1. INTRODUCTION

Awareness increases that the construction of infrastructure needs to become more efficient and sustainable. Rising prices for bitumen and disposal of reclaimed asphalt provide additional incentive to increase and enhance the recycling of asphalt for high quality road materials.

The main objective of the presented study is to analyze the impact of reclaimed asphalt on the performance of recycling asphalt in order to reuse as much as possible while keeping the quality of the product at a high level.

A trial section was constructed and the asphalt mixes with different percentages of reclaimed asphalt from binder and base layers were analyzed by performance based tests:

- the resistance to low-temperature cracking by means of thermal stress restrained specimen tests (TSRST),
- the resistance to rutting by triaxial cyclic compression tests (TCCT) and
- the stiffness/fatigue characteristics by 4-point-bending tests (4PBB).

By comparing results from mixes with a certain amount of reclaimed asphalt with results from the same mixes without reclaimed asphalt, the impact of reclaimed asphalt on the performance of the mix can be determined and limits for the proportion of recycling products in bituminous bound layers can be given.

2. PERFORMANCE-BASED LAB TESTS

To describe the performance of hot mix asphalt (HMA) in the lab thoroughly in terms of expected traffic and climate loading in the field three main indicators have to be taken into account. It is (1) the low-temperature cracking, (2) the stiffness and fatigue performance at intermediate temperatures and (3) resistance to permanent deformation at elevated temperatures (rutting). In the last five to ten years test methods to describe these performance parameters have been implemented into European standards (EN) and requirements for performance based type testing can now be set by each member state of the European Union (EU). In Austria requirements for the (TSRST) at low temperatures, the 4PBB at intermediate temperatures and the TCCT at elevated temperature have been added to its national standards for type testing [1]. Thus also recycling asphalt containing reclaimed asphalt can be described by means of performance based test methods and its performance can directly be compared to standard HMAs.

2.1 Resistance to low-temperature cracking

The performance of HMA at low temperatures can be characterized by the TSRST acc. to EN 12697-46 [2]. The test determines the temperature at which an HMA fails due to thermal or cryogenic stresses. A prismatic specimen (60x60x230 mm) is fixed between two load plates within a temperature chamber. Its length is held constant while the temperature is lowered from a starting temperature of 10°C with a constant rate of 10 K/h. Since the thermal shrinkage of the material is prevented, cryogenic stress is introduced into the specimen until the tensile strength of the material is reached and the specimen fails by cracking. The main results are the evolution of the cryogenic stress vs. temperature, the temperature at the point of cracking (T_{crack}) and the maximum stress ($\sigma_{cry,crack}$). Figure 1 shows the principle of the test, as well as a specimen within the climate chamber ready for testing.

The test simulates the situation in a pavement when the temperature drops quickly, e.g. after sunset at a harsh winter day. Since a flexible road pavement is fixed in longitudinal direction, cryogenic stresses will occur and eventually lead to top-down cracking if the mix does not show sufficient ability to compensate these stresses by relaxation.

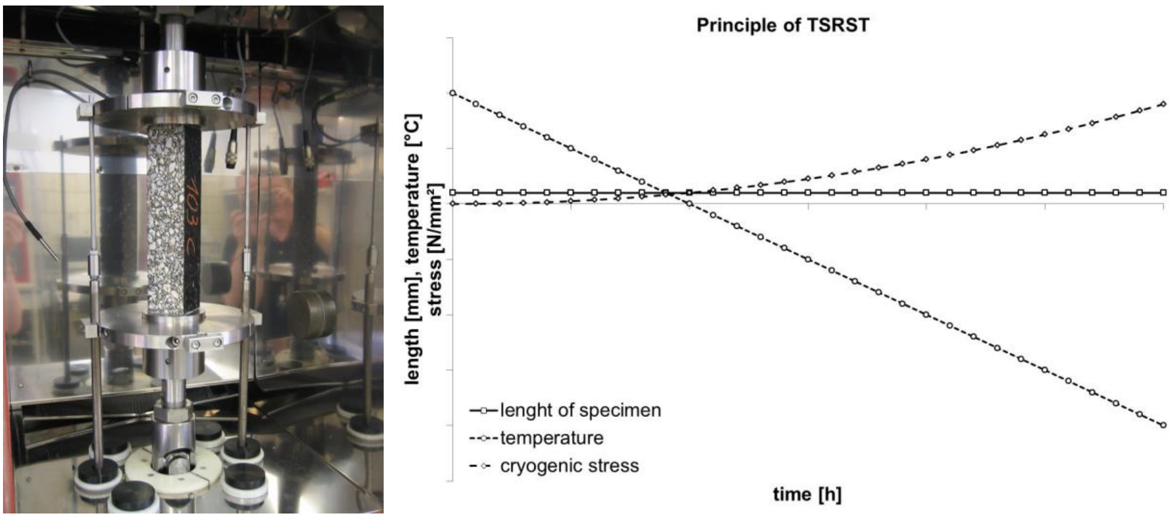


Figure 1 : Specimen in the TSRST test device (left) and principle of the TSRST (right) [3].

