GUDRUN GOLKOWSKI[1)]

LONG LIFE PAVEMENTS WITH RECYCLED CONCRETE IN UNBOUND GRANULAR LAYERS

DŁUGOWIECZNE NAWIERZCHNIE Z BETONU Z RECYKLINGU W NIEZWIĄZANYCH WARSTWACH ZIARNISTYCH

STRESZCZENIE. Konstrukcja niezwiązanych warstw ziarnistych (UGL) w budowie nawierzchni opiera się głównie na empirycznej wiedzy na temat zachowania kruszyw naturalnych. Czy możliwe jest przeniesienie tego zachowania na wydajność materiałów pochodzących z recyklingu w UGL? W sekcji testowej in-situ, podzielonej na 12 podsekcji, BASt ocenił wydajność UGL wykonanego z betonu z recyklingu i różnych procentów cegieł z recyklingu w porównaniu do UGL z kruszyw naturalnych przez dziesięć lat. Analiza danych z regularnie wykonywanych pomiarów ugięciomierzem wykazała wystarczającą nośność zgodnie z wymaganiami dla wszystkich różnych podsekcji. Istnieją jednak znaczące różnice wynikające ze składu UGL w różnych podsekcjach. Niezależnie od wystarczającej nośności zauważalne stały się inne uszkodzenia. Pęknięcia poprzeczne pojawiły się po pierwszej silnej zimie i w kolejnych latach na pododcinkach z wysokim udziałem betonu z recyklingu w UGL. Zaobserwowana liczba pęknięć silnie koreluje ze składem UGL. Aby jednak zapewnić długą żywotność takich nawierzchni, należy wziąć pod uwagę przyjętą konstrukcję i lepsze określenie ich wydajności w badaniach laboratoryjnych w odniesieniu do zachowania po utwardzeniu materiałów pochodzących z recyklingu, aby uniknąć wczesnych uszkodzeń.

SŁOWA KLUCZOWE: konstrukcje nawierzchni, niezwiązany materiał ziarnisty, materiały z recyklingu, nośność, zrównoważony rozwój.

ABSTRACT. The construction of unbound granular layers (UGLs) in pavement construction is mainly based on empiric knowledge of the behaviour of natural aggregates. Is it possible to transfer this behaviour to the performance of recycled materials in UGLs? In an in-situ test-section, divided into 12 sub-sections, BASt has evaluated the performance of UGL made from recycled concrete and different percentages of recycled bricks in comparison to an UGL of natural aggregates for ten years. The data analysis of regularly executed Falling Weight Deflectometer measurements show a sufficient bearing capacity according to the requirements for all different sub-sections. There are nevertheless significant differences due to the composition of the UGLs in the different sub-sections. Regardless of a sufficient bearing capacity other damage has become noticeable. Transversal cracks appeared after a first severe winter and during the next years in the sub-sections with a high percentage of recycled concrete in the UGL. The observed number of cracks correlates strongly with the composition of the UGLs. For a long service life of such pavements, however, an adopted structure and a better determination of their performance in laboratory trials have then been taken into account with regard to the post-hardening behaviour of recycled materials to avoid early damage.

KEYWORDS: pavement constructions, unbound granular material, recycled materials, bearing capacity, sustainability.

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1. INTRODUCTION

In Germany a major discussion was initiated by industry to use higher fractions of recycled bricks as material for unbound granular layers (UGLs) in pavement constructions. In 2004 a first research project [1] funded by the Federal Ministry of Digital and Transport was completed which showed similar performance behaviour especially concerning maximum deformation for UGLs with different fractions of recycled bricks in laboratory trials. Based on these laboratory test results the permissible fraction was increased from 25 to 30% for recycled bricks in unbound granular layers in the German Technical Delivery Terms for Aggregates in Road Construction [2]. However, there was no long-time experience of their performance in pavement constructions, therefore it was decided to implement an in-situ test section to compare UGLs with various fractions of recycled bricks mixed with recycled concrete in those layers.

For a detailed comparison and analysis of different UGLs in pavement construction an in-situ test section on a federal road with a standardised construction type according to the German guidelines for standardised pavement construction RStO 01 [3] was planned and built in 2007. This paper will discuss the set-up of the test section and the results of regularly executed measurements especially bearing capacity measurements and the evaluation of the performance of the test section over its lifetime.

After having observed the first damage – transversal cracks – a second discussion raised up about the use of recycled materials, here the recycled concrete. Recycled materials differ in its behaviour in pavement constructions compared to natural aggregates so the experience of pavement performance based on UGLs with only natural aggregates cannot simply be transferred to new types of material. The specific performance of recycled bricks and recycled concrete in UGLs, as they have been implemented in the test section, needs to be taken into account in the course of pavement design.

