Degradation in pavement concretes - Effects of cyclic loading on fluid transport processes and ASR

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Abstract

The Alkali-Silica-Reaction (ASR) in concrete pavements has been known for several years. The previous investigations of ASR focused mainly on potentially reactive aggregates and the assessment of the ASR-potential in concrete pavements. A study of the separate influences causing and accelerating an ASR has been missing. The ASR can be greatly affected by externally supplied alkalis such as de-icing agents. These penetrate into the concrete microstructure, which is damaged through traffic. One focus within this extensive research project is the characterization of the degradation in the concrete microstructure caused by cyclic loading. Further focus lies on the determination of the effect of degradation on the transport behavior of fluids into the concrete. These studies show the degradation of the concrete microstructure under a varying number of load-cycles and changing stress levels. A significant increase in penetration depth of alkaline solutions was not only determined for different stages of degradation but also caused by overrolling tires, which increase the pressure on the surface locally. The externally applied alkali-ions then ingress and accelerate an ASR drastically. Thus, the superposition of these effects are greatly relevant for a damaging ASR. These studies are of interest for researchers as well as for practitioners.

Introduction

Concrete pavements are generally exposed to static as well as cyclic / dynamic influences. Therein, significantly different stress frequencies have to be considered. Due to changing climate conditions, thermally and hygrally caused deformations are inevitable. If those deformations are restrained, restraint stresses are caused depending on the degree of restraint as well as the stiffness of the structural component (Springenschmid 1984, Mangold 1994). These stresses change continuously with the varying influences. Here, it has to be differentiated between daily temperature changes (day - night) as well as seasonal temperature and moisture changes (summer - winter). In both cases these effects have to be considered as low-frequent.

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Next to these low-frequent influences, also high-frequent load-dependent stresses due to traffic can act on a concrete structure. Especially for concrete pavements - in the same manner also for wind energy plants – a high number in load cycles by traffic occur day by day. These effects have to be considered as high-frequent.

Generally, such cyclic influences do not cause macrocracking, which would lead to a fatigue failure of the structure. However, during these loads very fine cracks can form in the concretes microstructure, which may then lead to a gradual degradation of the concrete properties. Correspondingly, the stiffness of the concrete decreases (Breitenbuecher and Ibuk 2006, Ibuk 2008, Breitenbücher 2006), which can be measured non-destructively by comparative ultrasonic runtime measurements (Schubert 1999).

The extent of this degradation is on the one hand affected by the number of load cycles. On the other hand also the magnitude of the stresses is of importance. Generally this is considered as the ratio between the stress σ_o and the adequate strength f. In pavements where degradation occurs under compressive as well as tensile stresses the tensile properties are relevant. Therefore, the $\sigma_o/f_{ct,fl}$ - ratio is important. Herein, it is essential to superpose the actual stresses also with those already existing in the concrete such as remaining stresses caused by former hydration heat release (Springenschmid 1984).

From (Holmen 1979) it is known that at a stress-ratio $\sigma_o/f_{ct,fl}$ below about 40 % the microcracks do not result in macrocracks even after millions of load cycles. At a stress-ratio above 65 % a fatigue failure of the concrete may occur significantly earlier (already after a few 10.000 - load cycles).

Nevertheless, the formation of microcracks during cyclic loadings is of high importance for concrete pavements. Such microstructural degradation alters the penetration behavior of fluids into the concrete compared to undamaged concrete structures (Wittmann 2009). In general, the transport of water in porous media depends on the size, type and form of the pores or microcracks and also on the transport mechanisms and the physical laws (i.e. chromatography effect), that are effective in the respective pores / microcracks. Crucial for the fluid transport is next to the diffusion the capillary transport. By this way, dissolved alkalis penetrate much deeper into the interior of the concrete structure and can so increase the ASR-damage potential.

