Maintenance and Rehabilitation

Influence on the material characteristics of asphalt mixtures reheated by radio waves

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Abstract

Reheating an asphalt pavement in combination with re-compaction offers the possibility to seal cracks and to even the surface. Within the project the combination of reheating and re-compaction of asphalt pavements is referred to as regeneration. In the laboratory scale the reheating was successfully performed using radio waves. Material characteristics of asphalt mixtures will change due to thermal and oxidative aging. And it is a well-known fact that fatigue, stiffness and rutting characteristics of the asphalt mixes have a major influence on the pavement performance. Thus, it is necessary to investigate the impact of the regeneration on the performance characteristics of asphalt mixtures. Within the research project an asphalt base course mix and an asphalt surface course mix were determined. The bitumen content was varied three times to evaluate the influence on the regeneration and the readjusted material characteristics. The regeneration was performed not only once but several times. This paper presents results of fatigue and stiffness tests to illustrate the effectivity of regeneration concerning the sealed cracks. Additionally, the bitumen characteristic were investigated to understand the influence of the reheating. The softening point ring and ball shows a clear influence regarding the number of regeneration cycles. The shear modulus values increase after each regeneration procedure due to aging. The fatigue performance increase after a single regeneration application if the bulk density of the specimen was constant. No further improvement of the fatigue performance could be observed after a second regeneration application. The stiffness performance after one regeneration application increased which is obviously due to thermal and not to oxidative aging. The described investigations concerning the material characteristics were completed with pavement design life calculations. Different case-scenarios considering the layer thickness were examined.

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1. Introduction

Roads are a very important factor of the mobility and the economy of the society. The constant growth of the economy and as a result, increasing traffic cause pavements to be loaded more heavily. Thus, pavements fail earlier than what they are designed for and maintenance measures have to be conducted earlier and more often. Most pavements are built with asphalt. By reheating of the asphalt, cracks can be closed due to the viscous behaviour of the binder. Research suggests some methods to reheat asphalt in-situ. The main problem with reheating of asphalt is the oxidation process of the bitumen and the potential overheating of the asphalt. Regarding these problems, only few methods for gentle heating have been established so far.

One method is the reheating via induction. It is necessary to add steel wool or steel fibres in the asphalt to heat the asphalt. Experiments of the Delft University [1][2] show that it is possible to heal cracks. Moreover, the optimal content of steel wool or steel fibres and the optimal heating time for the best "crack healing" without changing of the bitumen characteristics could be determined. The deficiency of this method is that the reheating without steel in the asphalt is not possible. Most of the asphalt pavements in Europe are constructed without any reinforcement.

Another possibility to reheat asphalt in-situ is to use microwaves. The Canadian researchers Bosisio, Spooner and Granger [3] showed the possibility of crack healing of asphalt during the winter period of 1973/1974. Two cracks were successfully healed using a Mobile Microwave Power Unit. In the publication of Müller-Rochholz [4] the heating behaviour of asphalt heated by microwaves is described. Only the aggregates are heated by microwave irradiation. However because of the increase of the aggregates temperature the bitumen temperature will also increase. The advantage of this method is that it does not need additives like steel wools or steel fibres necessary for the reheating via induction. The disadvantage is the large amount of power necessary to increase the temperature of the mixtures and the low penetration depth of the microwaves. The researchers Al-Ohaly and Terrel described that it is possible to reheat asphalt to depths of about 5 inches (12,7cm) without overheating the surface [5].

Radio-wave technology is another possibility for the dielectric heating of asphalt. In comparison to microwaves, radio-waves have lower frequencies and higher wavelengths. Thus, much deeper regions can be heated. As a result, it can be possible to reseal cracks in the asphalt base layer, which can prolong the lifetime of the pavement. This research shows the influence of radio-wave regeneration on the performance properties of asphalt concrete. The cyclic indirect tensile test (CIT CY) was used for determining the performance properties. Cylindrical specimens, were regenerated by heating after conducting the performance tests. Furthermore, the research also detects the influence of radio-wave regeneration on the bitumen rheology.

2. Asphalts mixtures and specimen preparation

For the laboratory tests an asphalt wearing course mixture AC8 D N 50/70 and an asphalt base course mixture AC 22 T N 70/100 were used. The bitumen content of these materials were varied three times to determine the influence on the material properties. Table 1 shows the material characteristics. All asphalts were mixed in an asphalt plant without additional amendments and were stored in metal bins, until it is reheated in the laboratory.

Table 1. Material characteristics

Mixture (DIN EN 13108-1)	AC 8 D N	AC 22 T S
Maximum aggregate size [mm]	8	22
Bitumen (DIN EN 1427)	50/70	70/100
Bitumen content [M.-%] (DIN EN 1427)	6.0/6.5/7.0	3.6/4.1/4.6
Softening point Ring and Ball [°C]	50.4	46.4
aggregate	hornfels, diabase, dolomite	diabase, dolomite

The asphalt materials were reheated in a heating cabinet in the laboratory. Asphalt slabs were produced using a segmented roller compactor after reheating the asphalt. The setup of the compaction was a deformation-controlled compression in the roller compactor. After that, the asphalt slabs were cooled down one day at ambient temperatures. At last, the cylindrical specimens were drilled out of the asphalt slabs for carrying out the various tests.

3. Regeneration method

Dielectric heating of material works with an alternating electromagnetic field, which produces a resonance of the polar molecules. The molecules align themselves parallel to the field lines of the electromagnetic field. This exerts forces on the molecules to the electric poles. These forces are dependent on the strength of the electric field. If the field is changing its strength, the forces also change their magnitude and this causes the resonance of the molecules. The temperature of the material rises due to intermolecular friction.

