

Cracking in Concrete Pavements Due to Alkali-Silica-Reactions

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Abstract

In the last few years cracking has been observed in various concrete pavements in some regions of Germany. Besides restraint stresses due to restrained hygric and thermal deformation alkali silica reactions (ASR) can be relevant for this. Regarding ASR in concrete pavements special conditions have to be considered. In opposite to common structures the external supply of alkalis by deicing agents plays an important role on the ASR-development in concrete pavements. The ingress of those alkalis is intensified by microcracking, which is the result of millions of load cycles, affecting the microstructure. The relationship between microcracking, external alkali ingress, ASR and final cracking was studied in extensive investigations in situ and in the laboratory. These studies are of interest for researchers as well as for practitioners.

Introduction

Cracking in concrete pavements is one of the main problems, which can impair their durability. In many cases cracks are raised by restraint stresses e.g. due to the restraint of thermal or hygric concrete deformations. Beside this in various German regions cracking in concrete pavements is often associated with an alkali silica reaction (ASR) in the last few years.

In Germany about 1/3 of the 12,000 km highways are constructed with concrete (4,000 km). In about 10 % of the concrete lanes (i.e. 400 km) extensive cracking has been observed within about 5 to 10 years after construction. In most cases ASR-products could be proved in these concretes. These damages are mainly concentrated in Eastern regions, where especially greywacke and rhyolite have been used as coarse aggregates.

However, even if relevant ASR-products are detectable in appropriate samples, cracks rarely result solely by an ASR. Rather it has to be assumed, that cracks in concrete pavements are raised by a superposition of several stress impacts.

In order (to be able) to define adequate technological measures for avoiding critical cracking in pavements, it is necessary to identify the most significant sources first. In this context, it should be considered that cracks in concrete pavements are raised in the rarest cases only by one reason. In the majority superposition or at least interactions between different mechanisms are responsible (Breitenbücher 2006).

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Alkali-Silica-Reaction (ASR)

In the well-known alkali-silica-reaction amorphous silica (SiO_2) reacts with alkali hydroxide ions (NaOH , KOH) to an alkali-silica-gel, if simultaneously an appropriate amount of humidity is available. Normally the amorphous silica is brought in into the concrete by aggregates like opal, greywacke and rhyolithe due to their SiO_2 content, while the alkalis derive mainly from the cement. The main problem of the ASR is that the reaction product (ASR-gel) expands significantly due to the absorption of water.

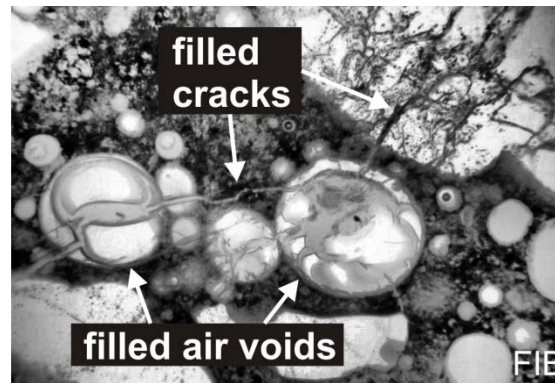


Figure 1. Voids and cracks in the matrix/ aggregates filled with ASR-gel

If this expansion is restrained to a large extent by the encircling concrete, an internal pressure up to 20 MPa can be raised in the surroundings of coarse aggregates (Stark et al. 2001). By such stresses, internal cracking can easily occur (Figure 1). Cracks due to an ASR are usually map-distributed and netlike in all three dimensions. So they are not limited only to the visible surface, but extend all over the concrete structure.

In normal concrete, such a hurtful ASR is avoided by the limitation of the alkali content in the cement. However, in concrete pavements also an external supply of alkalis plays an important role. In this context, the long-time behavior of the concrete microstructure under continuous cyclic traffic loads is important as well. Also these special aspects have to be considered, if the risk for damaging ASR-cracking in concrete pavements shall be minimized.