The penetration of alkalis into undamaged concrete structures and their effects on a damaging ASR have been sufficiently studied (Volkwein et al. 1991, Bérubé et al. 2000). However, the findings are not unambiguously. Usually, an increased alkali concentration in the concretes near-surface zone could be observed for specimens stored in a NaCl-solution. An ASR initiated as a result of that increased concentration could only be observed if the pH-value within the concrete was comparatively high (Bérubé et al. 2000, Stark and Wicht 2013). Thus, it was repeatedly proven, that the ASR-risk was significantly lower in concretes that used a cement containing ground granulated blast furnace slag(GGBS), because the latter

consume $Ca(OH)_2$ during the latent hydraulic and pozzolanic reactions and thus lower the pH-value (Stark and Wicht 2013, Dressler et al. 2010).

The influence of microcracks with widths between 1 and 10 µm on the alkali ingress and the hence resulting increased ASR have not been covered in the relevant studies because they were usually performed on undamaged specimens. Furthermore, orienting studies have shown that the penetration depth of alkalis is increased by overrolling traffic and correspondingly the ASR-potential is increased as well.

Experimental procedure

Degradation under cyclic stresses. In experimental studies large concrete beams measuring 180 x 50 x 27 cm^3 were cyclically stressed. All beams were produced with a typical pavement concrete mix corresponding to the German guideline "TL Beton StB 07". A cement CEM I 42. N was chosen. The maximum grain size was 22 mm. The concretes surface was textured by broom finish.

Within this research project a large-scale test setup was developed at the Ruhr-University Bochum for the simultaneous testing of up to six large concrete beams (Figure 1). The test setup is operated hydraulically. A large hydraulic cylinder introduces the pressure into the system where it is distributed to each of the six test positions so that it is ensured, that each beam is stressed with the same pressure and force resp.. The monitoring and controlling of the hydraulic pressure is realized through a pressure and force transducer on the main hydraulic cylinder as well as a pressure transducer on each of the testing positions. In order to transfer the hydraulic pressure into a load acting on the concrete beams, which are to be investigated, small hydraulic cylinders have specifically been designed. They allow the transfer of pre-defined pressures of more than 300 bar onto the concrete with a high frequency of 5 Hz despite the small stroke length of the cylinders. In several trial runs, the entire test setup was calibrated and it was proven, that each testing position is exposed to the same stresses.

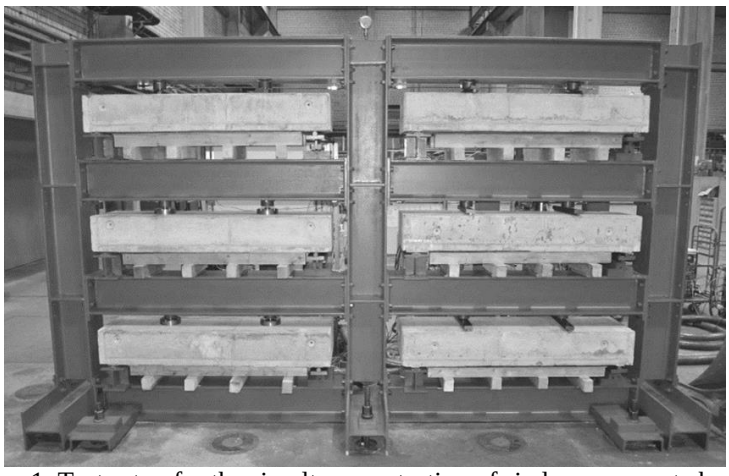


Figure 1. Test setup for the simultaneous testing of six large concrete beams

The cyclic stressing of the concrete beams took place at a minimum concrete age of 56 days and was realized in a four-point-flexural setup. The chosen upper and lower stresses herein represent different stress conditions of superposing loads acting in a concrete pavement. The slowly recurring thermal restraint stresses are to be superposed with high-frequent cyclic traffic stresses. Thus, a upper stress and a corresponding lower stress (σ_{max} and σ_{min}) can be derived from these boundary conditions. As a result of the cooling from the top (negative temperature gradient of 0.4 K/cm) a restraint stress of about 2.0 MPa forms on the concrete pavements surface. The overrolling of a 40-ton truck in the middle of the concrete slab additionally generates a flexural stress of approximately 1.0 MPa and thus acts relieving on the concretes top surface. Following, in this load combination the stress ratio amounts to $\sigma_{max}/\sigma_{min} = 0.5$ (Wittmann et al. 2009).