2. DESCRIPTION OF THE TEST SECTION

The test section was implemented on the interim by-pass (B 167n) for the town of Seelow by the Landesbetrieb Straßenwesen, Land Brandenburg (Germany) in 2007. The new by-pass of Seelow was planned as an interim by-pass and therefore the design life was fixed to only 10 years. Two different traffic estimations formed the basis for the evaluation of the relevant traffic load in equivalent 10t-axle overruns. According to this traffic evaluation a standardised construction class – class III according to RStO 01 [3] for a traffic load of 800.000 to 3.000.000 equivalent 10-ton axle overruns – was required (Fig. 1). For the construction of the by-pass a minor construction class – class IV – was chosen (Fig. 2). The idea behind was to really induce high stresses into the pavement construction to provoke pavement damage within the defined 10 years lifetime and to evaluate whether the higher amount of (weak) recycled bricks in the construction lead to pavement damage, especially to deformation of the unbound granular layers.

The test section itself is 1200 m long and it is equally split into two parts. One part lies on a dam and the second part lies in a cut. Each part (dam=D/cut=E) is divided into six subsections with six variations of material used for the UGL (Fig. 3). The basic material used in the UGL was recycled concrete and different fractions of recycled

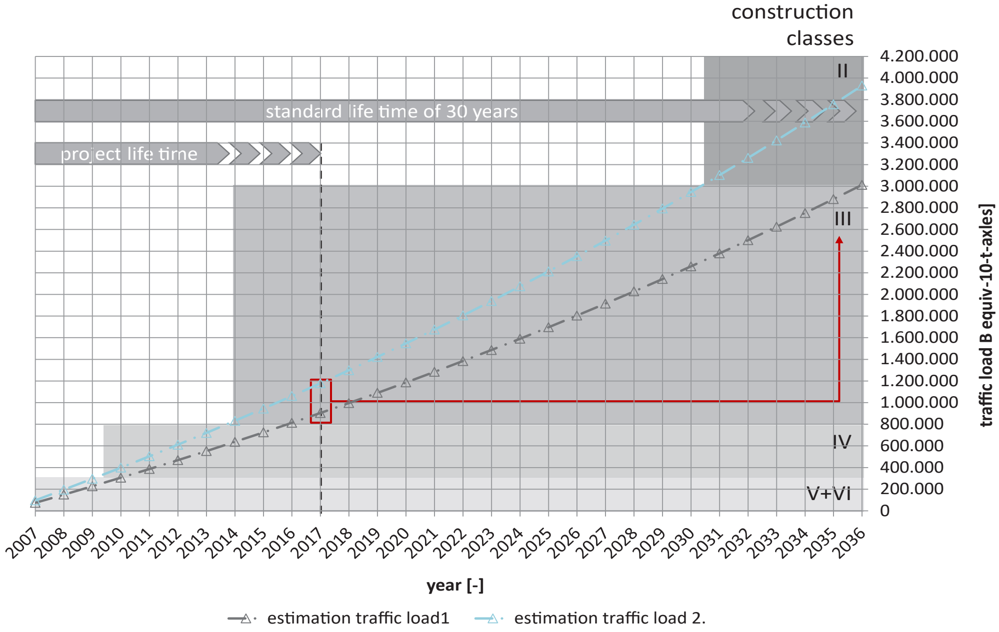

Fig. 1. Evaluation of relevant traffic load for the designed project lifetime

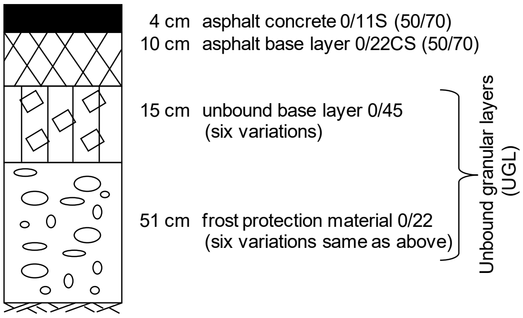

Fig. 2. Pavement construction according to RStO 01, construction class IV, for all test subsections

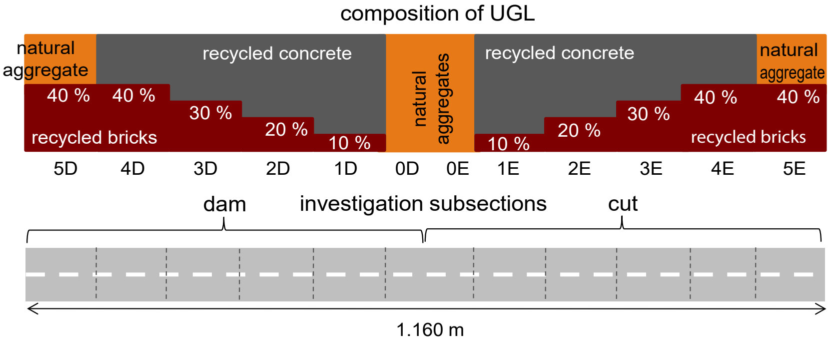

Fig. 3. Set up of the test section [4]

material with bricks were added. For comparative evaluation two sections were constructed with 100 % natural aggregates, and in two other subsections natural aggregate was used instead of the recycled concrete in the UGL with 40 % of recycled bricks.

