements have to consider these influencing parameters to avoid misinterpretations of the data.

2.3 Influence of temperature on resistivity

Apart from the degree of water saturation, concrete resistivity is also influenced by temperature, among other things. The calibration functions are only valid for the temperature at which the tests were conducted, in other words the influence of temperature on resistivity has to be considered when the calibration function is applied to measurements at a structure. Whereas concrete-specific parameters were considered by the calibration of the tested concrete, the temperature was taken into account by a compensation routine which bears in mind the simultaneously measured resistivity as well as the temperature measured at the structure. The Arrhenius equation (Equation 1) was used to compensate the influence of temperature on the resistivity of concrete. This equation enables the resistivity to be calculated at a temperature of 20°C, as in the calibration test, from the measured temperature and resistivity values at the structure. The constant b depends on technological aspects and the degree of saturation [9, 10].

$$\rho_{el} = \rho_{el,0} \cdot e^{b \cdot \left(\frac{1}{T} - \frac{1}{T_0} \right)} \tag{1}$$

ρ_{el} Electrolytic resistivity at temperature T in Ωm
$\rho_{el,0}$ Electrolytic resistivity at temperature T_0 in Ωm
T, T_0 Absolute temperature in K
b Constant in K

Owing to the variation range of the constant b, data from the structures was evaluated and laboratory tests carried out to consider the concrete mix design, degree of water saturation and conditions on site. In addition to TEM measurements and an evaluation of the data from the structures according to [11], MRE tests were carried out on partially saturated and sealed concrete cubes with an edge length of 200 mm. Inside these cubes, MREs and MTPs enabled continuous resistivity measurements during a 12-hour air temperature cycle in the range from +20°C to -15°C at a heating and cooling rate of 6.3 K/h. The air temperature was kept constant at -15°C for one hour. The heating and cooling rate of 6.3 K/h was based on the average extreme values observed at different structures during freezing and thawing. Additional tests were performed at a heating and cooling rate of 1.6 K/h to investigate whether this rate has an influence on the constant b. This was the range most frequently observed during freeze-thaw cycles at the structures. The correlation of the constant b to the degree of saturation was determined by transferring the measured resistivity into the degree of saturation with the aid of the calibration functions. The influence of the concrete mix design, concrete age and degree of saturation was considered in this way. The measurements were carried out at a high concrete age of several years because the data recording for the long term measurement also started at a high age. That way the influence of hydration was generally negligible. The effectiveness of compensating the influence of temperature on resistivity were mainly investigated for temperatures > 0°C, and there were pointers to a distinct influence of temperature in the temperature range from 10 to 50°C [12]. Investigations in temperature ranges below 0°C are described in [13]. Temperatures below 0°C are of special interest for freeze-thaw attack, which is why investigations were carried out in that direction. Two different states of concrete saturation were studied; the test surface was sealed with cling film during the test to minimize evaporation or water uptake during the temperature cycle. The first test was performed after storage in a climate chamber at 20°C / 65% relative humidity. After a ten-day period of capillary suction, the test was repeated with a higher degree of saturation. The gradient of saturation in both tests enabled a measurement over a wide saturation range.

3 Results

3.1 Calibration

The resulting calibration function of the concrete used for the lock is shown in Figure 2 for concrete stored in laboratory conditions and for cores taken from the structure at an age of about 5 years. Differences were observed in the degree-of-saturation range below about 50%. As the concrete of the cores is most representative, the calibration function for the core concrete was used to convert the data from the structure to the degree of saturation. The range of resistivity measured at the structure was covered by the calibration function.