Figure 1 shows the principal setup of the dielectric heating of an asphalt prism. The specimens are placed between two conductive electrodes. In form of a condenser setup. The electrode material for reheating of the specimens was aluminium.

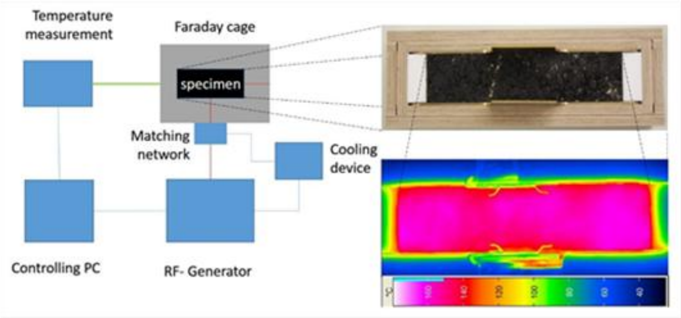

Figure 1: Radio-wave heating of a specimen

The specimens were dielectrically heated with an alternating electromagnetic field at 13.56 MHz. An infrared camera measured the surface temperature of the prismatic samples. Fibre sensors evaluated the average surface temperature of the cylindrical specimens. These measurements of the surface temperature have no effect on the electromagnetic field in the experimental setup. The specimen were reshaped by using a hydraulic press. The frame of the prismatic specimens was made out of wood in combination with PTFE. The framework of the cylindrical specimens for the regeneration were made from PTFE. The regeneration cycle includes the reheating process in combination with the compaction of the specimens.

4. Laboratory Tests

4.1. Bitumen investigation

The influence of the regeneration process was determined with prismatic specimens, which had the dimensions 40mmx40mmx160mm.The prismatic asphalt specimens were separated into two batches. One batch was regenerated one time and the other batch was regenerated five times. There were 6 specimens in one batch for each material. It is assumed that the reheating temperature had an effect on the bitumen ageing. The average surface temperatures of the reheating cycles were varied four times in order to detect the influence on the bitumen rheology. The reheating temperatures were 110°C, 130°C, 160°C and 180°C. The specimens were separated into three layers after one and five regeneration cycles; top (O), middle (Z) and bottom (U). It is assumed that the top of the specimens ages faster than the other layers. The bitumen was recovered by usage of trichloroethylene and a rotary evaporator after the regeneration cycles according to DIN EN 12697-3. The original bitumen was also recovered from the non-regenerated asphalt. In addition to the original, the bitumen was short-term aged with the Rolling Thin Film Oven Test (DIN EN 12607-1) and long-term aged with the Pressure Aging Vessels test (DIN EN 14769).
Afterwards, the softening point Ring and Ball values were determined and multistage frequency sweeps using the Dynamic Shear Rheometer (DSR) with the plate-plate system conducted.
Table 2 shows the configurations of the different measuring systems for the DSR-tests, which helped to determine the rheology properties of the bitumen.

Table 2. Configuration DSR

measuring system	PP 08	PP 25
Plate diameter [mm]	8	25
Frequency [Hz]	0.159-79.6	0.159-79.6
Temperature area [°C]	-10 - 30	30 - 70
Gap [mm]	2	1

The results of the DSR-tests were illustrated in Master curves of the complex modulus. The data was shifted with the Arrhenius approach. The sigmoid function simulates the stiffness curve of the bitumen. The function is shown in Equation 1.

$$G^* = y_0 + \frac{w}{1 + e^{-(\frac{x - x_0}{z})}} \quad (1)$$

G^* complex modulus [MPa]
y_0 intersection point on ordinate axis [MPa]
x_0 intersection point on abscissa axis[Hz]
x point on abscissa axis [Hz]
w material parameter [MPa]
z material parameter [-]

4.2. Asphalt investigation

The cylindrical specimens were tested with the Cyclic Indirect Tensile Test (CIT-CY). The CIT-CY analyses the stiffness behaviour and the fatigue behaviour of an asphalt. The results of these tests are stiffness functions with a loading frequency of 10 Hz and diagrams of the resistance fatigue curve. Furthermore, the results of the performance tests is used as input data for a design life time prognosis of a fictional pavement. The tests were carried out according to TP Asphalt Part 24 [6] and Part 26 [7]. It is necessary to test 12 specimens for a design life time prognosis. Table 3 shows the configuration of the performance tests for each Asphalt material.

Table 3. Configuration of the performance tests CIT-CY

	resistance of fatigue	stiffness behaviour
Temperature [°C]	20	-10/5/20
Frequency [Hz]	10	10/3/1/0.3/0.1
Number of specimens	9	3

The dimensions of the cylindrical specimens were different for the wearing course mixture and for the base course mixture. The wearing course mixture specimens were of height 40mm and had a diameter of 100mm. Specimens of the base course mixture had a height of 60mm and had a diameter of 150mm.
The specimens were regenerated two times after the performance tests. The reheating temperature of the asphalt specimens corresponded to 130°C. The temperature was chosen to allow the reshaping of the deformation of the specimens.
The specimens were loaded until cracking. The macro-crack criteria is defined as the maximum of the Energy Ratio function. The calculation of the Energy Ratio and the representation of the fatigue resistance are described in the TP Asphalt Part 24 or DIN EN 12697-24.
For the investigation of the stiffness behaviour a multistage test is conducted in order to address the temperature-frequency equivalence. The initial strain of the tests is limited to a value of around 0.0675 due to the requirement of constant material characteristics.
The test results of three specimens are shifted to get a Master curve of the stiffness behaviour according to TP Asphalt part 26 [7]. Equation 2 yields the stiffness master curve, which has a minimum stiffness modulus of 0 MPa. The maximum stiffness modulus is the result of the intersection point on the abscissa axis of the linearized phase angle (Equ.3).