3. CHARACTERIZATION OF THE MATERIAL FOR THE UGLs

The material composition was chosen equally within the variants for the unbound granular base course (0/45) and the frost protection layer (0/22). For the production of the construction material mixtures for the unbound granular base course (STS) and the frost protection layer (FSS), a maximum of three grain fractions were used in each case (Table 1). In all cases, the proportions of recycled bricks were selected to be higher than the requirement for the resulting construction material mixture, as the recycled brick material always contained minor proportions of recycled concrete and other impurities.

Table 1. Composition of the grain distribution for the materials of the different subsections [4]

M.-%	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
	frost protection layer (FSS)					unbound granular base course (STS)				
Z 0/22	15	25	35	45	-	15	25	40	50	-
Z 8/22	-	-	-	-	40	-	-	-	-	10
Z 22/45	-	-	-	-	-	-	-	-	-	40
B 22/45	-	-	-	-	-	-	10	15	25	-
B 0/22	85	75	65	55	-	-	-	-	-	-
B 0/45	-	-	-	-	-	85	65	45	25	-
KS 0/8	-	-	-	-	60	-	-	-	-	50

Z = recycled bricks (Ziegel), B = recycled concrete, KS = natural aggregates (Kiessand)

The material composition of the construction material mixtures used in subsections 1 to 5 was determined on samples of the layer material during installation. The results are presented in Table 2. It should be noted that the manual sorting of the samples is always subject to non-quantifiable uncertainty, which according to the test institute involved can be up to ± 10 wt.% in the worst case. The material composition of the subsections 5D and 5E, which deviates significantly from the specifications, illustrates the difficulty of producing a mixture of pure recycled bricks and natural aggregate, since the bricks grain fraction taken from the conventional recycling process is usually mixed with recycled concrete. A more precise sorting by hand would have been theoretically possible, but has no practical relevance and is therefore unsuitable for the task of this project.

Table 2. Material composition for the materials of the different subsections [4]

sub section	recycled bricks [M.-%]			recycled concrete [M.-%]			Natural aggregate [M.-%]		
	target value	STS	FSS	*target value*	STS	FSS	*target value*	STS	FSS
5D	*40*	45	37	*0*	33	35	*60*	21	27
4D	*40*	39	38	*60*	54	58	*0*	0	0
3D	*30*	29	29	*70*	66	60	*0*	0	0
2D	*20*	17	23	*80*	78	71	*0*	0	0
1D	*10*	10	10	*90*	80	80	*0*	0	0
0D	*0*	0	0	*0*	0	0	*100*	100	100
0E	*0*	0	0	*0*	0	0	*100*	100	100
1E	*10*	11	8	*90*	84	79	*0*	0	0
2E	*20*	21	19	*80*	68	70	*0*	0	0
3E	*30*	31	28	*70*	64	65	*0*	0	0
4E	*40*	41	38	*60*	53	57	*0*	0	0
5E	*40*	33	30	*0*	43	40[1]	*60*	22	27

STS – unbound granular base course, FSS – frost protection layer

Most of the used materials in the UGLs do not fulfil all the requirements of the German guidelines for material composition in the UGLs. Since the test section is intended to contribute to the proof of suitability of higher portions of recycled bricks in the unbound granular layers, exceeding the requirement values in this requirement is not a criterion for exclusion.

4. EXAMINATIONS

The main focus was laid on bearing capacity measurements with a Falling Weight Deflectometer (FWD). The FWD Measurements were regularly executed in spring and autumn every year in both driving directions by the Hochschule Anhalt on behalf of BASt. The spacing between FWD measurements points was 15 m, so six to seven measuring point were available for each subsection. This ensured a sufficient data basis for the evaluation. BASt itself executed supplementary FWD measurements at different points in time with a spacing of the measuring points of 10 m so more measuring points are available per subsections. The BASt measurements are used to confirm the analyses based on the regular FWD measurements.

The test section itself was additionally equipped with temperature sensors as well as with humidity sensors. In each subsection temperature was measured at two places at five different levels between -4 cm to -130 cm of the construction. Since 2007 the temperature in the pavement construction for the different subsections was measured hourly. Frost heave measurements were additionally foreseen in autumn as reference measurement and in winter time after a period of frost every year. An extensive data base of temperature data was available to evaluate possibly different behaviour due to the impact of weather conditions of the different materials (this evaluation is not part of this paper).

5. PERFORMANCE EVALUATION OF UNBOUND GRANULAR LAYERS

Bearing capacity measurements have been regularly executed two times a year (spring and autumn) with a Falling Weight Deflectometer (FWD) since 2007. The following indicators were taken for further evaluation:

- bearing capacity number (T_Z): derived from maximum deflection and the radius of curvature at the centre of the load [5],
- maximum deformation (w_{max}/d_0): maximum normalised deformation in the centre of the load [5],
- specific deformation modulus for the UGL(E_{ToB}).