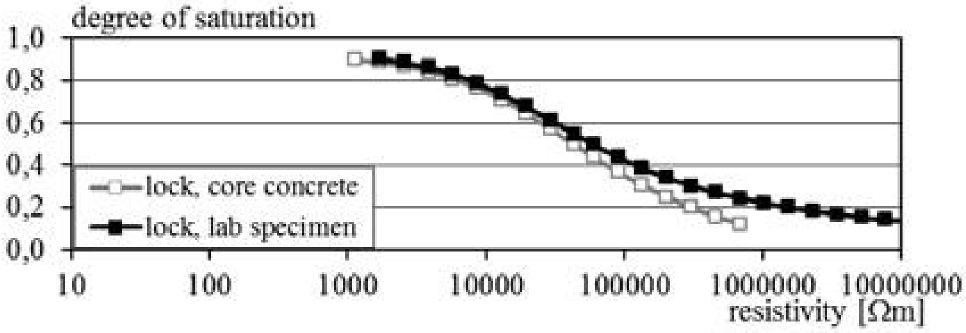

Fig. 2: Calibration functions of the concrete used for the lock

3.2 Influence of temperature on resistivity

In order to use the calibration function, the data from the structure has to be transferred to a temperature of 20°C according to Equation 1. It was possible to determine the constant b at temperatures below 0°C by means of MRE measurements as described in section 2.3. In addition to the lock concrete, 6 cubes of different concretes were tested and their resistivity transferred to the degree of saturation using the various calibration functions. The concretes used for a tunnel, a bridge and a quay wall all had water-to-cement ratios of about 0.5 but different types of cement as well as different cement and fly ash contents [7]. The constant b decreased as the degree of saturation increased. Depending on the 7 different concretes investigated, the constant b varied from about 7000 K at low degrees of saturation of approximately 0.1 to 0.2 to about 2500 K under water saturated conditions (degree of saturation approximately 0.9). The results enabled sufficient account to be taken of the influence of temperature on resistivity. Furthermore, the test revealed a special effect which occurred at high degrees of saturation and temperatures below about -2°C. Figure 3 shows the temperature compensated resistance during the temperature cycle described in section 2.3.

Figure 3 (top) shows an almost linear development of the concrete resistance during the test after storage in laboratory conditions (20°C / 65% relative humidity). No temperature effects can be detected, proving the efficiency of the compensation routine. Figure 3 (bottom) depicts the test results for the same specimen following a capillary suction period of about 10 days. An almost linear development is likewise observed at a measuring depth of 82 mm. Closer to the concrete surface an abrupt increase in the resistance is visible when the temperature falls below about -2°C. The compensation routine according to Equation 1 is not able to eliminate these temperature effects at low temperatures for highly saturated concrete. This increased resistance is accompanied by a deviation of the otherwise linear temperature decrease at a distance of 7 mm from the surface. This is a sign of a phase transformation from water to ice.

In other words, a phase transformation from water to ice can be detected using resistance measurements. The fact that the dry concrete (Fig. 3 (top)) does not exhibit these effects indicates that freezing of water in concrete is dependent on the degree of saturation. In rather dry conditions of the concrete, it is mainly fine pores that contain water. Freezing, or at least freezing as detectable by resistivity measurements, does not occur at temperatures relevant for practical conditions. The minimum degree of saturation at which freezing occurs was determined in further tests by means of the calibration function. The evaluation showed that freezing of water in the pore structure occurred at a degree of saturation in the region of hygroscopic saturation of the different concretes at a relative humidity of about 95%. This was deduced by transferring the resistivity values to the degree of saturation using the calibration functions. These results were compared with the hygroscopic saturation of the concrete, which was determined by storing concrete disks according to section 2.2 in exsiccators with a relative humidity between 65 and 95%. Similar degree-of-water saturation ranges at which frost problems can occur were observed for Portland cement pastes [14].

