Maintenance and Rehabilitation

Regeneration of asphalt using radio waves

Martin Arlt[1], Matthias Bisse[2], Bernd Karwatzky[1], Ulf Roland[1,3], Ulf Trommler[3], Christiane Weise[2]
[1]University of Applied Sciences Leipzig, Germany, [2]Technische Universität Dresden, Germany, [3]Helmholtz Centre for Environmental Research, Germany

Abstract

The maintenance of road infrastructure has received more and more attention during the last years. Therefore, pavement healing methods utilizing microwaves and induction energy were developed. Dielectric heating with radio frequency at 13.56 MHz sets a new attempt for the healing and regeneration of roads. The radio-wave technology allows the direct heating of any asphalt without additional amendments. At this frequency, the electromagnetic field energy heats the aggregate within the asphalt. Whereas the bitumen is less affected and is indirect heated via the hot rock. This represents a heat generation within the bulk material of the pavement rather than an energy input from outside or a heat development within the binder. Thus, the asphalt heats more uniformly throughout the whole medium. The paper will illustrate the potential of dielectric heating utilizing radio waves. Two relevant aspects of road maintenance will be evaluated, crack repairing and binder aging as a result of the thermal repairing process. The potential for crack repair will be evaluated at macro-cracks artificially induced by three-point bending tests at low temperatures. Since the effect of heating asphalt with radio waves is not well known, two asphalts concretes are used in this study, differing in maximal aggregate size and bitumen content. The innovative radio-frequency-based procedure of repairing cracks uses the intrinsic healing capacity of asphalt and applies an extrinsic force for compaction and recovery of the original specimen shape. As this procedure exceeds the bare healing of asphalt, this paper claims the recovery process as being in fact a regeneration of asphalt. The influence on the bitumen aging is investigated with fivefold repetitions of the regeneration. It is shown that the regeneration of asphalt utilizing the radio-wave technology is viable and the influence on the binder aging is examined showing an acceptable impact on its structure and properties.

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1. INTRODUCTION

Cracks in asphalt concrete are caused by different factors such as cryogenic stress or traffic loads. Although certain inherent healing already starts after the crack appears, this natural process is by far not sufficient to maintain the asphalt quality. Active supporting procedures in addition to natural healing of asphalt utilizing inductive or microwave heating are a viable option to repair a damaged asphalt concrete and, thus, maintain its lifetime. However, both techniques have significant disadvantages as they require the addition of electrically conductive particles to the asphalt mixture or have a limited effective depths.
Radio-wave technology allows direct dielectric heating of any asphalt without additional amendments at a frequency of, e.g., 13.56 MHz while just marginally affecting the bitumen fraction. This paper defines a theoretical frame and describes a procedure for the utilization of the radio-wave technology in this context. This procedure expands the intrinsic healing effects of bitumen and applies an extrinsic force for compaction and recovery of the original specimen shape and applied in-situ on road infrastructure the surface. As this markedly exceeds the bare healing of asphalt, this paper claims the recovery process as being, in fact, a regeneration of asphalt. The influence of the recovering procedure on the bitumen aging is investigated applying both a three-point bending test and fivefold repetitions of the regeneration. It is shown that the regeneration of asphalt utilizing radio-wave technology is viable and the influence on the binder aging is examined showing an acceptable impact on the bitumen aging.

2. THEORETHICAL BACKGROUND REGENERATION USING RADIO-WAVE TECHNOLOGY

During the last years, the healing process of asphalt concretes was studied by various authors [1-9] and a basic understanding of the mechanisms involved was developed. It can be concluded that healing, in principle, occurs permanently and at all temperatures. However, high temperatures or long duration promote the healing effect. Garcia [3] showed that high temperatures reduce the time that asphalt needs for healing, down to 1 min for a treatment temperature of 110°C. In general, high temperatures facilitate healing processes like wetting, capillary effects and molecular diffusion. If asphalt is heated the bitumen will expand with rising temperature due to its comparatively high thermal expansion coefficient, which is by a factor of 20 to 30 higher than that of the aggregate [10]. This behaviour leads to reversible deformation especially at temperatures above 110°C. At these temperatures, bitumen behaves as Newtonian fluid expanding within the voids of the mineral aggregate and closing open cracks. Thus, healing is done not just due to intrinsic effects but also due to the thermal expansion with the disadvantage of deforming the asphalt. Imposing a sufficient extrinsic load on the heated asphalt, not only the original shape is recovered but also the fractured lines of broken aggregate are merged together and gaps, too wide to allow wetting or capillary flow of bitumen, are closed. This way, the strength of asphalt courses can be recovered, via inherent healing and extrinsic reshaping, to a maximum. Healing of cracks is complemented and supported by the extrinsic effect of reshaping. As this procedure exceeds the bare intrinsic healing of asphalt, this recovery process is, in fact, a regeneration of asphalt.