In a first step it was analysed whether the different subsections could be distinguished based on a computational method for the determination of homogenous sections. For the determination of homogenous sections, the method of cumulative sums for the indicator maximum deflection d_0 was used (Fig. 4). The results show that especially the subsections with natural aggregates (0D, 0E) differ (statistically significantly) from the other sections concerning the maximum deflection of FWD measurements. A clear

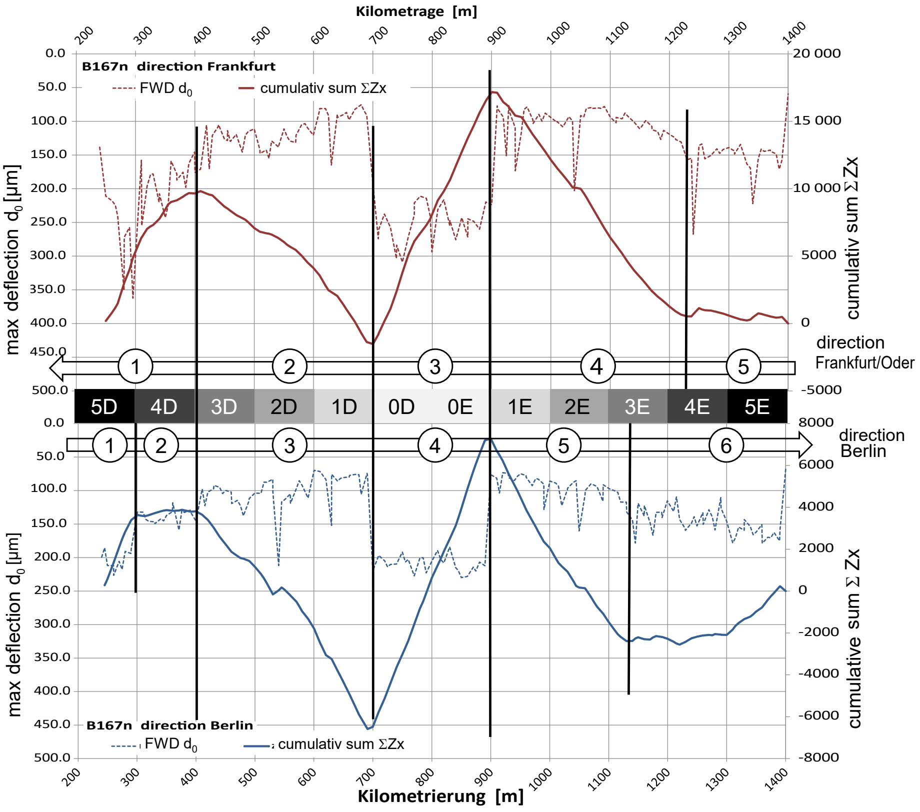

Fig. 4. Profile of FWD measurement of maximum deflection and division into homogenous sections

separation of the subsections with various fractions of recycled bricks is not possible. Only the sections with a fraction of 40% of recycled bricks (5D, 4D, 4E, 5E) have a significantly lower bearing capacity so that a separation of those subsections is possible.

In a second step the indicators were compared to evaluate the bearing capacity of the different subsections and their behaviour over time.

For the indicator T_Z minimum requirements exist for each construction class. The test section is determined for traffic loading higher than for the performed construction class IV. The subsections with natural aggregate have the lowest bearing capacity in comparison to the other subsections but even these subsections achieve the required values for construction class IV (Fig. 5). Due to the use of recycled concrete in the other subsections the bearing capacity exceeds the requirements for class IV. The subsections with a high percentage of recycled concrete and a fraction of only 10 %–20 % of recycled bricks even fulfil the requirements of the highest construction class SV (SV for very heavy traffic, usually chosen for motorways) according to RStO 01 [3].

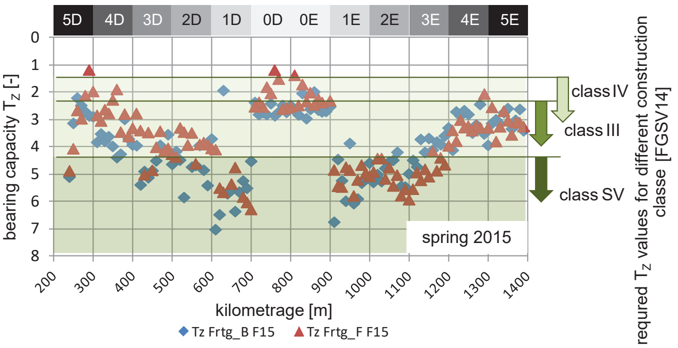

Fig. 5. Bearing capacity number T_Z of FWD measurement for the different subsections and both driving directions

The question came up whether the bearing capacity has changed over the lifetime of the pavement so far. The following Fig. 6 shows the evolution of the bearing capacity – indicator w_{max} – over the lifetime for the different subsections. The indicator w_{max} describes the maximum deformation of the pavement surface under the FWD loading of 50 kN and is an indicator for the bearing capacity of the whole pavement structure.

