Impact of Field Ageing on Low-Temperature Performance of Binder and Hot Mix Asphalt

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ABSTRACT

To monitor field ageing of bitumen and hot mix asphalt closely, a test field has been constructed in September 2012. The test field consists of two mixes, an asphalt concrete with 11 mm maximum nominal aggregate size (AC 11) with an unmodified 70/100 pen and an SBS-modified PmB 45/80-65. Pavement temperature and weather conditions are recorded continuously. First HMA samples were taken from the test field after 6 and 12 months. The low-temperature performance by cooling (TSRST) and tensile strength testing (UTST), as well as the viscoelastic behavior (dynamic modulus |E*| and phase lag φ) with temperature and frequency sweep are obtained. Results from unaged and field-aged specimens are compared. In addition, bitumen was extracted and recovered from HMA slabs to investigate field ageing. Penetration, Softening Point Ring & Ball, DSR tests with temperature and frequency sweep and BBR tests were run on fresh binder, lab-aged and field-aged samples.

This paper analyzes first data on the low-temperature behavior of binder and mixes. Significant differences start to occur after 12 months of field ageing on mix and binder level. A slight but non-significant adverse impact of double heating of the mix was found on the low-temperature behavior. Direct comparison of unmodified and SBS-modified mixes shows a 90% higher resistance to thermal cracking for the modified mix.

Keywords: field ageing, hot mix asphalt, performance based testing, low-temperature performance, master curve

1. INTRODUCTION

Bitumen as an organic material is subject to ageing due to thermal and atmospheric influences. When bitumen is used as a binder for hot mix asphalt as a paving material, its ageing can be divided into (a) short-term ageing during the mixing, transportation and compaction at the construction site and (b) long-term ageing in the field [1]. While short-term ageing is mostly affected by high temperatures during mix production within several minutes to hours, long-term ageing is a slow process taking several years. Ageing of bitumen leads to increased stiffness and brittleness of the material and has a major impact on the durability of pavement structures [2, 3]. Especially the low-temperature resistance to thermal cracking is reduced by bitumen ageing [4, 5].

While the process of short-term ageing of bitumen is well explained in literature by loss of volatiles and oxidation due to high temperatures and a large specific surface of the material while mixing [6], the mechanisms of long-term ageing are still subject to scientific discussion [7-10]. The chemical mechanisms are not thoroughly understood yet and the influence of different possible ageing agents available in the atmosphere (e.g. oxygen, UV radiation, ozone, aqueous solutions) are not clear [11, 12].

Analogue uncertainties can be stated for lab methods to simulate ageing of bitumen and mixes. While the rolling thin film oven test (RTFOT) is commonly used and seen as a capable tool to realistically simulate short-term ageing of bitumen, the pressure ageing vessel (PAV) is also commonly used, but the question whether it simulates 1 year, 3 years or 5 to 10 years of field ageing has not been answered clearly [13-16]. Or rather, it depends strongly on bitumen, mix and location of the field ageing whether the PAV represents several months or several years of field aging. When it comes to methods to simulate ageing of HMA in the lab, various methods have been developed [17-20]. In all of them HMA specimens are stored at significantly higher temperatures than in the field to accelerate ageing. It is questionable from a chemical point of view whether the processes activated at elevated temperatures are the same as the processes occurring in field ageing.

Thus, a detailed investigation and long-term study of field ageing of HMA and bitumen is necessary to increase knowledge on the chemical processes and mechanical changes in binder and mix during field ageing, understand ageing mechanisms and improve existing methods to simulate long-term ageing of binder and mixes.

2. OBJECTIVES AND APPROACH

Since there is only a minor number of studies monitoring field ageing of bitumen and asphalt mixes over an extended period of time with short intervals between testing, the following objectives are aimed for in the on-going study of a test field laid in September 2012:

- Investigate the change in performance of binders and asphalt mixes due to field ageing versus time and depth (distance to the pavement surface)
- Link changes in the performance of bitumen due to ageing to changes in the performance of asphalt mixes
- Analyze the differences in ageing of unmodified and polymer-modified (styrene-butadiene-styrene SBS) binders
- Understand ageing mechanisms better by combining mechanical and chemical testing as well as multi-scale modeling
- Analyze the effect of winter maintenance (de-icing by applying NaCl) on ageing
- Employ results of the comprehensive investigations to optimize methods to simulate short- and long-term field ageing of binder and asphalt mixes in the lab

To achieve these goals, the following approach is taken:

- Build a test field consisting of HMA slabs made from unmodified and SBS-modified binder.
- Install a weather station to monitor the most important meteorological data and thermal couples in various depths within the HMA slabs to monitor pavement temperature.