2.2 Stiffness and fatigue performance

The stiffness and fatigue behavior can be assessed by means of various test methods, e.g. the direct tension (DT), direct tension and compression (DTC) test or the 4PBB test. In Austria requirements for the 4PBB have been standardized for type testing [1]. For this test type a prismatic specimen is subjected to a cyclo-dynamic (sinusoidal), deformation-controlled bending. The principle of the test is presented in Figure 2. While the two outer supports of the specimen are fixed and allow rotation and translation in horizontal direction, the bending is realized by the two inner supports in

vertical direction perpendicular to the longitudinal axis of the specimen. The sinusoidal bending is carried out symmetrically around the zero position with a constant amplitude. The deformation of the specimen in vertical direction as well as the loading is recorded as a function of time. Since the bituminous bound material shows viscoelastic behavior, strain will always occur with a certain phase lag after the stress is applied to the specimen (see Figure 2).
In the first part of the test procedure the dynamic stiffness of the tested material is derived acc. to EN 12697-26 [4]. In order not to damage the specimen during stiffness testing, the amplitude of the horizontal strain on the lower side of the specimen is set to 50 µm/m. The test temperature is 20°C and a frequency sweep is carried out from 0.1 Hz to 30 Hz. From the data, the dynamic modulus $|E^*|$, as well as the elastic (E_1) and viscous (E_2) part of the dynamic modulus and the phase lag (φ) can be obtained [4]:

$$E^* = \frac{\sigma_0}{\varepsilon_0} \cdot (\cos\varphi + i \cdot \sin\varphi) = E_1 + i \cdot E_2$$
$$E_1 = \frac{\sigma_0}{\varepsilon_0} \cdot (\cos\varphi)$$
$$E_2 = \frac{\sigma_0}{\varepsilon_0} \cdot (\sin\varphi) \qquad (1)$$
$$|E^*| = \sqrt{E_1^2 + E_2^2} = \frac{\sigma_0}{\varepsilon_0}$$

After the stiffness test is completed, the fatigue performance is assessed for the same specimen in a second stage of the test acc. to EN 12697-24 [5]: The principle of loading is the same as for the stiffness test but the strain amplitudes are higher to provoke fatigue. The main result here is the number of load cycles until the specimen reaches a state of fatigue. In the case of the European standard [5] fatigue is defined as the load cycle when the dynamic stiffness has decreased to half of its initial value. The initial value is defined as the stiffness after 100 load cycles ($S_{mix,100}$). The number of load cycles until the state of fatigue is reached is defined as $N_{f/50}$. Fatigue tests are carried out at 20°C and 30 Hz. The test is run at three different strain amplitudes. The amplitudes are chosen so that the state of fatigue is reached after 10^4 to $2*10^6$ load cycles. When the test results are put into a diagram where the load cycle until fatigue $N_{f/50}$ is shown vs. the strain amplitude ε a logarithmic relation, the so called Woehler curve, can be determined for the tested material linking the loading in terms of strain amplitude ε with the fatigue performance in terms of load cycle until fatigue $N_{f/50}$.

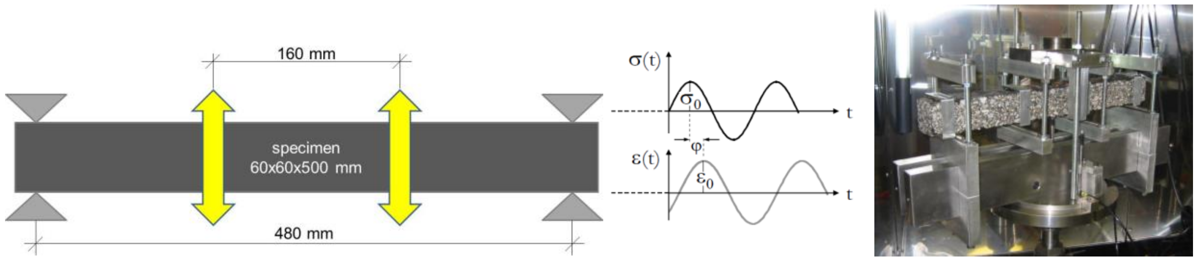


Figure 2 : Sketch of the 4PBB (left), stress and strain as a result of the test (middle) and specimen in the 4PBB-device (right).

