ASR Related Service Life Estimation for Concrete Pavements

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February 24, 2021

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Abstract

In a recently finished 5 year study on behalf of the German federal highway research institute (BASt), 71 pavement concretes from 53 highway sections across Germany were examined among other things regarding their residual potential for an alkali-silica reaction (ASR). An empirical approach could be derived for predicting the remaining service life of the concretes, based on residual expansion measurements. By using earlier correlation data for the climate simulation concrete prism test (CS-CPT) compared to field performance, a translation of the testing period into service life was possible by using a fitted natural exponential function. In the result, the service life of all the pavement concretes could be estimated, ranging from 11 to 51 years, depending on the ASR potential of the concrete mixes under consideration of an external alkali supply by NaCl de-icer solution. A first agreement between the prediction and the field performance could be found. An ongoing monitoring of the pavements in the field is supposed to verify and further improve the prediction. In this paper, the study will be introduced to the public for the first time, focusing on the approach to estimate the ASR related service life for concrete pavements.

Keywords*: climate simulation concrete prism test; pavements; service life estimation*

1. INTRODUCTION

Concrete has been used successfully for a long time to build highway pavements in Germany. Concrete pavements meet highest requirements regarding durability, sustainability, load capacity, safety and economy and can provide many decades of service with little or low maintenance and repair. However, the use of concrete was increasingly questioned since the late 1990s because of a growing number of damage on pavements that had been caused or assisted by an ASR (Figure 1.1, Figure 1.2). A number of studies were launched in the following years to find out the reasons for the unexpectedly large number of ASR affected pavements [1-8]. The most important results of these studies can be summarized briefly as follows:

- some aggregates outside the scope of the German guideline for ASR (“Alkali-Guideline”), classified as non-reactive on the basis of their rock type, geographical origin or German fog chamber test at 40 °C can cause deleterious ASR in pavements,
- the former Na_2O_{eq} threshold of 1.0 wt.% for pavement cements (CEM I) was not sufficiently low to avoid ASR damage with such aggregates safely,
- in concrete with alkali reactive aggregates ASR can be triggered and accelerated highly by an external application of alkalis as NaCl de-icers,
- in concrete with alkali reactive aggregates and exposed to external alkalis, low alkali Portland cements (CEM I) can delay but not prevent a deleterious ASR,
- microcracks in concrete induced by traffic loads promote the ingress of water and NaCl solution what further accelerates the ASR in concrete with alkali reactive aggregates,
- mortar-bar tests, as introduced 2007 in Germany, are unable to identify reliably if aggregates are sufficiently non-reactive for use in concrete pavements,
- currently ASR performance-tests are most appropriate to assess the ASR potential of pavement concrete job mixes.

In 2010 and 2011, the federal highway research institute (BASt) launched a large-scale survey on concrete pavements. That is around 5,800 km of German highways. The scope of the project was to obtain reliable information about the extent of ASR affected and suspected pavements. The result was that more than 1,500 km were more or less affected by an ASR, i.e. more than 25 %. Based on these results, the BASt starts a large research program in 2012 to clarify the reasons for the damage and to derive measures to safely avoid further damage to concrete pavements.

Figure 1.1: Example of an ASR-damaged highway pavement section with typical crack pattern and discolorations around the joints, especially at the cross points

As a joint research group, the Bauhaus-University Weimar, the Ruhr-University Bochum and the Federal Institute for Materials Research and Testing were assigned with that task. In the following 5 years, a selection of 53 highway sections across Germany (Figure 1.2) were sampled, diagnosed and tested in many different ways. Additionally, all available data about the highway sections and concrete compositions were investigated and linked to the laboratory results. The present paper focuses on the developed method to estimate the ASR-related service life for concrete pavements.

