ALKALI-SILICA REACTION (ASR) ON GERMAN MOTORWAYS: AN OVERVIEW

ALKALI-KIESELSÄURE-REAKTION (AKR) AUF DEUTSCHEN AUTOBAHNEN: EINE ÜBERSICHT

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SUMMARY

In a nationwide analysis of the German federal motorway network, it was determined that in 2012, approximately 1,500 km of directional lanes were suspected of ASR (alkali-silica reaction). In the coming years, we can expect major renewal measures on sections of the German motorway network damaged by ASR. This article gives an overview of the damage mechanisms, characteristics on the road indicating a damaging ASR and the effects this will have on renewal measures. Also included is a report on current available possibilities for recycling the concrete from ASR-damaged road pavement.

ZUSAMMENFASSUNG

Bei einer bundesweiten Analyse des deutschen Bundesautobahnnetzes wurde festgestellt, dass zum Zeitpunkt 2012 ca. 1.500 km Richtungsfahrbahn unter AKR-Verdacht standen. Es ist daher abzusehen, dass auch in den kommenden Jahren im gesamten Bereich des deutschen Bundesautobahnnetzes mit größeren Erneuerungsmaßnahmen AKR-geschädigter Streckenabschnitte zu rechnen ist. Der Beitrag gibt einen aktuellen Überblick über die Schadensmechanismen, welche Schadensmerkmale an der Fahrbahn auf eine schädigende AKR hindeuten und welche Auswirkungen daraus für Erneuerungsmaßnahmen entstehen. Auch wird berichtet, welche Möglichkeiten zur Verwertung der AKR-geschädigten Fahrbahndeckenbetone aktuell in Deutschland zur Verfügung stehen.

KEYWORDS: ASR, German motorways, concrete pavements, damaging process, cracks

1. INTRODUCTION

The road is regarded as Germany's main mode of transport and ensures mobility of people and goods. According to a study by the Federal Ministry of Transport and Digital Infrastructure, 84% of goods are transported by road. In the 2030 traffic network forecast, it is assumed [1] that between 2010 and 2030, the volume of freight traffic will increase from a total of 607.1 billion tonne-kilometres in 2010 to 837.6 billion tonne-kilometres in 2030: an increase of 38%. At the same time, heavy traffic has a special significance for the stress placed on the road structure. For example, a truck with an axle load of 11.5 tonnes places 280,000 times more strain on traffic routes than a car with an axle load of 0.5 tonnes [2]. This results in high road construction demands. The roads must have enough load-bearing capacity to withstand the stresses of heavy traffic without deformation. In addition, a long service life is required to carry traffic as failure-free as possible.

Concrete construction promises high load-bearing capacity and deformation stability, even at very high temperatures. In addition, concrete pavement is also judged to have a long service life - a service life of 30 years is usually assumed. Approximately 28% of the 13,009 km network of German federal motorways is constructed in concrete [3, 4].

However, a problem has currently arisen regarding this network of German federal highways. The planned 30-year service life of concrete pavements constructed before 2005/2006 will not be achieved. Aggregates with an ASR sensitivity were used in part for these concrete road pavements. This has resulted in quite pronounced ASR damage today. Obvious signs of damage, usually beginning with discoloration in the transverse and longitudinal joints, occur after 7 to 15 years.

2. ALKALI-SILICA REACTION

Basically, an alkali-silica reaction (ASR) is a chemical reaction between the highly alkaline (pH ≥ 13.5) pore solution (OH^--, Na^+-, K^+-, Ca^{2+}- ions), certain SiO_2 modifications in aggregates and water [5]. Under the influence of an external supply of alkalis [6, 7] and in combination with cyclic loading [8-14], the ASR-related damage process has intensified. Compared to damage-free concrete, this leads to a reduction in mechanical and fracture mechanical properties of concrete [15-17]. Among other things, the cause can be found in a decrease in the stiffness of alkali-sensitive aggregates [18-20].