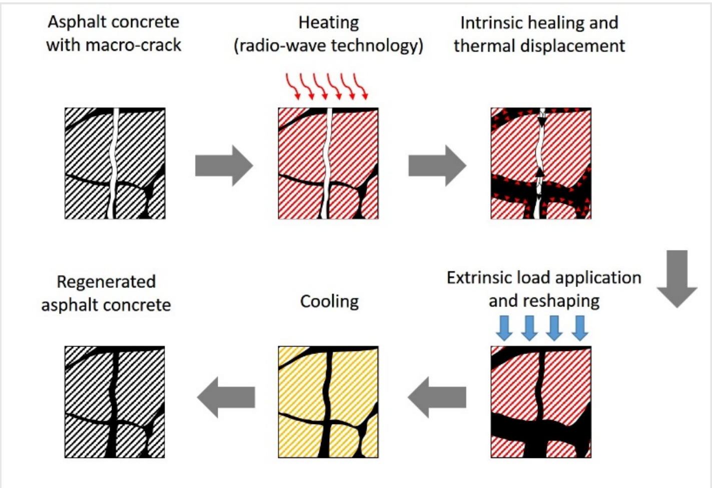

Figure 1: Regeneration of asphalt

The regeneration process is illustrated in Figure 1. The procedure shows the utilization of dielectric heating with radio waves. This is not a premise for regeneration but facilitates the process. Dielectric heating with a radio-frequency (RF) of 13.56 MHz allows the direct heating of any asphalt without additional amendments which is a clear advantage in comparison to alternative methods. At this frequency, the electromagnetic field energy heats the aggregate within the asphalt. The bitumen fraction is preferentially indirectly heated by heat conduction from the hot aggregate. This represents a heat generation within the bulk material of the pavement rather than an energy input from outside or a heat development within the bitumen. Thus, the asphalt heats more uniformly throughout the whole volume with the maximum temperature developing in the centre of the specimen which is due to the heat transfer to the environment. Here, the bitumen is not subjected to oxygen. The surface temperature can be taken as reference for the minimum temperature of the sample. Since heating by radio waves is followed by a compaction step surface temperature should not be lower than 100°C [11] at the beginning of compaction. Therefore, a minimum average temperature of 110°C at the end of heating should be targeted for the regeneration procedure.

3. METHOD

3.1. ASPHALT AND SPECIMEN PREPERATION

Two standard asphalt concretes produced in an asphalt plant were used for this study, a standard surface course layer material AC 8 D N (A) and a base course material AC 22 T N (B) classified according to the rules of German TL Asphalt-StB 07/13. In order to allow a better investigation of the bitumen aging, no reclaimed asphalt and non-modified bitumen were used for the production of the standard asphalt concretes. The mixture compositions are shown in the following table. No additional amendments were applied.

Table 1. Composition of the investigated asphalt mixtures

Aggregate		
Sieve size	Material A	Material B
[mm]	Aggregate weight% retained	Aggregate weight% retained
22.4		0.9
16.0		18.4
11.2		15.5
8.0	2.7	11.7
5.6	21.3	9.1
2.0	25.2	14.3
0.125	40.0	22.2
0.063	2.0	1.3
0.0	8.8	6.6
Bitumen		
Needle penetration [1/10 mm]	50/70	70/100
Mass content in the mixture / %	6.5	4.1
Softening point [°C]	50.4	46.4

After the production at the asphalt plant the materials were stored in sealed metal bins. Under laboratory conditions, the asphalt was heated and concrete slabs were compacted using a pneumatic roll sector compactor at 135°C using a path-controlled compression method for compaction. The slabs were sawn into prismatic specimen of 4 cm x 4 cm x 16 cm using a circular saw fitted for rock and asphalt cutting.

3.2. LABORATORY TESTS ARRANGEMENT

The three-point bending test at a test temperatures of -20°C was applied for crack induction. The prisms were stored to -20°C for 12 hours and then tested. After crack induction, the specimen temperature were equilibrated at room temperature. Subsequently, the prisms were heated in wooden frames between two braze plate electrodes being separated by a PTFE mould acting as spacer (Figure 2). This setup should resemble the conditions in an asphalt pavement, exposing only one surface to free air flow. The samples were dielectrically heated using radio-wave technology with a frequency of 13.56 MHz to four different average surface temperatures of 110°C, 130°C, 160° and 180°C. The temperature of 180°C was chosen as maximum temperature for asphalt concretes with the selected bitumen, leaving the asphalt plant [12]. For RF heating, the PTFE moulds containing the prisms were placed inside a Faraday cage. An RF generator provided a power of 500 W and a matching network adapted the samples internal impedance to the generator's internal resistivity of 50 Ω for optimal energy transfer. The prisms were in direct contact with an RF (high-voltage) and a grounded electrode (Figure 2). The electrodes were connected with the outlet of the matching network (RF) and the Faraday cage (ground), respectively. For continuous temperature measurement, an infrared camera was used.