- Take slabs from the test field at predefined dates after construction. Cut and core HMA specimens from the slab to investigate mix performance. Extract binder from the mix to investigate binder performance by means of mechanical and chemical analysis.

This paper discusses first analyses on the effect of field ageing on the low-temperature performance of HMA with unmodified and SBS-modified binder, as well as the extracted binders themselves after 6 and 12 months of field ageing.

3. MATERIALS AND TEST PROGRAM

3.1 Materials

For the test field, two binders were used: An unmodified 70/100 pen (PG 58-22) and an SBS-modified PmB 45/80-65 (PG 76-22). To ensure comparability of the binders, the 70/100 pen was the source for producing the PmB. The main characteristics of both binders are listed in TABLE 1.

TABLE 1 Main Characteristics (Mean Values) of Binders

Parameter	70/100 pen	PmB 45/80-65
Penetration [1/10 mm]	90.9	66.7
Softening Point Ring & Ball [°C]	46.7	70.4
SHRP PG [°C]	58-22	76-22

An asphalt concrete with a maximum nominal aggregate size of 11 mm (AC 11) was used for the test field. The coarse aggregate used for the mix is a porphyrite, the filler is powdered limestone. The binder content was set to 5.4 % by mass with a target void content of 7.0 % by volume. The maximum density of the AC 11 70/100 was determined to be 2.594 kg/m³ and 2.566 kg/m³ for the AC 11 PmB 45/80-65. The grading curve is shown in FIGURE 1.

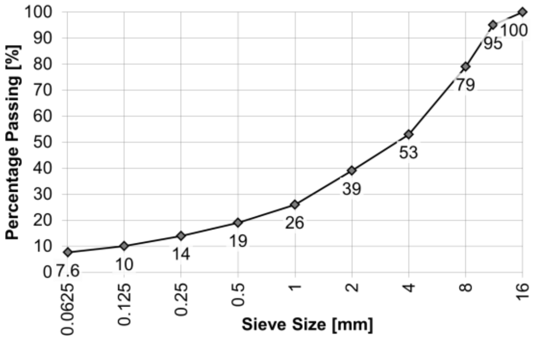


FIGURE 1 Grading Curve of AC 11

The mix for the test field was prepared in a commercial mixing plant with mixing temperatures of 160°C for the unmodified mix and 185°C for the modified mix, filled into bags of 25 kg and stored in the lab. In addition, samples of the fresh binders and the aggregates used for the mix were also taken and stored in the lab.

3.2 Preparation of HMA Slabs for the Test Field

The test field consists of 72 single HMA slabs compacted in the lab. The reason for using lab compacted slabs instead of one uniformly compacted pavement prepared by a commercial compactor is mainly because a substantial amount (30 to 130 kg) of asphalt mix is taken every 3 to 6 months from the test field to monitor field ageing closely. Removing slabs from the test field is more efficient than taking up to 32 cores every 3 months.

For the preparation of the slabs, the plant-produced mix was pre-heated for 5 hours and compacted in a roller compactor according to EN 12697-33 [21] to slabs with dimensions 50x26x10 cm. The radius of the roller segment of 55 cm corresponds to the size of standard roller compactors used in the field. The slabs were compacted with one lift.

3.3 Test Field

The test field is located in Vienna, Austria (coordinates: 48.189866, 16.394048). The field can be divided into four parts: one section consists of AC 11 70/100, the other section of AC 11 PmB 45/80-65. In each of these sections, winter maintenance is simulated on one subsection by removing snow and spraying a 20 % by mass NaCl brine on as needed. The other subsection is only taken care of in winter by removing any snow from the surface. An aerial view of the test field is depicted in FIGURE 2a. FIGURE 2b shows a cross section of the test field. The slabs were laid on a drainage with a slope of 3 %. The 1.0 cm joints between the slabs were filled with fine aggregates 0/2 mm and the joints were sealed by using hard bitumen 90/10 (5 - 15 1/10 mm penetration; 85°C - 95°C softening point). Two slabs were instrumented with thermo couples in various pavement depths to monitor surface and pavement temperatures. One slab is situated in the section with winter maintenance, the other one in the section without winter maintenance. FIGURE 2c shows a profile of a slab with the position of the five thermo couples: One was situated in a groove on top of the slab and sealed with bitumen, the other four were put in depths of 1.25 cm, 3.75 cm, 6.25 cm and 8.75 cm. In addition a weather station in the vicinity of the test field records air temperature, humidity, precipitation, wind speed and direction and global solar radiation. All instruments record data with a rate of 6 values per hour (every 10 min).