Impact of traffic on microcracking

Pavements are mainly stressed by traffic loads. Although the slabs are designed for this and do not fail for millions of load cycles degradation processes occur in the microstructure. Such effects can be proved by changes in the dynamic modulus of elasticity (E-modulus), which is normally determined by measuring ultrasonic wave run-times according to the following relation:

$$E_{dyn} = \rho \cdot \frac{(1 + \mu) \cdot (1 - 2\mu)}{1 - \mu} \cdot \left(\frac{s}{t}\right)^2$$

- s distance between transmitter and receiver, ($s = 0.15 \text{ m}$)
- t ultrasonic run-time
- ρ density of concrete $\rho = 2.35 \text{ kg/dm}^3$
- μ Poisson's ratio of concrete $\mu = 0.2$

The higher the decrease in the E-modulus, the higher the degree of already raised degradation. This could already be proved in appropriate tests of concrete

specimen under cyclic loadings. Even at upper stress levels between about 45 % and 70 % of the concrete strength, the dynamic E-modulus decreased significantly, which indicates degradation processes in the microstructure far before a final fatigue failure is exceeded (Figure 2).

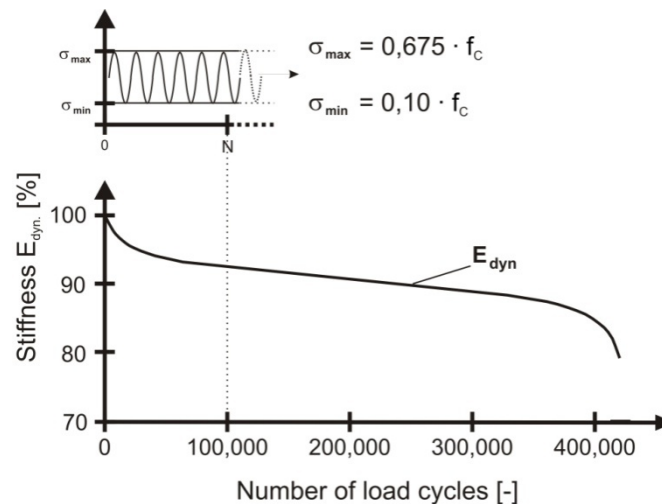


Figure 2. Decreasing stiffness (dynamic E-modulus) of concrete under cyclic load (Breitenbücher and Ibuk 2006)

Such degradation processes could also be proved in concrete pavements by comparing the dynamic E-modulus between different lanes. In appropriate tests ultrasonic velocities of Rayleigh waves were measured in situ at the surface of pavement slabs in shoulder, near side lane and passing lane of various German highways. With these Rayleigh waves only the relevant surface zone of about 50 to 70 mm is investigated. Thus, the influence of potential differences in the support can be neglected. Figure 3 shows relative dynamic moduli of elasticity within five sections of a highway, each in a distance of about 500 m, in which the dynamic E moduli of the near side lane and passing lane were related to the E-modulus of the shoulder (same concrete in all lanes). From the latter it is assumed to be nearly unloaded and thus it can be used as reference-basis.

The results demonstrate that the relative dynamic moduli of elasticity in the traffic lanes are approximately 10 % lower than the ones in the shoulder. This loss in stiffness can be attributed to the cyclic traffic loadings. Similar results were also obtained by analyzing other highways, thus they can be assumed representatively for concrete pavements of highways at all.

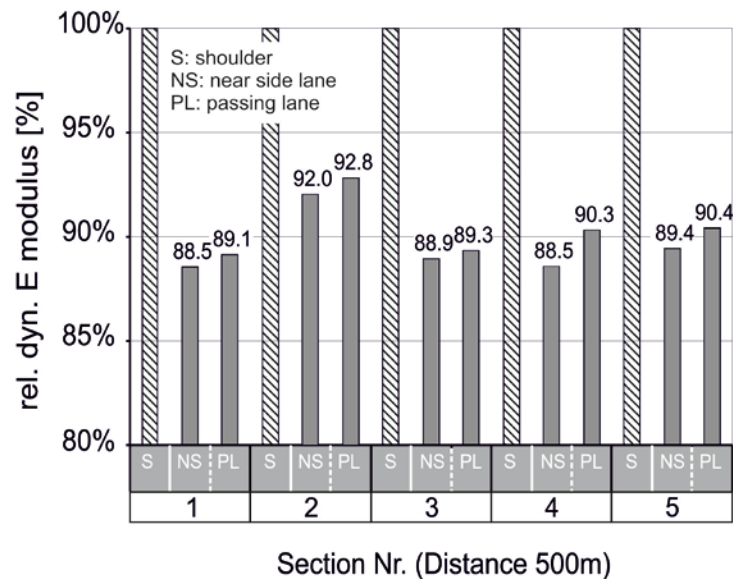


Figure 3. Relative dynamic moduli of elasticity in different highway lanes and sections