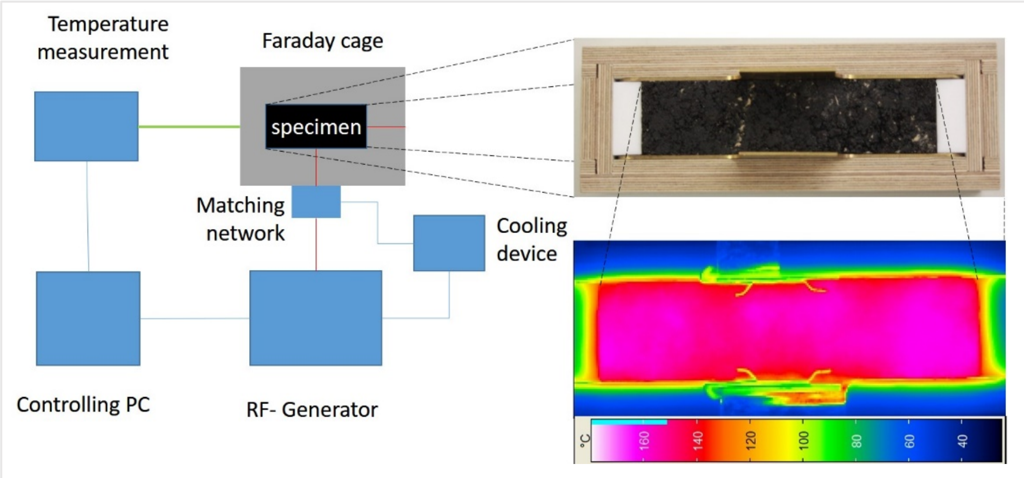

Figure 2: Setup for dielectric heating with radio waves at 13.56 MHz

After heating, the sample was removed from the Faraday cage and reshaped to its original dimensions with a maximum variance of 5 % using a hydraulic cylinder and counter bearing for compaction of the thermally deformed samples. The wooden frame was acting as containment. Then, the samples cooled down to room temperature under ambient conditions subjected to a free air flow. The whole procedure was repeated up to five times.
The experimental program started with twelve samples for each temperature. After the first regeneration cycle, six samples were used for bitumen analysis. The remaining six prisms were tested consecutively during the five regeneration cycles. After the fifth cycle and the associated bending test, the prisms were used for bitumen analysis.

$$\sigma_{BZ} = \frac{M}{W} \tag{1}$$

During the three-point bending test, the maximum force for crack induction was measured and the maximum flexural strength (σ_{BZ}) calculated according to equation (1) by the ratio of the maximum moment (M) and the resisting moment (W).

$$R_n = \frac{\sigma_n}{\sigma_0} \tag{2}$$

In order to evaluate and characterise the regeneration success throughout the investigation program, a dimensionless regeneration factor (R_n) was defined on basis of the healing factor by the ratio of the maximum flexural strength after the n-th regeneration cycle (σ_n) and the original maximum flexural strength at the beginning of the experimental program (σ_0). For investigation of the aging impact, the prisms were cut into the three layers top (O), middle (Z) and bottom (U), see also Figure 3. The bitumen was recovered by extraction with trichloroethylene (TCE) following DIN EN 12697 - 1 separately from each layer. Characterization of each bitumen sample was carried out using the standard softening point (SP) determined with the ring and ball method and the Fourier-Transformation Infrared spectroscopy (FTIR spectroscopy) in the Attenuated Total Reflection (ATR) mode. As basis for the comparison of the FTIR spectra, the 'Bitumen analysis by FTIR spectrometry: testing and analysis protocol [13] developed by the Belgian Road Research Centre (BCCR) was applied. For comparison, the A1700 index defined as the area between 1,530 cm^{-1} and 1,770 cm^{-1}, was calculated on the basis of the BCCR procedure.

Figure 3: Prism separation

As the experimental setup simulates the conditions in an asphalt pavement with only the surface part exposed to free air flow, the sample transformation should enable statements to the oxidation over the sample height. The bitumen of each layer was extracted for the first and the fifth regeneration cycle. A mixed sample was subsequently formed for each surface temperature and layer. For assessment of the measured aging, some bitumen was recovered before the regeneration process and aged under laboratory conditions. For laboratory aging two standardized aging techniques were utilized, the rolling thin film oven test (RTFOT) for short term aging, representing the aging during asphalt production and placement, and the Pressure Aging Vessel test (PAV) to represent the long-time-aging of the bitumen in its functional environment.