2.3 Resistance to permanent deformation at elevated temperatures
At elevated temperatures the permanent deformation behavior is an important benchmark for the performance of an HMA. To assess the resistance to rutting cylindrical specimens (d = 100 mm, h = 200 mm) are tested in the TCCT acc. to EN 12697-25 [6]. The specimen is conditioned at the test temperature of 40°C. It is then situated between two load plates within a triaxial cell (see Figure 3). The specimen is subjected to a constant confining pressure σ_c and a cyclo-dynamic axial loading $\sigma_{ax}(t)$ in the compressive domain at 3 Hz for 20,000 load cycles. The accumulated axial strain $\varepsilon_{ax,tot}$ vs. the number of load cycles is the resulting creep curve of the test. This curve (see Figure 3) consists of three parts: The first section of the curve (1) as the re-compaction phase is characterized by a decreasing slope of the creep curve, followed by a second quasi-linear phase (2) and a third phase with a strongly increasing slope when the specimen develops macro-cracks and starts to fail (3). At one point (4) the creep curve will change its flection.
According to the standard [6] the quasi-linear part of the creep curve shall be approximated by a linear:

$$\varepsilon_n = A_1 + B_1 \cdot n \qquad (2)$$

ε_n represents the accumulated axial strain at load cycle n. The benchmark parameter is the creep rate f_c in µm/m/n and can be obtained from B_1 by expanding it by 10^4. A high value of f_c corresponds to a low resistance to permanent deformation.

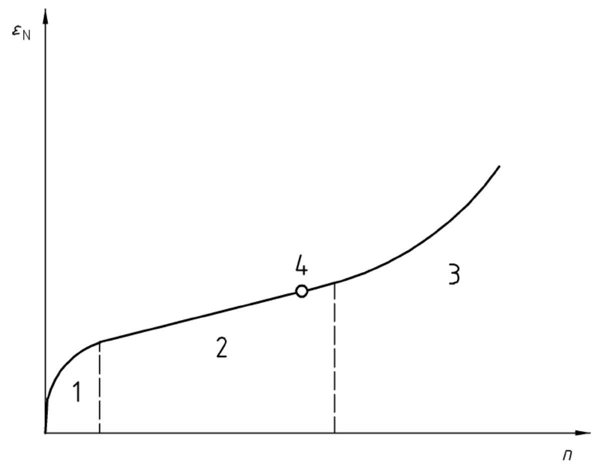


Figure 3 : Creep curve from TCCT (left) [6] and triaxial cell within temperature chamber (right)

3. PERFORMANCE OF RECYCLING ASPHALT – CASE STUDY

In an extensive case study the performance of recycling asphalt mixtures with different contents of reclaimed asphalt were tested to investigate the impact of reclaimed asphalt on the performance of HMA. Since only a little number of mixing plants with parallel drums operates in Austria, state of the art in asphalt recycling is to add the reclaimed asphalt cold and wet to the preheated aggregate in conventional mixing plants. This was also the case within this project.

3.1. Materials and test program

For the case study a test road was constructed consisting of surface, binder and base layer. The binder layer is an asphalt concrete with a maximum nominal aggregate size of 22 mm (AC 22 binder) and is mixed with a highly polymer-modified binder PmB 45/80-65 acc. to EN 14023 [7]. Three variations were used for the binder layer:

- without reclaimed asphalt (AC 22 RA 0),
- with 15% (m/m) (AC 22 RA 15) and
- with 20% (m/m) of reclaimed asphalt (AC 22 RA 20).

The base layer is an AC 32 base, an asphalt concrete with a maximum nominal aggregate size of 32 mm paving grade bitumen 70/100 according to EN 12591 [8]. Two variations were used for the base layer:

- with 20% (m/m) (AC 32 RA 20) and
- with 30% (m/m) of reclaimed asphalt (AC 32 RA 30).