3. VISUAL DAMAGE CHARACTERISTICS

Visual damage characteristics on the surface of concrete pavements are the decisive criterion for an assessment of sections with alkali-silica reaction. According to [21], three damage categories (acronym in German: SK) are distinguished. Damage evolution is first shown by a discoloration in the area of the joints (SK I), which is subsequently accompanied by an increased crack formation (SK II). As the process progresses, there is additional loss of substance due to corner fractures; this is accompanied by gravelling of the joint areas (SK III). In general, it has been observed that the development of the damage pattern is relatively slow at the beginning but accelerates as the degree of damage increases. It should also be noted that an increase in ASR damage is not linear; a significant increase in damage is usually observed after the first heat periods in early summer [22]. The consequence is that authorities are in constant conflict between an increasing need for maintenance and renewal as a result of increased damage and the potential possibilities from financial, personnel and traffic perspectives for annual services [22].

When assessing ASR-specific damage characteristics, [23] takes the construction of concrete pavements (one concrete mixture/single-layer constructed, one concrete mixture/double-layer constructed, two concrete mixtures/double-layer constructed) into account. Accordingly, in a two-layer construction with an alkali-insensitive top layer and an alkali-sensitive bottom layer, the known discolorations in the transverse and longitudinal joints are not the first signs of an ASR. The first signs in this case are corner fractures of an ASR (Fig. 1). The cause of corner fractures can be found in a horizontal crack in the concrete itself (Fig. 2). In addition, longitudinal cracks on the concrete surface caused by ASR-induced stress build-up in the bottom concrete can also be the result. Even in two-layer constructions, in which the ASR-induced reaction takes place faster in the bottom concrete than in the upper concrete (upper concrete also sensitive to alkali), the discolorations do not indicate incipient ASR, but rather corner fractures and longitudinal cracks [23]. The cause of corner fractures and longitudinal cracks must always be determined. As described in [23] for example, corner fractures can also be caused if there are no frost-proof and erosion-resistant or compaction defects in the sub-base layer. However, both causes play only a minor role [24]. A further possibility are changes in the sub-base layer due to insufficient drainage. First, surface water reaches the sub-base layer through damaged joints that cannot be effectively drained away. The base then decomposes and loosens under traffic stress. As a result, the slab lies hollow at the water penetration point and later breaks due to overload [24].