4. RESULTS AND DISCUSSION

In the following Figure 4 and Figure 5, the results of the experimental program for regeneration are summarized. For each material a series starting with twelve samples was carried out. The figures show the regeneration factor (determined using equation 2) versus the average surface temperature. Each column represents the average regeneration factor of twelve samples for cycle 0 and 1 and of six samples for cycle 2 to 5. The standard deviation is indicated for each column. In both figures, it can be observed that the average regeneration factors for all examined temperatures are above 0.9 after one regeneration cycle and not below 0.87 after 5 cycles. The standard deviation is for most measurement series higher for material B, which is most likely due a higher sieve fraction of the aggregate (Tab.1).

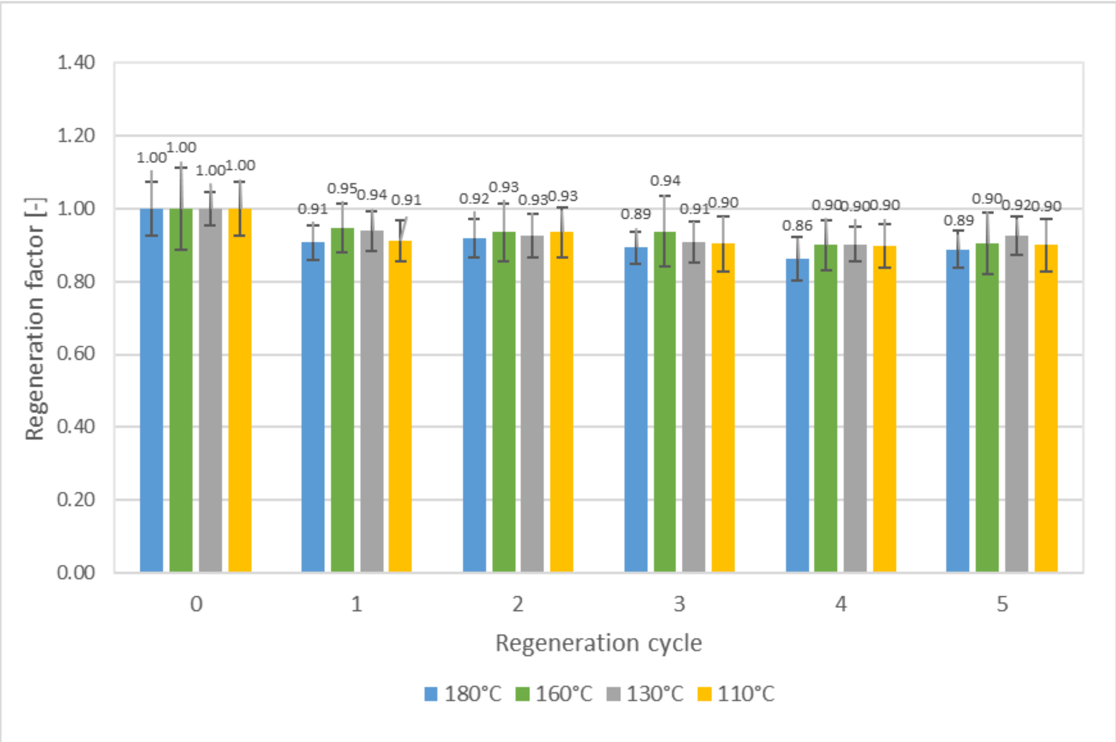

Figure 4: Regeneration of material A

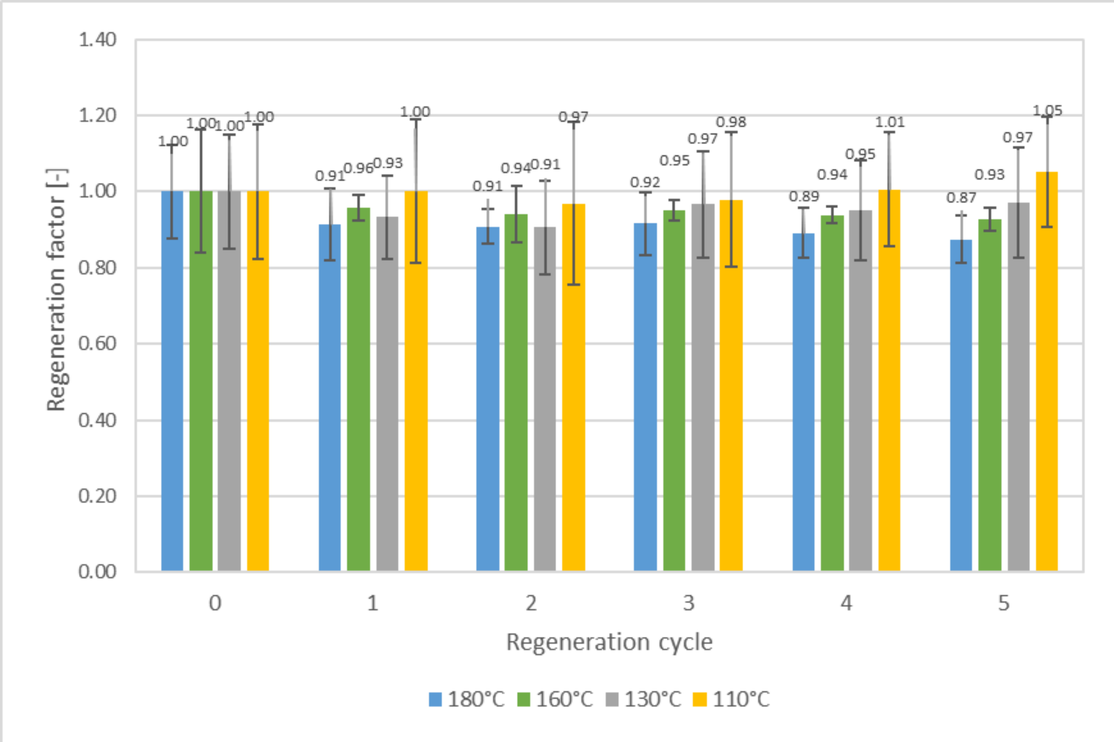

Figure 5 Regeneration of material B

Both figures show a slight decrease of the regeneration factor after the first fracture independent of the temperature. After the first reduction of the average healing factors, they reach a constant level scattering only within the standard deviation. As this decrease is inflicted at the first load cycle and does not occur in this scale over the following cycles, it can be attributed to some aggregate destruction during the first induced crack. This aggregate is not available during the following cycles. However, fracture surfaces are covered with bitumen during the next regeneration. During the following cycles, forces within the crack are conveyed via bitumen and not the aggregate fraction anymore. This might explain why a slight decrease of the flexural strength was measured after the first cycle but not after the next regeneration cycles.

In spite of relatively high standard deviations a cautious interpretation might come to the expected conclusion that higher regeneration temperatures lead to lower regeneration factors. This tendency cannot be seen for material A (fig. 3). As well as for the differences in the standard deviation, the different sieve fraction of the aggregate might play a role since radio waves are absorbed predominantly by the aggregate. In case of the smaller