To ensure comparable bitumen grading of all mix variations of the base layer containing reclaimed asphalt, the penetration acc. to EN 1426 [9] of the fresh bitumen used for the mix of the fresh HMA was taken as a benchmark (pen_{res}). Bitumen from reclaimed asphalt was extracted and the penetration was determined as well (pen_{RC}). To ensure the same penetration as the fresh bitumen, a paving grade bitumen with high penetration class 160/220 acc. to EN 12591 [8] was mixed to the respective HMAs to fulfill the following relationship in relation to EN 13108-1 [10]:

$$a \cdot \lg pen_{RC} + b \cdot \lg pen_{160/220} = \lg pen_{res} \quad a + b = 1 \tag{3}$$

If, for example, the bitumen from reclaimed asphalt had a pen_{RC} of 50, the bitumen of the fresh mix a pen_{res} of 90 and the bitumen 160/220 a $pen_{160/220}$ of 190, then a portion of 55% (m/m) of bitumen from the reclaimed asphalt and 45% (m/m) of the 160/220 bitumen would result to a penetration of 90. Furthermore, if a portion of 20% (m/m) of reclaimed asphalt with an assumed binder content of 5% (m/m) is added to the fresh HMA with the same binder content, the total content of bitumen from reclaimed asphalt in the mix would be 1% (m/m). An addition of 44% of this amount (=0.8% (m/m)) of the soft bitumen 160/220 would compensate the lower penetration of the reclaimed bitumen and the recycling HMA should exhibit the same penetration as the fresh HMA.

For the test program samples of each mix were taken directly after mixing in the plant. HMA-slabs were produced in the lab by segment-roller compaction acc. to EN 12697-33 [11] and specimens were cut and cored from these slabs.

Specimens from the binder layers were tested in the high- and low-temperature domain whereas for the base layer the fatigue performance is crucial. Table 1 gives an overview of the test program.

Table 1: Test Program.

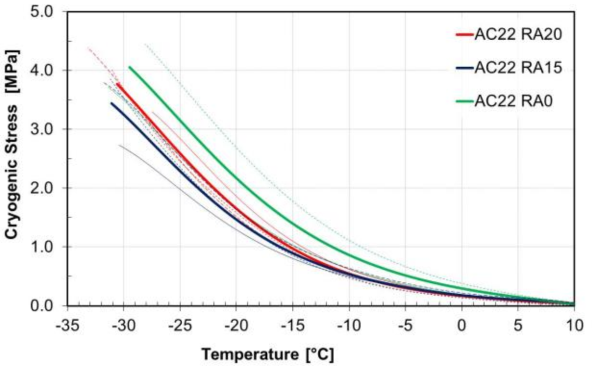
Mix Code	Content of reclaimed asphalt	Performance based tests		
		Low temperature	Stiffness / fatigue	High temperature
AC 22 binder RA 0	0 % [m/m]	X		X
AC 22 binder RA 15	15 % [m/m]	X		X
AC 22 binder RA 20	20 % [m/m]	X		X
AC 32 binder RA 20	20 % [m/m]		X	
AC 32 binder RA 30	30 % [m/m]		X	

3.2 Performance of binder layer

For the binder layer the low temperature performance in terms of resistance to cracking and the performance at elevated temperatures in terms of the resistance to permanent deformation are important parameters to describe the quality of an HMA.

Figure 4 shows the resistance to thermal cracking in two diagrams. The left picture depicts the evolution of the cryogenic stress vs. temperature for the three mix variations. The solid lines give the mean values of tests at three specimens, the single test results are shown as dotted lines. The right diagram summarizes the major results, the cracking temperature T_{crack} and the thermal stress at cracking $\sigma_{cry,crack}$. Obviously the binder layer without any reclaimed asphalt develops more cryogenic stress than the mixes with 15% (m/m) and 20% (m/m) of reclaimed asphalt. The pure AC 22 mix also fails at a slightly higher temperature (-29.5°C). AC 22 RA 15 cracks at -31.1°c and the mix with 20% (m/m) reclaimed asphalt at -30.6°C. When the scattering of results is taken into account by looking the standard deviations as the black bars in the right diagram it becomes clear, that the results of all three mixes are on the same level.

Reclaimed asphalt contains long-term aged bitumen. It is basic knowledge that bitumen tends to become stiffer and more brittle due to ageing. This also affects the performance of an HMA with less ability to relaxation and thus it is more prone to low-temperature cracking. The results of this study encourage the procedure to use highly modified binder for the fresh mix to compensate for the stiffening due to aged bitumen in the reclaimed asphalt.