Even though the concrete slabs are doweled to the adjacent slabs the loading condition of cooling off from the top may result in a raising of the edges of the slab. Here, the concrete lifts even though just slightly from the ground. In this case the traffic load in the middle of the slab acts stress-increasingly. Correspondingly the maximum stress amounts to $\sigma_{max} = 3.0$ MPa and the minimum stress to $\sigma_{min} =$ 2.0 MPa respectively. Thus, the stress ratio becomes $\sigma_{max}/\sigma_{min} = 0.66$. In both cases the stress amplitude is 1.0 MPa.

Based on an average bending tensile strength $f_{ct,fl}$ for concrete pavements of about 6.0 MPa, in these load combinations stress-ratios of $\sigma_o/f_{ct,fl} = 0.35$ and $\sigma_o/f_{ct,fl} =$ 0.5 arise respectively. Due to the specimen geometry as well as dehydration effects, the actual bending tensile strength of the tested specimens amounts to approximately 4.0 to 4.5 MPa. For the conducted tests the stress ratio was adjusted in order to obtain the desired $\sigma_o/f_{ct,fl}$ - relation accurately.

Within this study the variations were as follows:

- Maximum stress to bending tensile strength ($\sigma_o/f_{ct,fl} = 0.35; 0.50; 0.60$)
- Number of load cycles (N = 0; 1.0; 2.0; 5.0 million)

Ingress and transport of fluids. In a first step, investigations were carried out on undamaged concrete specimens. These test series were performed similar to the water penetration test of the European standard EN 12390-8 at an external water pressure of 5 bar. Therefore, separate specimens measuring 200 x 200 x 120 mm³ were produced. Differing from the European standard, the specimens were taken out of the test setup after 0.5, 1, 2, 4, 8, 24, 48 and 72 hours of water exposure and then split in two pieces. Then the penetration depth was determined on the cracked surface.

Additionally, specimens with a defined damage were produced in reference to (Marsavina et al. 2009) and then tested for the penetration behavior of water. In order to create a defined crack in the specimens surface a thin metal sheet of different thicknesses (0.2, 0.3 and 0.5 mm) was fixed in the formwork and later removed from the concrete 4 hours after casting. The generated “cracks” ran linear across one surface of the specimens that was later on subjected to the water pressure and had a

constant crack depth of 20 mm. These specimens were tested at an age of 28 days and exposed to an external water pressure of 5 bar for 8 hours.

The microstructural degradation also effects the penetration behavior of fluids into the concrete. In order to quantify that behavior, small specimens were cut from large concrete beams previously damaged in the four-point-flexural-setup. For reference also a sample was obtained from an undamaged section. On these samples the water uptake was measured using a horizontally applied Karsten-tubes.

The ingress of alkali solutions in concrete pavements in situ does not only take place through the capillary suction, in fact it is vehemently increased by the overrolling traffic (overrolling tires). In order to capture this effect efficiently, a test setup has been developed at the Ruhr-University Bochum within this research project.

In this test setup, the as mentioned large concrete beams are arranged in a circular array (Figure 2). They can be overrolled by six tires consecutively and allow an efficient testing procedure despite a high number of overrollings. The top surface of the beams was previously exposed to the flexural tension in the cyclic four-point-flexural setup. While the beams are being overrolled a sodium-chloride solution (usually 5%-NaCl) is on top of the beams. The tires are additionally equipped with a dead weight of up to one ton to represent nearly actual loads exposed per tire on a concrete pavement. Since the solution is overrolled only within the track width of the tires, the adjacent areas experience a solely capillary solution uptake. This allows for a comparative assessment of the two types of liquid penetration into the concrete.