sieve fraction (material A) heat conduction could be fast enough to avoid or limit local overheating (hot spots) within the prisms. In case of bigger aggregate within the prisms (material B) the formation of hot spots seems to be more likely. This interpretation would imply that the temperatures of the hot spots are significantly higher than the average temperature in the prisms, not to mention the averaged surface temperature. This adds up to the higher sensitivity for bitumen aging of material B due to its lower mass content in the mixture (Table 1).

According to the theory of regeneration, the intrinsic healing occurs when the bitumen starts behaving like a Newtonian fluid, flowing in the open cracks of the specimen. The following extrinsic compaction and reshaping supports the healing on one hand and gives an additional impulse for closing gaps between the broken aggregate on the other hand. In some cases, this might cause a healing of initially existing weak spots and reach a higher flexural strength than the original, non-regenerated sample. This can be seen in Figure 5 for the series with surface temperatures of 110°C where the average regeneration factor reaches 1.05 after five regeneration cycles. This is due to some weakly performing samples at initial crack induction. The following figure shows flexural strength development of six samples subjected to 5 regeneration cycles for material B. For better clarity, the results of the other six prisms of cycle 0 and 1 are not presented.

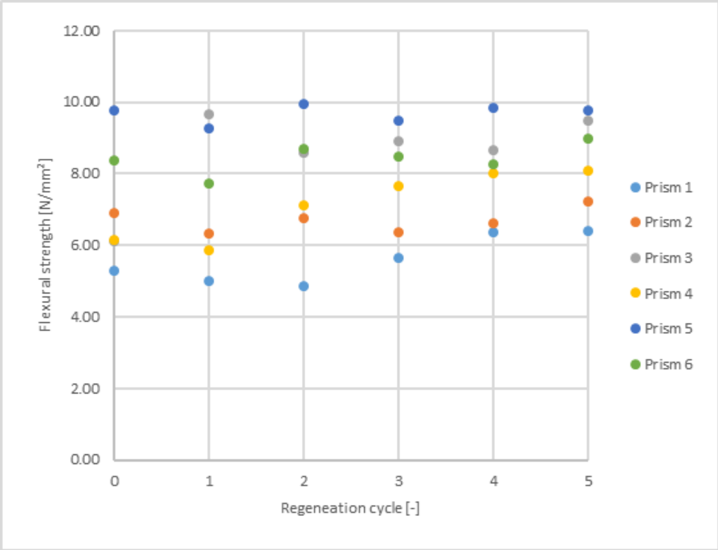

Figure 6: Flexural strength versus regeneration cycle for average surface temperature of 110°C, Material B

The data presented in Figure 6 show that the two initially worst-performing samples (1 and 4) develop over the five regeneration cycles more flexural strength than in the original, non-regenerated state. This could be explained with help of the regeneration theory. In the heated state the asphalt concrete is deformable to such an extent that it is not just possible to close cracks during compaction but also to relocate some aggregate and, therefore, make up for weak spots as well as improve the sample load bearing capacity. However, this is an incidental effect which is not observed to this amount in the other measurement series.