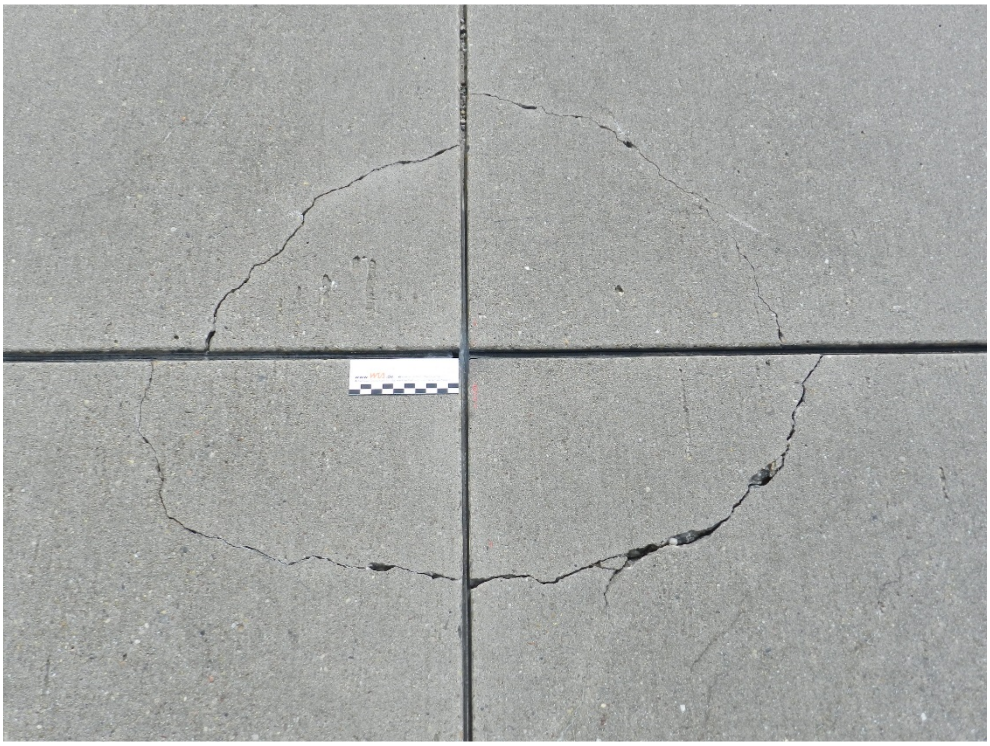

Fig. 1: Corner fracture

Fig. 2: Horizontal cracks related to corner fracture in Fig. 1

4. INFLUENCES OF CONSTRUCTION AND USE

The influences, resulting from the production and the utilization of concrete pavements on the damage development caused by ASR, are discussed in [25]. To this end, a total of 50 sections of federal German motorways were examined regarding ASR-specific damage characteristics (discoloration in the area of the joints and joint crosses, crack formation in the longitudinal and transverse directions, and tangential crack formation in the corner areas, as well as edge damage and corner fractures up to loss of substance and gravelling). For example, it was shown, that temperature conditions at the time of concrete paving and the water-cement ratio can contribute to the development of ASR-specific damage characteristics. An additional factor is the superimposition of operational boundary conditions (external alkali supply, traffic load) [25].

In [26], it is reported that damage to concrete pavements tended to increase with increasing temperatures during production (above approx. 15-20°C). According to this, damage to concrete road pavement produced in summer is mainly due to high, fresh-concrete temperatures. Crack initiation is then more strongly influenced by thermal stresses and cyclic traffic loads than by ASR itself. However, existing cracks (also micro cracks) then contribute to the ASR-related expansion of damage through the improved alkali input (alkali-containing de-icing salts) into the concrete [26].

A decreasing water/cement-ratio and, thus, reduced porosity reduces ASR damage. Conversely, increased porosity results in increased ASR damage [27]. The addition of an air-entraining agent has only a minor reducing effect on a damaging ASR [27].

In conclusion, it can be stated that emergence of ASR-related damage characteristics cannot be attributed exclusively to ASR. Rather, different load-independent and load-dependent stress components overlap with the microstructural stresses that result from the ASR-related damage process. This combination results in crack formations.

5. DISCOLORATION AND INTRUSION OF DE-ICING SALT

With non-destructive testing technology, it has been confirmed [28] that increased moisture penetration is responsible for dark discoloration in joint areas of concrete pavement surfaces. The question of whether increased moisture input is accompanied by increased intrusion of de-icing salt is investigated in [29]. This is of interest insofar as both factors are required for a damaging ASR. In the investigations, a minimum penetration depth for sodium of approx. 15 mm was determined using Laser-Induced Breakdown Spectroscopy (LIBS) on a single-layer constructed motorway section produced in 2004.

The enrichment of the alkali content in the cement stone of concrete road pavements was also determined by using a method developed at the TU Hamburg-Harburg [30]. The determined alkali profiles of concrete pavements showed an enrichment of sodium by the intrusion of de-icing salt only at the upper layer (0 to 1 cm), irrespective of whether it was a point near a joint or in the middle of a concrete slab. The samples were removed during the summer months. It is therefore possible that the accumulation of alkalis is higher in the winter months when de-icing salt is supplied [30]. However, the comparatively low alkali accumulation at the upper layer [28-30] with the visual damage up to gravelling on the other side is quite astonishing.