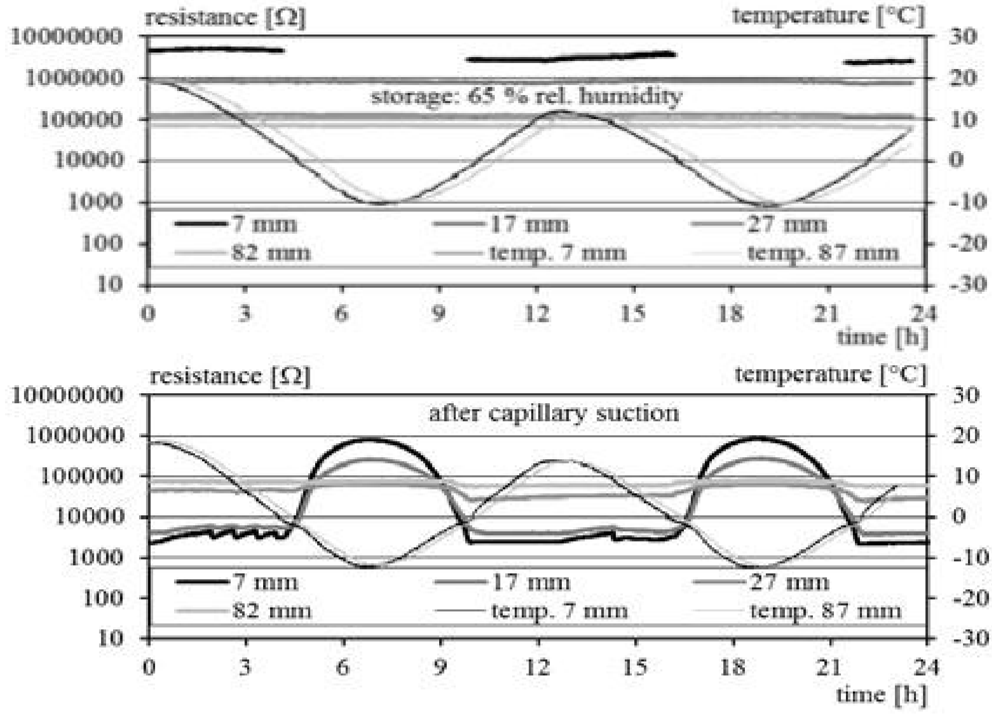

Fig. 3: Effectiveness of compensating the temperature influence on concrete resistance

In order to describe the effect of freezing water in the pore structure on the resistivity in Equation 2, a factor $F_G(T)$ is introduced [7] which describes the ratio of resistivity with a compensated temperature influence in the frozen state of the water to the liquid state. The data in Figure 3 was analysed and the factors $F_G(T)$ determined at a temperature of -11°C. The results are documented in Table 2.

$$F_G(T) = R_g(T) / R_f \qquad (2)$$

R_f	Temperature-compensated resistivity (liquid pore water) before freezing
$R_g(T)$	Temperature-compensated resistivity (frozen pore water) at a temperature T

Table 2: Factor $F_G(T)$ for the test results in Figure 3.

Depth	**F_G(-11°C)**
7 mm	200
17 mm	45
27 mm	2
82 mm	1
7 mm	200

It becomes obvious that at a measuring depth of 82 mm no change in resistivity occurs (F_G=1), whereas closer to the surface the factor F_G increases. This can be explained by the higher degree of saturation closer to the surface after the period of capillary suction. This higher degree of saturation implies that a higher amount of water is available, which is freezable in the tested temperature range. It is assumed that at higher degrees of saturation more water is present in the capillary pores than in a dryer state. This method of analysing the resistivity data seems to be suitable for investigating water freezing in the pores of concrete.

4 Evaluation of Freeze-Thaw Exposure at the Structure

4.1 Degree of saturation

The degree of saturation refers to the water absorption of the concrete at a pressure of 150 bar. The degree of saturation is 0.91 for the investigated concrete at atmospheric pressure. This specific value provides a basis for evaluating the calculated saturation degree of the concrete in the structure during operation. High degrees of saturation in the capillary saturation region of the concrete were calculated at the measuring point for class XF3 exposure during almost the entire observation period (Fig. 4).