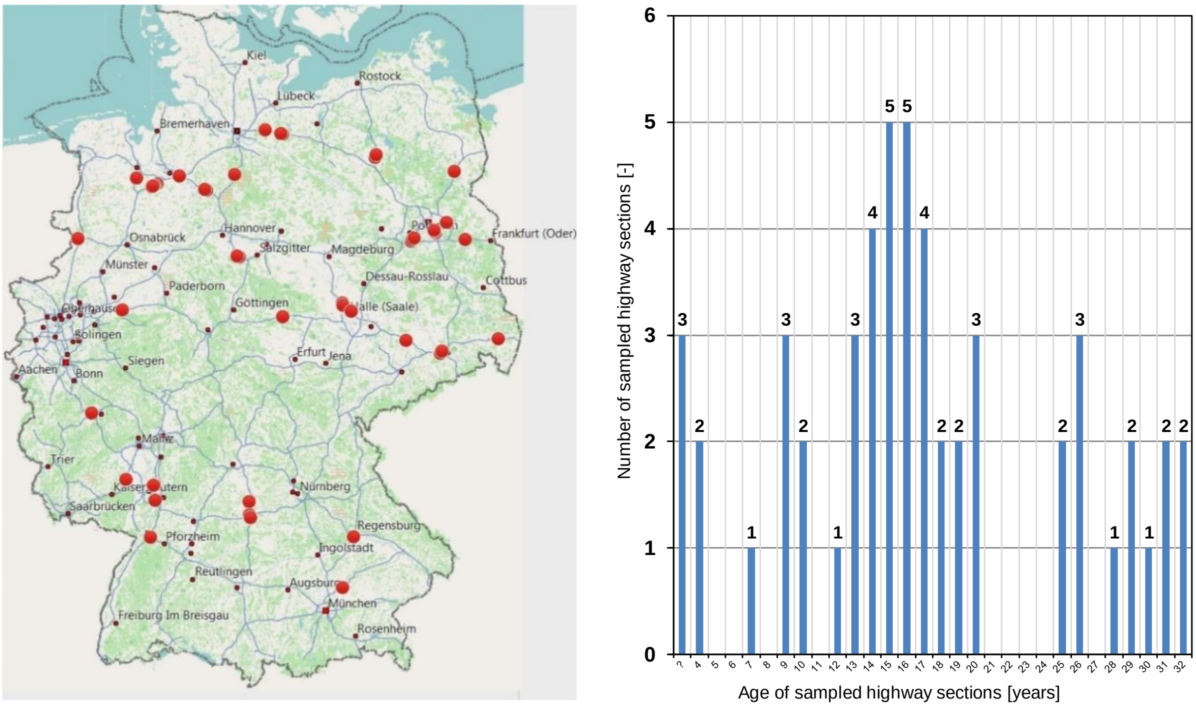


Figure 1.2: Locations (left) and age at the time of sampling (right) for the 53 sampled highway sections across Germany

2. MATERIALS AND METHODS

2.1 Selection and sampling of the highway sections

Overall, 53 highway sections across Germany were selected for the sampling (Figure 1.2, left). The selection was based on different criteria as visible signs for an ASR, service life, type of construction and used aggregates, i.e. the sections were not chosen randomly. For verification, 3 sections that were built after the introduction of the new advisory circular for concrete pavements in 2005 were sampled [9]. Until now, no damage could be detected on those sections. In total, 105 individual parameters as year and type of construction, type, origin and properties of the concrete raw materials, traffic load data, geographic characteristics, weather conditions during the placing and many more were tried to be collected for every section. However, for nearly 30 % of the sampled highway sections only limited or no data at all were available.

Among the 53 selected highway sections, 33 were built single-layered and 20 dual-layered with different concrete compositions in each layer. In total 71 different concrete compositions had to be investigated. About 15 cores of different diameter (Ø 100, 150 and 350 mm) were extracted from each section for different investigations. For the residual expansion measurements, 3 cores of Ø 150 mm were extracted from the single-layered pavements, each one from the centre of a truck lane slab. In case of the dual-layered pavements, 3 cores of Ø 350 mm were extracted, each one from the centre of a shoulder slab to prevent the traffic lane from damage (Figure 2.1).

Figure 2.1: Sampling of a large (Ø 350 mm) core from a shoulder slab

2.2 Climate simulation concrete prism test

Residual expansion measurements were performed with the climate simulation concrete prism test (CS-CPT). The CS-CPT was developed at the Bauhaus-University Weimar to test specific concrete compositions (job mixtures) for their ASR potential with the option to take external alkalis into consideration [1, 3-5, 7, 8, 13, 14]. Usually, concrete prisms (100×100×400 mm³) are cast, applied with a test solution (water, de-icer solutions etc.) and subjected to cycles of alternating temperature and moisture conditions.

One cycle runs for 21 days and consists essentially of 4 days of drying at 60 °C and ≤ 10 % relative humidity (RH), 14 days of wetting at 45 °C and 100 % RH and finally 3 days of freeze-thaw-cycling between +20 °C and –20 °C (Figure 2.2, left). Besides 3 initial sub-cycles between 5 °C and 65 °C within 12 hours, 3 more sub-cycles between +10 °C and –10 °C within 12 hours are done prior to the 6 freeze-thaw cycles in order to simulate rapid temperature changes that cause stresses in the prisms. The cycling is automated within a walk-in climate simulation chamber for a period of usually 9 months or 12 cycles (Figure 2.2, right). After every cycle the expansion and mass of the prisms are recorded.

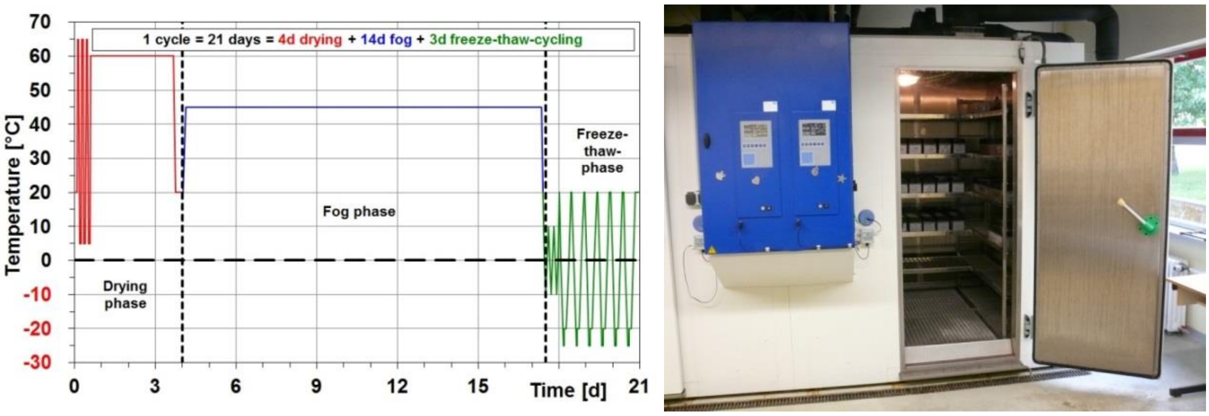
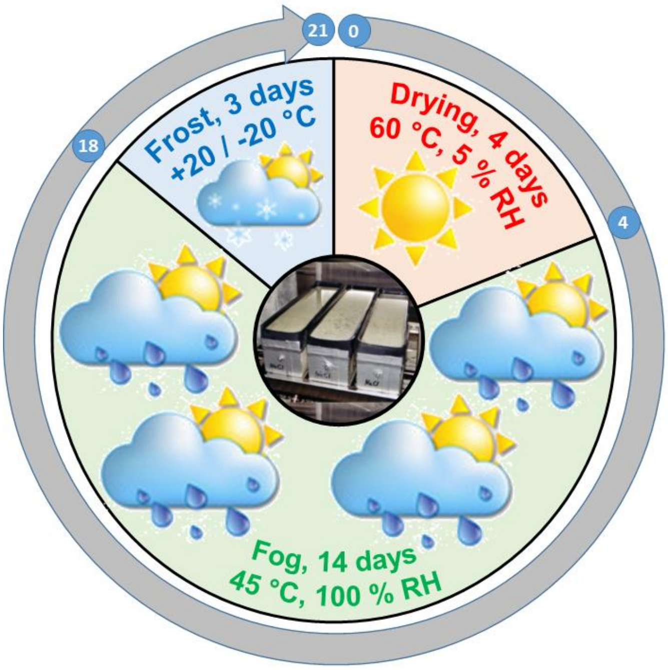