After the construction of the pavement a phase of post compaction was monitored by slightly increasing values for the maximum deformation. After that phase the values for the maximum deflection remained on a constant level, achieving a steady state for the bearing capacity. Impacts due to traffic loading and weather conditions have not led to damage or to a loss of the overall bearing capacity until 2014.

The results of the measurement conducted in spring 2015 and the following years point out that the requirements concerning bearing capacity were still fulfilled for all subsections even after a lifetime of eleven years (Fig. 7). It can be concluded that even if the level of bearing capacity varies for the different subsections due to the different compositions of UGL with various fractions of recycled bricks all subsections show sufficient bearing capacities so far. The data evaluation of the FWD indicators did not point out any significant changes of the bearing capacity for the different subsections with different materials in the UGL of the pavement over the lifetime.

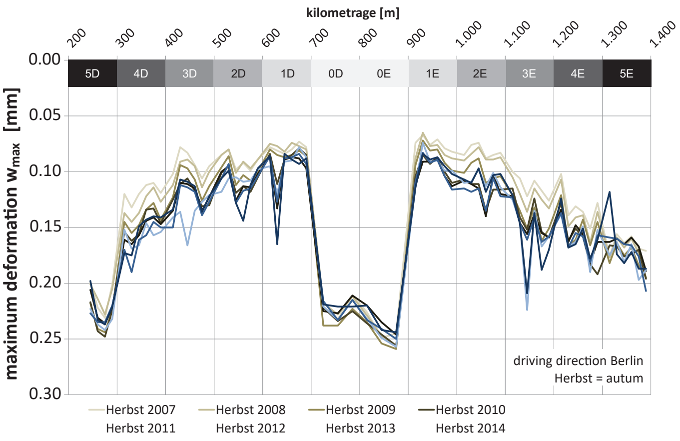

Fig. 6. Development of the profiles of FWD bearing capacity indicator w_{max} over the lifetime of the pavement (2007 light coloured to 2014 dark coloured)

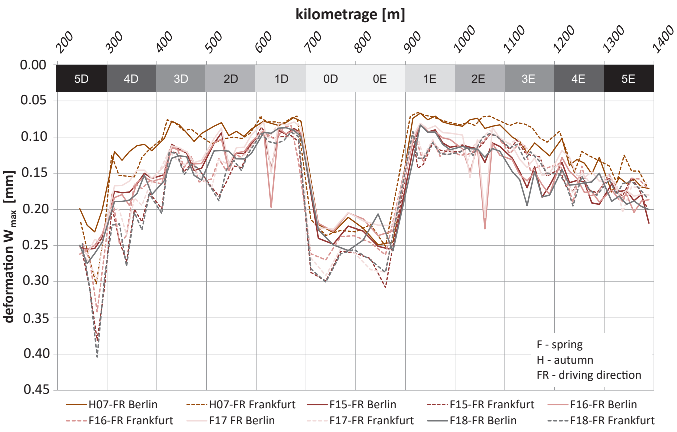

Fig. 7. Profiles of maximum deformation w_{max} of FWD measurement for the different subsections and both driving directions over the time

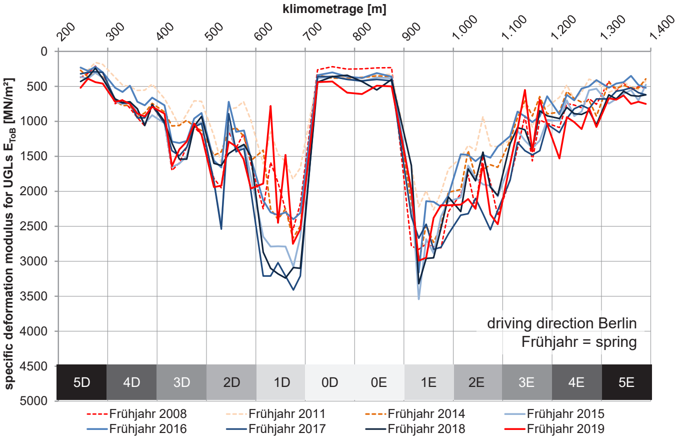

Fig. 8. Profiles of FWD bearing capacity indicator E_{ToB} over time [5]

Fig. 9. Discontinuities (cracks) in the asphalt pavement structure

To evaluate the pavement performance of the UGLs a closer look to an indicator describing the specific deformation modulus of the UGL became obvious.

For the specific deformation modulus E_{ToB} derived from the FWD deflection data comparable profiles occurred (Fig. 8). Over the course of the lifetime of the test section two observations have to be addressed.

Firstly, the profiles show a comparable course for the different subsections. The influence of the different composition of the material with different fractions of recycled bricks in the subsections can be distinguished. Subsections with higher fractions of recycled bricks show lower deformation modulus E_{ToB} for the UGLs. The absolute values are nevertheless not critical, even the least values of E_{ToB} for the natural materials (0D, 0E) achieve sufficient values.