Figure 2. Test setup for the simultaneous overrolling of six large concrete beams with a sodium chloride solution on top

Experimental results

Degradation. The microstructural degradation, that develops during the cyclic loading of the concrete beams is assessed through ultra sonic runtime measurements at the surface acoustic wave (Rayleigh-wave) when the stress is entirely relieved from the specimens. The measurements are conducted on the surface exposed to

tensile stress. Based on these results, the relative dynamic E-Modulus is calculated. The higher the loss in this parameter, the more microcracks and thus the more microstructural alterations can be assumed within the concrete beams. These non-destructive measurements have been performed after exposure to different numbers of load cycles.

Figure 3 shows the progress of the relative dynamic E-Modulus under different stress-ratios as well as over the course of different load cycles. As expected, the decrease in the E-Modulus was higher with higher stress-ratios. After five million load cycles, the remaining relative dynamic E-Modulus amounted to about 91 % for a stress ratio of $\sigma_o/f_{ct,fl} = 0.35$ and to about 87 and 75 % for $\sigma_o/f_{ct,fl} = 0.50$ and $\sigma_o/f_{ct,fl} = 0.60$ respectively.

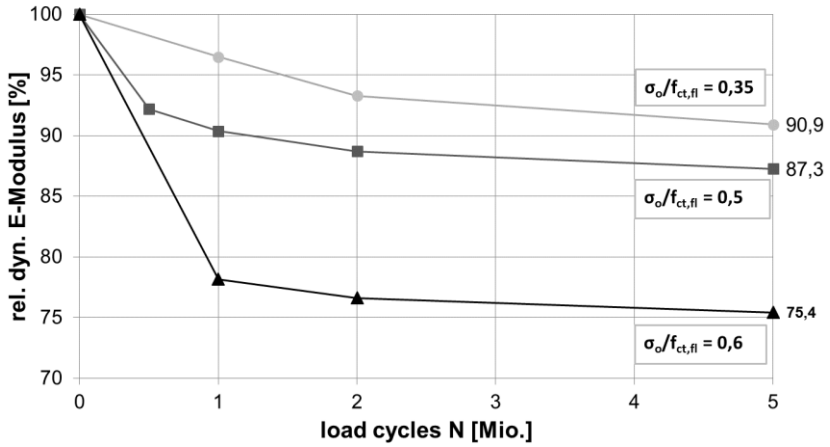


Figure 3. Decrease of the rel. dyn. E-Modulus on beams after 5 million load cycles and different stress-ratios

As can be seen in Figure 3, the most significant degradation that is assessed through the ultrasonic measurements takes place within the first load cycles. Figure 4 shows the decrease of the relative dynamic E-Modulus also after 10, 100, 1.000, 10.000, 100.000 and 250.000 load cycles at a stress ratio of $\sigma_o/f_{ct,fl} = 0.60$. It is obvious, that the formation of microcracks within the first load cycles is of great significance with respect to the further development of microstructural degradation under higher load cycles.

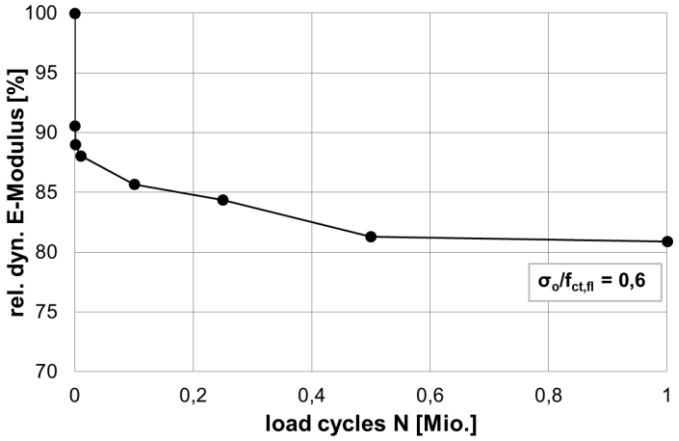


Figure 4. Decrease of the rel. dyn. E-Modulus on beams after 1 million load cycles under a stress-ratio of $\sigma_o/f_{ct,fl}$ = 0.60

In Figure 5, the relative dynamic E-Modulus is illustrated exemplary over the length of the beam. It can be seen that corresponding to the arrangement of the load points in the four-point-flexural setup (40 and 120 cm from the bearing) the loss in the E-Modulus between those two points is constant yet higher than in the points closer to the bearing support. For this reason, even within one large concrete beam different stress levels can be investigated.

