MEHDI KALANTARI[1)]

# COLD RECYCLING WITH FOAMED BITUMEN, GAINED KNOWLEDGE FROM A TEST TRACK IN GERMANY

# RECYKLING NA ZIMNO ZE SPIENIONYM ASFALTEM, WIEDZA ZDOBYTA Z TORU TESTOWEGO W NIEMCZECH

**STRESZCZENIE.** W ostatnich latach w UE znacznie wzrosło zapotrzebowanie na bardziej zrównoważoną infrastrukturę transportową. W Niemczech celem politycznym jest osiągnięcie neutralności klimatycznej do 2035 roku. Wśród różnych rozwiązań, recykling to ważny aspekt na drodze do osiągnięcia gospodarki o obiegu zamkniętym w odniesieniu do nawierzchni, jako jednej z głównych części infrastruktury transportowej. Recykling na zimno to technika, która wymaga mniej energii i może potencjalnie wykorzystywać większe ilości materiałów pochodzących z recyklingu. Uzyskany materiał może nie mieć takich samych właściwości jak konwencjonalna mieszanka asfaltowa na gorąco, ale dzięki zoptymalizowanej mieszance i projektowi strukturalnemu możliwe jest wykonanie nawierzchni o takiej samej lub nawet wyższej trwałości niż konwencjonalne rodzaje nawierzchni, ale o większym potencjale w zakresie zrównoważonego rozwoju. W 2018 r. w Federalnym Instytucie Badawczym Drogownictwa (BASt) we współpracy z Wirtgen GmbH zdefiniowano projekt badawczy na temat recyklingu na zimno z asfaltem spienionym. Głównym celem projektu było zebranie informacji i doświadczeń na temat zachowania zimnego materiału pochodzącego z recyklingu ze stosunkowo niewielką ilością bitumu i cementu, znanego na całym świecie jako Bitumen Stabilised Materials (BSM). W tym celu zbudowano 100-metrowy odcinek testowy na obszarze demonstracyjnym, badawczym i referencyjnym BASt (duraBASt) z dwoma różnymi typami konstrukcji (referencyjnym i z recyklingu na zimno). Oba odcinki zostały obciążone za pomocą mobilnego symulatora obciążenia (MLS30). W niniejszym artykule przedstawiono niektóre wyniki i ustalenia z nieniszczącego monitorowania (pomiary FWD i koleinowania) i badań wydobytych rdzeni. Program dowiódł, że możliwe jest zaprojektowanie i wykonanie nawierzchni z BSM o porównywalnych parametrach jak nawierzchnie konwencjonalne w Niemczech.

**SŁOWA KLUCZOWE:** recykling na zimno, asfalt spieniony, mieszanka stabilizowana emulsją asfaltową, Bitumen Stabilised Materials (BSM), przyspieszone testowanie nawierzchni (APT), duraBASt.

**ABSTRACT.** During the recent years, the demand on more sustainable transportation infrastructure has increased considerably in the EU. In Germany the political goal is to become climate neutral by 2035. Among different solutions, recycling is an important approach to achieve circular economy for pavements as one of the main parts of transportation infrastructure. Cold recycling is a technique which needs less energy and has the potential of using higher rates of recycled material. The resulting material may not have the same characteristics as the conventional hot mix asphalt, but through an optimised mix and structural design, it is possible to construct pavements with the same or even higher durability than the conventional types but a greater potential for sustainability. In 2018 a research project on the topic of cold recycling with foamed bitumen was defined at Federal Highway Research Institute (BASt) in cooperation with the Wirtgen GmbH. The main goal of the project was to gather information and experience on the behaviour of cold recycled material with relatively low amounts of bitumen and cement, known internationally as Bitumen Stabilized Material (BSM). For this purpose, a 100-meter test section was built at the demonstration, investigation, and reference areal of BASt (duraBASt) with two different construction types (reference and cold recycled). Both sections were loaded with the Mobile Load Simulator (MLS30). This paper presents some of the results and findings from the non-destructive (FWD and rutting measurements) monitoring and tests on the extracted cores. The program proved that it is possible to design and construct pavements with the BSM and the comparable performance as conventional pavements in Germany.

**KEYWORDS:** cold recycling, foamed bitumen, Bitumen stabilized material (BSM), Accelerated Pavement Testing (APT), duraBASt.

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[1)] Federal Highway Research Institute (BASt), Bergisch Gladbach, Germany; e-mail: Kalantari@bast.de

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## 1. INTRODUCTION

The increasing demand for more sustainable transportation infrastructure has also affected the construction and maintenance of the pavements. Currently, sustainability plays an important role during the development, evaluation and selection of different construction and maintenance methods. Beside other methods, recycling is always known as a sustainable approach which decreases the negative environmental effects of construction and rehabilitation. Generally, asphalt recycling methods can be classified into three major categories of hot, warm, and cold procedures. The main difference between them is the production temperature. Cold recycling methods are performed in ambient temperatures and there is no need to heat the aggregate mix. The cold process of the aggregate mix leads into noticeably lower energy consumption and produces less emission in comparison to the other recycling methods. Considering the heating of the RAP (reclaimed asphalt pavement) as one of the challenges of the asphalt plants for hot recycling, the cold recycling process is relatively simpler from a technological viewpoint and provides the possibility of applying higher rates of RAP.

It is not possible to mix the bitumen with aggregates in ambient temperature. To be able to that, the viscosity of the bitumen should be decreased. Generally, this is possible through three different methods: Diluting the bitumen in a petroleum hydrocarbon as solvent (cutback bitumen), suspending the bitumen droplets in water (bitumen emulsion) or making foamed bitumen. The first process is not used in cold recycling, whereas the use of bitumen emulsion in this context has been tried and tested in Germany. Present interest lies with the use of foamed bitumen which was applied rarely in Germany and maybe has the advantage of environmental sustainability. By injecting a little amount of water into the hot bitumen, the water droplets will evaporate and result in foaming of the bitumen [1]. The produced foam will stay for some seconds, which is enough to enable to mix it with cold and moist aggregates. Beside the bitumen, normally a hydraulic binder (cement or hydrate lime) is also added as the second binder to increase the moisture resistance of the recycled material and its early life strength. After compaction, the mix gains strength and stiffness over the time as the water evaporates (formation of the bitumen bonds) and the cement hydrates (the process known as curing).

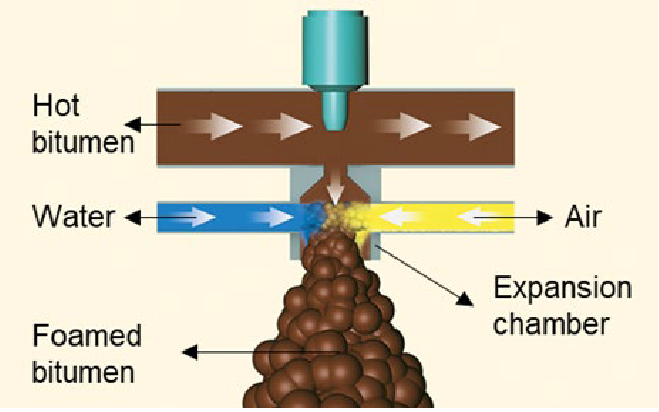


Fig. 1. Foamed bitumen production [1]

Cold recycling has been applied in Germany since its early introduction, but mainly in roads with low traffic volume and with relatively high amounts of cement. The main reason can be the lack of national-level performance data on material's behaviour. During the last decade, different laboratory research and monitoring activities were performed on this technology in Germany [2, 3, 4, 5, 6]. The results of these activities plus the positive international experiences increased the interest in this type of cold recycling. In 2018 a research project on the topic of cold recycling with foamed bitumen was defined at Federal Highway Research Institute (BASt) in cooperation with the Wirtgen GmbH to gather more data on the behaviour of cold recycled mixes with low amounts of foamed bitumen and cement known as bitumen stabilized mixes (BSM, [7]). Beside a knowledge transfer laboratory program, a test lane was planned to be constructed and tested at the BASt's demonstration, investigation, and reference areal named as duraBASt.

duraBASt is the BASt's outdoor test facility, located east of Cologne city parallel to A3 motorway north direction intersection with A4 motorway. The areal has a total length of approx. 1,000 m and area of 25,000 m$^2$, constructed between 2015 and 2017. There are three main areas in duraBASt: the reference area (R areal) which is for the approval of the surface characteristics' measuring vehicles and then the demonstration and investigation areas (D/U areal). The last two consist of nine lanes, six of them are in the central area (with different widths from 3.5 to 5.5 m and lengths up to 100 m). For more information about the duraBASt, the reader is referred to duraBASt website and [8].

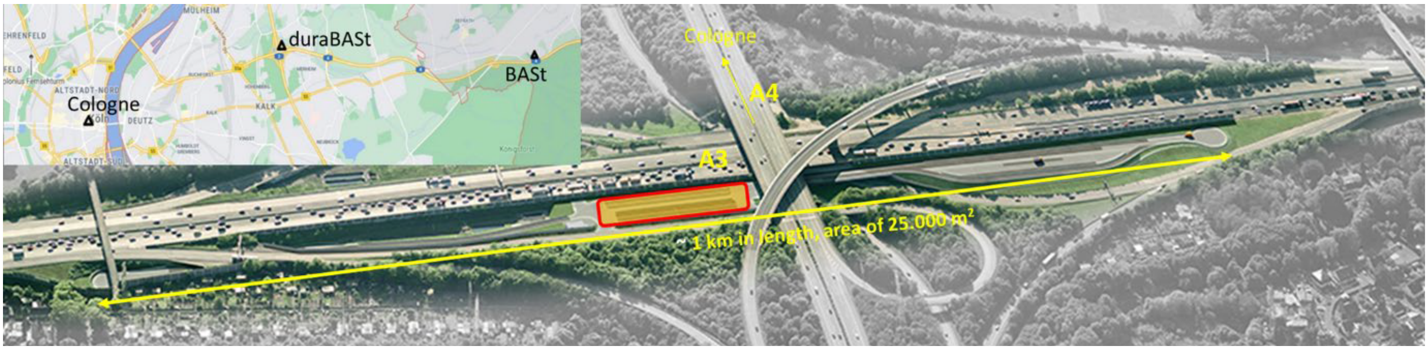


Fig. 2. duraBASt position

This paper aims to present the Accelerated Pavement Testing (APT) program applied for assessing the behaviour of cold recycled mixes with foamed bitumen and the important results derived from that.