Secondly, the course of the profiles is quite discontinuous in section 3D, 2D 1D as well as for the same subsections in E, they show irregular peaks. These discontinuities indicate a loss of E_{ToB} as well as a loss of bearing capacity. These discontinuities are also visible in the profiles of T_Z and w_{max}.

It is noticeable that those discontinuities only occurred in certain subsections. These are the subsections with low fractions of recycled bricks (10 to 20%) and correspondingly a high amount of recycled concrete (80 to 90%) in the UGL. In the subsections with natural aggregates (0D/0E) as well as in the subsections with natural aggregates and fractions of recycled bricks (5D/5E) no discontinuities are visible.

These discontinuities were also visible as cracks at the surface of the asphalt pavement structure (Fig. 9). A detailed surface inspection of the test section was initiated with a detailed recording of surface damage. The test section showed transversal cracks (Fig. 9) in the conspicuous subsections mentioned above. An accumulation of cracks was recorded for subsections (1D/1E and 1D/2E), single cracks also occurred in subsections 3D/3E and 4D/4E. The transversal cracks correspond to the discontinuities in the profiles of the FWD indicators.

In addition to the regularly executed FWD measurement twice a year, FWD measurements were executed around and directly on some of the transversal cracks (Fig. 10). The measured deflection bowl of the measurements before and behind the crack (green and red dots) do not show any influence of the crack nearby whereas the deflection bowl of the FWD measurement right on the crack (Fig. 10)

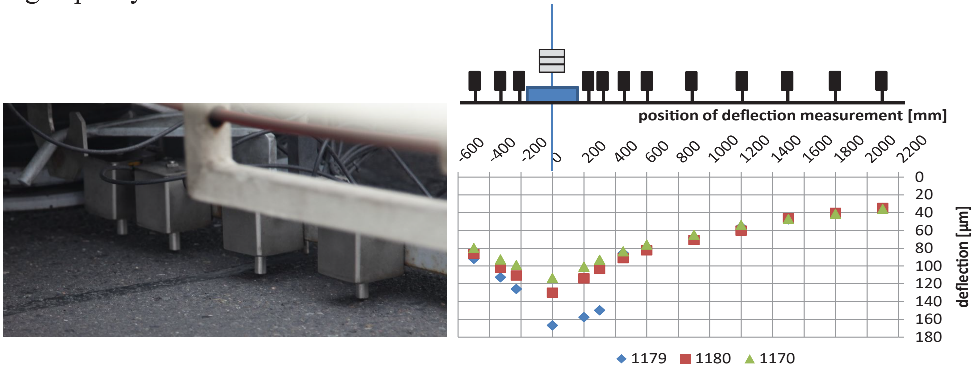

Fig. 10. Discontinuities in FWD indicators due to a crack in asphalt pavement structure at 1179 m in comparison to two measurement points nearby (at 1180 m and 1170 m)

Fig. 11. Visible cracks on top of the asphalt base course and excavation

show a significant discontinuity (blue dots) between the relevant deflection measurement points (geophones at 300 mm and 450 mm). These measurement results show no distinct area with a loss of bearing capacity so the cracks are punctual defects.

The deflection bowl of the measurement over the crack has a characteristic profile like a joint in concrete pavement. This discontinuity of the deflection bowl signifies a continuous crack through the upper asphalt structure.

Those cracks mostly occurred in subsections with a low percentage of bricks (coherent with a high percentage of recycled concrete). Single cracks were firstly noticed after a severe frost impact in winter 2010. The appearance of those cracks could not be related to the fraction of bricks (weak and hydrophilic material) in the composition of the UGL but to the self-hardening effects of the recycled concrete in the UGLs. It was assumed that the cement of the recycled concrete in the UGL was re-activated and formed a bound layer which cracked due to temperature changes and induced stresses in that layer. The cracks through the upper asphalt structure were supposed to be reflective cracks of re-bonded and cracked UGL with recycled concrete.

Due to the observed damage maintenance works were planned and executed in 2018. After milling the asphalt wearing course the cracks were still visible on the asphalt base course. At four subsections (0D, 1D, 3D and 4D) the asphalt base course was also excavated to evaluate the ULGs beneath (Fig. 8). In those excavations (=Ausgrabungen A) measurements with the Lightweight Deflectometer (LFG) and the Medium Weight Deflectometer (MFG) as dynamic plate loading tests were executed to monitor the deformation modulus of the different UGLs (Fig. 11).