6. MECHANICAL CONCRETE PROPERTIES

Studies have been carried out to determine mechanical properties of real ASR-damaged concrete pavements [31]. Accordingly, compressive strength and splitting tensile strength are only slightly affected by an ASR. In contrast, a modulus of elasticity decreases by up to 50% and tensile strengths by more than 70%. The direction in which test specimens are taken from the concrete slab is also decisive. Cyclically occurring load and load-independent stresses with simultaneous ASR cause higher structural damage over the entire cross-section (perpendicular to the road surface) than along the road surface. Modulus of elasticity and tensile strength are then smaller in this direction than longitudinal to the road surface and decrease in the order of slab centre, longitudinal joint, transverse joint, joint crosses.

7. METHODS FOR EVALUATING OF CONCRETE PAVEMENTS

To observe the development of horizontal cracks and to plan maintenance actions, a target-oriented monitoring is necessary. In [32, 33], it is reported that a field-suitable, non-destructive device for concrete structures is available that can scan small-scale crack formations based on the impact-echo method. This enables information to be obtained on the extent to which horizontal cracks extend into the concrete slab. Further approaches for monitoring, which considers not only deformations but also the load-bearing capacity of a road construction, can be found in the use of the Falling Weight Deflectometer (FWD). However, the results are difficult to interpret since temperature and humidity influences and ASR-induced expansions lead to a total stress state in the constructions so far. This plays a significant role in deformation measurements with the Falling Weight Deflectometer.

8. PROGNOSIS OF DAMAGE PROGRESS

Until now, damage development has been predicted using ASR-provocated concrete tests [34, 35] on test specimens obtained from large drill cores in the concrete pavements. After special exposure to moisture and alkali, strain measurements are carried out and evaluated. In addition, polarised microscopic investigations are carried out on thin sections to identify ASR characteristics and possible structural damage. However, a systematic prognosis of damage development is not possible with these investigations alone. It is only possible to assess whether an ASR can still be expected or whether there is still further residual damage potential. However, it cannot be assessed to what extent a horizontal crack caused by the ASR extends into the slab and then leads to a corner fracture under traffic load. The crack propagation of the horizontal crack in the road surface is the reason for frequently fast, non-linear and almost incalculable damage development. In [22], rapid damage progress was observed in individual cases, leading from damage category SK I to SK III in a very short time. It can be assumed that the crack propagation in an affected section is not uniform and depends on many boundary conditions.

9. USE OF ASR-DAMAGED CONCRETE

When disassembling ASR damaged concrete, one negative impact is that resultant recycling material (RC-ASR material) is unsuitable for construction of new concrete pavements. Therefore, it must be clarified whether and under what conditions the demolished material obtained during the removal process can be used as secondary raw material in base layers without binding agents (acronym in German: ToB) or hydraulically bound base layers (acronym in German: HGT) [36]. Examinations directly after processing have shown that use of RC-ASR material might be of interest in ToB (anti-frost layer, crushed-rock layer) and HGT. Results gained from lab tests, existing surfaces and scientifically monitored new construction work reveal that use in ToB has no negative impact if subsequent ASR can be excluded. When applying concrete recycling (RC material), it must, in general, be considered that RC material might have a negative impact on water permeability or the capillary-breaking effect in ToB. In contrast, use of recycling material from concrete road surfaces damaged by ASR is not recommended in HGT. The reason is the adhesion of RC-ASR material to the cement stone matrix which is damaged by subsequent ASR impact and which might cause local stress concentration. This, in turn, causes failure of the total cross-section in case of flexural stress. Finally, it should be mentioned that the above findings could not be applied to airfields operating areas. The reasons are the use of alkali de-icing agents based on alkali acetate and alkali formiate. These de-icing agents lead to other ASR-damaging processes in concrete as de-icing agents on basis of NaCl.