$$|E^*| = |E^*|_{-\infty} + \frac{|E^*|_{+\infty} - |E^*|_{-\infty}}{1 + e^{(\dot{z}_1 * x + \dot{z}_0)}} \quad (2)$$

$|E^*|$ absolute stiffness modulus [MPa]
$|E^*|_{-\infty}$ minimum stiffness modulus [MPa]
$|E^*|_{+\infty}$ maximum stiffness modulus [MPa]
x point on the abscisse axis [Hz]
$\dot{z}_1, \dot{z}_0$ material parameter [-]

$$\delta = m_1 * |E^*| + m_0 \quad (3)$$

δ phase tangle [rad]
m_1, m_0 material parameter [-]
$|E^*|$ absolute stiffness modulus [MPa]

5. Results of the bitumen tests

5.1. Softening point Ring and Ball

Figure 2 and Figure 3 show the softening point temperatures of the bitumen 50/70 after the first regeneration cycle and after the fifth regeneration cycle. The softening point temperatures of the original bitumen (50/70), the short-term aged bitumen (RTFOT) and the long-term aged bitumen (PAV) are also depicted. The softening point temperatures are close to the original bitumen with a small increase after the first regeneration cycle (Figure 2). Some softening point temperatures are lower than the original value. Sample O showed the highest increase of the softening point temperatures after reheating at a reheating temperature of 180°C.

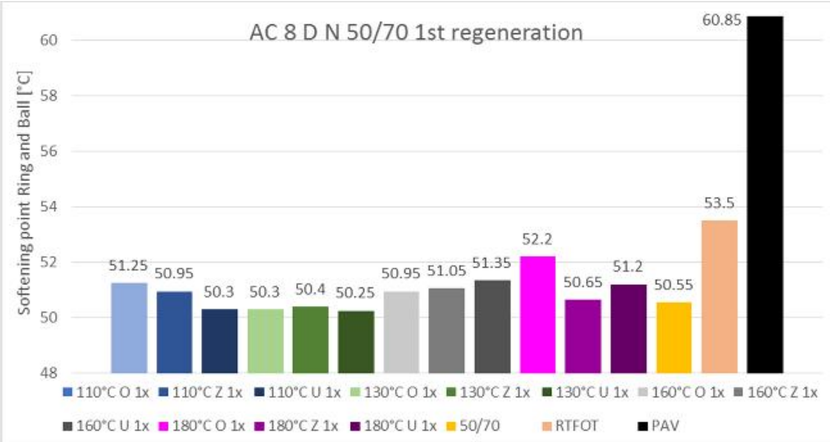

Figure 2: Softening point Ring and Ball 50/70, 1st regeneration

The regenerated samples given in Figure 3 show the same softening point value as the short term aged bitumen. The differences between the reheating temperatures are very small. It can be observed that the bitumen showed the same increase of the softening point temperature after the fifth regeneration cycle as the bitumen aged with the RTFOT.

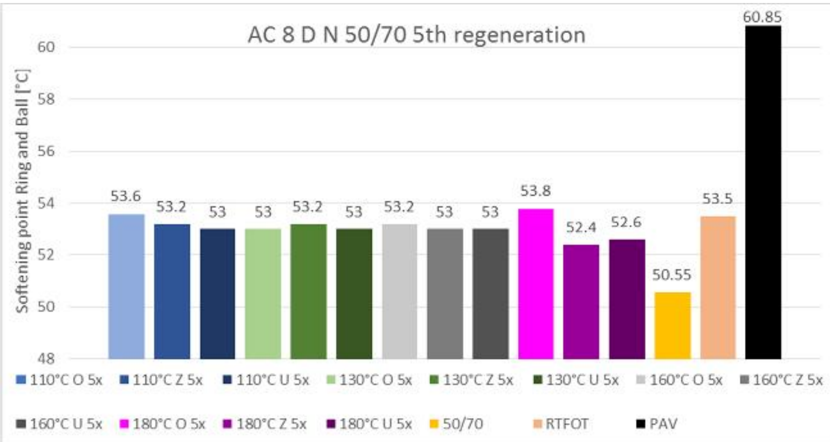

Figure 3: Softening point Ring and Ball 50/70, 5th regeneration

Figure 4 and Figure 5 show the softening point temperatures of the bitumen 70/100 after the first and after the fifth regeneration cycle. An increase could be observed around 2°C to 5°C after the first regeneration cycle (Figure 4). The softening point temperatures are located near the bitumen aged with the RTFOT. There are no relationships between the increase of the softening point temperatures and the reheating temperature.

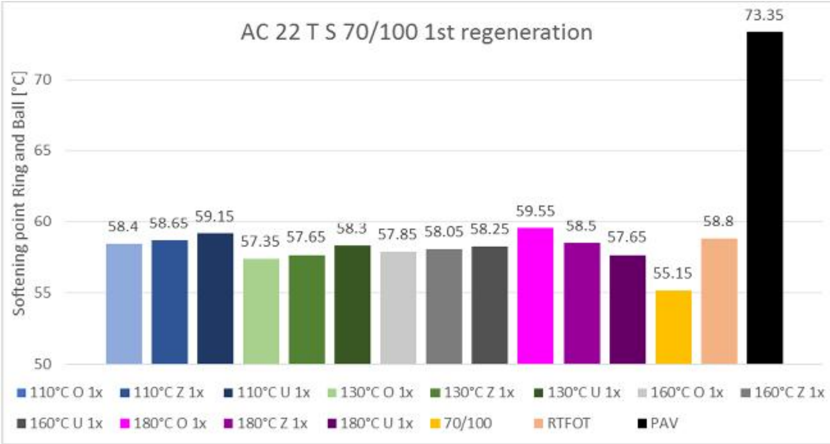

Figure 4: Softening point Ring and Ball 70/100, 1st regeneration

An increase of the softening point values could be observed for the RTFOT-values after the fifth regeneration cycle. It is noticeable that the top layer of the bitumen, which is reheated at the temperature of 180°C, has the biggest increase of the softening point temperature. The middle layer of this bitumen shows the smallest increase. It can be assumed that there is a relationship between the increase of the softening point temperature and the reheating temperature.