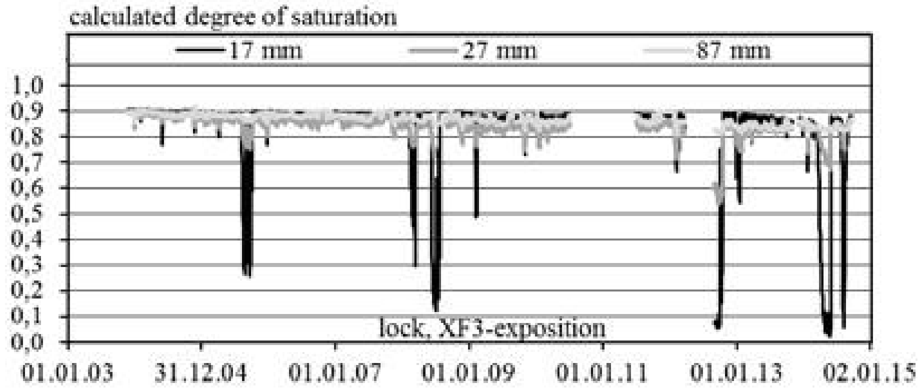

Fig. 4: Calculated degree of saturation of the look for class XF3 exposure

The concrete only dried during lock inspection intervals. No significant changes in the degree of saturation were observed during normal operation of the lock. A lower, mainly constant degree of saturation was observed at measuring point MP4 at a distance of more than 40 mm from the surface. Higher average degrees of saturation were determined closer to the surface during winter periods and lower average degrees of saturation during summer periods (Fig. 5). Degrees of saturation in the order of saturation at atmospheric pressure also occured for a short period during single events at this XF1 measuring point close to the surface.

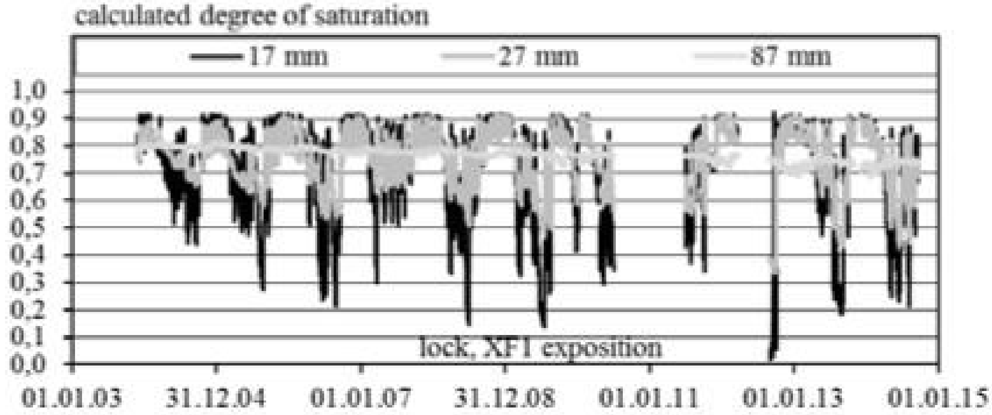

Fig. 5: Calculated degree of saturation of the look for class XF1 exposure

4.2 Freezing of water in the pore structure

In order to determine the transferability of laboratory test results to practical conditions, the monitoring data was analysed with regard to the effects described in Figure 3. An example is given in Figure 6. If the concrete temperature decreases below about -5°C in exposure class XF3 the resistance rises abruptly. A factor F_G=6 at a distance of 87 mm from the surface can be deduced by analysing the data at a temperature of -11°C. According to [7], a tendency was observed for the factor $F_G(T)$ to increase when the degree of saturation increases.

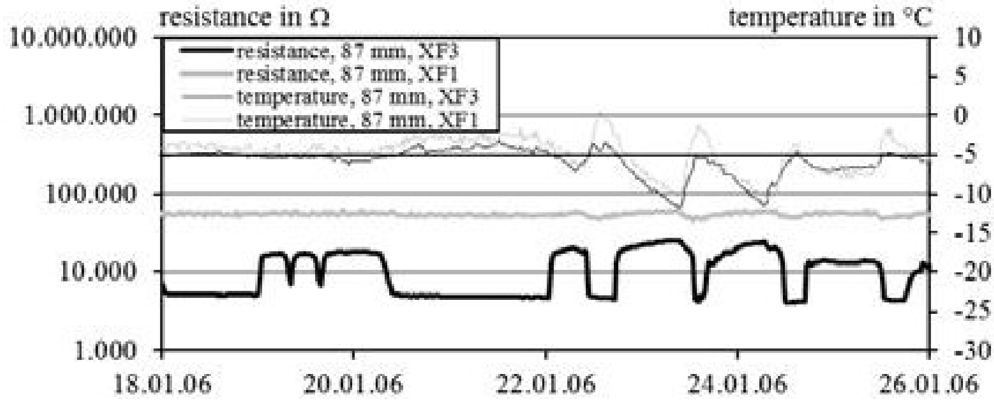

Fig. 6: Freezing of water in the pore structure as detected by resistance measurements

A factor $F_G(T)=1$ was determined in exposure class XF1. Regarding the lower degree of saturation compared to exposure class XF3 at this measuring point, the different resistivity effects can be explained by the different amounts of water in the pore structure. According to the results of the laboratory tests described in section 3.2, a phase transformation from water to ice hardly seems possible for this concrete at the structure in exposure class XF1.