Figure 12 shows the deformation modulus of the four different subsections, the numbers of the excavations correspond to the numbers of the subsections with different fractions of recycled bricks in the UGL (A0 → 0E, A1 →1E, A3 → 3E, A4 → 4E). In subsection 0E with only natural aggregates for the UGL the lowest deformation moduli were measured, subsections with fractions of recycled concrete showed significant higher moduli. The UGLs with recycled concrete form a very stiff basis for the upper asphalt structure. A very stiff basis can be dangerous for the upper asphalt structure, in case of no bonding between the upper asphalt structure and the UGLs the stiff basis acts like an anvil which leads to high stresses and strains at the bottom of the upper asphalt package while loading. The results of the measurements in the subsections with recycled concrete in the UGL also scatter strongly, which indicates inhomogeneous conditions of the UGLs. Downward deviations of single measuring points are an indication for the loss of bearing capacity probably due to cracking of the re-bonded UGLs with recycled concrete at this point.

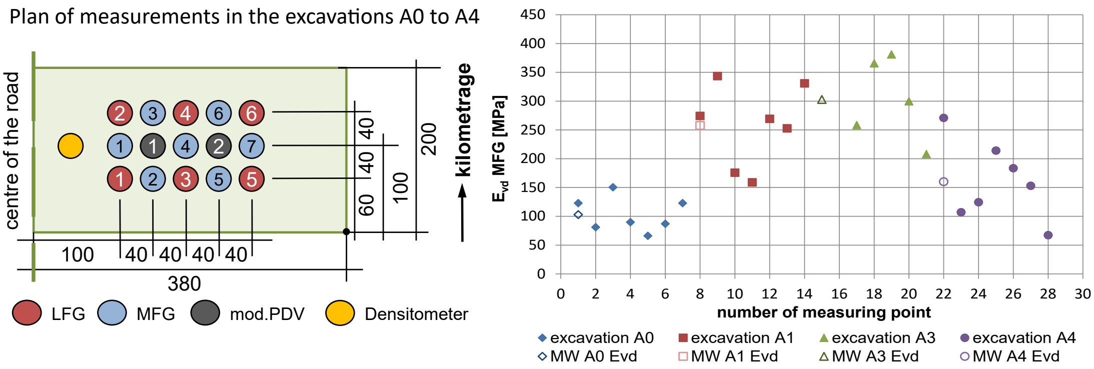

Fig. 12. Measuring plan for bearing capacity measurements and results of MFG measurements in excavations of four subsections

The evaluation of the test section based on the regular FWD measurements and the observed damage was included in the planning of the maintenance works. For the new construction the implementation of an additional 6 cm binder course in addition to a new 4 cm wearing course was fixed.

6. PERFORMANCE OF PAVEMENT SUBSECTIONS AFTER MAINTENANCE WORKS

The by-pass of Seelow was subjected to maintenance works in autumn 2018. After finalization of this works FWD measurements were executed to monitor the status quo after the maintenance works in spring 2019 in comparison to the status beforehand (Fig. 13).

An increase of bearing capacity (indicated by less maximum deformation under the loading plate (w_{max})) is observed for all subsections after the lifetime of 10 years. Only the subsections with 90% of recycled concrete and only 10% of recycled bricks in the UGL (1D, 1E) point out a very small increase in bearing capacity. This is attributed to the stiffness of the re-bonded recycled concrete in the UGL

The single irregularities of the measurement results – which indicated transversal cracks through the asphalt structure – are still visible, the new binder and wearing course led to a reduction of the irregularities but were not able to compensate these irregularities as the cracks are still present in the asphalt base course even if filled with hot bitumen.

In the subsections with natural aggregates in the UGLs (5D, 5E, 0D, 0E) the bearing capacity increased significantly due to the new thicker construction of the asphalt pavement in comparison to the measurements right after construction of the test section in autumn 2007.

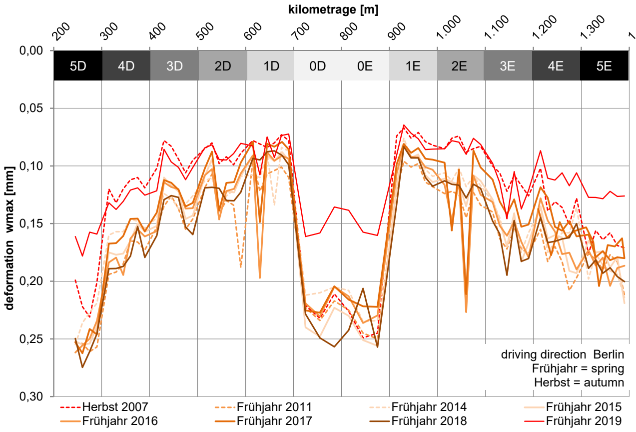

Fig. 13. Results of FWD measurements after maintenance work in comparison to former measurement results

7. DISCUSSION OF SUSTAINABILITY ASPECTS OF THE USE OF RECYCLED MATERIALS IN PAVEMENT CONSTRUCTION

Sustainability for pavements implies high lifetimes of the construction with the least maintenance activities as possible as well as reduced consumption of harmful emissions and reduced consumption of natural resources of aggregates. Then a first comparative balancing of the used resources and its energy consumptions was carried out to provide a first insight into sustainability aspects of different pavements constructions and the use of recycled materials.