This degradation process and the formation of microcracks in the concrete microstructure could be proved also in microscopic images (Figure 4, Breitenbücher and Ibuk 2006). In unloaded concrete specimens ($N=0$, Figure 4 left) not any microcrack could be detected. In specimens of the same concrete mix multiple of such typical microcracks with a width of about 1 to 10 μm could be found after 600,000 load-cycles (Figure 4 right).

By such increasing microcracks the penetration of moisture, other liquids and also alkalis into the concrete structure is enhanced to a large extent. In this context, it has to be considered that in the past decades the volume of the overall traffic and in particular of the heavy traffic has drastically increased in most countries. The transported cargo volume in Germany increased from 80 billion ton kilometers up to 400 billion ton kilometers, i.e. by five times between 1970 and 2005. By this, also the dynamic/ cyclic loads and in consequence the stressing of the concrete microstructure are intensified significantly.

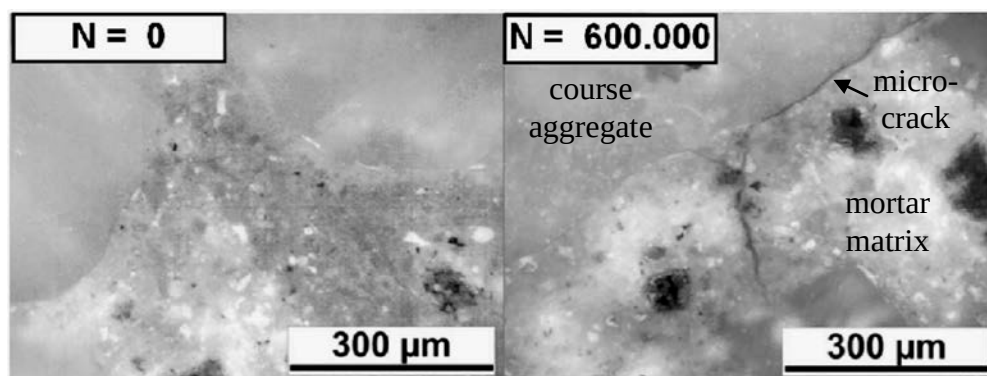


Figure 4. Increasing microcracking due to cyclic loading (Breitenbücher and Ibuk 2006)

Left: unloaded concrete without any failure

Right: typical microcrack ($w \approx 1 \dots 10 \mu\text{m}$) after 600,000 load-cycles in the bonding zone between coarse aggregates and mortar-matrix

External alkali supply to pavements

The production of the ASR-gel is mainly influenced by the amount of alkalis in the pore solution of the concrete. In the case of concrete pavements not only internal sources but also external sources have to be considered. In this context, the extensive supply of sodium by de-icing agents in winter – commonly sodium chloride (NaCl) is used – plays a decisive role for the risk of an ASR in concrete pavements.

In the last few years, there was a modification in the application of de-icing agents, too. In former times salt was dispersed, only when ice or snow were already present on the pavement. For some years these agents have been already applied, when such conditions were forecasted. By this way, the alkalis are in touch with the concrete surface in a stage at which the concrete is well absorptive. The absorption in the concrete is particularly enhanced by the above mentioned microcacks. Further the de-icing agents are pressed quite intensely into the concrete microstructure by the over rolling traffic. Hence, in combination with the prophylactic application of NaCl the external support of alkalis into concrete pavements currently is significantly intensified in comparison with the past.

Investigations of cracked pavements by analyzing of construction documents and testing on in-situ samples

Thermal Influences on cracking in concrete pavements To get more quantified information about the relation between degradation in the microstructure of concrete pavements, intensity of external alkali support and finally ASR in such members, extensive investigations were performed in Germany. The main motive for those tests was the fact, that only 8 to 15 years after construction in various regions an increasing number of concrete pavements with ASR-related damages have been observed.