Figure 2.2: Temperature scheme of the CS-CPT (left) and open chamber with prisms (right)



Day	Action
0	**Start of the cycle** Begin of the **drying phase**
4	Zero readings for expansion and mass of the prisms (only after 1st drying phase, i.e. once in the 1st cycle)
	Application of water (reference) and/or de-icing solutions onto the prisms
	Begin of the **fog phase**
18	Transition into the **frost phase** (6 freeze/thaw cycles)
21	**End of the cycle** Readings for expansion and mass
0	**Start of the next cycle**

Figure 2.3: Schematic diagram of the 3 phases of a climate simulation cycle (12 cycles are required to evaluate the suitability of pavement concrete compositions with the CS-CPT)

Since prisms of the regular size could not be obtained from the highway sections, two alternative kinds of samples were prepared after a pre-storage of the cores at 20 °C and 65 % RH for about 6-8 weeks. For the single layered pavements, 3 cores (Ø 150 mm, l ≥ 250 mm) per section were cut lengthwise into halves and each 3 of them were exposed to water (control) and NaCl solution respectively (Figure 2.4, left). In case of the dual-layered pavements, 3 cores (Ø 350 mm, l ≥ 250 mm) per section were prepared in a way that 4 prisms (100×100×300 mm³) could be obtained, each 2 representing the top and bottom layer concrete (Figure 2.4, right). In total 12 prisms were obtained for the dual-layered pavements, each 6 representing the top and bottom layer concrete with 3 prisms each exposed to water (control) and NaCl solution respectively. In every sample 2 stainless steel studs are embedded for expansion measurements and a flexible foam rubber tape is glued around the edges of the upper side to form a guard that will retain the applied test solution later on.

At the end of the first drying phase the initial length and mass of the samples are measured at 20 °C and 300-450 g (depending on the surface area of the samples) of the test solution is applied to each sample for the first time. The test solution remains on the samples until the end of the cycle. After the cycle, the test solution is removed to measure length and mass of the samples at 20 °C and is replaced once the readings are obtained. During the second drying phase, the test solution evaporates, leaving behind dissolved substances as NaCl from the applied NaCl de-icer solution. At the end of the second drying phase new test solution is applied again on each prism. This routine is repeated until 10 cycles are completed. The NaCl de-icer solution was prepared at a concentration of 0.6 mol/l based on earlier studies [1, 7]. With some assumptions, the amount of NaCl that is applied within 8 cycles (about 2800 g/m²) corresponds to nearly the average amount of NaCl that is applied during one winter period in the field on German highways. The standard expansion limits are 0.4 mm/m for application of water (control) and 0.5 mm/m for application of de-icer solutions. The additional 0.1 mm/m in case of the de-icer solution treatment is due to an allowance for the higher expansion of the prisms caused by hygroscopically absorbed water. For residual expansion measurements, however, the limits are 0.6 mm/m for application of water (control) and 0.7 mm/m for application of de-icer solutions, adopted from [12].