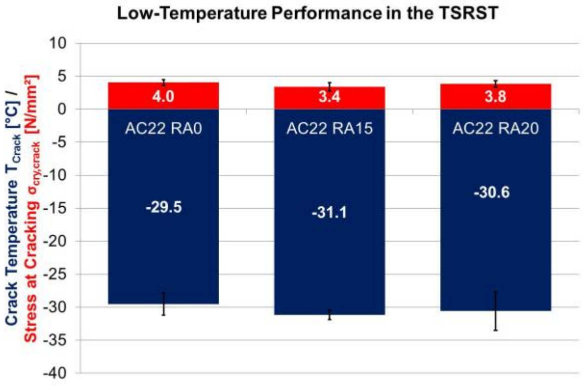
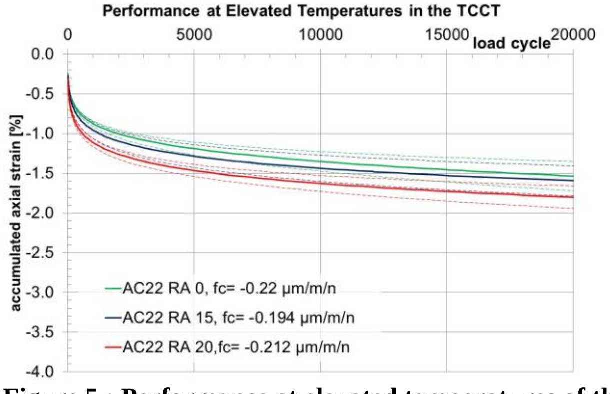


Figure 4 : Low temperature performance of the binder layer: evolution of cryogenic stress vs. temperature (left) and crack temperatures and the respective stress at cracking (right).

The resistance to permanent deformation at elevated temperatures was tested in the TCCT at 40°C, 3 Hz for 20,000 load cycles. Figure 5 presents the results for the three AC 22 binder mixes. From the creep curves (left diagram) it seems that the mix with 20% (m/m) reclaimed asphalt (red) shows a slightly worse resistance to rutting than the other two mixes. This diagram contains the mean values of the creep curves from three single tests per mix as solid lines and the standard deviation around the mean values in dotted lines. The right diagram shows the creep rate as the slope of the linear in the quasi-linear part of the creep curve. A higher absolute value of f_c indicates a lower resistance to permanent deformation. All three mixes show an excellent high-temperature behavior since the creep rate is around or even above -0.200 in all cases. The black bars represent the standard deviation. From this it is obvious that there are no significant differences between the three mixes. From the conventional view it would have been expected that the resistance to permanent deformation gets better with higher contents of reclaimed asphalt due to the higher stiffness of the aged binder. Again the use of highly modified binder in the recycling asphalt compensated this effect and thus all three mixes perform alike.



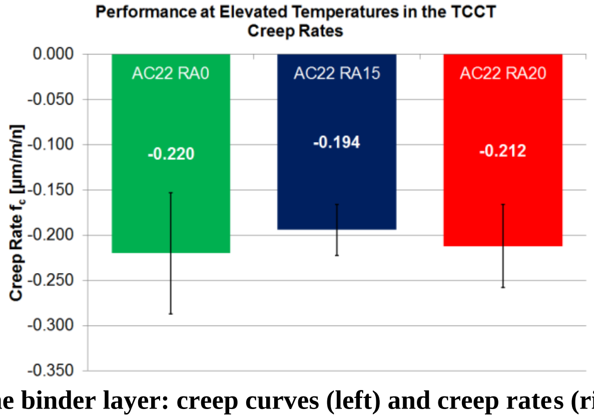


Figure 5 : Performance at elevated temperatures of the binder layer: creep curves (left) and creep rates (right).

3.3 Performance of base layer

The base layer AC 32 base 70/100 was tested for stiffness and fatigue performance in the 4PBB. Unfortunately the mix was not available without reclaimed asphalt. Only two variations with 20% (m/m) and 30% (m/m) of reclaimed asphalt could be used for testing. Thus no comparison to the pure mix can be carried out. Still some interesting findings could be made.

The dynamic stiffness is shown in Figure 6 in two diagrams. The left picture contains data for the dynamic modulus $|E^*|$ vs. frequency from 0.1 Hz to 30 Hz at 20°C. The right diagram presents the phase lag φ vs. frequency for both mixes. The solid line represents the mean value from 12 single tests and the dotted lines show the standard deviation. Interestingly enough both mixes exhibit similar behavior in terms of dynamic stiffness at low frequency up to about 3 Hz. From this point on the stiffness of the mix with 30% (m/m) of reclaimed asphalt reacts slightly stiffer (+4% at 30 Hz). The phase lag shows a larger difference at low frequencies (3° at 0.1 Hz) which is leveled out towards higher frequencies. This indicates that the mix with a larger portion of reclaimed asphalt reacts more viscous in the low frequency range and stiffer in the high frequency range. However, when the standard deviation is taken into consideration the differences do not seem to be significant.