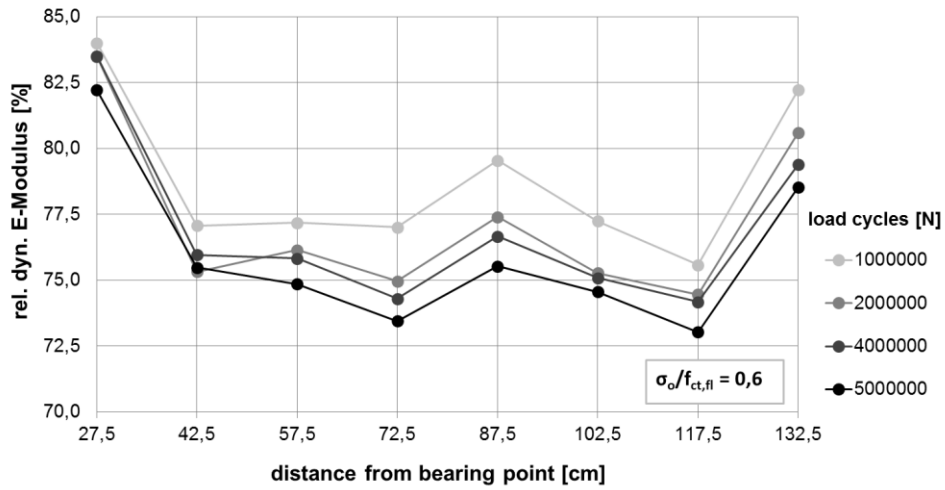


Figure 5. Decrease of the rel. dyn. E-Modulus over the length of the beam under a stress-ratio of $\sigma_o/f_{ct,fl}$ = 0.60

Since the exposure to the flexural stress can take place in any of the six test positions within the test setup, different positions with the same stress-ratios are illustrated in Figure 6. It becomes apparent, that the hydraulic pressure distributes uniformly throughout the testing positions and therefore the introduced damage is reproducible regardless of the position.

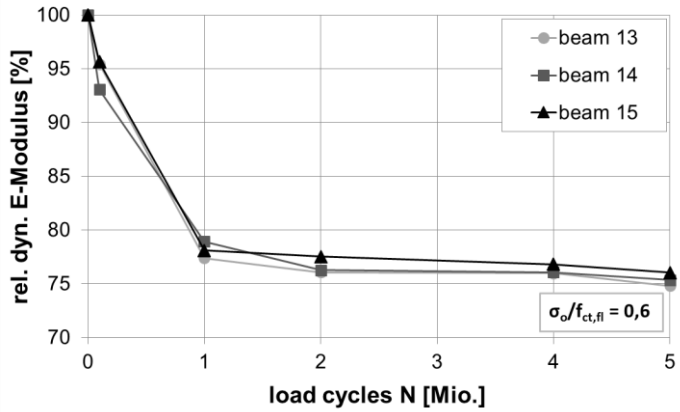
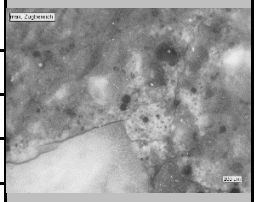


Figure 6. Decrease of the rel. dyn. E-Modulus under a stress-ratio of $\sigma_o/f_{ct,fl} = 0.60$ for three different testing positions

After the final load cycle was completed, polished thin sections (6.0 x 10.0 cm²) where extracted from the large concrete beams in order to conduct a microscopic analysis of the crack characteristics. The thin sections were prepared parallel to the surface exposed to the tensile stress. In an area of 5.0 x 5.0 cm², the number of microcracks, the crack width, crack length and crack area (crack width x crack length) were determined.