## 2. ACCELERATED PAVEMENT TESTING PROGRAM AND ITS DIFFERENT PHASES

Accelerated pavement testing (APT) is an international approach to simulate the truck loads in a short and compressed time [9]. BASt's APT program has been defined and standardized based on in-house gained experiences over the years of performing that [10].

The APT program can be divided into four different steps:

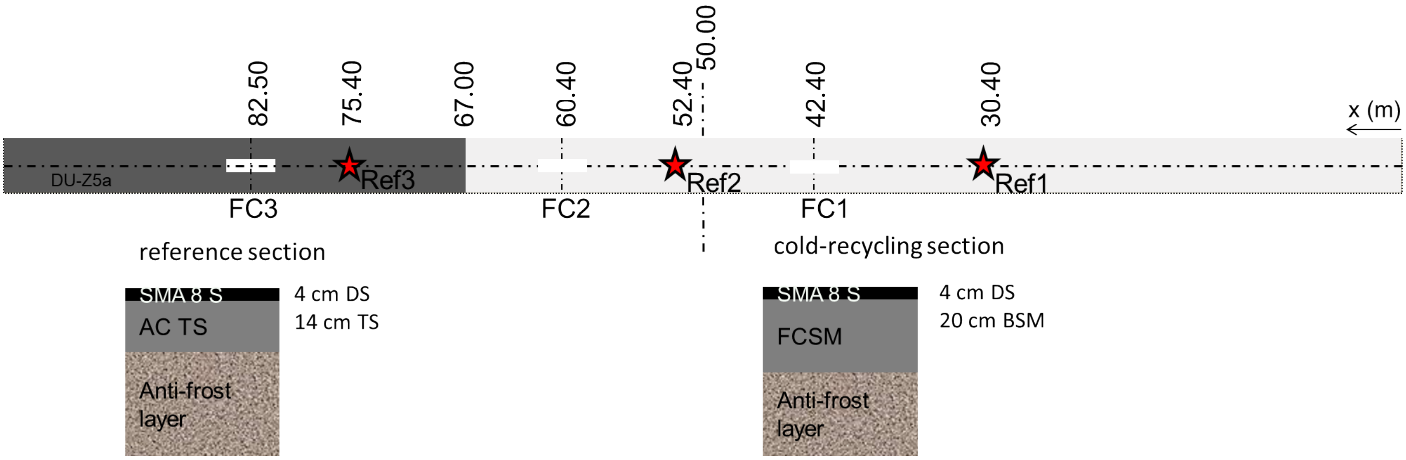
- Planning activities: planning the test concept and the test lane layout, mix design of the applied materials, structural design of the test sections, preparing the loading and monitoring plans.
- Construction activities: preparing the test lane, producing the mixes, installing the sensors, laying and controlling tests.
- loading and monitoring: preparing the loading areas, loading with Mobile Load Simulator (MLS30), monitoring during and after the loading.
- Analysis and evaluation of the data which, in some cases is parallel with loading.

Each of the mentioned activities will be explained in the coming text sections.

### 2.1. TEST LANE LAYOUT

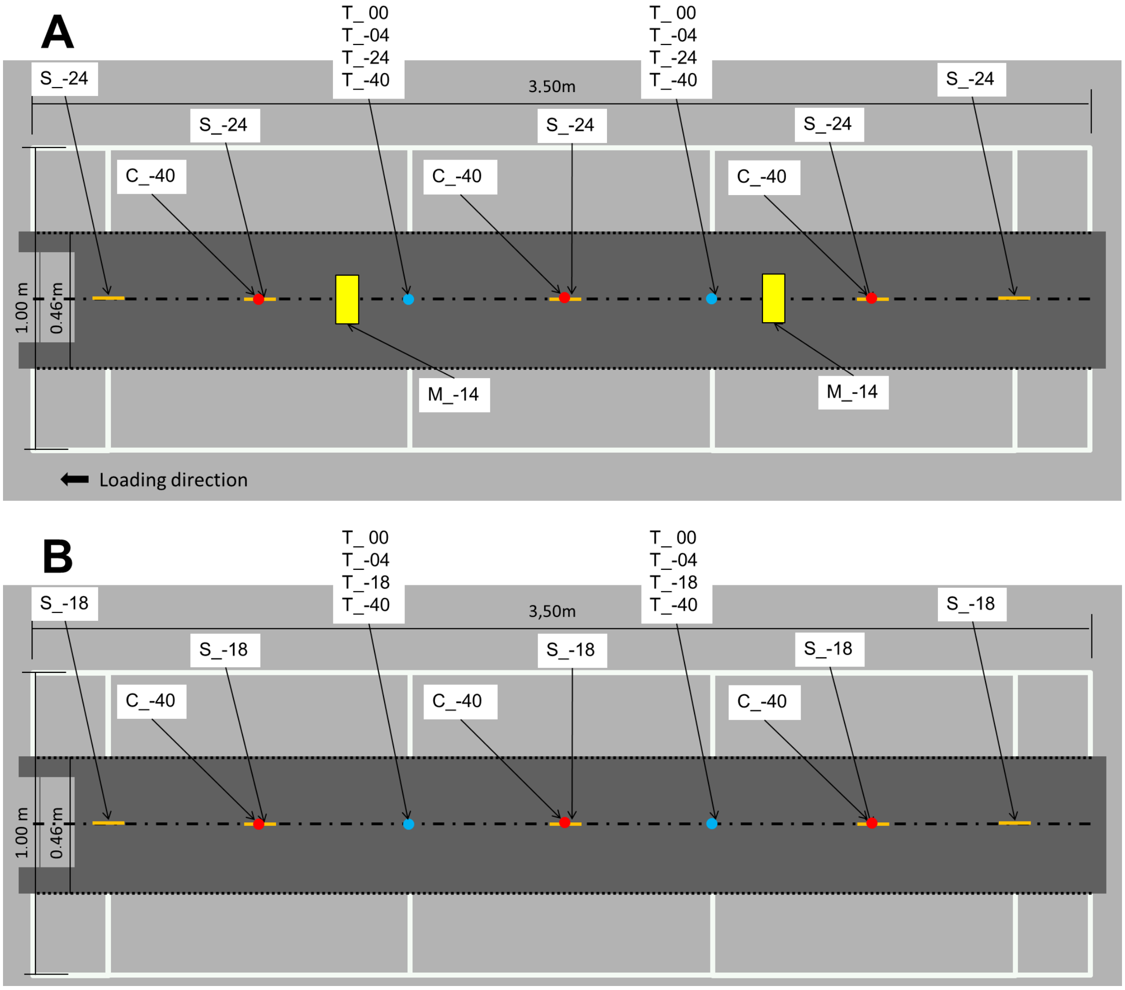
A test lane with 100 m length and 3.5 m width was selected form the D/U part of the duraBASt for this project. To have a reference for comparison, a conventional pavement section type was also planned to be constructed. Two thirds of the test lane was planned for the cold recycled pavement and the rest for the conventional pavement. The section with the foamed bitumen cold recycled base layer will be referred as cold recycled (CR) section and the section with the hot mix asphalt base will be referred as the reference (RF) section. For the CR section two loading areas (one as reserve) were planned and for the RF section one loading area was planned. Each loading area has a reference point far enough out of that, which is instrumented with embedded sensors and is measured each time when a non-destructive measurement is performed on the loading areas. The aim of these reference points is to be able to check the difference between the loaded and not loaded pavement and to control if the devices are measuring correctly.

Figure 3 shows the sketch of the test lane with its two sections, loading areas in each section and their reference points. The loading areas in the cold recycled section are named as FC1 and FC2 with Ref1 and Ref2 as the reference points for each. The loading area of the reference section is named as FC3 with its reference point named as Ref3. Each loading area has a length of 3.5 m and was marked before loading. Different sensors including pressure cells, strain gauges, temperature and moisture sensors were installed at different depths of the pavement in loading areas and reference points. Figure 4 shows type and position of the installed sensors in the loading areas. The letters show the sensor's type, and the numbers show their depth in cm. T stands for temperature sensors, S for strain gauges, C for pressure cells and M for moisture sensors. Strain gauges and pressure cells measure during the loading, every 15 minutes for a duration of 30 but the temperature and moisture sensors measure continuously every 15 minutes.



*Source: BASt, Project data*

Fig. 3. Sketch of the test lane, its pavement sections and different loading areas



*Source: BASt, Project data*

Fig. 4. Schematic picture of the loading areas and sensors. A: FC1 and FC2 and B: FC3

## 2.2. MATERIAL AND STRUCTURE OF THE TEST SECTIONS

The structure of the reference section was selected from the existing national guideline for design of pavements in Germany, known as RStO 12 [11] for 1 million of 10-ton equivalent single axle loads (10-ton ESAL) bearing capacity. It consists of 4 cm wearing coarse and 14 cm hot mix asphalt (HMA) base coarse. Stone mastic asphalt with nominal aggregate size of 8 mm was selected for the wearing course (SMA 8S) and asphalt concrete with nominal aggregate size of 22 mm (AC 22 T N 50/70 BAS RA) with around 30% of RAP as the base course.