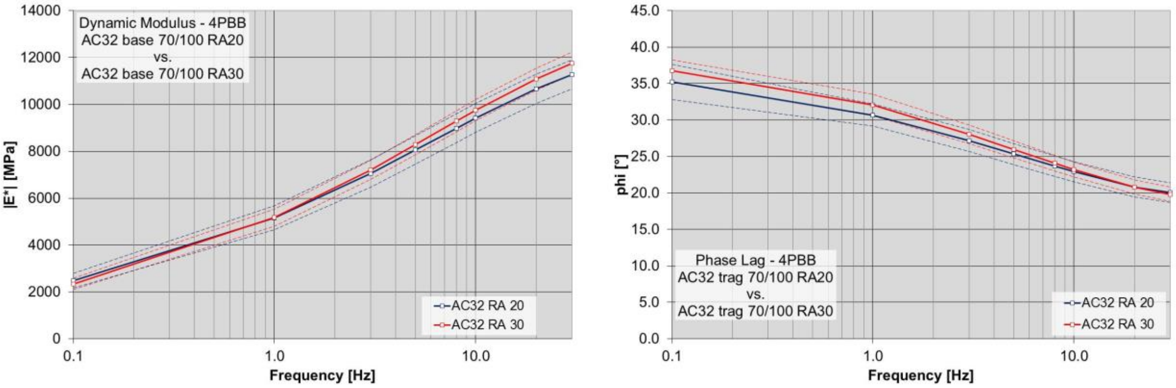
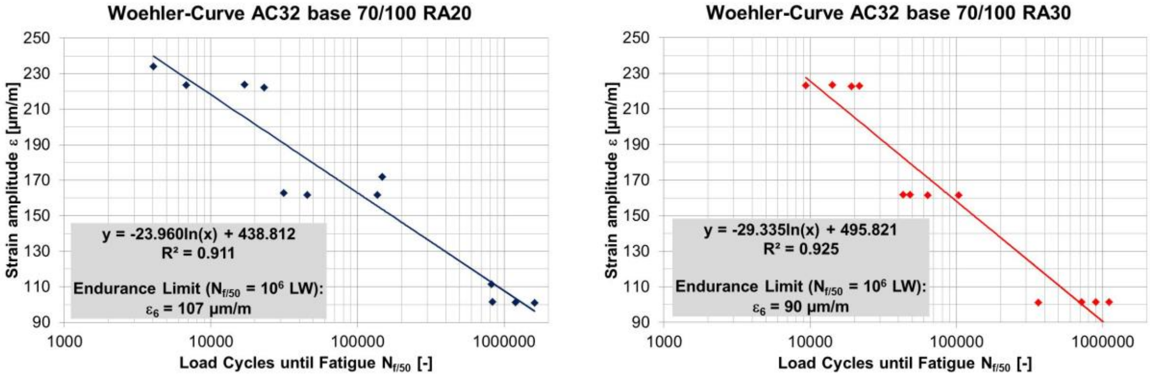


Figure 6 : Stiffness behavior of the base layer: dynamic modulus (left) and phase lag (right) vs. test frequency.

One of the most important parameters for the performance of a pavement structure is the fatigue resistance of the bound base layer since the maximum strain will occur on the bottom of the bound layers. Thus both AC 32 base mixes were also tested towards their fatigue behavior in the 4PBB. At each strain amplitude (100 µm/m, 160 µm/m and 220 µm/m) six specimens were tested at 20°C and 30 Hz until they failed due to fatigue cracking. Only four of the six specimens at each strain amplitude were tested successfully and are used for further analysis of results. Figure 7 shows the three diagrams. The two top diagrams show the test results for each single test in terms of applied strain amplitude vs. the number of load cycles until the fatigue criterion (half of the initial stiffness) was reached. In addition the Woehler-curve derived from the single tests is also presented in the diagrams. The endurance limit ε_6 is defined as the strain amplitude where the material resists 10^6 load cycles before the fatigue criterion is reached. This benchmark parameter is shown in the bottom diagram in Figure 7. Both mixes exhibit a low resistance to fatigue. The AC 32 RA 20 shows an endurance limit of 107 µm/m, the AC 32 RA 30 90 µm/m. These results indicate that the addition of a 160/220 binder to the recycling asphalt to compensate for the aged binder in the reclaimed asphalt does not affect the fatigue resistance in a positive way. A higher portion of reclaimed asphalt clearly lowers the performance in terms of fatigue. This effect may be increased since the recycling asphalt was produced in a conventional mixing plant where the reclaimed asphalt is added wet and cold to the pre-heated aggregate. It is probable that this procedure does not enable the fresh bitumen and the bitumen on the reclaimed asphalt to mix to a new homogenous binder.