Within the scope of these investigations more than 20 highway sections with a total length of 104 km and an average age of 14 years were selected for studies referring to the cracking causes. In these analyses sub-sections with and without cracking – map cracking as well as longitudinal cracks – within comparable conditions were included. In order to quantify the intensity of cracking, typical characteristics, e.g. the number of cracks per slab, the average width and length of cracks per slab and the cracking opening area – defined by the product of crack length and width per slab – were determined.

In addition to the evaluation of the crack formation the available construction documents, i.e. daily construction records, reports on initial tests and quality control tests, weather records etc. were compiled and evaluated with respect to probable effects on the noticed cracking. In this context, Figure 5 shows a representative correlation between air temperatures during concrete casting and the determined crack opening area.

From these analyses it can be deduced that even after 10 to 15 years in use nearly no cracking was observed in the pavements, if the temperature during concrete casting was below 15°C to 20°C. Exceeding this temperature range, i.e. if the concrete was placed in the summer season, the observed cracking increased progressively. This can be explained by the fact, that a higher casting temperature is combined with a higher temperature rise due to hydration heat. In consequence higher restraint stresses at an early age are induced. Even if they do not evoke cracks in the first few days, these stresses cannot be neglected and they are implemented in the concrete structure and also relevant in the subsequent history.

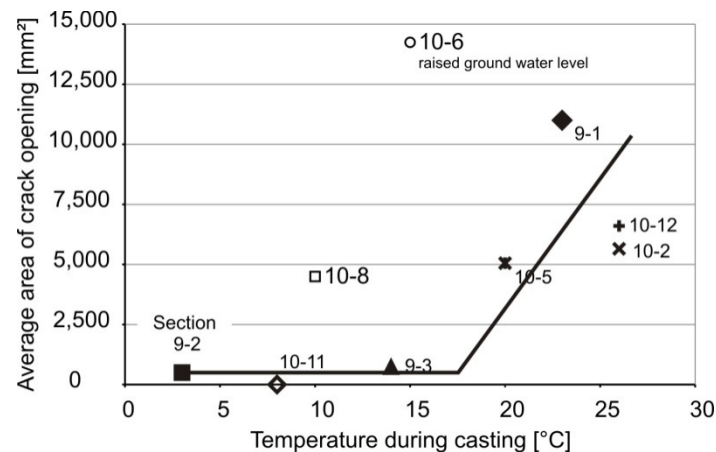


Figure 5. Influence of the air temperature during concrete casting on crack opening area

Specific ASR-Tests on Concrete Cores at 60°C – with and without external alkali impact

In most of the investigated pavements coarse aggregates had been used, which – according to the knowledge of today – are ASR-sensitive to a certain degree. Mainly these aggregates are greywacke, rhyolite and granodiorite, which can partially contain amorphous silica. To evaluate the residual ASR-potential within the inspected fields at least 6 specimens (cores) were sampled out of the investigated sections and tested by specific accelerated ASR-tests in the lab. To obtain information as soon as possible, the tests were performed in special climates at 60°C. In this context also the influence of an external alkali supply was considered. For this purpose the cores were divided into two parts lengthwise. One sub-specimen was stored constantly at 60°C above water according to the “AlkaliGuideline (2006)” (DAfStB 2006), which is very similar to the “RILEM Recommended Test Method TC 191-ARP AAR-4” (Rilem 2000). The second sub-specimen was exposed to following cyclic procedure:

- 6 days above water at 60°C,
- 1 day at 20°C,
- 5 days at 60°C in a dry air and
- 2 days immersed in a sodium chloride solution with a concentration of 0.6 mol/l.

With this regime the specimens were loaded for 16 cycles. During the complete test phase the deformations of the specimens were determined under both storing conditions (above water/ external alkali supply).

Even if no ASR takes place within the test procedure, deformations will occur to some extent only due to thermal and hygric effects. In the tests without external alkali supply those non ASR-related deformations can result in an expansion up to about 0.3 to 0.4 mm/m, in case of an external alkali supply an increase up to 0.5 mm/m can be assumed. Thus only deformations exceeding these values may be linked with an ASR and will be considered within the evaluation.

In Figure 6 the results of the deformation measurements (expansions) without (Figure 6, left) and with (Figure 6, right) external alkali supply are documented for three various highway-sections, each with a length between 2 and 6 km. The illustrated expansions are gained as the average of three cores each.