Mix design of the foamed bitumen mixture was performed based on the proposed method by Wirtgen [12]. To produce the foamed bitumen, Nyfoam80® (from Nynas company) was selected. After performing foaming tests with the laboratory foaming machine (WLB 10 S from Wirtgen), the bitumen temperature of 160°C with 2% foaming water satisfied the desired foaming parameters (expansion ratio of 13 times and half-life of 14 seconds). Cement type I-425 N was selected as the secondary binding agent. The RAP material for the project was selected from the same asphalt plant for the HMA layers. Enough amount was stockpiled separately in the asphalt plant for the mix design and later the construction of the CR test section. The RAP has not been crushed and only sieved into two fractions of 0–8 mm and 8–22 mm sizes. The activity tests of the bitumen in RAP (according to [12]) showed that the RAP bitumen could be classified as active and therefore, addition of crushed aggregates or crushed dust was recommended according to the Wirtgen guideline [1]. The grading curve also showed the lack of fines, which is necessary for foamed bitumen mixes. In laboratory, different mix combinations of the two RAP fractions and 0–2 mm sand with different amounts of foamed bitumen and 1% cement were produced and the compacted specimens were tested. Based on indirect tensile strength tests results (ITS wet and dry), the final mix combination of 75% RAP (40% 8–22 mm and 30% 0–8 mm) and 25% sand (0–2 mm) was selected as the granular mix (Fig. 5) with 2.2% foamed bitumen, 1% cement and 4.5% water. The amounts of the binding agents and water are based on dry weight of the granular mix.„”

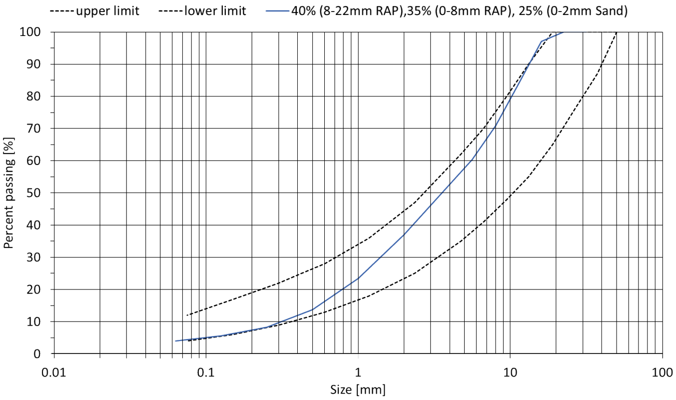


Fig. 5. Grading curve of aggregate mix in the selected mix design. Upper and lower limits are from Wirtgen [1]

According to the existing national guidelines for cold recycling [13, 14] and to have the same bearing capacity like the reference section, the CR pavement should have 4 cm of wearing coarse, 6 cm of HMA base and 18 cm of CR layer. According to international literature and author's structural design [3], the recommended design is conservative and therefore, it was decided to adjust it to 4 cm of wearing course and 20 cm of cold recycled layer with foamed bitumen (CRF) as the base layer.

## 2.3. COLD RECYCLED MIX PRODUCTION

A Wirtgen KMA220 mobile plant was used to produce the mixture at the same place where the RAP was stockpiled (Figure 6). The amount of added water was calculated based on the mix design and the in-situ moisture of the granular mix measured before the production.

Source: BASt, Project data

Fig. 6. Production of the cold recycled mix with mobile plant (KMA 220)

## 2.4. TEST SECTION CONSTRUCTION IN DURABAST

Construction was started with milling and excavation up to the desired depth (-40 cm). After compaction and installation of the pressure cells, the anti-frost layer was laid and compacted.

Beside the ITS controls, the Medium Falling Weight Deflectometer (MFWD) was applied on middle points of the 2 loading areas (FC1 and FC2) and their reference points (Ref. 1 and Ref. 2) to monitor the evolution of the stiffness at early life of the material. More information on the device and its specifications can be found in [15].


*Source: BASt, Project data*

Fig. 7. Strain gauges installation, laying and compaction of the cold recycled layer

First the CR section was constructed by laying the recycled layer with an asphalt paver and compaction with a steel drum and rubber tire rollers. Before laying the layer, the strain gauges were installed at planned positions. Moisture sensors were installed in the fresh laid layer before the start of the compaction.

For quality control, fresh samples of recycled mix were taken from the field and compacted in the laboratory at the same day to produce specimens for ITS tests. After curing (72 hours at 40° C) they were tested in dry (cured state) and wet (24 hours at 25° C) states at 25° C. Table 1 shows the ITS and the TSR (Tensile Strength Ratio) for the positions at which the samples were taken (each one is the average of 3 replicates).

Table 1. The results of the ITS tests on fresh samples compacted and tested in laboratory

| Parameters | Positions of the samples [m] | | | |
|---|---|---|---|---|
| | 30 | 40 | 50 | 60 |
| $ITS_{dry}$ [kPa] | 339 | 224 | 252 | 341 |
| $ITS_{wet}$ [kPa] | 303 | 133 | 207 | 276 |
| TSR [%] | 89 | 59 | 82 | 81 |

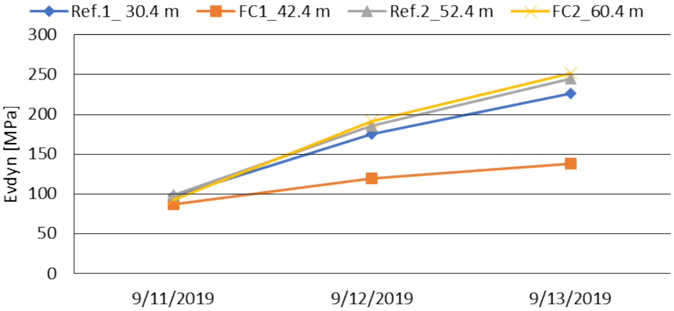
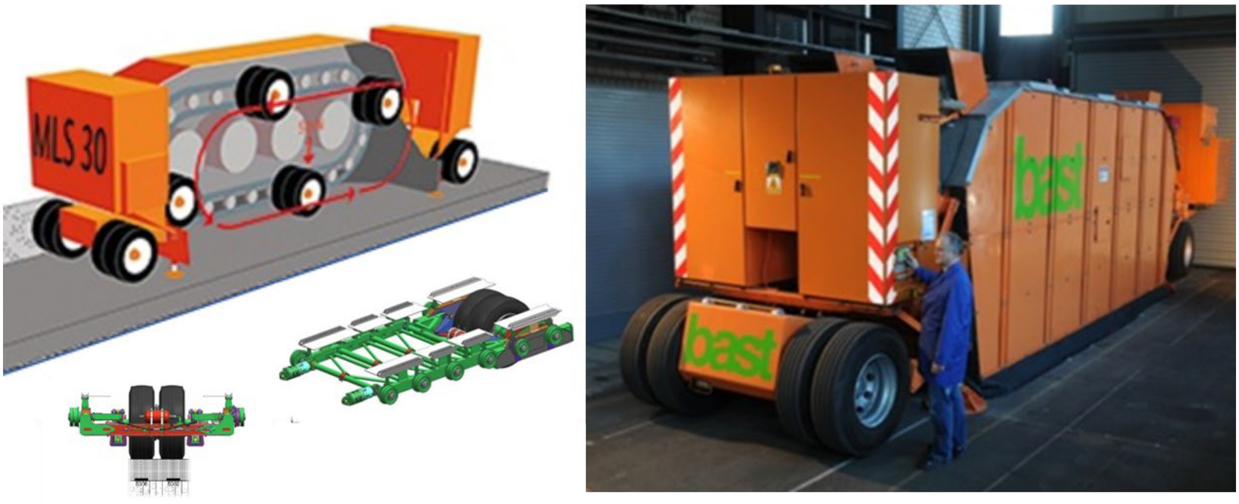


Fig. 8. The results of the MFWD measurements

Figure 8 shows the $Ev_{dyn}$ over the first 3 days after construction. The stiffness on FC1 midpoint (at 42.40 m) is lower than the other points, the same as the ITS and TSR results (Table 1). These two results showed that there is a difference in the quality of the RC mix around the first loading area (FC1).

The in-situ density results with the balloon method satisfied the required target density (target dry density 2.2 gr/cm$^3$).



*Source: BASt, Project data*

Fig. 9. Mobile load simulator of BASt (MLS30)

Table 2. The results of in-situ dry density tests (in gr/cm$^3$)

| Positions [m] | 20 | 30 | 40 | 50 | 61 |
|---|---|---|---|---|---|
| Density | 2.26 | 2.24 | 2.25 | 2.28 | 2.21 |

The HMA base layer of the RF section was laid a week later (17.09.2019). A polymer modified fluxed bitumen was sprayed on the surface of the cold recycled layer at the same day (Viaflex® C60 BP-4-S) and the whole was overlaid with the wearing course the day after.

## 2.5. LOADING OF THE TEST SECTIONS

BASt uses a Mobile Load Simulator (MLS30) since 2013 for its APT programs. The device simulates the wheel passes of the heavy trucks in a compressed time duration. It has four bogies with one wheel on each that rotate in a closed frame. Each time one of them rolls on a linear strip over the loading area. Wheel loads between 45 to 75 kN with different types (single, super single or dual) can be set for the loading. Variable loading speeds of 6.5 up to 22 km/hr (6.1 m/s) are also achievable. At its maximum speed, it is possible to get around 6000 passes per hour which is equal to one pass every 600 ms on the same position [16]. To load each area, the MLS30 is positioned on the desired place and rests on its four corner jacks.