The following figures show the scale for the measured softening point according to the ring-and-ball method on the left side and the already mentioned A1700 according to the BCCR method on the right side. The presented error bars visualize the repeatability of 1°K according to DIN EN 1427:2015 [14]. For FTIR measurements, the average value of three measurements is shown with error bars representing the standard deviation. In general, higher values for the SP as well as for the FTIR A1700 index can be interpreted as an indication for bitumen oxidation or aging.

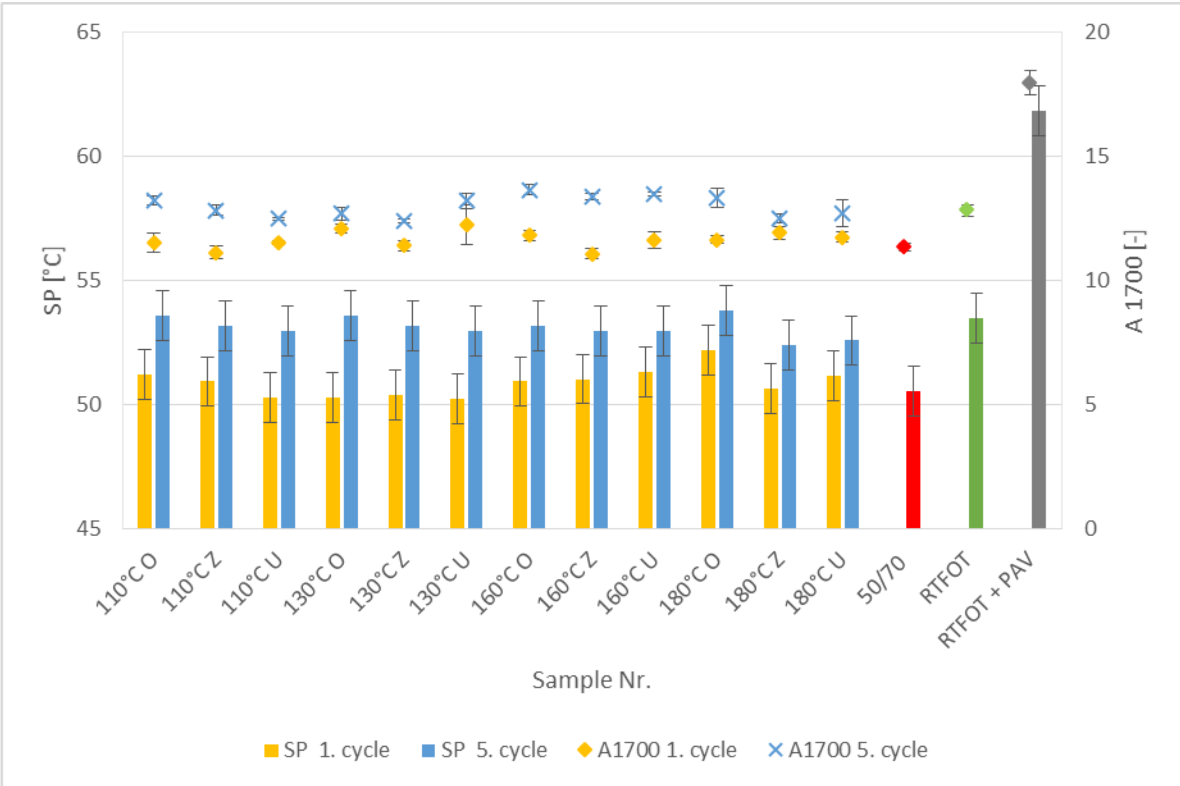

Figure 7: Material A softening point and A1700 versus surface temperature for the different analysed layers

Figure 7 shows the measured bitumen aging for material A. The softening point values after one regeneration cycle (yellow columns) do barely exceed the initial values of the non-regenerated recovered bitumen (red column). A slight scattering within the repeatability of the method can be observed. The minor increase of the SP values from the first to the fifth cycle (blue columns) of approximately 2 to 5 %, shows an impact of the regeneration on the bitumen characteristics. This increase is almost identical to the change in the SP value for the non-regenerated and the RTFOT-aged bitumen. However, the SP values for all regeneration tests were significantly lower than the SP value for the long-term PAV aged reference.
The A1700 index is represented as yellow and blue diamond for each layer and temperature measured after the first and the fifth regeneration cycle, respectively. The scattering of the measured values exceeds the standard deviation and varies around the A1700 index of the untreated bitumen (red diamond). After the fivefold repetition, the index values scatter similar to the ring-and-ball softening point temperatures around the RTFOT-aged bitumen. But they do not exceed the long-time aging represented by the grey diamonds.