10. CONCLUSIONS

In 2012, approx. 1,500 km of directional roads of the German federal motorway network were thought to be damaged by ASR. Therefore, it can be anticipated that in the coming years, major renewal measures of concrete road pavements damaged by ASR are to be expected. The planning of renewal measures requires a tool that makes it possible to determine the remaining service life of the road pavement. This would also make it much easier for the authorities to plan maintenance requirements from a financial, personnel and traffic point of view. It is difficult that damage evaluation is slow at the beginning. But with the increasing degree of damage it is becoming faster and faster. In addition, discolorations at the transverse and longitudinal joints are not always the first signs of an ASR. Such is possible if an ASR has its origin in the bottom and not in the upper concrete. In this case, corner fractures and longitudinal cracks are the first visible signs of an ASR. Corner fractures could be caused by horizontal cracking in the concrete pavement itself. As a result, loads from each wheel (loading and unloading) lead to vertical de-formations [37] that promote the progression of horizontal cracks into the concrete. Over time, the concrete collapses at this point due to overloading. The collapse is visually visible on the surface. This is probably intensified by the entry of surface water and alkaline de-icing agents through often-leaky joints.

REFERENCES

[1] BUNDESMINISTERIUM FÜR VERKEHR UND DIGITALE INFRASTRUKTUR: *Verkehrsverflechtungsprognose 2030.* https://www.bmvi.de/SharedDocs/DE/Artikel/G/verkehrsverflechtungsprognose-2030.html, Zugriff: 01.08.2019

[2] RSTO 12: *Richtlinien für die Standardisierung des Oberbaus von Verkehrsflächen.* Forschungsgesellschaft für Straßen- und Verkehrswesen, FGSV, Köln

[3] INFORMATIONSZENTRUM BETON GMBH: Bundesfernstraßen: *Dauerhafte Betondecken - störungsfreier Fernverkehr.* https://www.beton.org/wissen/infrastruktur/bundesfernstrasse/, Zugriff: 01.08.2019

[4] BUNDESMINISTERIUM FÜR VERKEHR UND DIGITALE INFRASTRUKTUR: *Längenstatistik der Straßen des überörtlichen Verkehrs, Stand: 1. Januar 2018.* Ausgabe August 2018

[5] STARK, J.: *Alkali-Kieselsäure-Reaktion.* Schriftenreihe FIB Nr.3, Bauhaus-Universität Weimar, April 2008

[6] GIEBSON, C.: *Die Alkali-Kieselsäure-Reaktion in Beton für Fahrbahndecken und Flugbetriebsflächen unter Einwirkung alkalihaltiger Enteisungsmittel.* Dissertation, F.A. Finger-Institut für Baustoffkunde, Bauhaus-Universität Weimar, 2013

[7] DRESSLER, A.: *Einfluss von Tausalz und puzzolanischen, aluminiumhaltigen Zusatzstoffen auf die Mechanismen einer schädigenden Alkali-Kieselsäure-Reaktion in Beton.* Dissertation, Technische Universität München, München, 2013

[8] BREITENBÜCHER, R.: *AKR unter kombinierten Einwirkungen – Gesamtüberblick über die DFG-Forschergruppe*. 20. Internationale Baustofftagung IBAUSIL, 12.-14. September 2018 in Weimar. Tagungsbericht Band 2, S. 43-49

[9] GIEBSON, C., SEYFARTH, K., LUDWIG, H.-M.: *Einfluss von Vorschädigung und Einwalken*. In: Alkali-Kieselsäure-Reaktion in Betonbauteilen bei gleichzeitiger zyklischer Beanspruchung und externer Alkalizufuhr, Sonderausgabe zu den Tagungsbeiträgen der 20. Internationalen Baustofftagung IBAUSIL der DFG Forschergruppe 1498, 2019, S. 19-26

[10] ISKHAKOV, T., TIMOTHY, J.J., MESCHKE, G.: *Expansion and deterioration of concrete due to ASR. Micromechanical modeling and analysis.* Cement and Concrete Research 115 (2019), pp. 507–518
DOI: 10.1016/j.cemconres.2018.08.001.