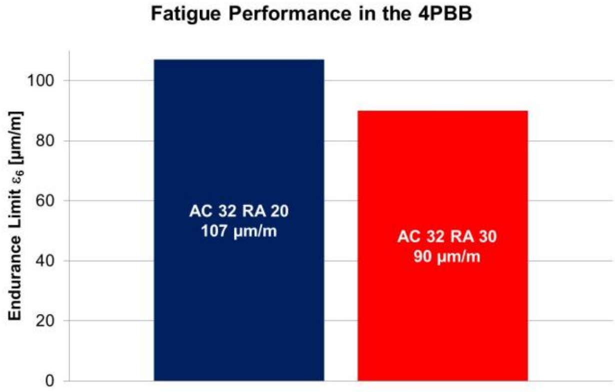


Figure 7 : Fatigue performance of the base layer: Woehler-curve for AC 32 RA 20 (upper left) and AC 32 RA 30 (upper right) and endurance limit (below).

An interesting detail is presented in Figure 8. It shows the mean value of the four specimens tested at a strain amplitude of 100 µm/m in the 4PBB fatigue test. The blue line represents the AC 32 RA 20, the red line the AC 32 RA 30. The y-axis shows the ratio between the stiffness at the load cycle *n* (S_N) and the initial stiffness $S_{100,mix}$. Thus different tests with varying initial stiffness can be compared. The fatigue criterion is also shown in the diagram as the dotted black line. The x-axis shows the number of load cycles. While the mix with the lower portion of reclaimed asphalt (blue) is still in a state with a quasi-linear slope of the curve when the fatigue criterion is reached, the other mix (red) is already in a state with a strong decline of the stiffness when approaching the fatigue criterion. This shows that the material already exhibits macro-cracks [12] and is far beyond of what a fatigue criterion from a lab test should be: the beginning of fatigue with micro-cracks in the quasi-linear part of the curve.
With the increase of road construction with recycling asphalt it is an urgent matter to start a discussion whether the classic fatigue criterion used in the European standard [5] at the present time meets the demands of new developments in road construction. From the data of this case study it is strongly recommended to find alternatives, e.g. a fatigue criterion based on the energy approach [13, 14].

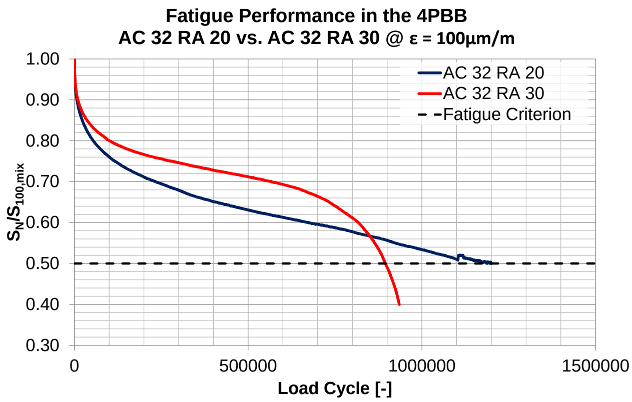


Figure 8 : Behavior of both base layers in the fatigue test at a strain amplitude 100 µm/m.

4. CONCLUSIONS

An extensive case study was carried out for which a trial section was built consisting of surface, binder and base layer. For the binder and base layer HMAs with different percentages of reclaimed asphalt were used. The reclaimed asphalt was added in the mixing plant cold and wet to the pre-heated aggregate since no mixing plant with parallel drums was available within the vicinity of the construction site.
This paper investigates the behavior of the binder material in the high- and low-temperature range. The low-temperature performance was assessed by the thermal stress restrained specimen test (TSRST) to simulate the resistance to low-temperature cracking and the performance at elevated temperatures was tested by means of the triaxial cyclic compression test (TCCT) to analyze the resistance to permanent deformation. The base layer material was tested in the 4-point-bending beam test (4PBB) to investigate the stiffness and especially the fatigue performance.

From the results, the following findings and recommendations can be given:

- The use of highly modified binder for the binder layer to compensate for the long-term aged binder in the reclaimed asphalt is an efficient method for the short-term performance at low-temperatures and does not seem to affect the rutting resistance at elevated temperatures. In the TSRST the two AC 22 binder mixes with 15% (m/m) and 20 %(m/m) of reclaimed asphalt showed similar crack temperatures and developed less thermal stresses during the cooling phase than the AC 22 binder mix without reclaimed asphalt.