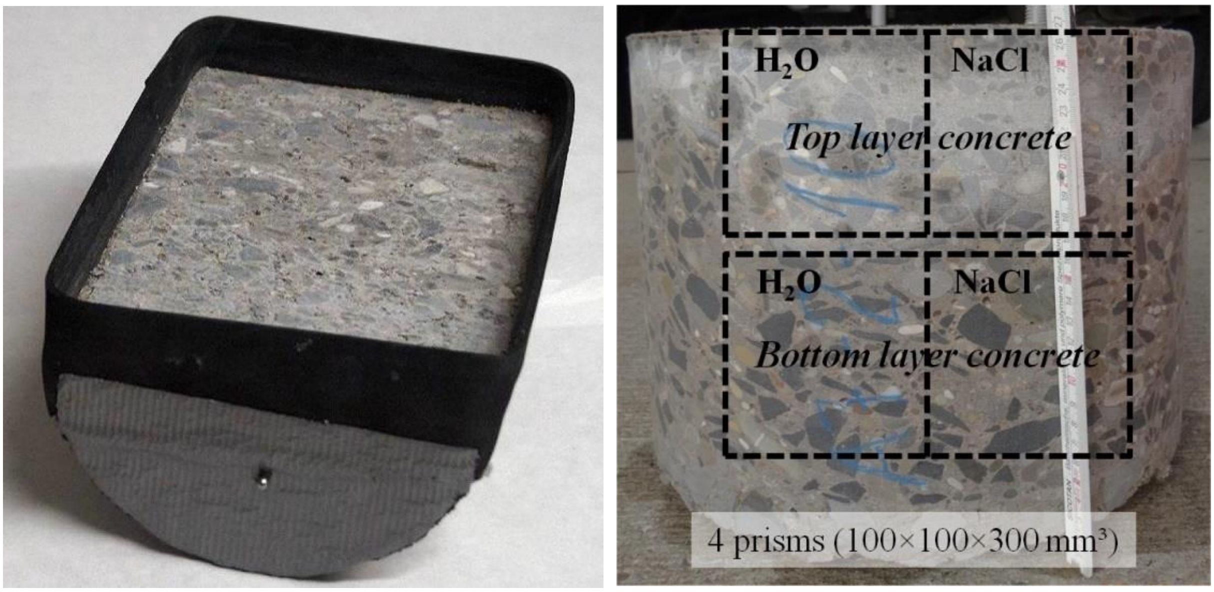


Figure 2.4: Samples for the CS-CPT, Ø 150 mm core half for single-layered pavements (left) and scheme for obtaining 4 prisms (100×100×300 mm³) from a Ø 350 mm core for dual-layered pavements (right)

3. RESULTS

The expansions for the samples exposed to NaCl solution during the CS-CPT range between 0.21 and 3.45 mm/m, representing very different ASR potentials from very low to very high (Figure 3.1). The expansions for the samples exposed to water (results not presented) are significantly lower, confirming the strong influence of externally applied alkalis in promoting ASR as reported earlier [1, 3-8, 10, 13]. In addition, the results for the samples exposed to water turned out to be helpful in identifying other durability issues as frost damage or delayed ettringite formation. This paper is focused on ASR for what in the following, the results for the samples exposed to NaCl solution are further analysed.

A major difficulty emanates from the different age of the concretes. A conventional evaluation of the results by assessing the expansions after a fixed testing period would not allow comparing the different concretes directly to each other or to estimate their remaining service life. Hence, an evaluation that considers the age of the concretes, which ranges between 4 to 32 years, was required.

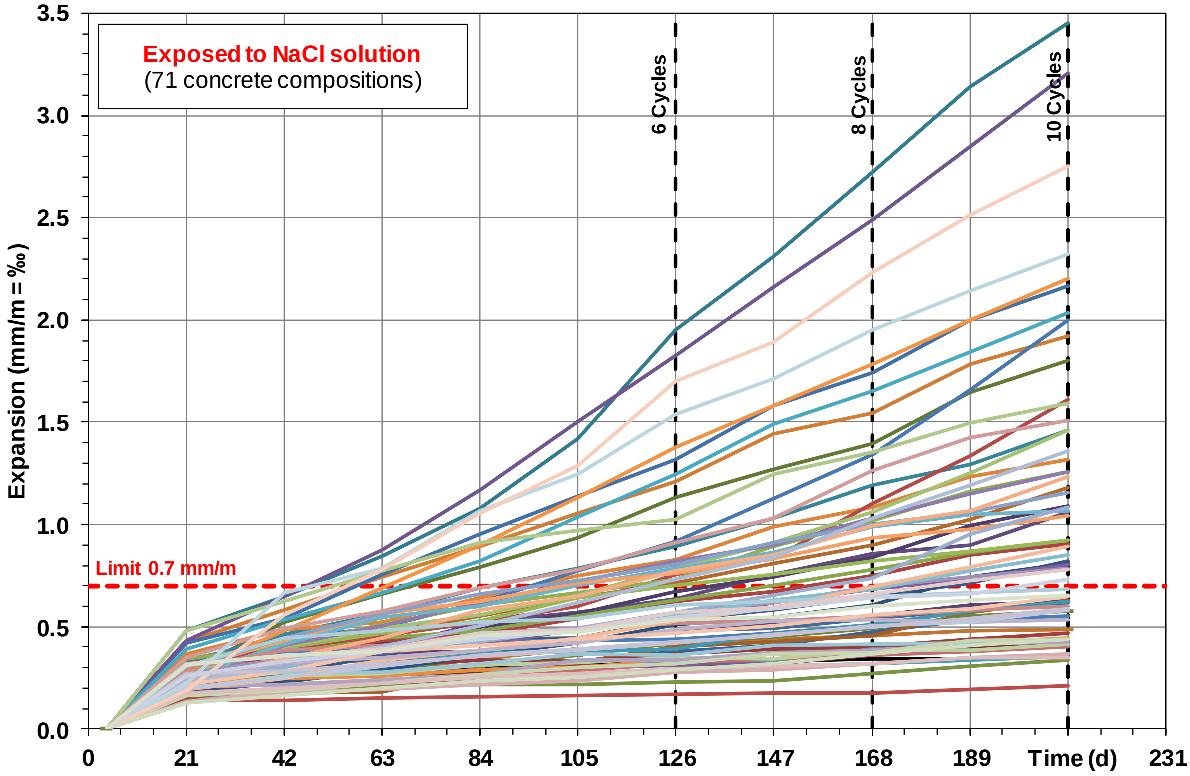


Figure 3.1: Expansions during the CS-CPT for the 71 different concrete compositions exposed to NaCl solution

