Acta Polytechnica CTU Proceedings **33**:45–51, 2022
https://doi.org/10.14311/APP.2022.33.0045

SUSTAINABILITY OF CONCRETE PAVEMENTS CONSIDERING TRAFFIC AND DE-ICING AGENTS

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Abstract.

In concrete pavements, special conditions, that increase the likeliness of damaging reactions, as for example an alkali-silica reaction (ASR), prevail. Especially to the superposition of microstructural degradation caused by cyclic loading with an external alkali supply can influence the sustainability negatively. Concrete pavements are subjected to cyclic loadings by traffic and climate changes. These cause microcracks (about 5 μm) within the concrete matrix during service. Additionally, an ASR in pavements is promoted by externally supplied alkalis (de-icing agents). By superposition of both effects the alkali capacity close to the ASR-reactive aggregate aggregate is increased substantially as the externally supplied alkalis can easily penetrate through the microcracks. Thus, both effects intensify the ASR in concrete pavements. Within cooperative research projects the different interdependent influencing factors for a damaging ASR in concrete pavements are studied by experiments as well as by numeric modelling. On the micro-level the ASR-related processes within the aggregate, such as gel-formation or ion-transport, are investigated. On the meso-level, the project focuses on the characterization of degradation effects in the concrete microstructure due to cyclic loading. Further, special attention is paid to the transport behavior of fluids in such pre-damaged concrete structures. A significant increase of the penetration depth of alkaline solutions could not only be observed at different stages of progressing degradation. It becomes also obvious that the ingress of externally supplied alkalis is enhanced by the overrunning traffic. Finally, on the macro-level, the risk of an ASR-damage is assessed.

Keywords: Degradation, durability, transport.

1. Introduction

Concrete pavements are subject to static, cyclic and dynamic influences. In order to assess theses loads, different stress frequencies should be considered. Due to changing climate conditions, thermally and hygrally-induced deformations are inevitable. If those deformations are restrained, restraint stresses are caused that depend both on the degree of restraint and on the stiffness of the structural component [1**?**]. These stresses are changing when exposed to varying influences. In this context, it has to be distinguished between daily temperature changes (day - night) and seasonal temperature and moisture changes (summer - winter). These effects are characterized as low-frequent. Apart from these low-frequent influences, high-frequent load-dependent stresses due to traffic also act on a concrete structure. Especially concrete pavements - and likewise wind energy plants - are exposed to a high number of load cycles day by day. These effects should be considered as high-frequent. Such cyclic influences only rarely cause macrocracking, which would lead to a fatigue failure of the whole structure. However, due to these loads fine cracks might form in the concrete's microstructure, which may then lead to the gradual degradation of the concrete properties, while, at the same time, the material's stiffness decreases [2–4].

Comparative ultrasonic runtime measurements are an appropriate non-destructive method to assess these effects [5].

The extent of degradation is dependent on two factors: the number of load cycles and the magnitude of stresses. This relation is usually described as the ratio between the stress σ_o and the adequate strength f. In pavements, in which degradation is caused by compressive as well as tensile stresses, the tensile properties are more relevant ($\sigma_o/f_{ct,fl}$). At the same time, it is essential to superpose the actual stresses with those that are already active in the concrete itself, i.e. residual stresses caused by former hydration heat release [1].

As suggested by Holmen [6], at a stress-ratio of $\sigma_o/f_{ct,fl}$, below approx. 40 %, microcracks will not turn into macrocracks, even after millions of load cycles. At a stress-ratio above 65 %, fatigue failure of the concrete may occur considerably earlier (already after a few 10.000 load cycles).