[11] PRZONDZIONO, R.. BREITENBÜCHER, R.: *AKR unter kombinierten Einwirkungen - Wie Beeinflussen zyklische Beanspruchungen die Degradation und den Alkalieintrag in Beton*. 20. Internationale Baustofftagung IBAUSIL, 12.-14. September 2018 in Weimar. Tagungsbericht Band 2, S. 85-92

[12] WEISE, F., KRÜTT, E., MENG, B.: *AKR unter kombinierten Einwirkungen - Rissbildungs- und Transportmechanismen.* 20. Internationale Baustofftagung IBAUSIL, 12.-14. September 2018 in Weimar. Tagungsbericht Band 2, S. 93-105

[13] WIEDMANN, A.; KOTAN, E.; MÜLLER, H.S.: *AKR unter kombinierten Einwirkungen - Schadensrisiko und Schadensentwicklung in Betonfahrbahnen*. 20. Internationale Baustofftagung IBAUSIL, 12.-14. September 2018 in Weimar. Tagungsbericht Band 2, S. 107-114

[14] BREITENBÜCHER, R., PRZONDZIONO, R., MENG, B., KRÜTT, E., WEISE, F.: *Alkali-Kieselsäure-Reaktion in Betonfahrbahndecken unter Berücksichtigung von Verkehr und Taumitteln*. Straße und Autobahn 70 (2019), H. 8, S. 655-664

[15] MIELICH, O., REINHARDT, H.W.; ÖZKAN, H.: *Strength and Deformation Properties of Alkali-Silica Reaction (ASR) Damaged Concrete Exposed to External Alkalis.* Key Engineering Materials, Vol. 711, pp. 665-672, 2016

[16] MIELICH, O., REINHARDT, H.W.; ÖZKAN, H.: *Kriechen und mechanische Eigenschaften von Straßenbetonen nach AKR-provozierender Lagerung.* Beton- und Stahlbetonbau 114 (2019), H. 6, S. 419-429

[17] WIEDMANN, A., WEISE, F., KOTAN, E.; MÜLLER, H.S.; MENG, B.: *Effects of fatigue loading and alkali-silica reaction on the mechanical behavior of pavement concrete.* Structural Concrete 18 (2017), pp. 539-549

[18] REINHARDT, H.W.; MIELICH, O.: *A fracture mechanics approach to the crack formation in alkali-sensitive grains.* Cement and Concrete Res. 41 (2011), No. 3, pp. 255-262

[19] REINHARDT, H.W., MIELICH, O.: *Fracture toughness of alkali-sensitive rocks in alkaline solution.* International Journal of Rock Mechanics & Mining Sciences 70 (2014), pp. 552-558

[20] REINHARDT, H.W., ÖZKAN, H., MIELICH, O.: *Creep of concrete as influenced by the rate of expansion due to alkali–silica reaction.* Structural Concrete. 2019;1–11. https://doi.org/10.1002/suco.201900133

[21] RUNDSCHREIBEN DES DAMALIGEN BUNDESMINISTERIUMS FÜR VERKEHR, BAU UND STADTENTWICKLUNG: *Empfehlungen für die Schadensdiagnose und die Bauliche Erhaltung von AKR-geschädigten Fahrbahndecken aus Beton.* Bonn, April 2012

[22] MARQUORDT, D., KRELLE, C.: *Fahrbahndecken aus Beton aus Sicht des Auftraggebers.* Betonstraßentagung 2015, Vorträge der Tagung der Arbeitsgruppe „Betonbauweisen“

[23] MIELICH, O.: *Empfehlungen zur Schadensdiagnose AKR-geschädigter Betonfahrbahndecken unter Berücksichtigung der Bauweise.* Straße und Autobahn 70 (2019), H. 8, S. 666-672

[24] EHRLICH, N., HENSEL, O.: *Straßenbau heute - Betondecken.* 6. Aufl. Hg. v. BetonMarketing Deutschland GmbH. Düsseldorf: Verlag Bau+Technik GmbH, 2010