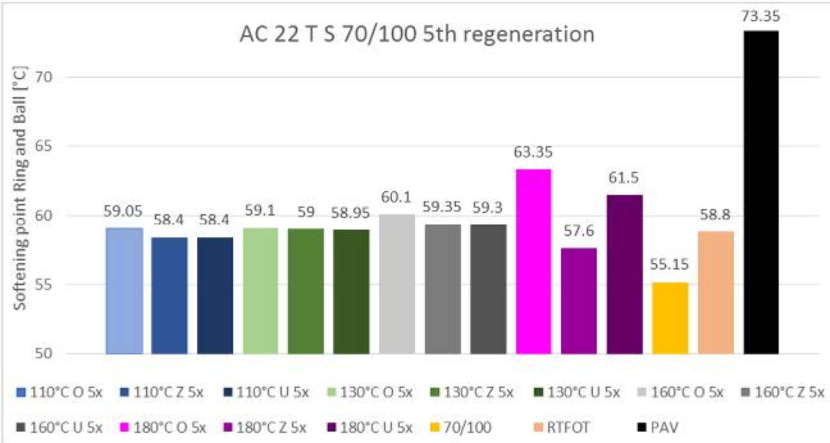

Figure 5: Softening point Ring and Ball 70/100, 5th regeneration

5.2. Master curves of the complex modulus

In Figure 6 and Figure 7 the master curves of the complex modulus G* of the bitumen 50/70 are shown. There are two diagrams illustrated, because the measurement system changes at the temperature of 30°C. The complex modulus increases after the first regeneration cycle (Figure 6). It is noticeable, that all regenerated specimens had nearly the same increase of the complex modulus in the whole temperature range. These increases are smaller than the increase after the short-term aging with the RTFOT.

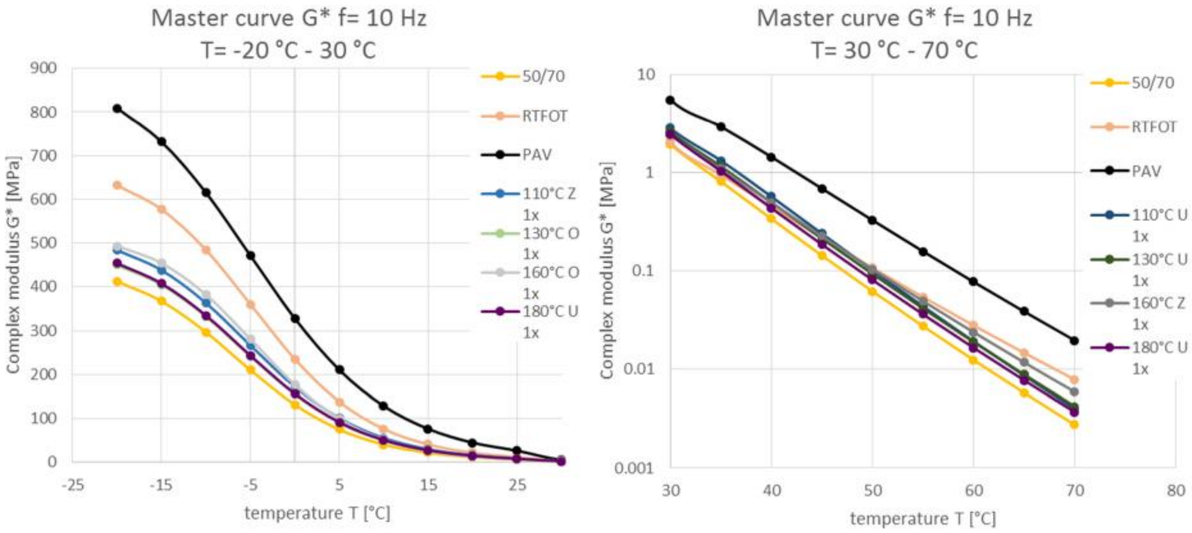

Figure 6: Master curves complex modulus 50/70, frequency 10 Hz, 1st regeneration

After the fifth regeneration the bitumen had a different increase in the complex modulus (Figure 7). The samples have lower complex modulus values than the RTFOT-sample in the lower temperature range. In the higher temperature range some samples have higher complex moduli than the RTFOT-sample. It is noticeable, that the sample 180°C O 5x has higher complex moduli than the PAV-sample. There is also a relationship between the increase of the complex modulus and the reheating temperature.