Based on an earlier correlation between the CS-CPT and field performance [10, 13, 14], the testing period until reaching the acceptance limit (0.5 mm/m for lab concrete samples, 0.7 mm/m for field concrete samples) and the time when first damage (cracks) appeared in the field was plotted against each other. This could be done, however, for a very limited number (2) of concretes only because both field data as well as corresponding testing results were required. Another issue is the determination of the point in time when first damage appeared in the field which can be done only very roughly. Also, the pavements still can be in service for several years beyond this point, so it does not necessarily represent the end of its service life. Nevertheless, the available data were used for a first regression analysis together with the following 3 boundary conditions (Figure 3.2):

1. the 0/0 criteria, which defines the starting point,
2. the need for a testing period of 12 cycles to evaluate pavement concretes for the intended service life (in Germany) of about 30 years
3. and the observation in the field that the ASR in pavements often follows an exponential function, i.e. the pavements show no damage for many (8-12) years but often have to be replaced a few (2-5) years after the first damage appeared.

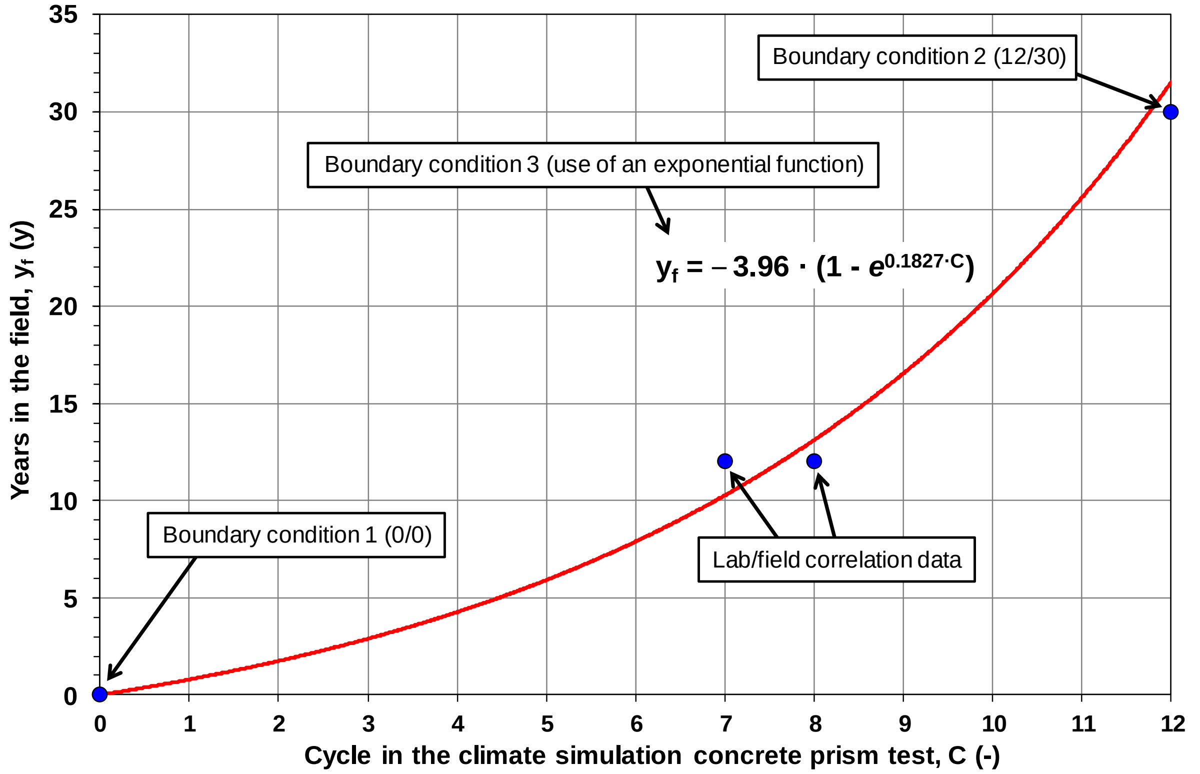


Figure 3.2: Exponential function for converting the cycles of the CS-CPT into an equivalent number of years in the field