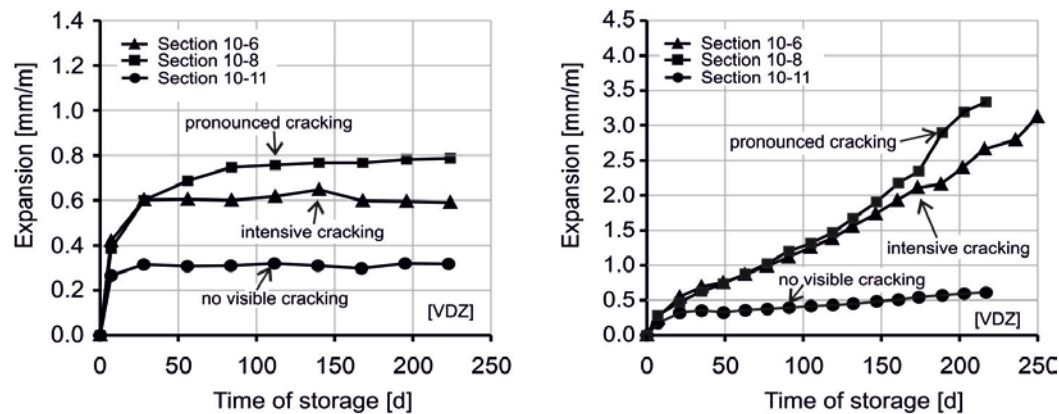


Figure 6. Expansion of drilled cores due to storage at 60°C
(average of three cores)
Left: without external alkali supply
Right with external alkali supply
(Attention: different scales at y-axis)

It can be identified, that within the first few days a considerable increase in deformation took place which can be mainly attributed to hygric swelling. In the case of pure moist storage the expansion came to rest after about 1 to 2 months. On the other hand, if alkalis were supplied to the specimens externally in each test cycle, the expansion increased continuously up to the end of the tests after 8 months. This can be explained only by a long running ASR. So the very important effect of an external alkali supply on the ASR could be proved. Similar effects have been observed also in other investigations (Stark et al. 2006).

Furthermore it became obvious that the expansions in cores, gained from cracked areas, were 3 to 8 times higher than those from non-cracked sections (Figure 6). As already mentioned above, it could be also proved by these tests that especially the ingress of externally supplied alkalis into the concrete structure is strongly influenced by the intensity of already implemented microcracks. In consequence also an intensified ASR can be expected finally.

Laboratory investigations on alkali penetration

In order to determine the impact of the degree of degradation in the concrete on the penetration of de-icing agents (NaCl) into the structure, further laboratory investigations were performed. Therefore 10 beams characterizing concrete pavements (140 x 40 x 27 cm³) were made of typical pavement concrete. These were cyclically loaded at an age of 28 days. The load applied simulated a superposition of stresses raised by restrained thermal deformations and traffic loads. This means, that the maximum stress $\sigma_{\max}$ corresponded to thermal restraint stresses, which appear due to casting of the concrete pavement in summer months. The amplitude of the cyclical load ($\sigma_{\max} - \sigma_{\min}$) characterizes the traffic load, which is raised by an over-rolling truck with an axle-load of 11.5 tons. Based on these configurations, the concrete beams were cyclically loaded for various cycles N (up to 5 million) with a frequency of 7 Hz in order to accelerate the test. The maximum stress $\sigma_{\max}$ amounted to 2.3 MPa, $\sigma_{\min}$ to 1.3 MPa. So $\sigma_{\max}$ corresponded to about 50% of the concrete flexural strength.

After various load cycles the dynamic E-modulus was determined in the same way as described above by measuring the ultrasonic velocity of Rayleigh waves at the

tensile zone of the concrete beams. All determined dynamic E-moduli were related to the E-modulus before starting the cyclic loading. By this relative dynamic E-moduli also the advance of the degradation process due to cyclic loading could be comprehended (Figure 7).