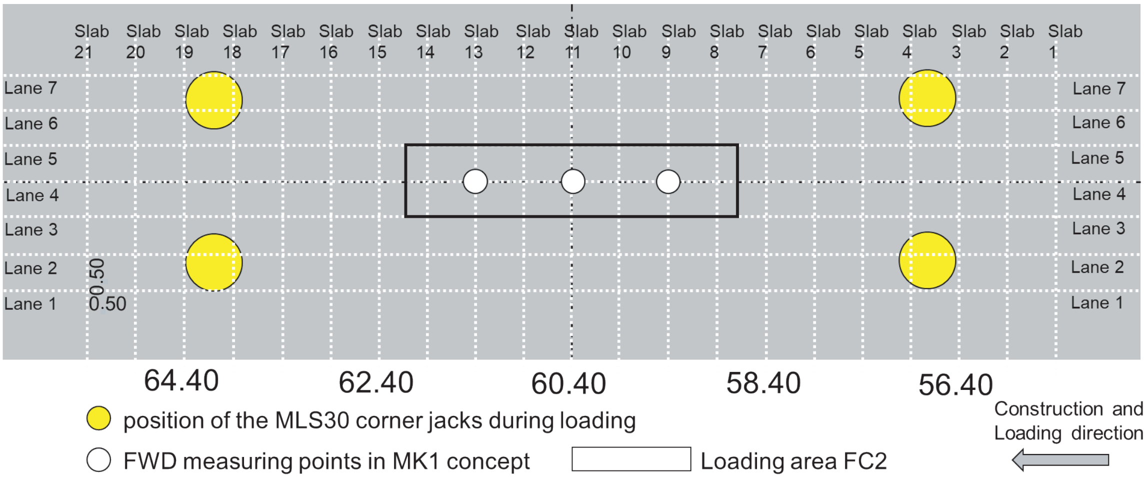
A super single tyre with 50 kN load and the speed of 6000 passes per hour was used for this project. Based on the gained experiences from the last projects, it was planned to load each section with 3 million passes. To minimize the effect of weather changes, it was decided to load both sections (reference and cold recycling loading) together by changing the loading in weekly periods between them. The loading started in Feb. 2020 on FC2 (CR section) and the FC3 (RF section) till reaching 3 million passes for each. Then changed to FC1 till 1.7 million passes and then back again on the two areas FC2 and FC3 till reaching the total of 5 and 4.2 on each accordingly. The loading duration was 2 years with a total of 10.9 million passes.

## 2.6. INVESTIGATION PLAN OF THE PROJECT

The investigation plan of the project consisted of two main parts: field monitoring and tests plus laboratory tests on the extracted cores. Field monitoring plan consisted of bearing capacity measurements with Falling Weight Deflectometer (FWD), subsurface scan with a 3D Ground Penetration Radar (GPR), transverse profile measurements along the loading areas and monitoring with the installed sensors.

### 2.6.1. FWD measurements

Bearing capacity measurements aim to figure out if any kind of change has happened during the loading. They are performed before the loading and then at different intervals during the loading. They are performed at different points in the loading area. Besides the standard measurements, a grid of points are measured around each loading area



*Source: BASt, Project data*

Fig. 10. FWD grid measuring concept points of the FC2 loading area

(covering also the position of the corner jacks) aiming to have a detailed picture of the bearing capacity (Fig. 10).

Two extra concepts were defined for this project. The first one was to measure the whole test lane on its centreline at each 50 cm and at different time intervals after the construction (named as whole lane concept). The aim was to assess the construction homogeneity considering the ITS and MFWD results after construction and to monitor the curing process of the recycled material over time. The second concept aimed to look closer to the effect of temperature changes over the response of the cold recycled section. Different points were selected through the centreline of the CR section and FWD measurements were performed on them through the whole day at different temperatures.

### 2.6.2. Transverse profile measurements (evenness)

The measurement is performed along the loading area at 5 different cross lines with a profilometer. The measured data are used to determine the rutting depth based on the difference between the minimum (Min.) and maximum (Max.) amounts calculated for each profile measurements. The Min. amount is determined by averaging results over a cord length in the loading strip and the Max. amount is the average of the two side points (Fig. 11).

### 2.6.3. Laboratory tests

Parallel to the field monitoring, a comprehensive laboratory investigation was planned to monitor the evolution of CR material's stiffness over time (curing process) and to assess its characteristics and performance parameters.

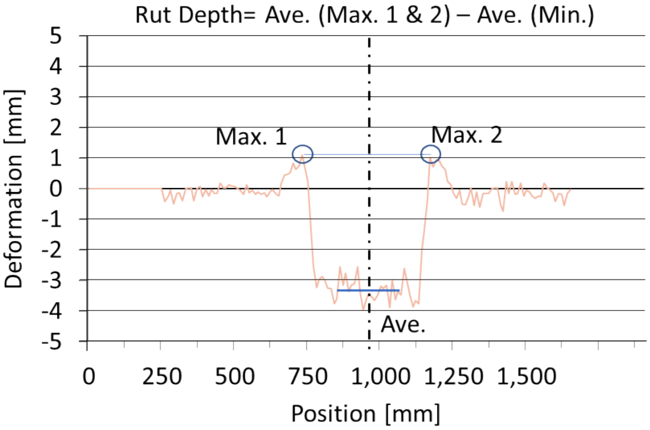


Fig. 11. Rut depth calculation method

Cores were extracted at different time intervals after the construction and used for stiffness, indirect tensile strength, and fatigue tests.

The cores from the RF section were cut to separate the wearing and the base courses. The specimens were used for cyclic indirect tensile stiffness tests at different temperatures and frequencies according to German guideline (TP Asphalt-StB Teil 26-2018) which is based on EN 12697-26: 2012-06 (annex F). The base coarse specimens were later used for indirect tensile fatigue tests at 20° C and 10 Hz (also based on the German method (TP Asphalt-StB Teil 24-2018) which is based on EN 12697-24: 2012-08 (annex E).

The CR cores for monitoring the curing were cut to get specimens with 60 mm height. They were conditioned in the oven at 40°C for 72 hours to accelerate the loss of coring and cutting moisture. They were tested under the cyclic indirect tensile test (at 20° C and 10 Hz) at different stress levels (up to 0.1‰ horizontal strain level) to obtain their stiffness modulus at different horizontal strain levels. This test is named as a multi-step stiffness test; the method and the way to analyse the results was developed by the author during his PhD course [3]. It suggests to test a minimum of four specimens. The test captures the stress/strain dependency of the stiffness as one of the main characteristics of the foamed bitumen recycled/stabilized mixes. Based on the results it is possible to determine the stiffness at different strain levels with a desired probability level. As the stiffness tests in the mentioned strain range doesn't affect the ITS amount [3], it was possible to use the specimens for ITS tests (at 25°C). As mentioned before, this group of cores were drilled at different times to evaluate the effect of curing on mechanical characteristics of the CR material. The second group of cores were planned for about a year after the construction (considering that the curing is mostly completed) to obtain the stiffness master curve and the fatigue behaviour of the recycled mix. The tests were the same as HMA based specimens. The stiffness tests were performed at lower horizontal strain levels than the ones for HMA (around 0.03 to 0.04‰) to be sure that the internal damage of the specimens remains in an acceptable range. The author has developed a method to produce the general stiffness model of the material by combining the results of the multi-step stiffness tests and the stiffness master curve tests [3]. This general model captures both the strain dependency of the stiffness (which comes from the granular part behaviour) and its temperature dependency (which comes from the asphaltic part behaviour).

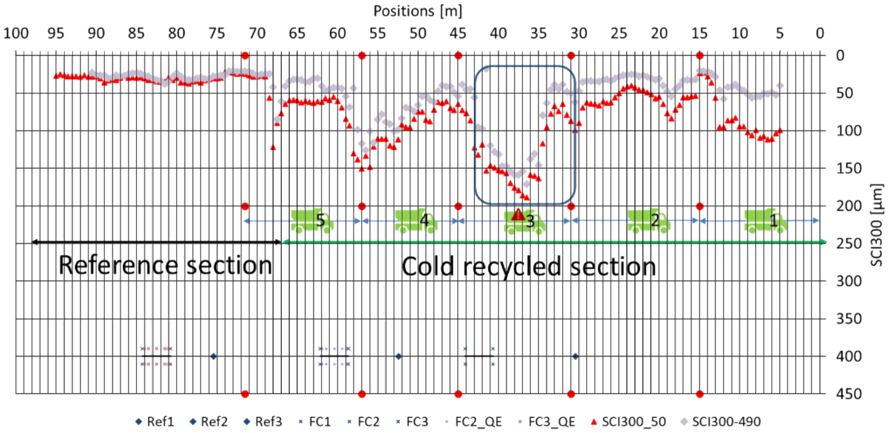


Fig. 12. SCI300 at the centreline of the test lane, 50 and 490 days after construction

### 2.6.4. Detailed investigation after the end of loading program

After the end of the loading, a forensic investigation was planned aiming to get a better insight into the construction homogeneity and the effect of the loading. For this purpose, an intensive coring plan was prepared from the loading areas (in both test sections) and the other parts of the test lane. Besides that, different cuts were planned along the loading areas to look at the permanent deformation of CR layer.

## 3. RESULTS AND DISCUSSIONS

This section presents the main results from different measurements and tests during the project. The three loading areas were loaded with a total sum of 10.9 million (10-ton ESAL) cycles as mentioned before, 1.7 million on FC1, 5 million on FC2 and 4.2 million on FC3 (RE section). None of the areas showed any signs of surface cracks but all had permanent deformation, which is discussed in this section.

### 3.1. FWD MEASUREMENTS RESULTS

The first whole lane bearing capacity measurement, proved the findings from the quality control tests. Figure 12 shows the SCI300 parameter (as the difference between the surface deformations measured at the centre of the loading plate and 300 mm apart from that) in the centreline of the whole test lane at different measurement intervals (50 and 490 days after construction). SCI300 reflects the status of the upper layers of the pavement. Higher amount shows lower bearing capacity of the pavement due to the status of the upper layers.

Comparing the covered distance of CR mix paved per truck load, the SCI300 value shows which truck load has had a suspicious mix within the cold recycling section. It also can be seen that the regions of changing from one truck to the other cause inhomogeneities. It can be the result of closing the paver's side hopers at the end of each truck's material. On the other side, the reference section results show more homogeneity than the CR section. These observations opened the question on the effect of mix grading and the laying method on the resulted homogeneity of the pavements with CR layer.