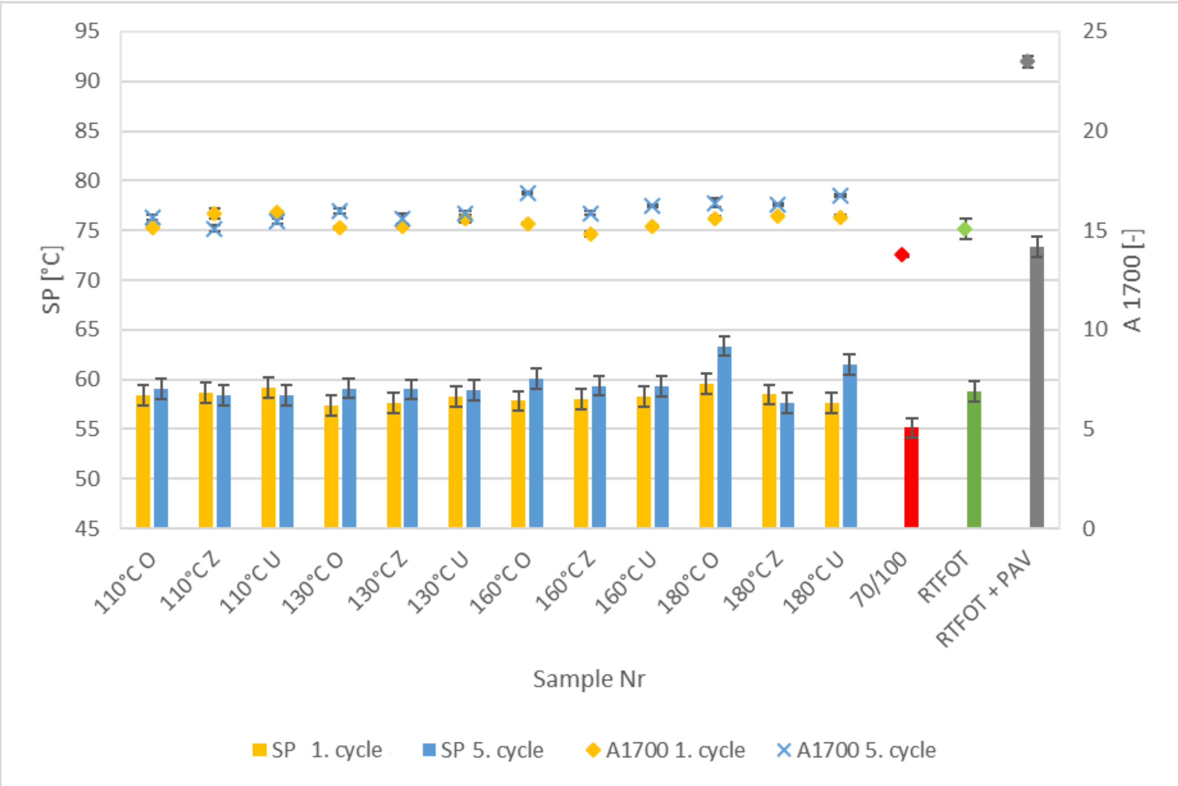

Figure 8: Material B softening point and A1700 versus surface temperature for the different analysed layers

Figure 8 shows the measured bitumen aging for material B. The ring and ball values after one regeneration cycle (yellow columns) exceed the initial values of the non-regenerated recovered bitumen (red column) and reach fivefold repetition of the regenerating cycles (blue columns) the comparative values of the RTFOT aged bitumen with the exception of two values for the top and bottom layer for the prisms regenerated at 180°C. Here, a markedly stronger aging occurred. As for material A all measured SP values are considerably lower than the long-term PAV aged reference. Here all values for the A1700 index measured after the first cycle (yellow diamonds) exceed the A1700 index of the untreated bitumen (red diamond). After the fivefold repetition the index values are slightly above the A1700 index of the RTFOT aged bitumen (green diamond), but do not exceed the long-time aging represented by the grey diamond. The stronger aging shown in the SP values for the average surface temperature of 180 °C can be explained due to destillative aging as this is not covered under the A 1700 index.
Comparing the results of both material series with each other, it is noticeable that the softening point of the recovered 50/70 bitumen is unexpectedly lower than the 70/100 grade, indicating a softer bitumen. The higher aging values could be explained by the smaller amount of bitumen in the mixture (4.1 wt.-% versus 6.5 wt.-%, Tab. 1) and, therefore, by a higher sensitivity of the mixture towards aging. The difference in the softening point could be explained either by oxidational or by destillative aging both leading to a higher softening point. As the A1700 reflects the degree of oxidation [13] and the index is also higher for the 70/100 grade bitumen, it can be deduced that the

measured values are mainly caused by oxidation aging. Eventually and with regard to a thinner bitumen film caused by less bitumen in the mixture covering the aggregate comparatively, more bitumen is subjected to thermal treatment during the production process in the asphalt plant. This suggests that the asphalt concrete B is more sensitive respectively reacting faster to aging then mixture A, explaining the higher softening point of the recovered bitumen after asphalt production.