The balancing was executed with a new software tool which is right now under development in a research project funded by the Federal Ministry for Digital and Transport called "ÖKOPOST" [6]. With this tool it will be possible to calculate greenhouse gas emissions for specific pavement structures and its maintenance works over the lifetime. The calculations are based on international data for energy consumption and all other features.

The tool is based on the following lifecycle (Fig. 14) taking into account the special conditions for pavement constructions and its maintenance works. The tool does not cover a realistic service life for pavements, it is a balancing, mathematical method to compare pavement constructions.

In the balancing calculations the of the greenhouse gas emissions for the two construction types, the original ones and the new one are compared to each other. The emissions are calculated for a lifecycle of 50 years. Due to the cracks in the original construction type the service-life is set to 10 years based on the experience of the test track. For the new construction type the service-life is fixed to 20 years. All other parameters and boundary conditions are the same for both construction types.

The balancing results show that the total amount of emissions is slightly less for the new construction type in comparison to the original construction type. The observed damage in form of horizontal cracks lead to more maintenance work over the lifetime, which leads to higher emissions of green house gases over the lifetime of 50 years. As the tool is still under development and is not published yet, detailed information or figures showing the detailed results of the calculation for the life cycle cannot be presented here at this stage.

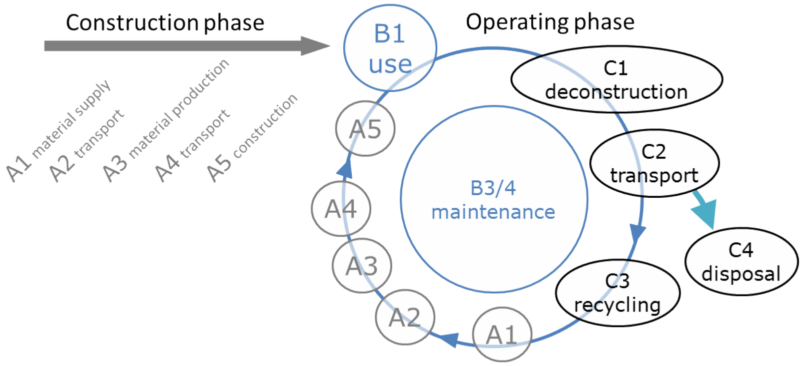

Fig. 14. Lifecycle for pavement construction as basis for the balancing tool “ÖKOPOST” [6]

This first balancing of the greenhouse gas emissions show that it is worth to have a closer look to the lifecycle of a pavement. This first evaluation only covers the constructional aspects of a life cycle analysis, so a holistic analysis will also point out other differences which need to be covered in further investigations.

8. SUMMARY AND CONCLUSIONS

In order to evaluate the material and its performance of recycled material with various fractions of recycled bricks in the UGL over time, a test section was implemented in the federal state of Brandenburg. The aim of the project was to prove the performance of UGLs with higher fractions of recycled bricks than 25% in an in-situ test section after the evaluation of laboratory trials already showed that UGL materials with higher fractions of recycled bricks do not lead to critical plastic deformations.

Various regular measurements have been executed and analysed since the construction of the test section in 2007 until 2016. The effect on the performance of the different compositions in the different subsections was proven by bearing capacity measurements. The maximum deformation of the pavement increases with a higher fraction of recycled bricks in the composition the UGL. Conspicuously the subsections with traditional natural aggregates show the highest maximum deformations and the lowest bearing capacity. The analysis points out that the fraction of recycled bricks in the composition but also the use of recycled concrete for the composition of UGL has a major influence on the performance. It can be noted that all subsections fulfil the requirements of the construction class (class IV according to RStO [3]) of the pavement. No degradation of subsections or any other negative effects due to the higher percentage of bricks in the UGL have been observed so far. As resume of the project it can be stated that the higher admissible fraction of 30 % of bricks in the composition of UGL is rated as uncritical for the performance of the UGL. The increase of permissible content of recycled bricks in UGLs to 30% in the German Guidelines was confirmed.

One new significant aspect however arose during the investigations, which needed to be addressed to avoid future problems in the performance of pavement structures. The appearance of cracks in the asphalt layer is quite a complex topic which could not be analysed by using simplified models based on the multi-layer theory.

The observed damage (cracks in the surface layer) of the test section are assumed to be the outcome of re-bonding of the recycled concrete in the composition of UGL. Further investigations were executed, especially excavation of single spots in different subsections, to render evidence about the cause of the crack initiation. The visual inspection as well as the sampling of the material of the UGLs showed that the UGLs were subjected to self-hardening effects due to the cement in the recycled concrete.

Recycled concrete in UGLs tends to self-hardening effects and to form a very stiff re-bonded layer beneath the asphalt structure. To avoid reflective cracking and as a consequence to early maintenance actions the specific performance of recycled concrete in UGLs and its self-hardening effects need to be taken into account in the course of pavement design. Recycled materials differ in its behaviour in pavement constructions so the experience of pavement performance based on UGLs with only natural aggregates cannot simply be transferred to new types of material.

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