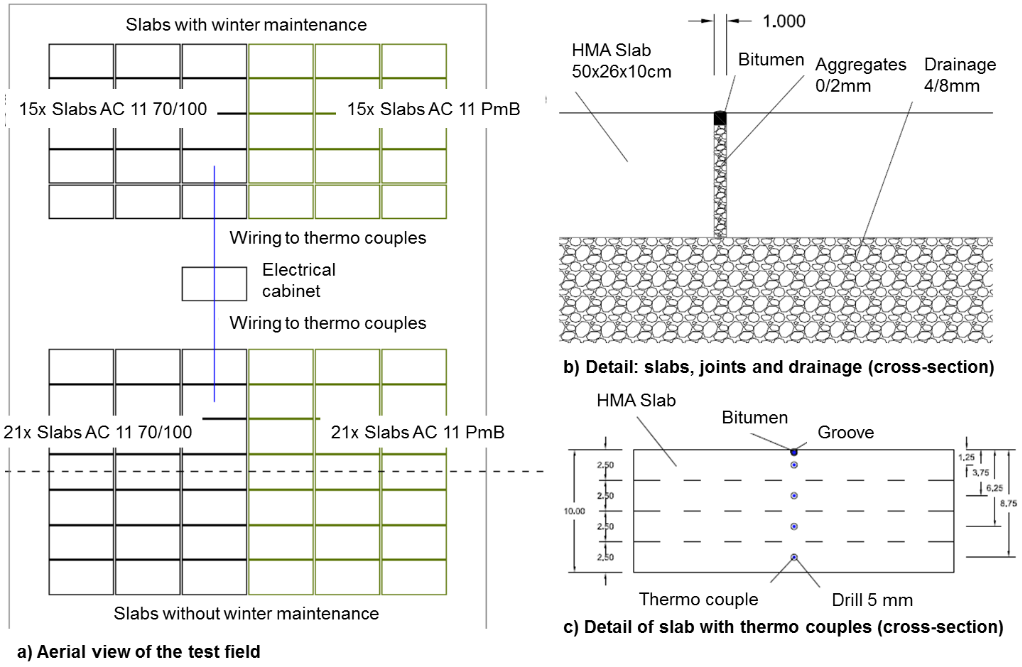
As it can be seen from FIGURE 3 the test field is located on a non-trafficked part of the laboratory side. This means that the HMA is only exposed to loading due to weather and climate and no traffic loading or emissions from traffic are considered. Since the common understanding [6, 22] is that mainly climatic conditions (temperature, humidity, UV radiation) are responsible for bitumen ageing in the field, the lack of traffic on the test field is a minor setback. All slabs for the test field were produced in the lab in August and early September 2012 and the test field was laid on September 18th 2012. By June 2014 the test field will have been aged for 21 months.

Since no significant difference between slabs with and without winter maintenance can be found at this time, only data from slabs without simulated winter maintenance are taken into consideration.

3.4 Specimen Preparation for Testing

HMA specimens and bitumen samples are extracted from the test field at predefined dates after construction to monitor field ageing closely. For testing of the mix characteristics, the slabs with a height of 10 cm are cut into two halves to obtain HMA specimens from the upper and lower layer. Specimens are then obtained by coring and cutting, the dimension of the specimens as well as the bulk density is determined according to EN 12697-6 [23] and the void content according to EN 12697-8 [24].

For bitumen testing the slabs taken from the test field are cut into four layers with 2.5 cm each. For each layer, bitumen is extracted according to EN 12697-3 [32] with tetrachloroethylene (C_2Cl_4) as a solvent. The solvent-bitumen solution is distilled according to EN 12697-3 to recover the bitumen. The residual solvent in the recovered bitumen is determined by gravimetric analysis. Samples with a residual solvent content of larger than 0.5 % by mass are discarded. By extracting one bitumen sample for each layer, ageing can not only be monitored versus time but also versus depth, i.e. distance to the surface.



a) Aerial view of the test field

b) Detail: slabs, joints and drainage (cross-section)

c) Detail of slab with thermo couples (cross-section)

FIGURE 2 Details of the Test Field: a) Aerial view, b) Detail of Slabs, Joints and Drainage, c) Detail of Instrumentation