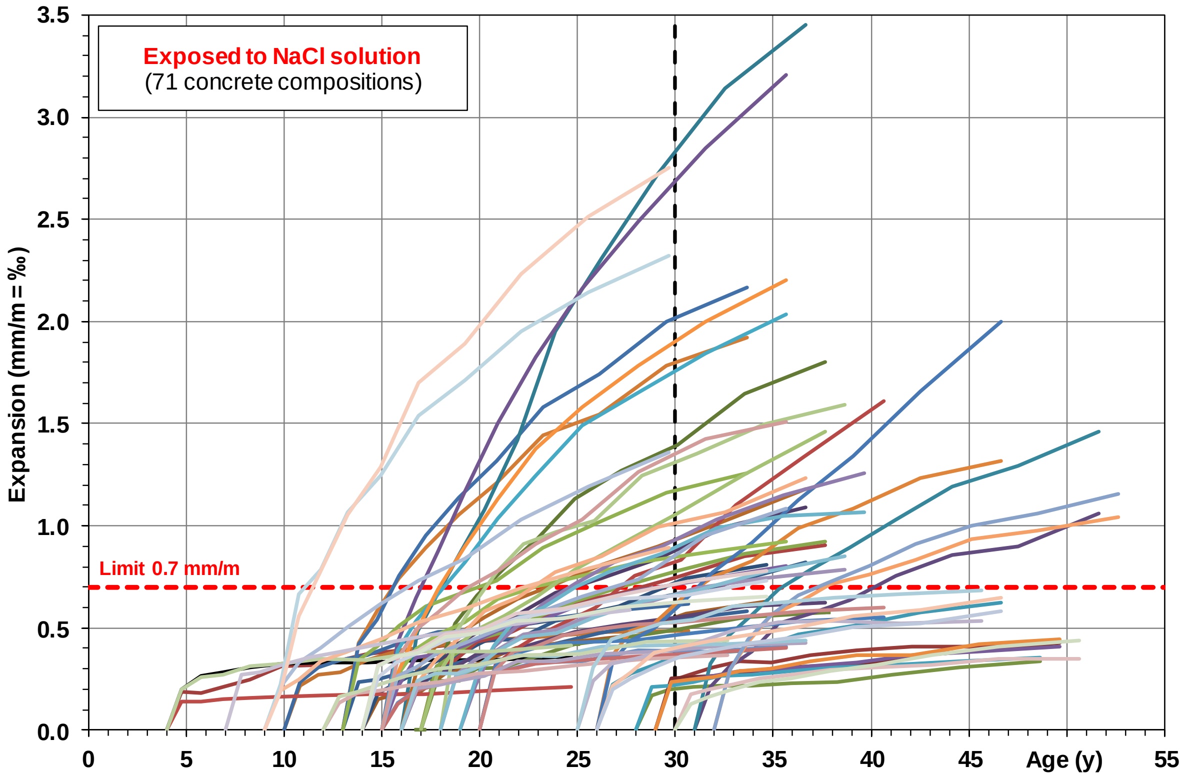


Figure 3.3: Expansions during the CS-CPT for the 71 different concrete compositions exposed to NaCl solution and considering the age of the concretes

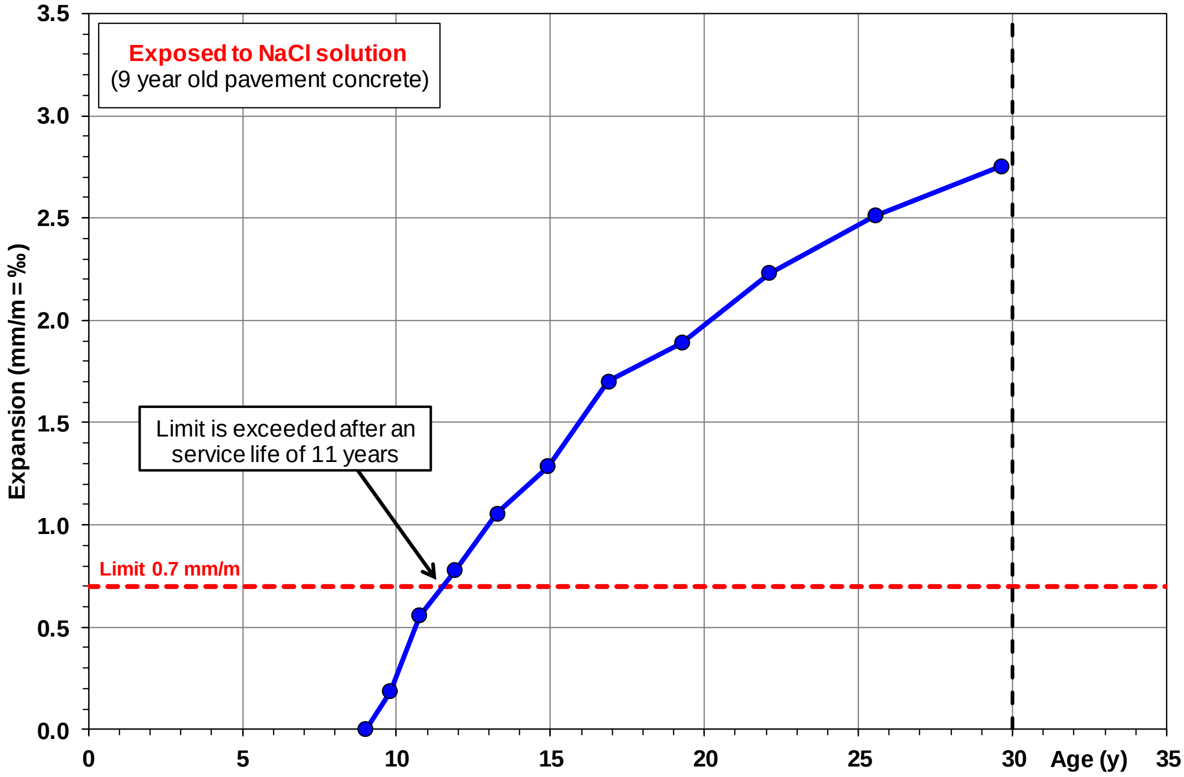


Figure 3.4: Expansion for a single-layer concrete (9 years old at the time of sampling) after converting the testing period of the CS-CPT into years in the field

The function that fits best to the data points and boundary conditions are shown in Figure 3.2 and was used in the project to convert the period of testing into a corresponding time in the field (Figure 3.3). By using the data from Figure 3.3, the service life could be estimated for every concrete individually. For example, a pavement built in 2004 (Figure 3.4) and 9 years old at the time of sampling shows a considerable expansion exceeding the limit after about 11 years, what would be around 2015. In fact this highway section was replaced in 2016.