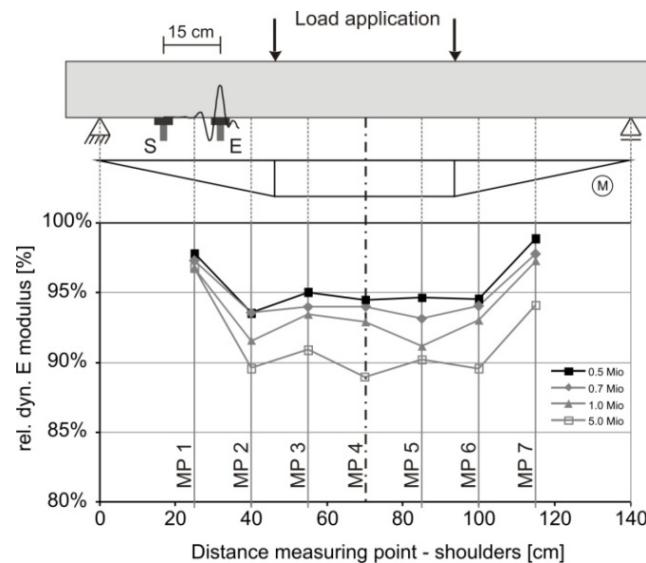


Figure 7. Decrease in the relative dynamic E-modulus in the tensile zone of tested concrete beams due to cyclic loading

Figure 7 demonstrates that the relative dynamic E-modulus decreased already within the first 500,000 load cycles to about 95%. In the following a further reduction continued even if not in the same intensity as before. This correlates with the well-known behavior under such loads, as it is also demonstrated by the so-called “S-curve” in Figure 2. After 5 million load cycles the relative dynamic E-modulus has been reduced to about 90 %, which is in the same range as observed in situ (see Figure 3). This can be related to an adequate degradation of the concrete microstructure.

In order to determine the influence of such degradations on the penetration of a NaCl-solution, further experiments were conducted. For this purpose a sodium chloride solution (3.0 w % NaCl) was pressed into the tensile zone of variously pre-damaged beams (0, 2 million and 5 million load cycles N) by tire passes (TP), where, at the wheel was additionally loaded with a weight of 1 ton (Figure 8).



Figure 8. Penetration-test of sodium chloride solution due to over-rolling tire

After 1 million tire passes 7 sub-specimens ($40 \times 10 \times 10 \text{ cm}^3$) were cut transversally out of the beam. These specimens were split in longitudinal direction (transversal axis of the beam) thereupon. Afterwards silver nitrate was sprayed on the split surface to detect the depth of chloride penetration by a color change ($c_d = 0.07 \text{ mol/l}$) (Figure 9).

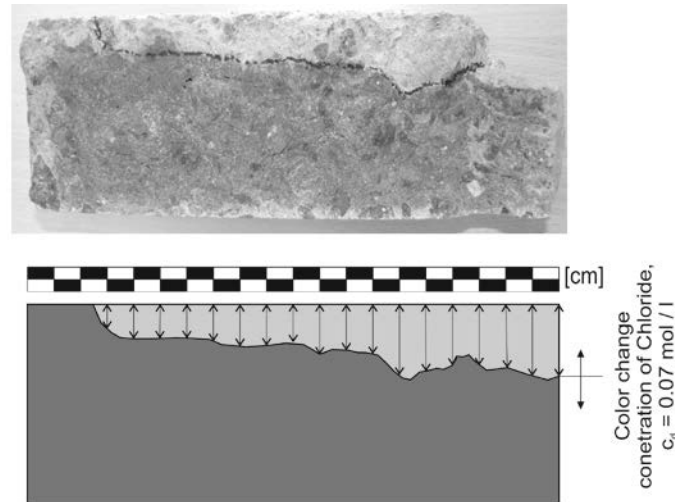


Figure 9. Depth of color change due to sprayed silver nitrate

Even if the silver nitrate test identifies only the presence of chlorides – the presence of sodium, which is relevant for the ASR, cannot be identified by this – this test is suitable for scanning large concrete specimens in a very short time. However, approximately it may be assumed, that the penetration of chloride and sodium are similar or even in line.

After measuring the penetration depth in steps of 10 mm a two-dimensional mapping was generated. In Figure 10 three penetration maps are shown exemplarily, which differ in pre-damaging ($N = 0$, 2 million and 5 millions of load cycles). The tire passing was 2 million in each case.

In the specimen, which were not pre-damaged ($N = 0$), the sodium chloride solution penetrated 19 mm (mean value) into the concrete due to the 2 million tire passes. In those cases with cyclic loads before the penetration depth of sodium chloride increased to 22 mm ($N = 2$ million load cycles) and 28 mm (5 million load cycles). Thus also by these tests the important influence of pre-damaging on the alkali ingress into the concrete microstructure could be proved.