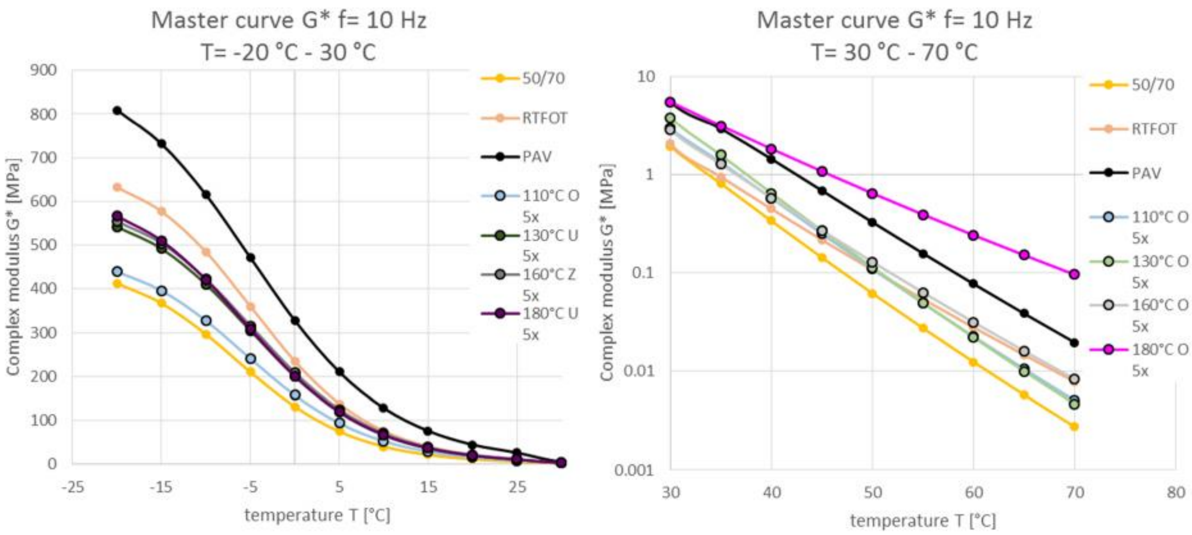

Figure 7: Master curves complex modulus 50/70, frequency 10 Hz, 5th regeneration

Figure 8 and Figure 9 show the diagrams of the master curves of the bitumen 70/100. The complex modulus values increase after the first regeneration at lower temperatures above the values of the specimens aged with the RTFOT and the PAV. However, the increase of the complex modulus is in the higher temperature range identically with the RTFOT and lower than the PAV. It is noticeable that all samples have the same increase of the complex modulus in the higher temperature range and after the first regeneration cycle. Figure 9 shows that samples had an increase of the complex modulus after the fifth regeneration cycle higher than the improvement of the complex modulus after the RTFOT. There is a dependence of the number of the regeneration cycle on the growth of the complex modulus.

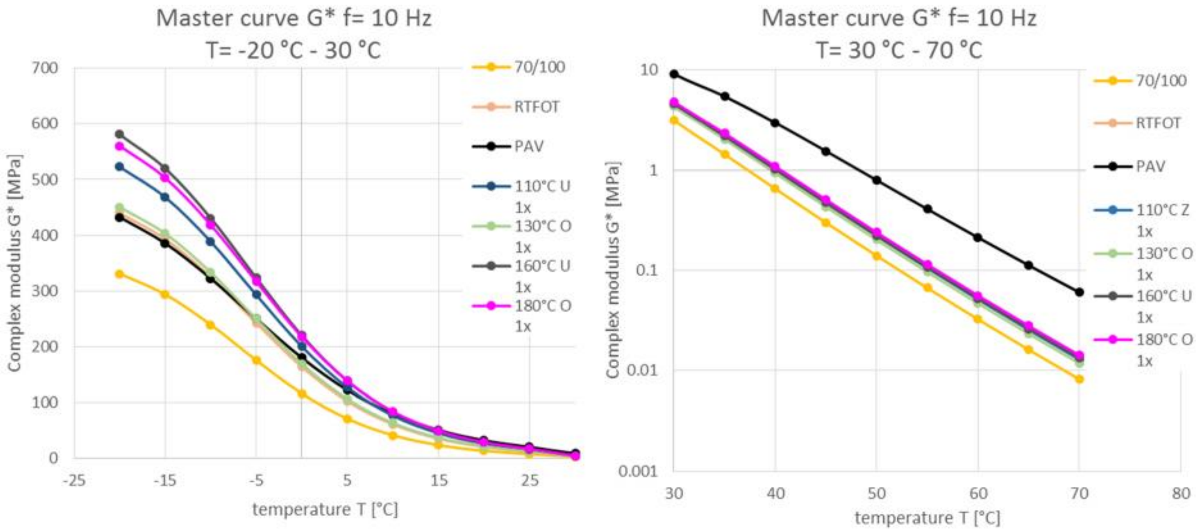

Figure 8: Master curves complex modulus 70/100, frequency 10 Hz, 1st regeneration