The microscopic investigations showed a significant difference between samples from the area of maximum tensile stress and samples from the undamaged reference area above the bearing support. Table 1 displays the corresponding crack characteristics. Especially the number of cracks as well as the total crack area increased in the pre-damaged samples by factor 3. It furthermore is notable that the crack width and crack length remained rather constant at about 5 µm and 1.5 mm respectively. It can be concluded, that the increasing degradation results from an increasing number of new cracks rather than a widening and spreading of already existing cracks.

Table 1. Crack characteristics

		Predamaged (full stress)	Undamaged (Reference area)	Microcrack (ITZ)
Number of cracks	**[-]**	403	174	
Total area	**[µm²]**	3.500.000	1.500.000	
Average area	**[µm²]**	8.520	8.610	
Average width	**[µm]**	4,56	5,15	
Average length	**[µm]**	1504	1569	

Transport and ingress behavior. The fluid transport into undamaged concrete specimens under pressure (5 bar) showed a rapid increase of the penetration depth

within the first four to eight hours of exposure to the external water pressure (Figure 7). In this time, the penetration depth reaches 20 to 30 mm. The penetration curve then increases slowly but steadily. Thus, it can be assumed, that the externally applied pressure reduces itself in the pore system of the concrete sample within the first 20 to 30 mm so that afterwards only capillary suction is responsible for the further increasing penetration depth.

Additionally, Figure 7 illustrates the penetration depth of specimens with an induced artificial crack after an exposure to externally applied water pressure of eight hours. Regardless of the width of those artificial cracks it seems, that the maximum penetration depth of those specimens increases by approximately the depth of the induced cracks. In this case by about 20 mm.

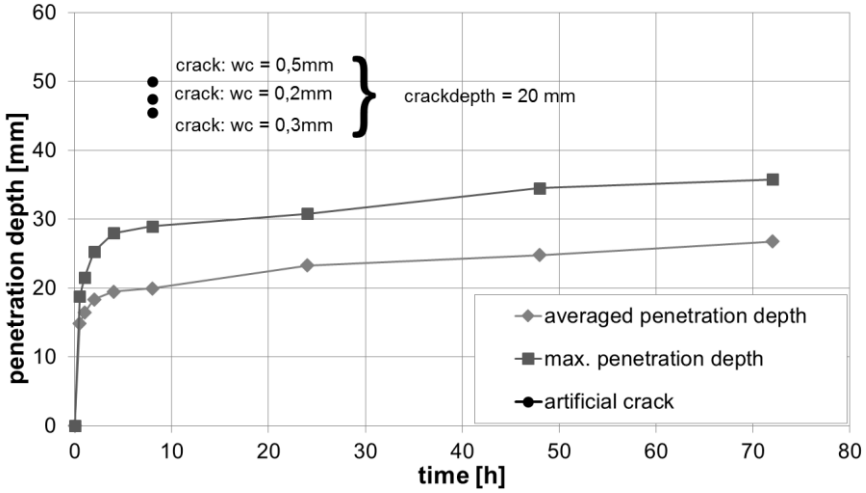


Figure 7. Water penetration depths in undamaged specimens and specimens with an artificial crack

The penetration of water into undamaged concrete specimens depends greatly on the externally applied pressure, which acts at the concrete's surface. Figure 8 compares the water uptake under pressure with the water uptake only due to capillary suction (0 bar). The penetration under pressure is as expected significantly faster and higher than that of capillary suction. Within the first hours of testing, both curves run steeper than in the consecutive hours. Concluding, the resistance against water penetration is lower in the near-surface area of the concrete specimens.

One focus within this study lay in the numerical modeling of the alkali ingress into the concrete microstructure. Figure 8 illustrates the numerical models describing the water uptake, both under pressure and in capillary suction (Przondziono et al. 2015). It can be seen that the numerical model and the experimental results are in a satisfactory agreement.