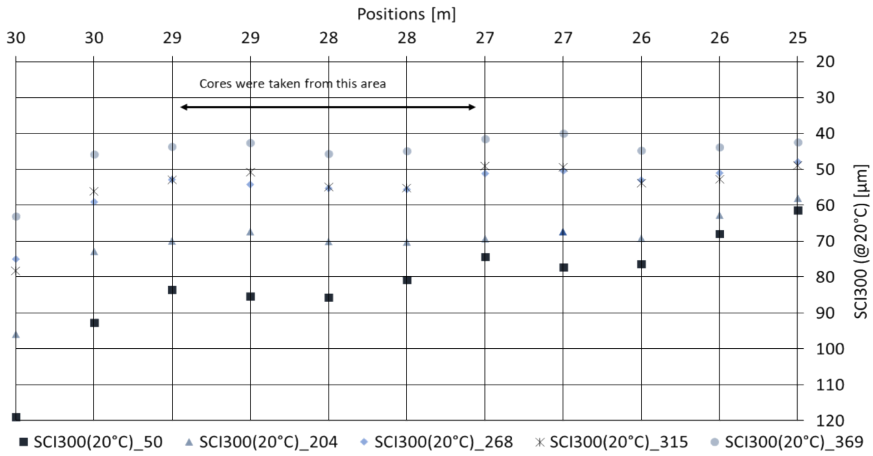


Fig. 13. Evolution of the bearing capacity (SCI300@ 20° C) over time in CR material (SCI300(20°C)_xxx, while xxx is the number of days after construction)

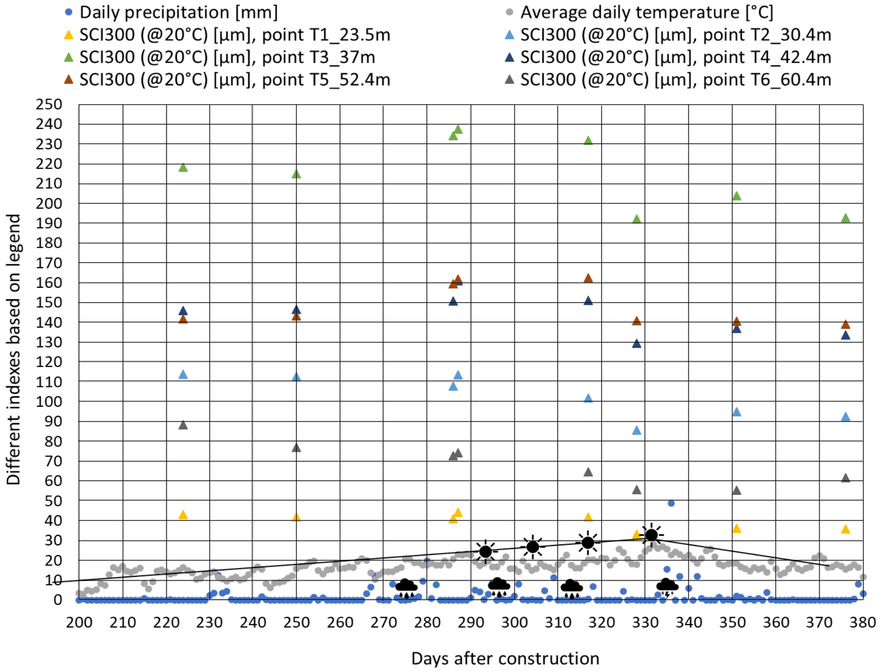


Fig. 14. Change of SCI300@ 20° C at 6 different points in combination with weather parameters

The measurements were continued at different time intervals to also monitor the curing of the CR layer. Figure 13 shows the SCI300$_{@\ 20°C}$ calculated from these measurements on a part of the CR section, where the cores were also extracted to monitor the stiffness value over time. Decrease of the SCI300 value over time, shows the increase of the stiffness in cold recycled layer due to the curing.

To assess the effect of temperature changes on the FWD results, 6 different points from the RC section (as the weakest, strongest, 2 reference points and the middle of each loading area) were selected and measured at different days. To look at the changes of the SCI300 at different temperatures, a linear equation was fitted to the results of each point and used to determine the SCI300 at 20° C for that point at that measurement day (which can be related to days after construction). Putting all the calculated SCI300$_{@\ 20°C}$ together in a time order after construction, showed that their values have a decreasing trend over the life of the pavement, which is because of the curing. Besides that, there are some localized changes which fit with the weather conditions (temperature and precipitation) (Figure 14). The results showed that the bearing capacity of the CR pavement is not only temperature dependent (like normal HMA) but is influenced also by the wet-dry cycles (or seasonal variations). This finding is important for pavement structural design; as instead of using the full cured material properties, it is necessary to adjust them based on an equilibrium moisture state which is more representative of the field conditions.

It is possible to determine the stiffness of the pavement layers from the FWD measurements by a back calculation process. For this purpose, a five layer (wearing course, cold recycled layer, anti-frost layer, upper and lower subgrade) linear elastic pavement model was considered. As the aim was to determine the stiffness of the CR material, the wearing course and the CR layer were modelled separately. The stiffness of the wearing course was determined based on the temperature during each FWD measurement and the stiffness master curve of the material (from the laboratory stiffness tests on the cores) and used as the input in the back calculation model. With this approach, the only temperature dependent material was the CR and, therefore, its stiffness could be back calculated at each FWD measurement's temperature. The back calculated stiffnesses at different temperatures (from FWD Temperature concept measurements), were used for temperature normalization of the stiffness.

Figure 15 shows the back calculated stiffnesses on the middle of the FC1 loading area, before and after

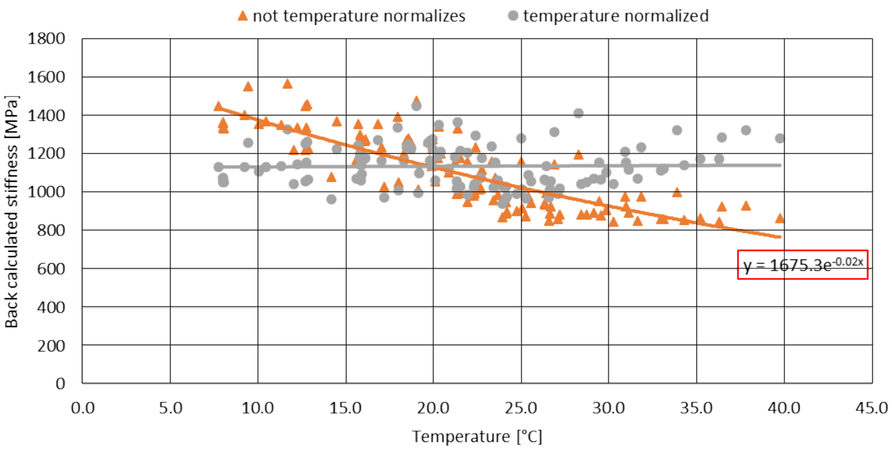


Fig. 15. Back calculated CR stiffness on the midpoint of FC1 loading area

temperature normalization. The back calculated stiffnesses from different FWD measurements were temperature normalized and then put together in a timeline to assess the possible change in the CR behaviour over time and during the accelerated loading period. Figure 16 shows the stiffness of the CR in the middle of the FC1 loading area, from the construction till the end of loading. The stiffness increases over the first year which is the curing period and then remains relatively constant till the start of loading. By the loading progress, it starts to decrease, which shows the possible occurrence of damage.

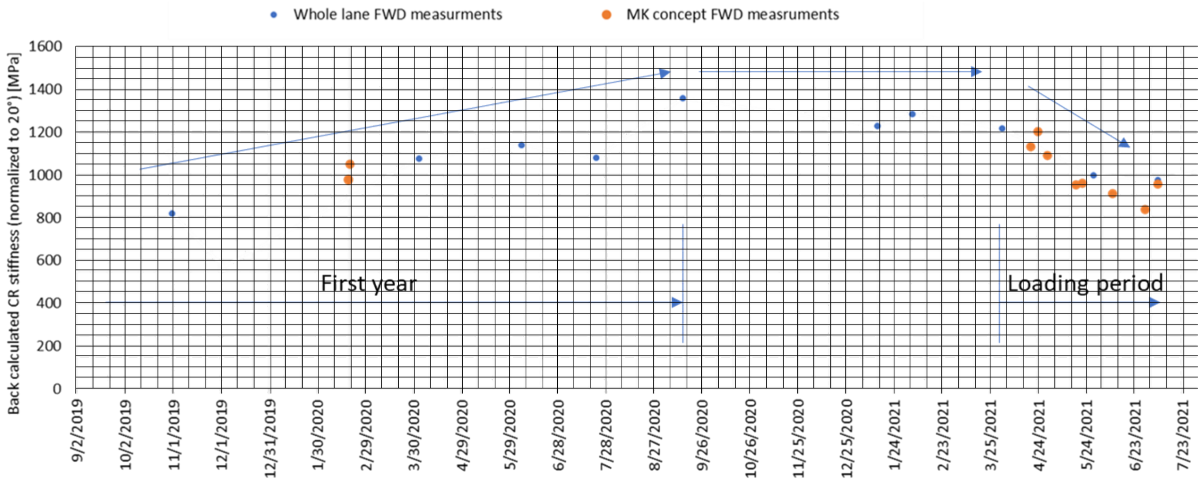


Fig. 16. CR stiffness change with time (curing) and with loading

As mentioned before, to get a detailed insight into the changes of the bearing capacity, a dense FWD measurement was performed around each loading area at several timings. As an example, Fig. 17 shows the difference of the parameter $d_0$ (which is the deformation under the centre of FWD loading plate) between the two measurements for the FC3 loading area (RF section) and around that. The first measurement was before the loading and the second one after 1.5 million loading cycles.

The loading strip has got some damage as the difference is with negative values. The sides with positive values show the decrease of $d_0$ because of the loading. This is because of the side effect of loading on consolidation of the granular anti-frost layer and the subgrade which leads to a decrease in the whole deformation mould response. The upper and lower left sides show the damaging effect of the heavy (10 t each) corner jacks of the MLS30 which did not affect the loading strip.

The same calculation was done for the results on FC2 (cold recycling) area. Figure 18 shows the results. Here also the loading strip shows damage and the around points show a decrease in the $d_0$, which in this case is a combination of not only the consolidation of the granular and subgrade but also the cold recycled layer too. As the material is semi bound, it has partly responses like granular material. The second point is the increase of its stiffness because of the curing, which is more obvious on not loaded areas.