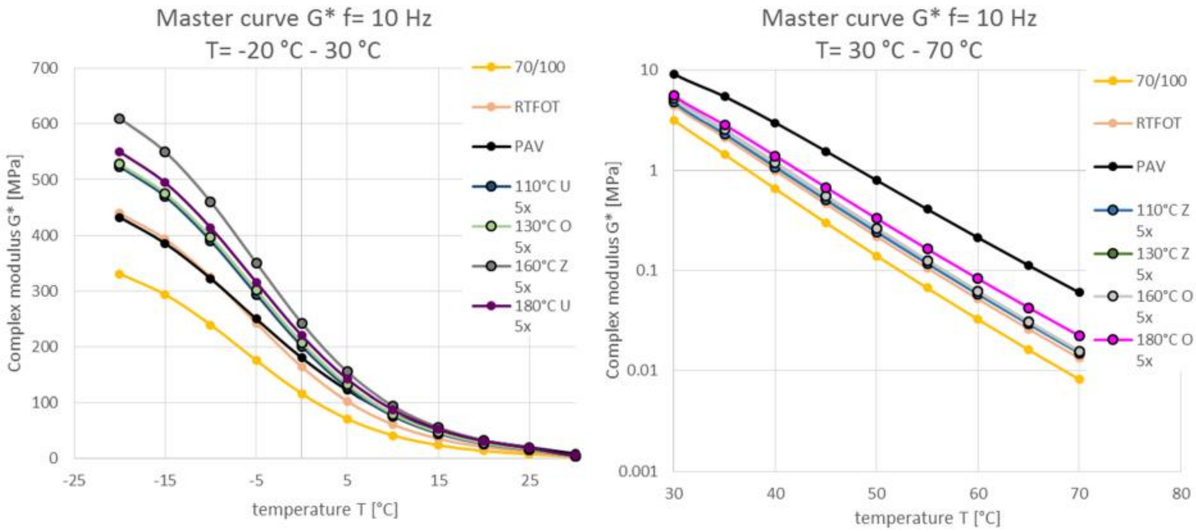

Figure 9: Master curves complex modulus 70/100, frequency 10 Hz, 5th regeneration

6. Results of the CIT-CY

6.1. Results of the base course mixtures

The results of the CIT-CY of the base course mixture with a bitumen content of 3.6 M.-% are shown in Figure 10. The base course mixture shows a deterioration of the fatigue resistance and a deterioration of the stiffness modulus after the first regeneration cycle. The fatigue resistance shows an improvement after the second regeneration cycle compared to the first regeneration cycle. The stiffness modulus also improve after the second regeneration.

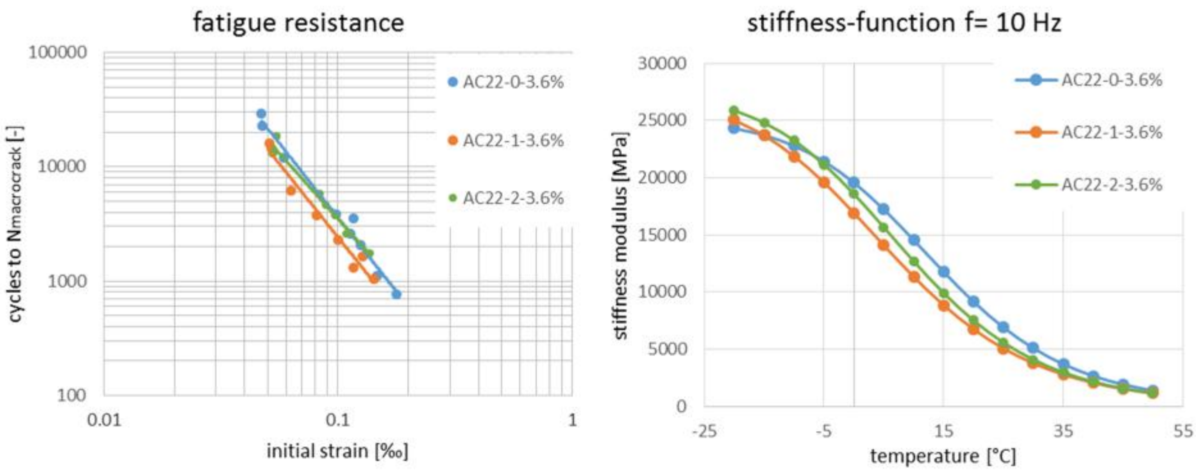

Figure 10: Results of the performance tests for AC22 T S 70/100 3.6 M.-%

Figure 11 shows the results of the CIT-CY of the base course with a bitumen content of 4.1 M.-%. No changes in the fatigue and stiffness behaviour could be observed after the first regeneration cycle. The stiffness modulus improve after the second regeneration cycle. However, the stiffness modulus is lower than the non-regenerated asphalt after the second regeneration cycle.

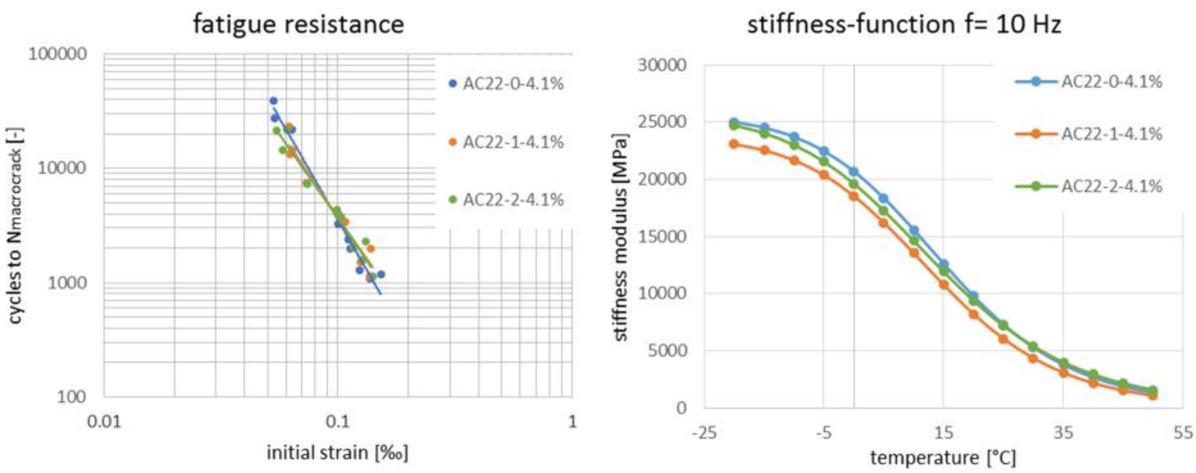

Figure 11: Results of the performance tests for AC22 T S 70/100 4.1 M.-%

Figure 12 shows the results of the CIT-CY of the base course material with a bitumen content of 4.6 M.-%. The fatigue resistance of the base course mixture improved and the stiffness modulus deteriorated after the first regeneration. The fatigue resistance did not change significantly after the second regeneration cycle. Also the stiffness modulus showed small improvements in the low temperature regions.