The estimated service lives range between 11 to 51 years (Figure 3.5). In Figure 3.5, the start of the bars indicate the year of construction for the respective sections and its ends represent either:

- red bars: the approximate year ASR damage is expected before 30 years of service, based on the concrete expansion exceeding the limit in the CS-CPT before 30 years (Figure 3.3),
- green bars: the approximate year no ASR damage is expected for at least 30 years, but maybe later, based on the concrete expansion not exceeding the limit in the CS-CPT before 30 years (Figure 3.3),
- grey bars: the approximate year no ASR damage is expected based on the concrete expansion not exceeding the limit in the CS-CPT (Figure 3.3), but the testing period (10 cycles) was too short to test for a full 30 year service life.

In total, 51 % of the sampled highway sections would reach a service life of at least 30 years without ASR damage (Figure 3.6). For the dual-layered highway sections, the respective higher expansion from either the top or bottom layer concrete was used. Some of those sections were around 30 years old at the time of sampling and without any ASR damage. Consistently, only low residual expansions were measured in these cases and high residual service lives were obtained. Since the CS-CPT was stopped after 10 cycles, the estimation was restricted to a period of about 20 years. In many cases, however, the low expansions suggest an even longer service life without ASR damage. In some other cases, the expansions exceed the limit after 30 years, indicating a low but acceptable ASR risk. For the three younger highway sections built after 2005, the testing period was too short for an estimation of 30 years. However, the low residual expansions suggest that they will reach at least 30 years without showing ASR damage.

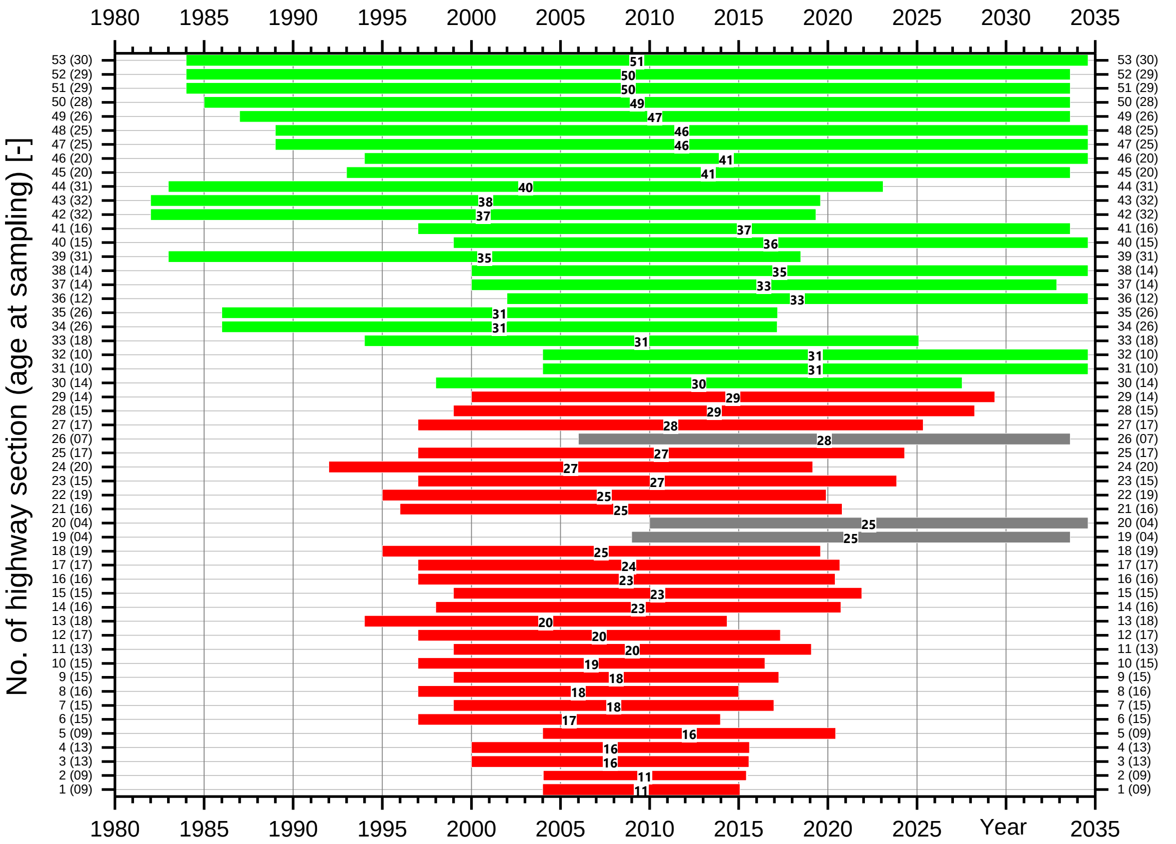


Figure 3.5: Estimated service lives (given years in the bars) for all 53 sampled highway sections