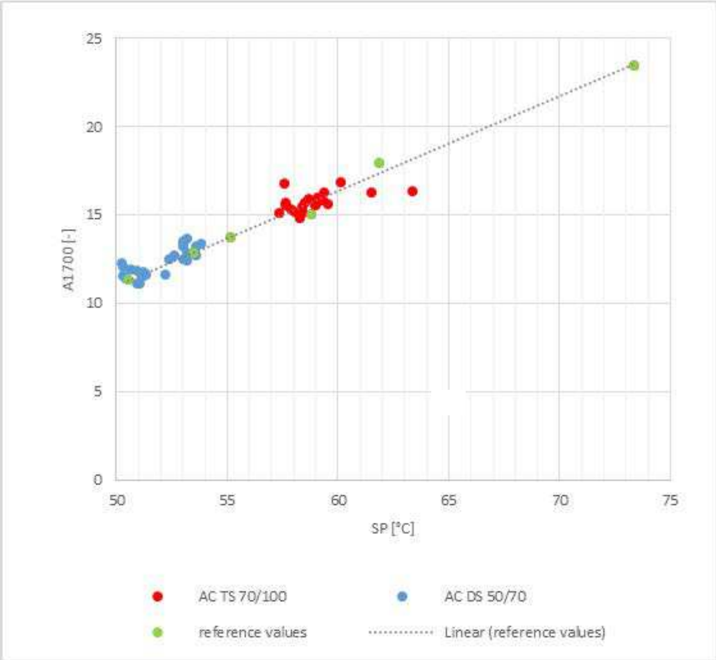

Figure 9: Correlation A1700 over softening point for material A and B

This hypothesis is further supported when all measured values are evaluated together and correlated as shown in Figure 9. The initial values of the reclaimed bitumen (material A and B) and the reference samples aged under laboratory conditions are presented as green dots. An almost linear correlation can be found between the measured values of softening point and the A1700 index. As visible from the diagram, higher oxidation values represented by high A1700 values are correlated with higher SP temperatures. This is found for both examined bitumen samples. It can be observed that the reference points of both materials can be fitted with one slope. In Figure 9, almost all measured A1700 values are correlated to their softening point counterparts in addition to the reference values. It is shown for material A as well as for material B that the regeneration utilizing the radio-wave technology has an impact on the bitumen depending only on the heating itself without additional effects related to this non-conventional heating method. Since heat develops within the bulk mass of the material when using the radio-wave method, thermal aging can thus be reduced.

In both series (Figure 7 and Figure 8) it was demonstrated that the highest aging occurs at surface temperatures of 160°C and 180°C after five regeneration cycles. Moreover, aging starts already with the first regeneration cycle. This could be expected and is in agreement with the theory of aging. However, the bitumen aging never exceeds the long-time aged reference (RTFOT + PAV). If the short-term aging, RTFOT, is interpreted as one conventional recycling cycle of reclaiming asphalt mixing and repeated placement then five regeneration cycles would correspond with one conventional recycling procedure. A strong impact of regeneration temperature on the average flexural strength could not be observed in both series as the decrease in stability between regeneration cycle 1 and 5 is not exceeding the standard deviation. However, the slight decrease of flexural strength, after the initial loss due to aggregate destruction, could be attributed to the thermal aging of the bitumen during the regeneration cycles. This is also supported as the effect slightly increases with higher temperatures.

5. CONCLUSION

In this paper, it has been found that the flexural strength of asphalt can be recovered several times to almost 100 % with the help of an asphalt regeneration procedure combining radio-wave heating and compacting. It could be shown in detail that the regeneration of asphalt utilizing the radio-wave technology is feasible and the influence on the

binder aging is acceptable. Artificially induced macro-cracks could be reliably closed and a satisfying amount of flexural strength was restored even after five regeneration cycles. The tests were carried out at very low temperatures (-20°C), due to this no direct resilient predication for the in-situ road performance can be made. However, it can be expected that the bitumen acts similarly with regard to crack closure and aging as in the case of the experiments described in this publication. Consequently, a suitable method for asphalt regeneration can be introduced by continuing the development of this promising innovative radio-wave-based technique. The results also show that the surface temperature can be used as reference measurement to control the heating process in future practical application. Surface temperature can be easily monitored by cost-effective IR sensors.
Further research will focus on utilizing more practical but complex methods for crack induction like the cyclic indirect tensile test on cylindrical specimens (CIT-CY) and on test of options utilizing the earth as ground or skilfully arranged RF and grounded electrodes on the surface of the asphalt course.

6. ACKNOWLEDGEMENTS

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