FIGURE 3 Photo of the Test Field with Winter Maintenance Section (left), Electric Cabinet (center) and Section without Winter Maintenance (right)

3.5 Test Program

Testing of HMA specimens consists of the following test methods:

- Thermal stress restrained specimen tests (TSRST) according to EN 12697-46 [25]. TSRST are carried out from an initial temperature of +10°C with a cooling rate of 10°C/h on prismatic specimens (50x50x200 mm). Results of TSRST are the cryogenic stress versus temperature $\sigma_{crack}(\tau)$ and the cracking temperature T_{crack} by triple determination.
- Uniaxial tensile stress tests (UTST) according to EN 12697-46. UTST are run at temperatures of +5°C, -10°C and -25°C with a strain rate of 112.5 µstrain/sec. The tensile strength against temperature $\beta_t(\tau)$ is obtained from the test.
- The difference between cryogenic stress from TSRST and tensile strength from UTST gives the tensile strength reserve $\Delta\beta_t(\tau)$. It correlates to the stress that can be applied on a pavement by traffic loading in addition to the thermal stress at a certain temperature τ before failure. [26]
- Direct tension/compression tests (DTC) are run at temperatures of -20°C, 0°C and +20°C and frequencies ranging from 0.1 Hz to 20 Hz according to EN 12697-26 [27]. From test data the norm of the complex modulus or dynamic modulus $|E^*|$ and the phase angle φ against temperature and frequency can be determined [28].

TABLE 2 gives an overview of the test program on HMA specimens. Since slabs for the test field were compacted in the lab from plant-produced mix (C_L000), the mix was heated twice for compaction. To compare the impact of double heating on short-term ageing, slabs were also produced from a lab-produced mix where fresh binder and aggregates were only heated once for compaction (C_F000). For slabs from the test field two series of specimens were obtained: one series from the upper 5 cm (upper layer UL) and one series from the lower 5 cm (lower layer LL). Up to now specimens from the lab-mixed slab, the plant-mixed slab and from the test field after 6 and 12 months have been tested. The paper contains results from low-temperature tests (TSRST, UTST).

TABLE 2 Test Program for HMA Specimens (x = test completed, (x) = test planned)

Source	Code	TSRST	UTST	DTC
slab from lab-mix slab	C_L000	x	x	x
slab from plant-mix slab	C_F000	x	x	x
slab from test field after 6 months	C_F006	x		x
after 12 months	C_F012	x	x	x
after 18 months	C_F018	(x)		(x)
after 24 months	C_F024	(x)		(x)
after 36 months	C_F036	(x)	(x)	(x)
after 60 months	C_F060	(x)	(x)	(x)

Bitumen samples recovered from HMA will be subjected to various physico-chemical analytical techniques to supplement mechanical testing with a solid physico-chemical background. This holistic approach will provide the basis for the formulation of a new and enhanced ageing theory for bitumen. For mechanical testing the following methods are employed:

- Needle Penetration at 25°C according to EN 1426 [33]
- Softening Point Ring & Ball according to EN 1427 [34]
- Dynamic Shear Rheometer (DSR) tests with a temperature and frequency sweep according to EN 14770 [35]. At temperatures from -10°C to +30°C tests with the small plate (diameter: 8 mm) and a 2 mm gap are run, from +30°C to +80°C with the large

plate (diameter: 25 mm) and a 1 mm gap. A frequency sweep between 0.1 Hz and 10 Hz is employed.

- Bending Beam Rheometer (BBR) tests according to EN 14771 [36] to assess the low-temperature behavior at -12°C, -18°C and -24°C

TABLE 3 shows the test program for the binder samples. In addition to samples extracted from the test field, samples of the fresh binder (A), RTFOT-aged (B_LRTF) (according to EN 12607-1 [37]) and RTFOT+PAV-aged (C_LPAV) (according to EN 14769 [38]) binder are taken into account to compare lab to field ageing. Also, extracted samples from a lab-mix slab (C_L000), the plant-mix (B_F000) and the plant-mix slab (C_F000) are tested to investigate effects of double heating and compare lab to plant mixing. At this time all samples up to 12 months have been tested. This paper contains results from low-temperature testing (BBR) of the samples.