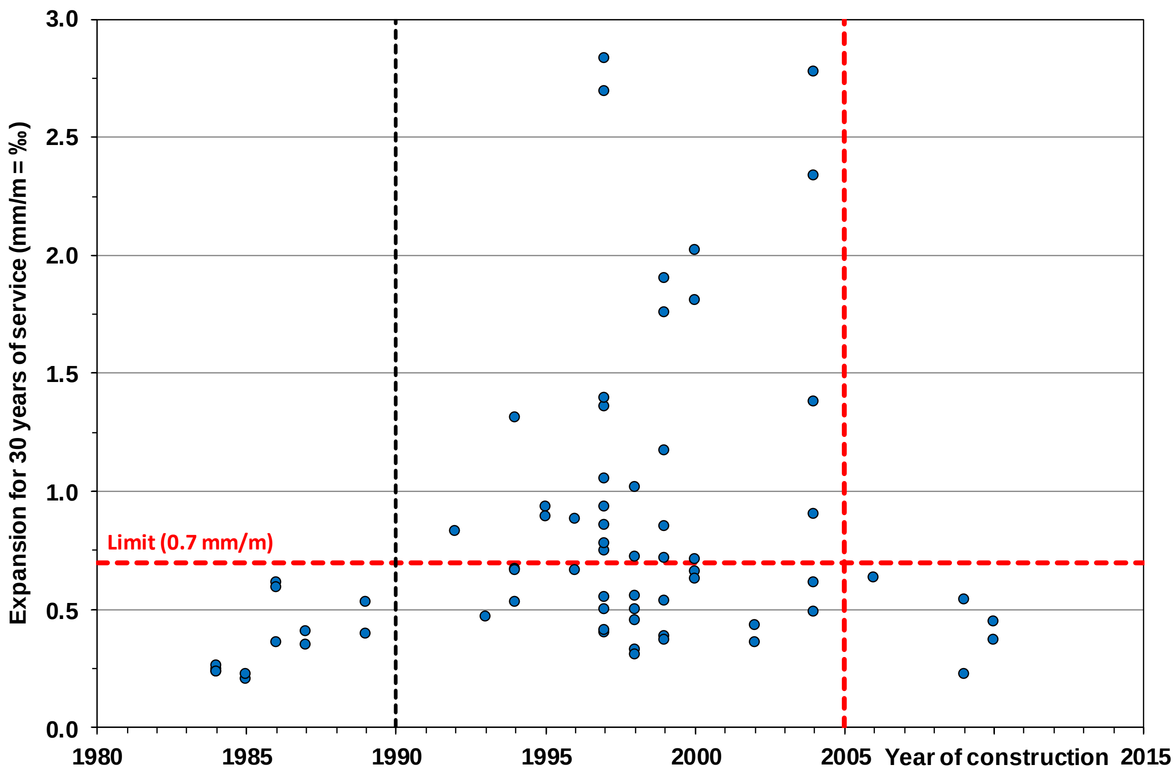


Figure 3.6: Comparison of year of construction and 30-year expansion exposed to NaCl solution for all sampled highway sections (sections ≥ 30 years old not included, in case of dual-layered highway sections, top and bottom concrete separately)

On the other hand, the results indicate that for 49 % of the sampled highway sections ASR damage is likely to occur before an age of 30 years (Figure 3.6). For some of them, ASR damage can be expected after about 11 years only. Those sections were built exclusively between 1990 and 2004, i.e. prior to the introduction of the advisory circular for pavements in 2005 and the availability of better test methods as the CS-CPT. For all the sections built before 1990 and still in good condition, the expansions nicely confirm a sufficiently low ASR potential. However, this does not mean in general that sections built before 1990 had no ASR issues at all, because there is no doubt that ASR affected sections from that time had to be replaced long ago and were not available anymore for the sampling.

It is important to note that the estimation assumes that the service life ends after the limit of 0.7 mm/m has been exceeded in the CS-CPT. However, this is a simplification and not necessarily true because it is unknown so far what exactly happens in the field to the pavement at the time the expansion limit is exceeded in the laboratory. Hence, at this point it is obvious that the actual service life will fluctuate several years around the calculated year. Also, every concrete composition is likely to have its very own conversion function, which depends on the alkali-reactivity of the aggregates, the alkali content, thy type of the binder and the exposure conditions (temperature, moisture, external alkalis etc.). Hence, the derived conversion function allows a very first, average conversion of the CS-CPT testing period into a corresponding lapse of time in the field, valid for pavement concretes with slowly reactive aggregates and exposed to externally applied NaCl. It is provided as a very first tool for better planning maintenance and repair measures in the field. A further monitoring of the sampled highway sections would help to verify the predictions and to refine the approach in the future.

4. CONCLUSIONS

In a 5 year study on behalf of the German federal highway research institute (BASt), 71 pavement concretes from 53 highway sections across Germany were extensively examined and tested regarding their residual ASR potential.

For an ASR related service life estimation of the sampled sections, an empirical approach for converting the period of testing into a corresponding lapse of time in the field was derived based on a natural exponential function. In the result, about 50 % of the sampled sections already have reached or are very likely to reach a 30 year service life without ASR damage. About another 50 %, however, are suspected to show ASR damage prior to a 30 year service life.

For highway sections built after 2005, a sufficiently low ASR potential was found. This confirms the effectiveness of the new regulations for preventing ASR in highway pavement concrete (ARS 04/2013) in Germany, introduced in 2005. For one highway section, a first agreement between the service life estimation and the field performance could be found. More highway sections will be monitored over the next years to obtain a greater data base to verify and further improve the approach. The derived service life estimation for highway pavement concretes is provided as a tool for better planning and conducting maintenance and repair measures in the field.

With the current state of knowledge and a consistent application of the CS-CPT, ASR damage can be reliably avoided when building new concrete highways.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of the Federal Ministry of Transport and Digital Infrastructure (BMVI) and the BASt and the fruitful collaboration with the project partners.

This report is based on the research project carried out at the request of the Federal Ministry of Transport and Digital Infrastructure, represented by Federal Highway Research Institute, under research project No. 08.2014/2011/LRB.

The authors are solely responsible for the content.

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