Looking to the sides, it is possible to also see the effect of the corner jacks of the MLS30. As the section was not homogenous before the loading, the resulted damage from the side columns is also different in each side but they did not affect the loading strip.

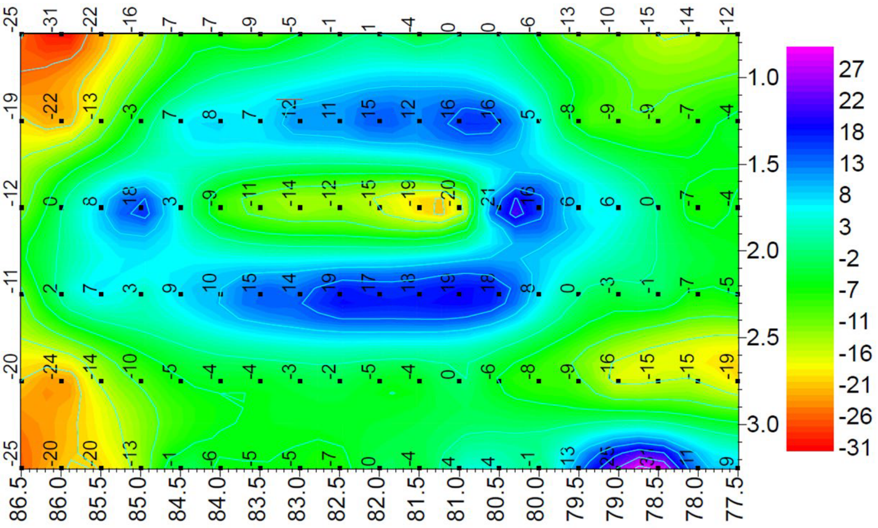


Fig. 17. Difference of the parameter $d_0$ (temp. normalized) [μm], between 0 and 1.5 million loading cycles at FC3 (reference section)

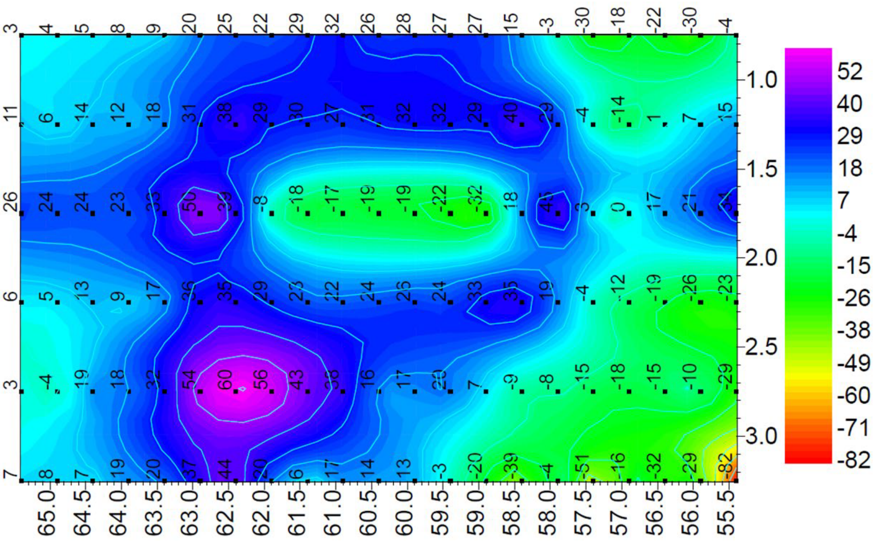


Fig. 18. Difference of the parameter $d_0$ (temp. normalized) [μm], between 0 and 1.5 million loading cycles for FC2 (cold recycled section)

## 3.2. TRANSVERSE PROFILE MEASUREMENTS RESULTS

The value of rutting was determined for each loading area at different loading cycles based on the results of transverse profile measurements.

Figure 19 shows the total rutting in three different loading areas versus the loading cycles. It is possible to see that the FC1 reached the defined failure criteria after 1.5 million cycles. It was also expected as the FWD measurements and the QC test results clearly showed that the CR material is weaker in this loading area. The important point is that, besides this weakness or even not acceptable CR material, the section has fulfilled the design life. Comparing the other CR area (FC2) with the reference loading area (FC3) shows a slightly better permanent deformation result although it was loaded more than the reference pavement. One important point is that the weather (temperature) has a significant influence on permanent deformation response of the pavement especially when the total HMA layer is thicker as in the case of the reference section. It is important to try to have the same weather conditions during the loading in projects that have more than one loading area. As the FC1 was loaded continuously, the temperature was relatively high at the last weeks of loading, which has led to higher permanent deformation in wearing coarse and influenced the whole surface rutting of the section.

For a closer look to temperature's effect on rutting, the data from the temperature sensors were used to calculate the temperature during the first 1 million cycles for the reference FC3 area (Table 3). The sensors were successful to record the surface temperature for about 75% of the 1 million loading cycles. The temperature in each cumulative loading range (loading ranges in the first column of the table) was calculated based on a weighted averaging on the temperatures during each loading range. Looking to the table and comparing it with the rutting values, it can be seen that each jump in the rutting value of the reference section (FC3) is related to a temperature increase.

The author showed in his PhD that a factor of 1.4 to 1.5 can be considered to transfer the HMA thickness to CR thickness with a relatively high safety factor [3]. Comparing the thickness of the CR base to HMA base (20 to 14 cm), a ratio of 1.43 can be defined between them. Considering that the FC1 field was not completely acceptable in case of the CR material quality but still could bear up to 1.7 cycles and on the other side the FC2 performed well even up to 5 million cycles, prove that the factor 1.5 is a conservative value but covers the whole quality range of the CR too. Therefore, in cases with high variability in the CR quality, it is a reliable factor for a rule of thumb design.

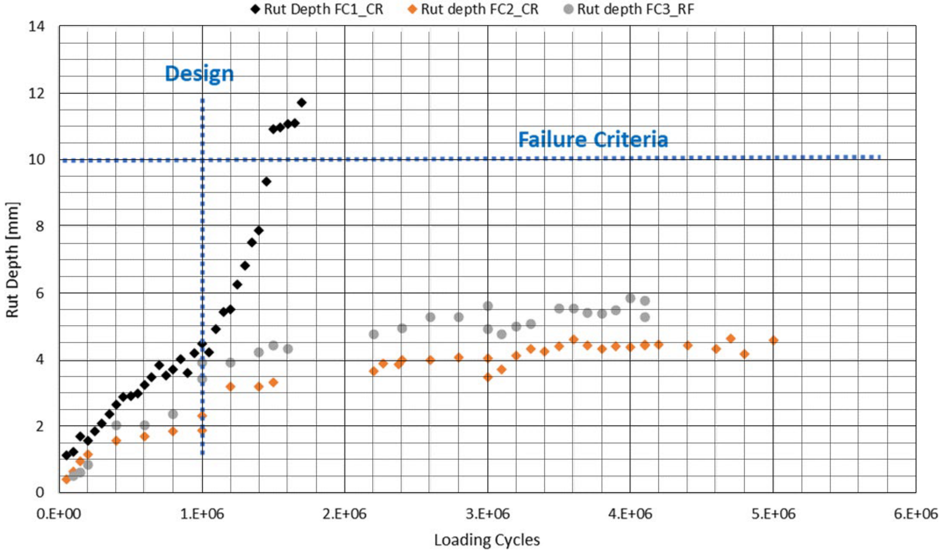


Fig. 19. Rutting versus loading cycles for CR loading areas and the RF

Table 3. Average weighted temperature (AWT) on the surface of FC3 loading area during the first 1 million loading cycles

| Reference section (FC3) | | |
|---|---|---|
| loading range [x1000 rolling] | % of the total loading | AWT [°C] |
| All | 75.0 | 23.5 |
| 0–200 | 20.0 | 16.1 |
| 200–400 | 20.0 | 22.7 |
| 650–800 | 15.0 | 25.0 |
| 800–1000 | 20.0 | 30.5 |

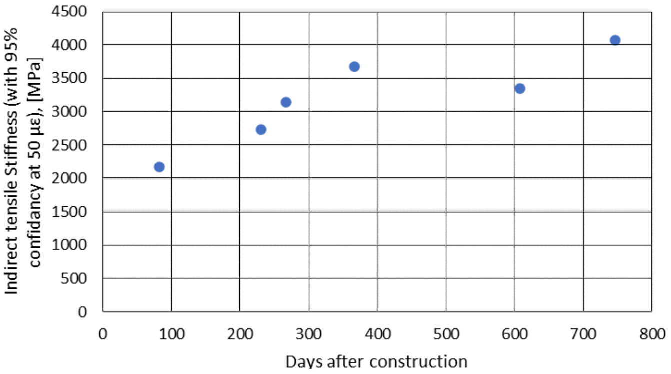


Fig. 20. Stiffness of the CR material from the cores at different days after construction

## 3.3. LABORATORY TESTS RESULTS

As explained in the laboratory plan, the CR cores were taken at different intervals after the construction from a section which had a homogenous layer of cold recycled material (between 26 to 29 m of the test lane). Figure 20 shows the evolution of the stiffness over the time which was calculated from the results on upper part of the CR cores' specimens. They are at 20°C and 10 Hz and determined for 0.05‰ horizontal strain level with 95% level of confidence. Looking to the trend clearly shows the curing process of the material happened mainly during the first year. The trend is also in agreement with the SCI300 values over time (Fig. 13) and the back calculated stiffnesses (Fig. 15).

Figure 21 shows the evolution of the ITS results over time and was calculated from the test results on the same specimens for the stiffness tests. The average of the ITS value in Table 1 (without the 40 m one) is 310 kPa. Looking to Figure 21, almost the same value can be considered for 360 days after the construction. This shows that the fast-curing method in laboratory (72 hours at 40°C) is almost equal to one year of field curing in duraBASt climate (can be considered as west Germany and Central European climate).