- The creep rate f_c resulting from the TCCT which indicates the deformation behavior at elevated temperatures is similar for all three mixes. No significant difference could be found.
- The dynamic stiffness of the two base layer mixes AC 32 base with 20% (m/m) and 30% (m/m) of reclaimed asphalt is similar in the low frequency range and slightly higher in the high frequency range (+4%) for the AC 32 RA 30. This mix reacts more viscous in the low frequency range (+3° phase lag). However, the stiffness data support the use of paving grade bitumen from a high penetration class (160/220) for compensation since both mixes although clearly different in the content of reclaimed asphalt react similar in term stiffness.
- The long-term behavior of recycling asphalt does not benefit from the addition of a paving grade bitumen 160/220. The base layer mix with higher content of reclaimed asphalt results in a lower endurance limit (ε = 90 µm/m) compared to the mix with lower content of reclaimed asphalt (107 µm/m). This may also be connected to the fact that the recycling asphalt was produced in a conventional mixing plant where the reclaimed asphalt is added wet and cold to the pre-heated aggregate.
- It was also found that the present fatigue criterion in the European standard EN 12697-24 which states that the state of fatigue is reached when the stiffness of the specimen has dropped to half its initial value does not seem to take into account the fatigue behavior of mixes with high contents of reclaimed asphalt. These mixes show a different fatigue behavior: The quasi-linear part of the fatigue curve starts at a much higher level of stiffness and reaches half the initial stiffness in a state where macro-cracks have already developed and the material is approaching the state of failure rapidly. Thus it is recommended to discuss alternative fatigue criterions, e.g. based on the energy approach to meet the demands of road construction with recycling asphalt.
- From the data collected within this study it is also clear that an addition of 30% (m/m) of reclaimed asphalt to a base layer with paving grade bitumen does not guarantee an acceptable fatigue resistance and is not recommended for use. It must be added that this restriction can only be given if the reclaimed asphalt is added to the mix in a conventional mixing plant cold and wet to the pre-heated aggregate. If the mixing process is carried out in a plant with parallel drums other (possibly higher) limits may apply.

REFERENCES

[1] Austrian Standard ON B 3580-2, Bituminous mixtures, Material specifications, Part 2: Asphalt Concrete, Performance based requirements, Rules for the implementation of EN 13108-1, 2010

[2] European Standard EN 12697-46, Bituminous mixtures, Test methods for hot mix asphalt, Part 46: Low temperature cracking and properties by uniaxial tension tests, 2010.

[3] Spiegl, M.: Low-temperature behavior of bituminous materials - assessment of performance behavior by means of laboratory testing and numerical simulation. PhD-Thesis at the Vienna University of Technology, 2007.

[4] European Standard EN 12697-26, Bituminous mixtures, Test methods for hot mix asphalt, Part 26: Stiffness, 2004.

[5] European Standard EN 12697-24, Bituminous mixtures, Test methods for hot mix asphalt, Part 24: Resistance to fatigue, 2004

[6] European Standard EN 12697-25, Bituminous mixtures, Test methods for hot mix asphalt, Part 25: Cyclic compression test, 2005

[7] European Standard EN 14023, Bitumen and bituminous binders, Specification framework for polymer modified bitumens, 2010.

[8] European Standard EN 12591, Bitumen and bituminous binders, Specifications for paving grade bitumens, 2009.

[9] European Standard EN 1426, Bitumen and bituminous binders, Determination of needle penetration, 2007.

[10] European Standard EN 13108-1, Bituminous mixtures, Material specifications, Part 1: Asphalt Concrete, 2006.

[11] European Standard EN 12697-33, Bituminous mixtures, Test methods for hot mix asphalt, Part 33: Specimen prepared by roller compactor, 2007.

[12] Fuessl, J.: Multiscale fracture modeling of bituminous mixtures - from fatigue behavior to ultimate strength properties of asphalt concrete. PhD-Thesis at the Vienna University of Technology, 2010.

[13] Shen, S. and Carpenter, S.H.: Application of the Dissipated Energy Concept in Fatigue Endurance Limit Testing. Journal of the Transport Research Board, Volume 1929/2005, pp. 165-173, 2006.

[14] Roque, R.; Birgisson, B.; Drakos, C. and Dietrich, B.: Development and field evaluation of energy-based criteria for top-down cracking performance of hot mix asphalt. Journal of the Association of Asphalt Pavement Technologists, Volume 73, 2004.