Nevertheless, the formation of microcracks due to cyclic loading plays a crucial role for the durability of concrete pavements. As compared to undamaged concrete structures, such microstructural degradation alters the penetration behavior of fluids into concrete

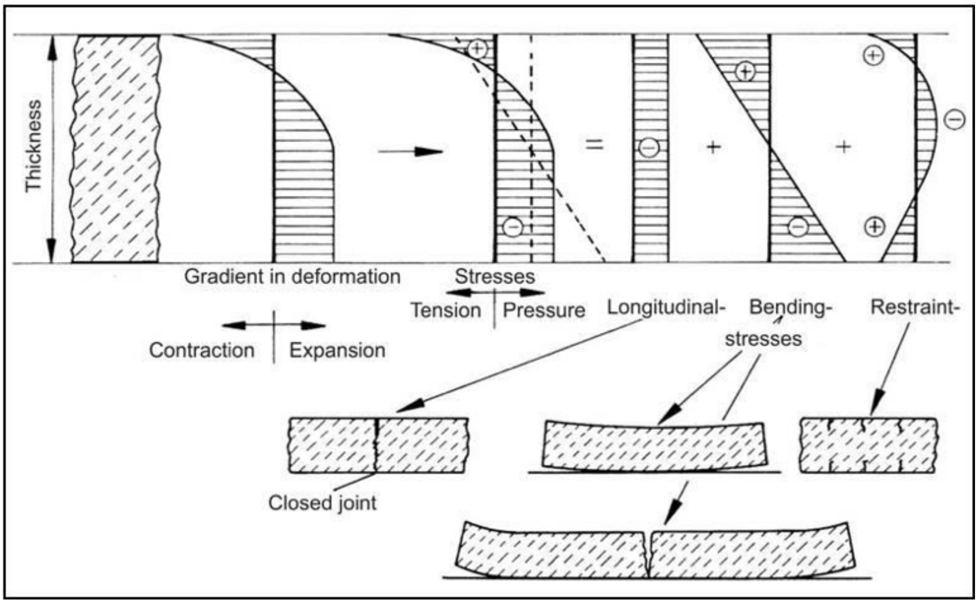

FIGURE 1. Stresses and cracks in concrete pavements due to negative gradients of deformation [7].

[8]. In general, the transport of water in porous media depends on the size, type and form of the pores or microcracks. In addition, it also depends on the transport mechanisms and the physical laws that are effective in the respective pores / microcracks (i.e. chromatography effect). Apart from diffusion, capillary transport is essential when it comes to fluid transport processes, since dissolved alkalis penetrate much deeper into the interior of the concrete structure and may hence increase the ASR-damage potential.

The penetration of alkalis into undamaged concrete structures and their influence on damaging ASR have been sufficiently studied [9, 10]. However, the findings of these studies are not definitive. Usually, an increased alkali concentration in the concrete's near-surface zone could be observed for specimens stored in NaCl-solution. ASR as a result of such an increased alkali concentration could only be observed, if the pH-value of the concrete was comparatively high [10, 11]. Accordingly, the ASR-risk was significantly lower in concretes that used cement which contained ground granulated blast furnace slag (GGBS), because it consumes $Ca(OH)_2$ in a latent hydraulic and pozzolanic reaction and thus lowers the pH-value [11, 12].

In this context, it should be noted that exhaustive studies on the interaction of an increased alkali ingress due to microstructural degradation of cracks with a width between 1 and 10 μm in relation to ASR progression are yet to be performed; previous studies were conducted on undamaged specimens. Related studies have shown, however, that the load of the surface traffic increases the penetration depth of alkalis and correspondingly, the ASR-potential is promoted as well.

2. Influencing Factors on Concrete Pavements

2.1. Degradation

Due to the continuous construction of concrete pavements, deformations in them are practically completely restrained. In the case of thermal or hygral changes, which extent over the complete cross-section, longitudinal restraint stresses are generated. During the wintertime, tensile stresses are raised while during summertime adequate compressive stresses are induced. Although, to some extent a movement is enabled in transverse direction, restraint stresses cannot be excluded completely in this case.

Such longitudinal restraint stresses, constant over the complete cross-section, can result in through-cracks with nearly constant width. Besides these, bending stresses can also be generated by a temperature gradient. In the case of a cooler surface, the slab would tend to warp. This however is prevented by its own weight, so that in the surface zone tensile stresses are provoked, while in the lower zone (next to the sub-base) compressive stresses develop. If these bending stresses exceed the concrete flexure strength, uniform cracks arise with a larger crack width at the surface. Furthermore, map cracking can be provoked by residual stresses (often also named as "Eigenstresses"), when a non-linear temperature gradient arises. In this case, the net-like cracks extend only to a depth of a few millimetres. An overview of stresses acting on concrete pavements and corresponding potential damages is given in Figure 1.