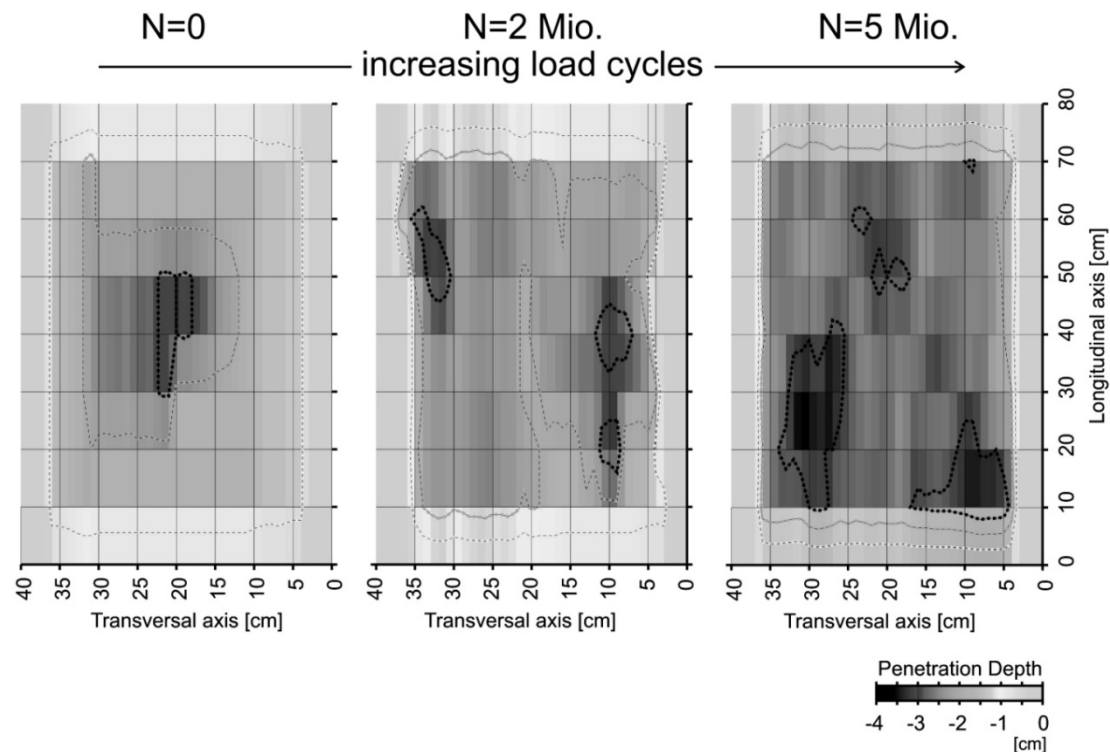


Figure 10. Penetration depth of the sodium chloride solution after 2 million tire passes

Final discussion and conclusion

Because of the multiplicity of potential causes for pavement cracking all possible influences have to be considered in order to reveal the relevant causes. As presented in Figure 5, the air temperature during concrete casting has already significant influence on the cracking of concrete pavements. With increasing pouring temperature higher temperature rise during hydration has to be expected, which results in increased restraint stresses. Thus, for prevention of extensive cracking it could be recommended (theoretically) to limit the fresh concrete temperature to about 20°C for casting. However, especially in summer such cannot be realized in practice in all cases.

Due to cyclic loads by the continuous traffic in combination with restraint stresses it has to be taken into account that in most cases concrete pavements show some microcracking. In combination with an external alkali supply by de-icing-agents in winter the risk for a damaging ASR is enhanced significantly in pavements in comparison to common concrete structures. This could be proved in the described investigations. These special effects have to be considered already in the design of pavements. To reduce the risk of ASR-damaging, on the one hand – beside cements with low alkali content – especially aggregates without amorphous silica (SiO_2) should be used. On the other hand, the stresses raised by the cyclic traffic can be reduced, if the slab is constructed larger in thickness. If the maximum stress at cyclic loading $\sigma_{\max}$ can be kept below about 40% of the concrete flexural strength also the degradation effects in the microstructure are minimized. By this, the important influence of microcracks on the external alkali ingress and in consequence the risk of an ASR can be reduced, too.

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