Figure 22 shows the stiffness master curves of the HMA base from the reference section and the CR material from the cold recycled section. The CR specimens were prepared from upper and middle part of the cores as

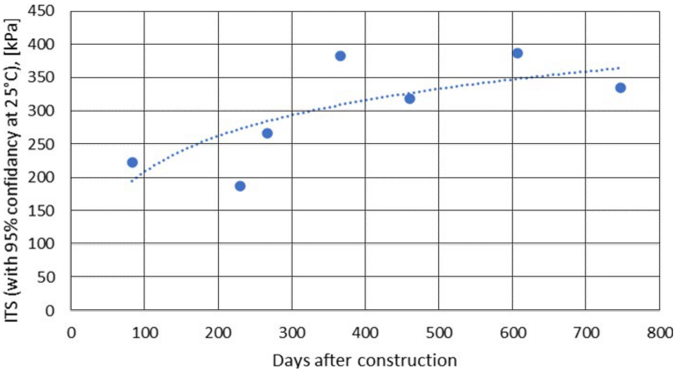


Fig. 21. ITS of the CR material from the cores at different days after construction

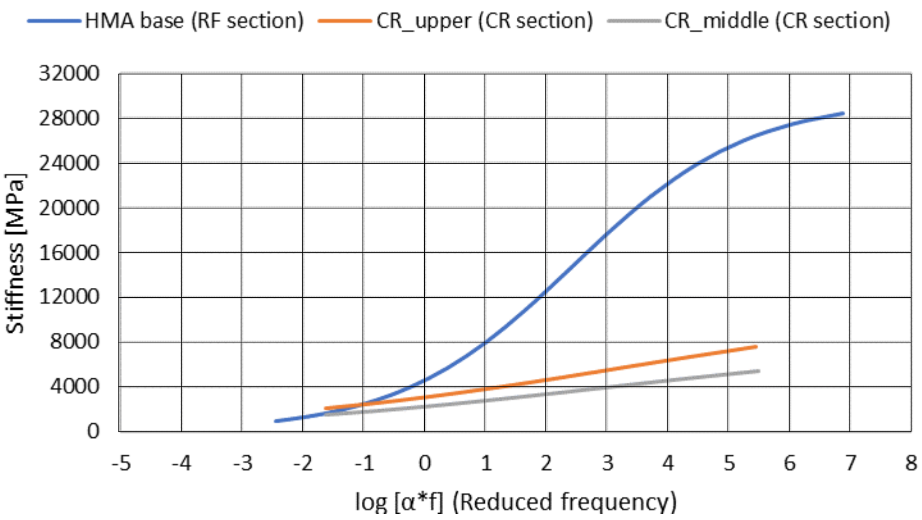


Fig. 22. Stiffness master curves of the cold recycled material and the HMA base

described before. As expected, it is possible to see that the CR material has considerably lower temperature dependency compared to HMA base layer.

Figure 23 shows the fatigue lines of the HMA base and the CR determined from the fatigue tests on the prepared specimens from the cores. The fatigue lines of the upper and middle CR specimens are the same. The HMA base fatigue line has a downward shift and a small higher slope of the line comparing to the CR lines. The author showed in his PhD thesis that: higher stiffness shifts the fatigue line (in this fatigue test type) downward with a change in its slope. In case that this higher stiffness is not the result of higher rigidity (like cement amounts more than 1%), the change in slope is small [3]. This argument is valid for the fatigue results of the HMA and CR bases. As by looking to the stiffness master curves (Fig. 22) of these two mixes, at 20°C and 10 Hz (the fatigue test's conditions), the HMA has higher stiffness than the CR, which is not because of higher rigidity but higher flexibility of the HMA comparing to CR, therefore the HMA fatigue line is shifted downward with the small change in the slope.

## 3.4. FORENSIC INVESTIGATION RESULTS

After the end of loading, several cores were drilled out of the two CR loading areas (Fig. 24). The measurements on the cores showed that the thickness of the wearing course in the first half of the FC1 section was less than the designed thickness of 4 cm, which is also one reason that the FC1 area failed sooner than the FC2 area.

The FC1 area cores showed a kind of inhomogeneity along the CR layer, which in some cases was the plane of brockage during the extraction of the cores. Figure 25 is an example of two adjacent cores from FC1; it is possible to see the difference in the color of the CR material and the broken plane position in the other core comparing to the completely extracted adjacent core.

Figure 26 shows the cuts at the same transverse sections from both CR loading areas (see Fig. 24 for orientation). Measurements on the FC1 section (which reached to the rutting limit after 1.7 million rolling cycles), showed that the wearing course had contributed into the total deformation. As mentioned before, the higher temperature during the last weeks of loading on FC1, led to higher deformation in wearing course and influenced the total deformation.

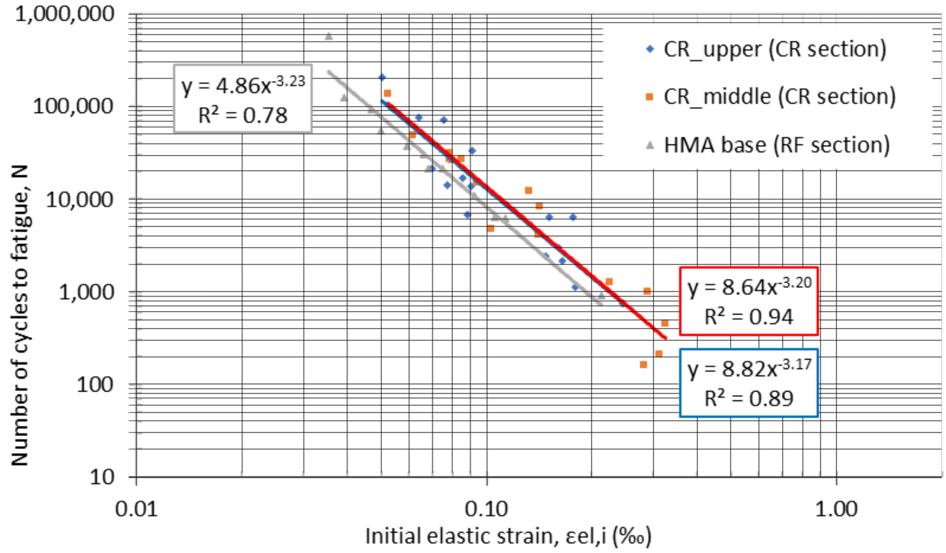


Fig. 23. Fatigue lines of the cold recycled material (CR section) and the HMA base (RF section), tests at 20°C, 10 Hz

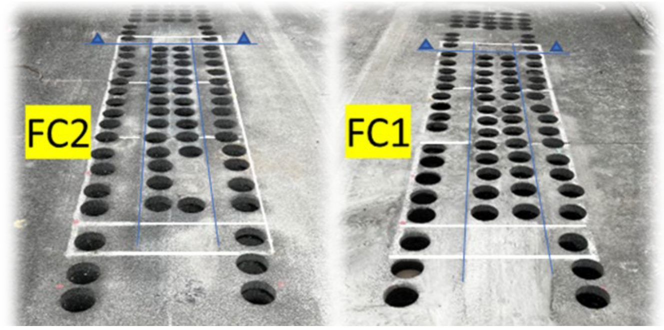


Fig. 24. Drilled cores from two loading areas FC1 & FC2 in CR section and the HMA base

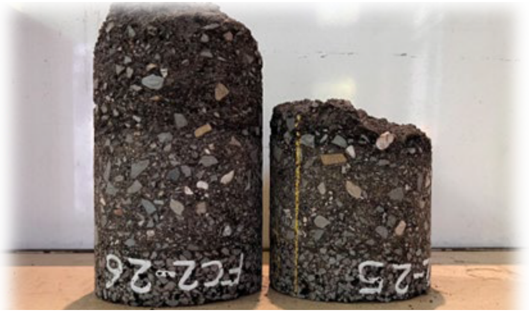


Fig. 25. Two adjacent cores from FC1 loading area, the colour difference in the CR is visible

On the other side, it is possible to see that the CR layer had considerably higher permanent deformation in FC1 cut than the FC2. Comparing the texture of the two CR layers (especially the lower parts), proofs the difference between their quality, which was already reflected in FWD measurements and loading results.

Figure 27 shows the thickness of the CR Part of the extracted cores from the FC1 and FC2 areas, only in the loading strip. It is possible to see the intact cores are more in FC2, which is a confirmation of its better performance under the loading. To evaluate the shear parameters of the cold recycled layer, big cores (50 cm diameter) were drilled from the CR section and 3 axial test specimens (15 cm diameter with 30 cm height) were cored out of them by side (horizontal) coring. The results showed a higher value of cohesion in the FC2 area than FC1 (496 kPa comparing to 289 kPa), which means higher bonded material behaviour in FC2 than the FC1. This could also be seen from the cuts and the cores. The cohesion from mix design specimens was 307 kPa. Considering that the cores were extracted two and half years after the construction and were oven dried for 72 hours at 40°C, whereas the mix design specimens were cured to an equilibrium moisture state [12], which was double the field ones, it

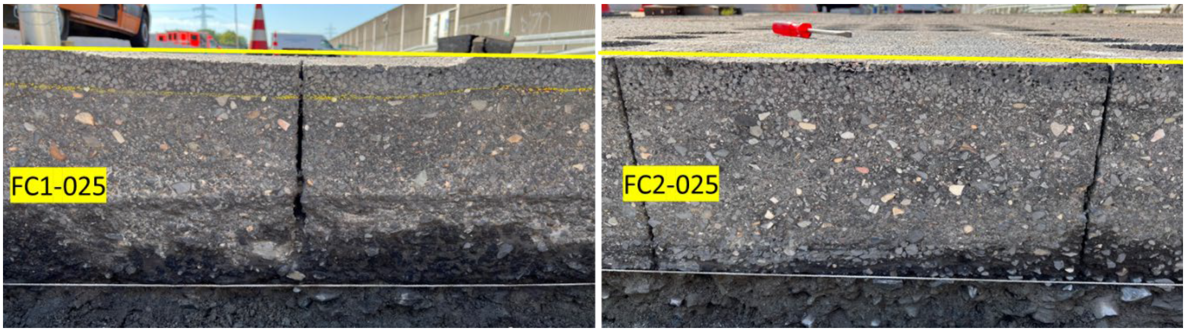


Fig. 26. Transverse cuts at two points of the FC1 and FC2 loading areas in CR section

Fig. 27. The thickness of the CR layer part in extracted cores from two CR areas (FC1 and FC2), green: complete core recovery, blue: the core with conic end and red: the cores with broken face

is logical that the cohesion values of the field specimens should be higher than the mix design. In this case, the FC1 did not reach the design cohesion. The analysis of the bitumen extracted from the samples at different parts of the recycled section showed that the RAP material's composition in the weaker parts was different from the other parts of the section.