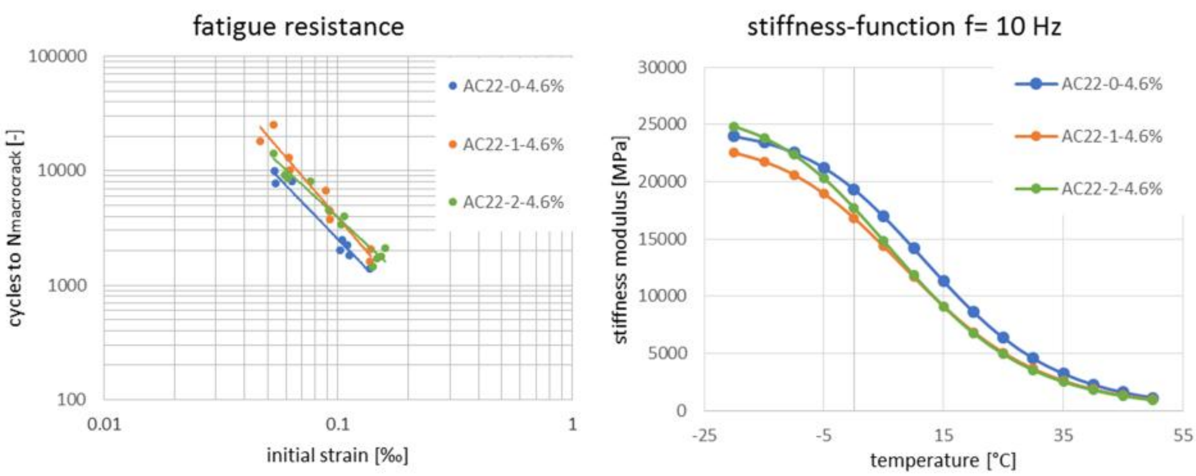

Figure 12: Results of the performance tests for AC22 T S 70/100 4.6 M.-%

It is noticeable that all base course materials had a deterioration of the stiffness modulus after the first regeneration cycle. A mass loss after the first regeneration cycle, which can be a loss of water was determined. It is possible that the water improved the stiffness modulus of the non-regenerated asphalt. The changing of the fatigue resistance can be due to the changing of the bitumen content in the centre of the specimens. The bitumen flows to the edge of the specimen after the regeneration cycles and this results in a redistribution of the bitumen in the specimens. The studies of Dragon shows that the bitumen content of asphalt can influence the fatigue resistance [11].Thus, the existence of an optimum bitumen content can be deduced.

6.2. Results of the asphalt wearing course mixtures

In Figure 13 the results of the CIT-CY of the asphalt wearing course mixture with a bitumen content of 6.0 M.-% are depicted. The diagrams show an improvement of the stiffness-modulus after regeneration. There is a relationship between the number of the regeneration and the improvement of the stiffness modulus. The same behaviour after the regeneration can be observed for the mixture with a bitumen content of 6.0M.-% in Figure 15. Only the stiffness modulus of Figure 14 decreases after the second regeneration.

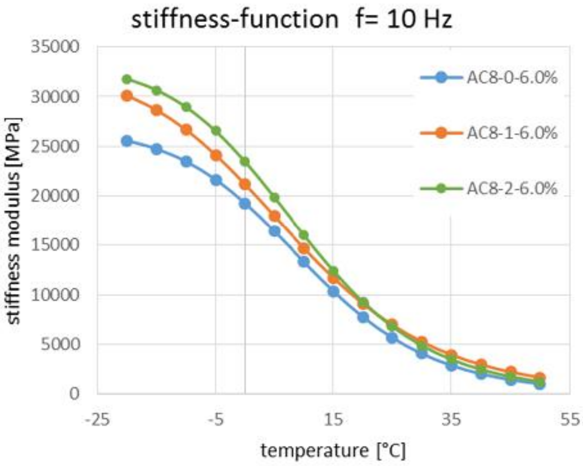

Figure 13: Stiffness-function AC8 D N 50/70 6.0 M.-%

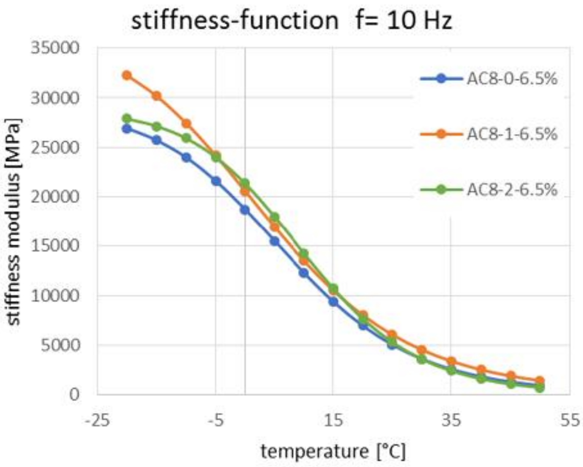

Figure 14: Stiffness-function AC8 D N 50/70 6.5 M.-%

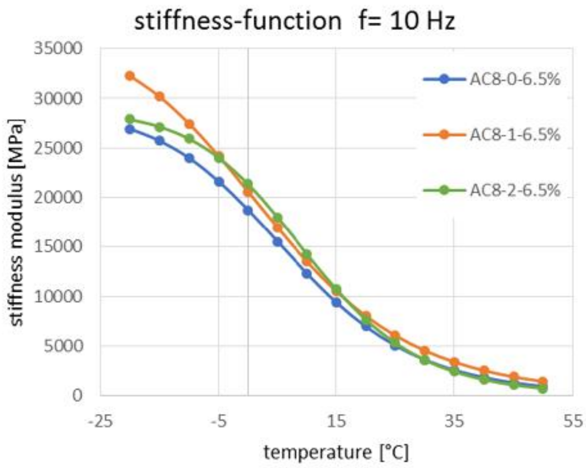

Figure 15: Stiffness-function AC8 D N 50/70 7.0 M.-%

The increase of the stiffness modulus after the regeneration cycles can be explained by the oxidative processes of the bitumen. The reheating process with radio-waves result in the oxidation and ageing of bitumen.