Microstructural degradation as a result of the concrete's cyclic loading can be assessed on the basis of ultra-sonic runtime measurements of the longitudinal acoustic wave close to the concretes surface. Based on the results of the ultrasonic runtime measurements,

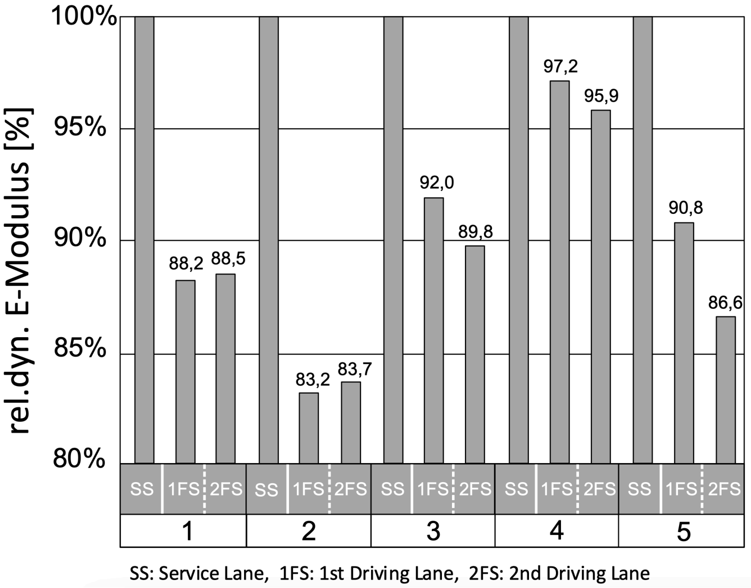

Figure 2. Relative Dynamic E-Modulus of the service lane (SS) and the driving lanes (1.FS and 2. FS) [13].

the relative dynamic E-Modulus can be calculated [13].

Thereby, comparative ultrasonic runtime measurements are an appropriate non-destructive method to assess these effects. Sievering [13] measured the surface-near ultrasonic runtime on concrete pavements of German highways. Herein the service lane was compared to the driving lanes, as it was exposed to significantly less cyclic traffic loads. Correspondingly, the ultrasonic runtime was higher in the driving lanes and thus the calculated relative dynamic E-Modulus significantly lower in those lanes (Figure 2). This indicates a higher microstructural degradation within the driving lanes, which is caused by the additional traffic loads compared to the service lane.

2.2. External Alkali Supply

In common concrete structures an ASR can be prevented by the limitation of the alkali content in the cement as this is normally the single alkali source. In concrete pavements, however, the external alkali supply by de-icing salts plays an important role on the ASR-gel-formation as so, the total amount of reactive alkalis is increased significantly.

In this context, also a modification in the application of the de-icing salt is relevant. 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 forecast. That 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 microcracks. Further the de-icing agents are pressed quite intensely into the concrete microstructure by the overrolling 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.

3. Experimental investigation

3.1. Degradation

In experimental studies, large concrete beams measuring 180 × 50 × 27cm^3 were exposed to cyclic stresses. All beams were produced using a typical pavement concrete mix according to the German guideline "TL Beton-StB 07" [14]. As for a cement, CEM I 42 N with a maximum aggregate size of 22ămm was chosen. Finally, the concrete surface was broom finished.

The concrete beams were exposed to cyclic stresses at a minimum age of 56 days. The tests were conducted in a four-point-flexural setup, in which the chosen upper and lower stresses represent different stress conditions of superposing loads acting on a concrete pavement. Slowly recurring thermal restraint stresses were to be superposed with high-frequent cyclic traffic stresses. Thus, an upper stress level and a corresponding lower stress level (σ_{max} and σ_{min}) could be derived from these boundary conditions [6]. The study yielded the following variations:

- Maximum stress to bending tensile strength ($\sigma_o/f_{ct,fl}$ = 0.35; 0.50; 0.60; 0.70).
- Number of load cycles (N = 0; 1.0; 2.0; 5.0; 10.0 million)