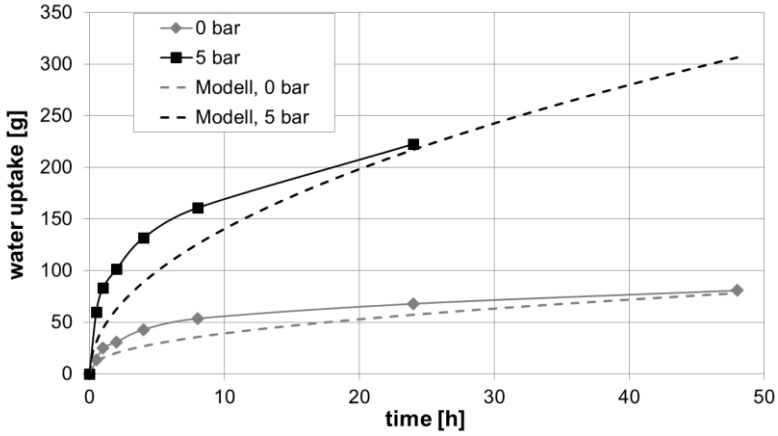


Figure 8. Water uptake in undamaged specimens under pressure (5 bar) and in capillary suction (0 bar)

Figure 9 compares the water uptake in undamaged and predamaged concrete samples. The depicted curves show the water uptake for the predamaged area of a beam that has been cyclically loaded before in the four-point flexural test setup and the undamaged reference area of that beam above the bearing support. The water uptake was assessed with horizontally applied Karsten-tubes. The figure shows, that water penetrates into predamaged concrete significantly faster than into undamaged concrete.

Herein, also the numerical models are depicted and display a satisfactory agreement with the experimental results.

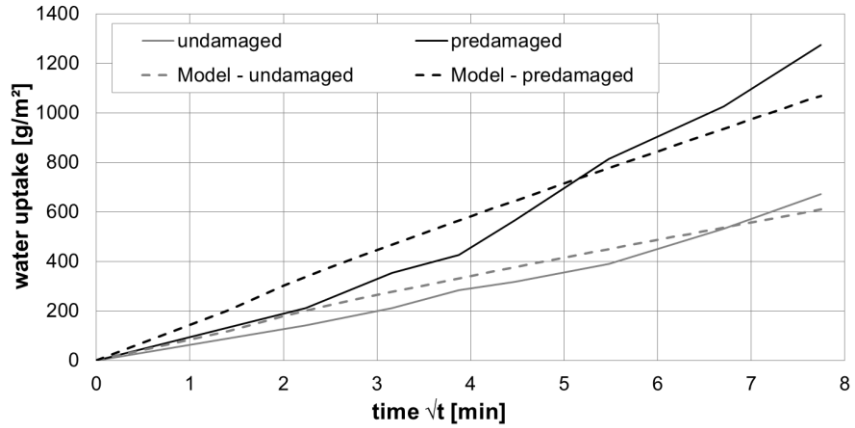


Figure 9. Water uptake in undamaged and predamaged specimens through a Karsten-tube

Final discussion and conclusion

The presented results showed a distinct influence of cyclic mechanical loadings on concrete due to microstructural degradation on the penetration behavior of liquids into the porous concrete and therefore on the potential of an intensified damaging ASR.

The dependence of the degradation on the number of load cycles and especially on the ratio of maximum stress acting on the concrete to its bending flexural strength becomes obvious by the accompanying ultrasonic measurements. Additionally, the degradation could be characterized by microscopic analysis of the crack characteristics.

Different investigations on the penetration behavior of water into concrete showed a significant influence of the externally applied pressure on the overall water uptake as well as the penetration depth. Furthermore, concrete that was previous subjected to tensile stresses showed a deeper penetration depending on the amount of damage that has been induced into the concrete.

Lastly, the numerical models that have been developed within this research project show a satisfactory agreement with the results of the experimental studies and

can therefore be used as basis for a model, which simulates the entire interaction of influences that may lead to an intensified damaging ASR in concrete pavements.

Acknowledgments

The authors are grateful to the German Research Foundation (DFG) for the financial support of this research project. The authors wish to acknowledge the cooperation with the Institute for Structural Mechanics of the Ruhr-University Bochum, the Federal Institute for Materials Research and Testing, Berlin, the F.A. Finger-Institute for Building Materials, Weimar and the Institute for Concrete Structures and Building Materials, Karlsruhe for the outstanding work since the foundation of this research group in 2012.

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