6.3. Results of the prognosis calculations

The design life time calculations were evaluated with the program AD2Pave. The AD2Pave calculations are based on the multilayer theory with the material characteristics from the CIT-CY tests. The RDO Asphalt 09 [8] regulates dimensioning asphalt pavements. Table 4 shows the assumption for the fictive pavement. The thickness of the bounded layers were iteratively adjusted until the pavement failed due to fatigue after 30 years. The considered structures are summarised in Table 5. The bounded layers are placed on top of a frost-protection layer. The name of the layers include the name of the material, the number of the regeneration cycle and the content of the bitumen.

Table 4. Assumptions of the fictive pavement

location	Dresden, Germany
Total combined axle load	977,531
thickness of the frost-proof foundation [cm]	55
axle load classes according to [9]	BAB local traffic (connection function level III "regional")
temperature zone according to [10]	3
Surface layer thickness [mm]	40
Base layer thickness [mm]	100

Table 5. Considered structures

1st regeneration	
var 1.1	AC8-1-6.0%
	AC22-1-3.6%
var 2.1	AC8-1-6.5%
	AC22-1-4.1%
var 3.1	AC8-1-7.0%
	AC22-1-4.6%
2nd regeneration	
var 1.2	AC8-2-6.0%
	AC22-2-3.6%
var 2.2	AC8-2-6.5%
	AC22-2-4.1%

var 3.2	AC8-2-7.0%
	AC22-2-4.6%

The results of the prognosis calculation are shown in Figure 16. The calculations show a prolonged service life time of the pavements after the regeneration cycles, except the first regeneration of the variant 1.1. The base course material showed an increase in the stiffness modulus after the regenerations and in some cases the fatigue resistance improved.

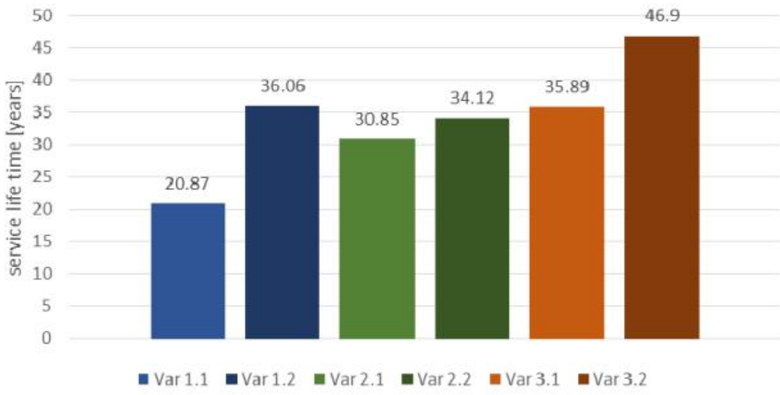

Figure 16: Prognosis calculations of a fictive pavement located in Dresden, Germany

7. Conclusion

This study shows the influences of regeneration of asphalt mixtures using the radio-wave technology on the asphalt performance. The heating process shows a thermal aging of the bitumen, which influence the properties of the asphalt.

The softening point temperatures of the bitumen increase after the regeneration cycles, which is dependent on the number of the regeneration cycles. It can be noticed, that the reheating temperature has a small influence on the increase of the softening point temperatures after the fifth regeneration cycle (only a reheating temperature of 180°C). The two different investigated mixtures also show a different increase of the softening point temperature, which is due to the different bitumen sort and the different content of the bitumen in the mixture. The DSR measurements show an increase of the complex modulus depending on the number of the regeneration cycles. After the fifth regeneration cycle the bitumen showed an increase of the complex modulus, which is sometimes higher than the values of the artificial short-term aging with the RTFOT. The reason for the increase of the softening point temperatures and the increase of the complex modulus values are the thermal and the oxidative aging of the bitumen during the reheating process. The measurements of the FTIR shows an increase of the oxidative indicators of the bitumen.

The performance tests show an increase of the stiffness modulus with the number of regeneration cycles. Furthermore, the tests of the asphalt base course mixtures show a dependency of the resistance of fatigue on the bitumen content of the mixture. The base course material with the highest bitumen content show an improvement of the fatigue resistance and the asphalt base course material with the lowest bitumen content show a deterioration of the fatigue resistance after the first regeneration cycle. It can be assumed, that this is a result of the retribution of the bitumen and the changing of the relative bitumen content in the specimens due to the heating process. Bitumen is carried from the inside of the specimen to the outside, which results in a bitumen content reduction in the centre of the sample. The presence of water could also effected the fatigue resistance. The prognosis calculations shows an increase of the service life time after the regeneration cycles, due to the ageing of the bitumen. It can be noticed, that the regeneration process can reset the asphalt without bigger deteriorations of the asphalt properties. The influence of the radio-wave regeneration on the deformation behaviour of the asphalt wearing course mixtures was also tested by using the cyclic compression test. Further researches are focusing on the radio-wave technology for heating an asphalt pavement with a mobile power unit.

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