4.3 Surface condition of the structure

After ten years in service, the condition of the structure was investigated during an inspection. There were large areas of the concrete surface where the hardened cement paste and mortar were eroded and the coarse aggregate was visible. The deterioration process was not yet complete (Fig. 7).

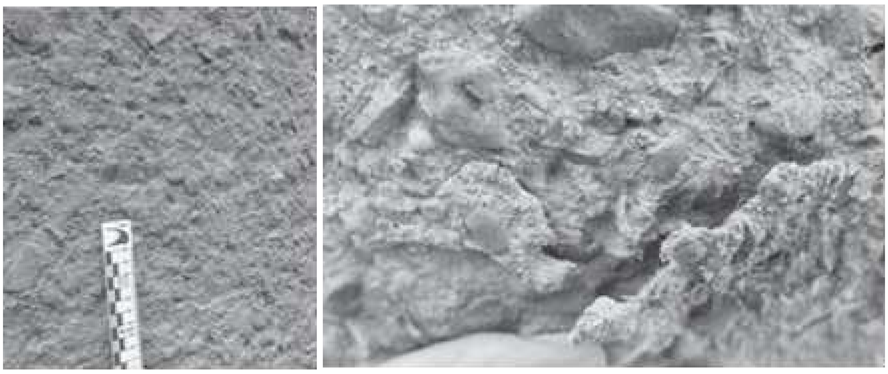

Fig. 7: Condition of the lock surface after 10 years in service

This indicates that freeze-thaw attack has been taking place during the last ten years, leading to damage to the concrete surface. The requirement for damage – freezing of the water in the pore structure – was observed under practical XF3 conditions, accounting for the results of the monitoring system. This does not necessarily mean that damage has to occur, because the critical degree of saturation of this concrete is unknown; however, the freezing and thawing of water can induce the micro-ice lens pump effect according to [6], which may ultimately result in concrete damage if the pore structure has insufficient freeze-thaw resistance. Carbonation of the blast furnace slag cement concrete could also be responsible for the scaling, as the pore structure and thus the freeze-thaw resistance of carbonated concrete are different. The XF1-exposed parts of the structure showed no degradation of the surface. The monitoring data at these parts revealed no freezing of water in the pore system, meaning that the requirements for damage were not met.

5 Summary

The actual freeze-thaw exposure of concrete – comprising temperature exposure, degree of water saturation and freezing of water in the pore structure – was investigated at a lock for exposure classes XF1 and XF3. The results were obtained by monitoring data in addition to laboratory tests. The main difference between XF1 and XF3-exposed concrete was that with XF3 exposure a mainly constant, high degree of saturation was observed in the complete 90 mm measuring zone whereas with XF1 exposure, seasonal and short-time changes were visible close to the surface. Fairly constant degrees of saturation were also determined above a concrete surface depth of about 40 to 50 mm, though at a lower level than with XF3 exposure. Furthermore, a decisive difference was noted between XF1 and XF3 exposure: resistivity measurements revealed effects which can be explained by water freezing in the pore structure. To enable these effects to be described and quantified, a factor was introduced. These effects were only observed with XF3 exposure. An inspection of the structure after ten years in service revealed large areas of the concrete surface in exposure class XF3 where the hardened cement paste and mortar were eroded and the coarse aggregate was visible. This combination of an indirect degree-of-saturation measurement and a typical resistivity effect occurring when pore water freezes seems suitable for evaluating the intensity of a freeze-thaw attack.

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Autoren

Frank Spörel
Federal Waterways and Research Institute (BAW)
Kussmaulstrasse 17, 76187 Karlsruhe, Germany
frank.spoerel@baw.de