Figure 3 shows the development of the relative dynamic E-Modulus for the different stress-ratios as well as over the course of different load cycles as an average of three specimens each. As expected, the rel. dynamic E-Modulus decreased stronger with a higher stress-ratio. After five million load cycles, the remaining relative dynamic E-Modulus amounted to

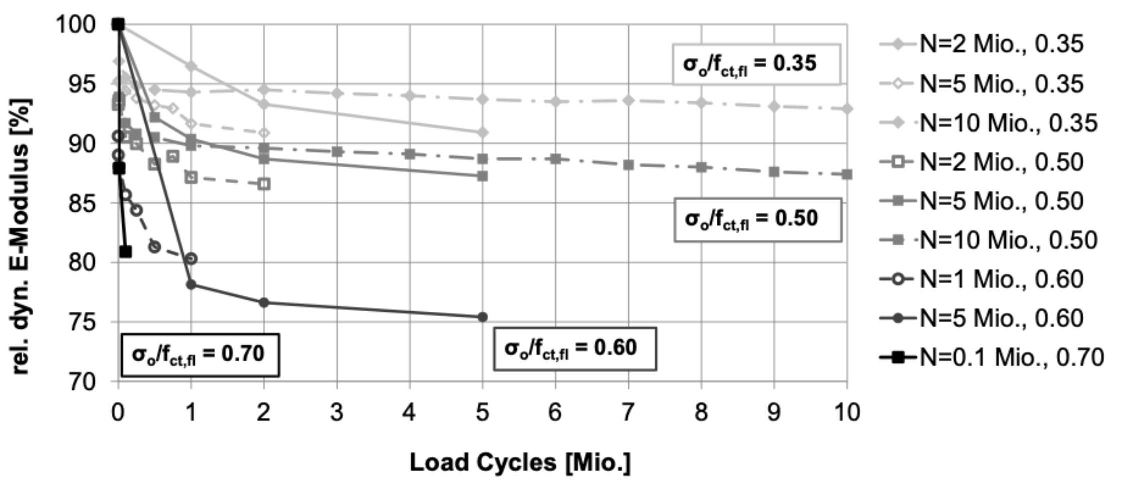

Figure 3. Decrease of the rel. dyn. E-Modulus of beams after 5 million load cycles and at different stress-ratios.

		rel. dynamic E-Modulus [%]					
		100	92.7	91.5	86.5	80.2	70.2
Number of cracks	[-]	12	74	104	128	203	403
Average crack width	[μm]	6.6	5.2	5.3	4.8	5.7	4.6
Average crack length	[μm]	1,400	1,600	1,000	1,400	1,600	1,500
Average crack cross section	[μm^2]	13,400	8,100	6,100	6,700	9,200	8,500
Total cross section	[μm^2]	160,000	600,000	630,000	860,000	1,800,000	3,450,000

Table 1. Crack characteristics.

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.

After completion of the cyclic loading a microscopic investigation of the crack characteristics on thin polished sections ($5 \times 5\text{cm}^2$) has been conducted. Table 1 lists the corresponding crack characteristics. Compared to the undamaged reference specimens (rel. $E_{dyn} = 100\%$), with decreasing relative dynamic E-Modulus, the number of cracks increased significantly. At a relative dynamic E-Modulus of about 70.2 % the number of cracks increased by more than factor 30. Consequently, the total cross section of cracks within the thin polished sections increased similarly. Nevertheless, the average crack width and length stayed rather constant at about 5 μm and 1.5 mm, respectively. It can thus be concluded that the observed increased degradation rather resulted from the formation of new cracks than from the expansion of already existing cracks.

3.2. External alkali supply

The described microstructural degradation also influenced the penetration behavior of fluids into the concrete. An investigation of the capillary water uptake in concrete was carried out on specimens previously subjected to cyclic loads with varying degrees of damage. Therefore, each three Karsten-Tubes were applied on the surface exposed to tensile stresses. The water uptake was assessed over time. It showed, that the water uptake (more or less merely through capillary suction) occurred faster and higher with increasing damage (figure 4). In a pre-damaged concrete with a relative dynamic E-Modulus of approximately 92.7 % the water uptake already increased by about 60 %. At a damage of rel. E_{dyn}ă = ă70.2ă% the water uptake increased by about 250 %.