[25] KUNZ, S.: *Einflüsse aus der Konstruktion, Herstellung und Nutzung von Betonfahrbahndecken auf die Schadensentwicklung infolge einer Alkali-Kieselsäure-Reaktion.* Dissertation, Ruhr-Universität Bochum, 2013

[26] SIEVERING, C.: *Dauerhaftigkeit von Betonfahrbahndecken unter besonderer Berücksichtigung des externen Alkalieintrags.* Dissertation, Ruhr-Universität Bochum, Schriftenreihe des Instituts für Konstruktiven Ingenieurbau, Heft 2012-4, Shaker Verlag, Aachen 2012

[27] VOLAND, K.: *Einfluss der Porosität von Beton auf den Ablaufeiner schädigenden Alkali-Kieselsäure-Reaktion.* Dissertation, F.A. Finger-Institut für Baustoffkunde, Bauhaus-Universität Weimar, 2015

[28] WEISE, F., KIND, T., STELZNER, L., WIELAND, M.: *Dunkelverfärbung der Betonfahrbahndecke im AKR-Kontext.* Beton- und Stahlbetonbau 113 (2018), H. 9, S. 647-655

[29] WEISE, F., MILLAR, S., WILSCH, G.: *Analyse des Tausalzeintrags in Fahrbahndeckenbetone mit neuartiger Prüftechnik.* Beton- und Stahlbetonbau 113 (2018), H. 9, S. 656-666

[30] JEHN, C., SCHMIDT-DÖHL, F., FRANKE, L.: *Nachträgliche Alkaliaufnahme der Betondecken von Verkehrswegen und der Prüfkörper in Performance-Tests zur Alkalireaktion infolge von Taumittel-Beaufschlagung.* beton 62 (2012), Heft 10 S. 380-384

[31] MIELICH, O.: *Rissbildungen und mechanische Betoneigenschaften an einem Fahrbahndeckenbeton mit Alkali-Kieselsäure-Reaktion.* beton 69 (2019), H. 11

[32] GROSCHUP, R., GROßE, C.U.: *Development of an Efficient Air-Coupled Impact-Echo Scanner for Concrete Pavements.* 19th World Conference on Non-Destructive Testing, 13-17 June 2016 in Munich, Germany

[33] GROSCHUP, R., GROßE, C.U., FREUDENSTEIN, S., WIELAND, M., BECKER, C.: *Fast Impact-Echo Scanner: Mit IE schnell und kontaktfrei große Bauteile untersuchen.* In: Fachtagung Bauwerksdiagnose 2018, Berlin

[34] TP B-STB – TEIL 1.1.10: *Technische Prüfvorschriften für Verkehrsflächen-befestigungen - Betonbauweisen* TP B-StB – Teil 1.1.10*: AKR-Potenzial und Dauerhaftigkeit von Beton (Klimawechsellagerung).* Forschungsgesellschaft für Straßen und Verkehrswesen – Arbeitsgruppe Betonbauweisen, Ausgabe Juni 2018

[35] TP B-STB – TEIL 1.1.09: *Technische Prüfvorschriften für Verkehrsflächen-befestigungen - Betonbauweisen TP B-StB – Teil 1.1.09: AKR-Potenzial und Dauerhaftigkeit von Beton (60°C-Betonversuch mit Alkalizufuhr).* Forschungsgesellschaft für Straßen und Verkehrswesen – Arbeitsgruppe Betonbauweisen, Ausgabe Juni 2018

[36] MIELICH, O.: *Wiederverwendung von RC-Baustoffen aus AKR-geschädigten Betonfahrbahndecken.* Abschlussbericht BASt-gefördertes Forschungs-projekt (FE 06.0111/2015/FRB), in Bearbeitung (voraussichtlich Ende 2019)

[37] MIELICH, O., ZWERGER, V.: *Zustandserfassung von Betonfahrbahndecken mit Verdacht auf eine schädigende Alkali-Kieselsäure-Reaktion.* Beton- und Stahlbetonbau 114 (2019), H. 12