Fig. 28. 50 cm diameter cores and the side coring to prepare 3 axial test specimens

Observing the level of the remaining water (after rain) in the cores of the adjacent test lane revealed the areas of the CR section with lower bearing capacity, having a good agreement with the positions where the water drained slower. This observation proved that the drainage quality of the layer beneath the CR layer was different in weaker areas. Lower drainage of the beneath layer can result in more moisture damage.

The forensic investigation revealed that there are different reasons for the lower bearing capacity measurement results as variation in the RAP composition, production quality, variation of wearing course thickness and drainage quality of the anti-frost layer. It showed that the homogeneity is an important requirement for achieving a high quality cold recycled material with superior performance under the loading. Homogeneity can be considered from different aspects starting from RAP composition and preparation (RAP management) to CR production and construction.

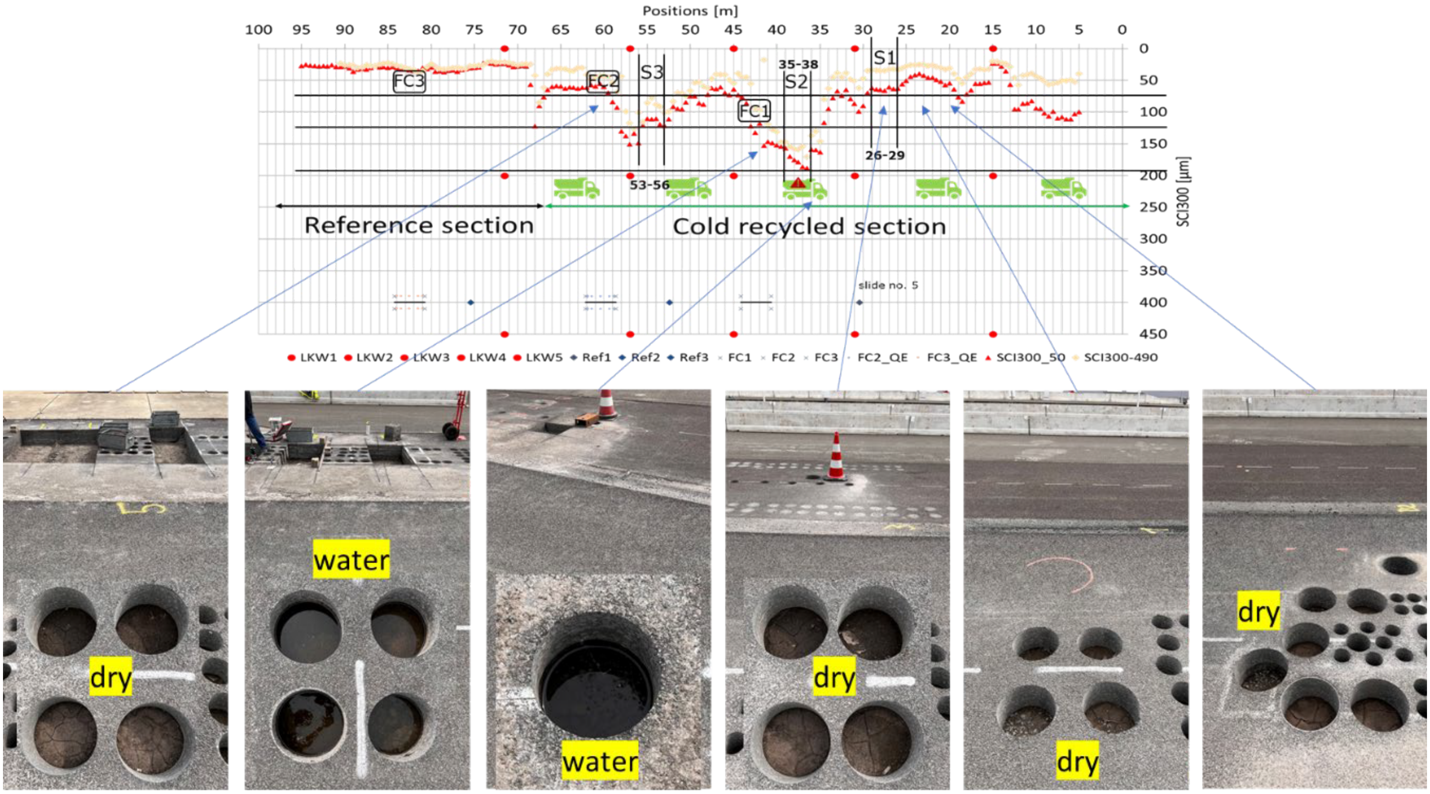


Fig. 29. The state of the water in cores of the adjacent test lane and the CR bearing capacity

## 4. SUMMARY AND CONCLUSIONS

Cold recycling is a method which has gained an increased interest during the recent years in Germany. It has the benefits of lower energy consumption and up to 100% use the of stockpiled RAP in asphalt plants. Positive international reports on the behaviour of cold recycled mixes with low amounts of foamed bitumen and cement (BSM), and lack of experience and performance data on this type of material, encouraged BASt to define a research project in cooperation with Wirtgen GmbH. The project applied the APT concept to evaluate the performance of a pavement with foamed bitumen recycled layer. The project started end of 2018 and continued with the preparation tests and activities till the construction of the test lane in Sep. 2019. The loading with MLS30 started in Feb. 2020 and continued till the end of 2021. This paper aimed to present the APT program and the main results.

The main finding of this project was the proof that it is possible to implement the BSM concept for design and construction of pavements with cold recycled layers in Germany and it has the potential to achieve the same performance as the conventional pavements. The findings will pave the way for bigger projects and experiments with this type of material and open its way as a standard material type in pavement construction. Besides that, different points and lessons have been learned from this research project: preparation and production of the foamed bitumen recycled mix, construction, and quality control to field monitoring and non-destructive and laboratory tests to assess the material's behaviour. Some of them can be mentioned as below items:

- RAP material characteristics have a great impact on behaviour and performance of the resulted recycled mixture. It is recommended to crush the RAP to get a better size distribution and internal angle of friction in the compacted aggregate skeleton. This also increases the possible rate of RAP usage in the mix as the need for virgin aggregate to adjust the grading curve will decrease. It is believed that the bitumen in the RAP will not be activated because of the cold recycling and the RAP can be considered as black rock. This assumption can be right as the bitumen in RAP is not activated but if it is still active (not aged and hard), it will affect the recycled mixes' characteristics and performance. Therefore, for projects that a high-quality CR is required, it is important to consider the homogeneity and source of the RAP plus the state of its bitumen. It is important to monitor the moisture of the stockpile and to consider that for the production time to adjust the amount of added water.
- To produce laboratory specimens, experiences with the vibratory hammer showed that it can be an appropriate compaction method, from ease of operation and repeatability of the results. More experience is needed to be gained with different mixes. It is recommended to use the vibratory hammer compaction also for determining the OMC (optimum moisture content).
- The experience with this project showed that the mobile plant for CR production needs a short setup time (half a day) and a small working place. This is an advantage to be able to bring it near the construction site and decrease the transport distances. It is recommended to prepare the RAP in a way that the need for additional aggregate fractions is reduced. This will not only increase the rate of RAP usage but also decrease the risk of production failure and segregation.
- The experience in this project showed that Medium Falling Weight Deflectometer (MFWD) tests are a fast and reliable method to check the daily work, to evaluate the construction homogeneity. It is also possible to perform them (or Light Weight Deflectometer tests) as a guide to monitor the strength evolution in the layer and to determine the appropriate time for laying the next layer or opening the road to traffic. Still more data should be collected to be able to define acceptance thresholds for the measurement results.
- Bearing capacity measurements revealed different aspects of the material's behaviour. It was possible to monitor the changes during the curing period and the loading cycles with stiffness back calculation approach. The results also proved the lower temperature dependency of the cold recycled material compared to HMA, which agreed with the stiffness master curves from the cores too. Beside that they showed that the material's field response is affected by the seasonal weather changes (wet-dry cycles) too.
- The stiffness and ITS results of the CR material cores over different time intervals showed that the material reached its final curing stand after one year. The ITS results showed that the fast-curing method (72 hours at 40°C) is almost equal to one year of field curing in test section, which can be considered as central Europe's climate.
- Considering the permanent deformation results, both cold recycled loading areas fulfilled the design criteria without any cracks. One had even a better performance compared to the reference section with conventional construction. The results also proved that 1.5 as the factor to transfer the thickness of HMA base to cold recycled layer is conservative but assures

that the wide ranges of the cold recycled material quality can be considered.

- Forensic investigations showed that there are different factors which affect the performance of a cold recycled pavement. Among them, the thickness of the wearing course has an important role especially pavements with this HMA layer. It is recommended having a minimum of 4 cm wearing course when the design traffic is higher than 1 million (10-ton equivalent single axle load).
- Homogeneity is the main point in achieving a good material quality and performance in cold recycled mixes with foamed bitumen. It can be considered from different aspects. The input material homogeneity, the production and construction homogeneity and also the homogeneity of the foundation layer beneath the cold recycled layer.

As the next step, the gained knowledge will be applied to construct a test section in road network to evaluate the higher scale production and construction under real field conditions. Simultaneously the findings of this project will be integrated into the existing guidelines for cold recycled mixes with foamed bitumen.

## ACKNOWLEDGMENTS

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