Alkali solutions not only penetrate in in-situ concrete pavements through capillary suction, their ingression is in fact considerably increased by the load of the surface traffic. In a test setup that was developed at the Ruhr University Bochum to specifically explore these effects, the aforementioned concrete beams were arranged in a circular array, to ensure that they could be loaded with six tires consecutively. The top surface of the beams had previously been exposed to flexural tension in the cyclic four-point-flexural setup. While the beams were loaded, their top surface was treated with a sodium-chloride solution of 5%-NaCl. The tires that were used to apply the load were additionally equipped with a dead weight of up to one ton in order to achieve near to real-life loading conditions for each beam. Since the solution was only pressed into the material within the track width of the tires, a merely capillary solution uptake was to be expected for the adjacent areas. This setup thus allowed the comparative assessment of the two types of liquid penetration into the con-

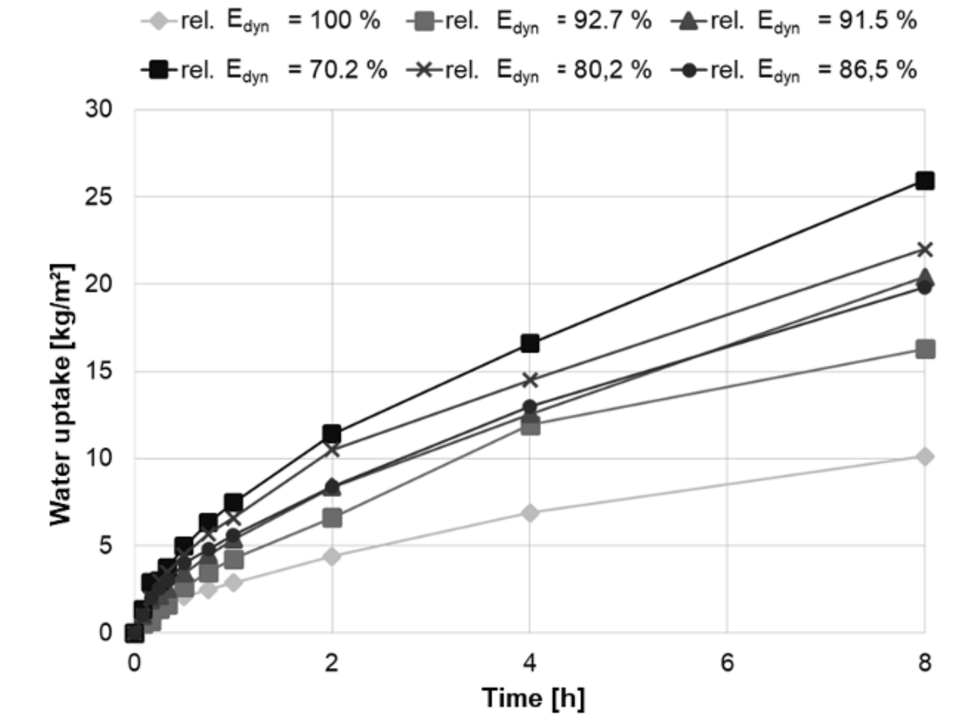

Figure 4. Water uptake in concrete with different relative dynamic E-Modulus.

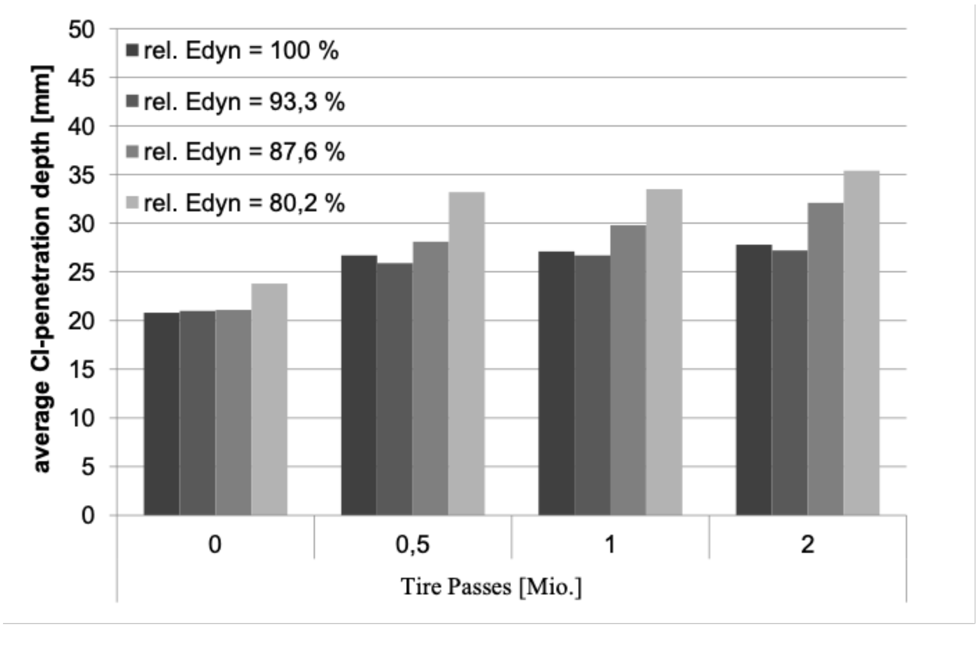

Figure 5. Average chloride penetration depth dependent on the number of tire passes and microstructural damage

crete [15].

After the overrolling of the large-format concrete beams up to two million times, two small specimens ($10 \times 10 \times 200 cm^3$) were cut from each of the different areas of liquid penetration. The specimens were then split perpendicular to the overrolled surface. The freshly broken surfaces were sprayed with silver nitrate to visualize the chloride penetration depth. The average penetration depths over the cross section of the specimens are visualized in figure 5. The average penetration depth on the specimens with the most damages (rel. $E_{dyn} = 80.2\%$) without tire passes amounted to about 23.8 mm already 3ămm above the penetration depth on the undamaged specimens (rel. $E_{dyn} = 100\%$). This effect was also observable for the less damaged specimens (rel. $E_{dyn} = 87.6\%$ and rel. $E_{dyn} = 93.3\%$) but less distinctive. The average penetration depth increased only by 0.3 and 0.4ămm respectively. It can further be noticed, that with increasing tire passes, the penetration increases in damaged as well as undamaged specimens. The average penetration depth of an undamaged specimen after 2 million tire passes already amounted to 27.8 mm, whereas for a strongly damaged specimen (rel. $E_{dyn} = 80.2\%$) the average penetration depth amounted to 35.2 mm. The influence of the overrolling traffic could not be observed for comparatively little damage (rel. $E_{dyn} = 93.3\%$). Concludingly, it can be stated, that the influence of the locally induced external pressure through the tire passes is increasing fluid penetration. However, this effect is limited to a depth of about 2 to 4 cm and becomes more significant with increasing microstructural damage.

4. Final discussion and conclusion

The presented results showed a distinct influence of cyclic mechanical loadings on concrete. Due to microstructural degradation, the penetration of liquids into porous concrete is altered and therefore the potential of an intensified damaging ASR increases considerably.

The dependence of degradation on the number of load cycles and especially on the ratio between the maximum stress acting on the concrete and its bending flexural strength also becomes obvious through the performed ultrasonic measurements. Furthermore, the occurred degradation was additionally described through a microscopic analysis of the crack characteristics.

Previous investigations of the penetration behavior of water towards concrete showed a significant influence of the externally applied pressure on the overall water uptake as well as on the penetration depth. In addition, concrete that had previously been exposed to tensile stresses showed a higher penetration depth, depending on the extent of damage that had been induced before.

Last but not least, the numerical models that were developed in the context of this research project highly agree with the results of the experimental studies [16, 17]. They can hence be used as a basis for a model, which simulates the entire interaction of influences that may lead to an intensified damaging ASR in concrete pavements.

Acknowledgements

The authors would like to thank the German Research Foundation (DFG) for their financial support of this research project. Further, the authors would like to acknowledge the fruitful cooperation with the RUB Institute for Structural Mechanics, 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. Since the foundation of this research group in 2012 outstanding results in the field of ASR have been accomplished on the basis of joint projects.

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