TABLE 3 Test Program for Binder Samples (x = test completed, (x) = test planned)

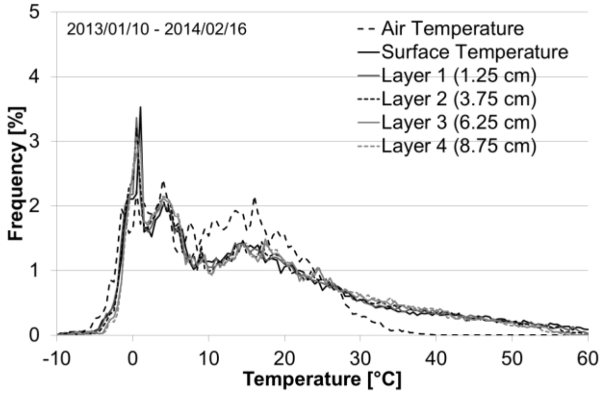
Source	Code	Pen	R&B	DSR	BBR
Fresh Binder	A	x	x	x	x
RTFOT-aged	B_LRTF	x	x	x	x
RTFOT+PAV-aged	C_LPAV	x	x	x	x
from lab-mix slab	C_L000	x	x	x	x
from plant-mix	B_F000	x	x	x	x
from plant-mix slab	C_F000	x	x	x	x
from test field 6 m	C_F006	x	x	x	x
from test field 12 m	C_F012	x	x	x	x
from test field 18 m	C_F018	(x)	(x)	(x)	(x)
from test field 24 m	C_F024		(x)	(x)	
from test field 36 m	C_F036	(x)	(x)	(x)	(x)
from test field 60 m	C_F060	(x)	(x)	(x)	(x)

4. RESULTS AND DISCUSSION

4.1 Weather Data and Pavement Temperatures

Since field ageing is crucially dependent on the climatic conditions of the test site, FIGURE 4 and FIGURE 5 give details about the weather conditions from January 2013 to February 2014. The test field was constructed in September 2012, which is also the starting point for monitoring weather and pavement temperature. Due to malfunction of the data logger for the instrumentation, data is only available from the beginning of January 2013 on. FIGURE 4 shows a diagram with the temperature distribution of air, surface and pavement temperatures in various depths. On the right side in FIGURE 4, a table shows quantiles for the temperature distribution, as well as the absolute maximum and minimum of temperatures and the frequency by which certain temperatures were exceeded and undercut. The air temperature was below 0°C at around 12% of the time, and around 10% at the surface and in layer 1. Due to the thermal capacity of the material and the constant thermal flow from the subgrade, the frequency of lower temperatures decreases with lower layers to around 8% in layer 4. Although the air temperature did not exceed 40°C, the surface temperature of the test field was higher than 40°C in 9% of the time, and even exceeded 50°C (3%) and 60°C (0.4%). Even in layer 4, around 9 cm from the surface, the maximum temperature was 56.8°C.

FIGURE 5 shows the distribution of humidity (a) and precipitation [mm/24 h] (b) at the test site. In around 50% of the time the humidity is between 60 % and 80 %. No precipitation was recorded in 77% of the days, and a sum of 234 mm of rain was recorded between January 2013 and February 2014.



Quantile [%]	Temperature [°C] Air Temperature	Surface Temperature	Layer 1 (1.25 cm)	Layer 2 (3.75 cm)	Layer 3 (6.25 cm)	Layer 4 (8.75 cm)
min	-9.6	-10.0	-9.8	-9.3	-8.7	-8.4
1	-4.6	-3.5	-3.4	-3.0	-2.5	-2.2
5	-2.0	-1.2	-1.3	-1.1	-0.8	-0.6
50	10.9	13.0	13.0	13.1	13.3	13.3
95	26.6	46.7	45.0	43.4	42.6	41.9
99	32.0	57.2	55.0	53.1	51.8	50.9
max	39.0	64.1	61.7	59.5	58.0	56.8

Temperature [°C]	Frequency above given temperature [%]					
60	0.0	0.4	0.1	0.0	0.0	0.0
50	0.0	3.4	2.7	2.0	1.5	1.2
40	0.0	8.9	8.1	7.3	6.7	6.1
30	1.9	16.7	16.3	16.0	16.0	15.8
Temperature [°C]	**Frequency below given temperature [%]**					
0	11.8	9.8	10.4	9.9	8.5	8.0
-5	0.8	0.4	0.3	0.3	0.3	0.2
-10	0.0	0.0	0.0	0.0	0.0	0.0

FIGURE 4 Temperature Distribution for Air, Surface and Pavement Temperatures on the Test Field from 2013/01/10 to 2014/02/16

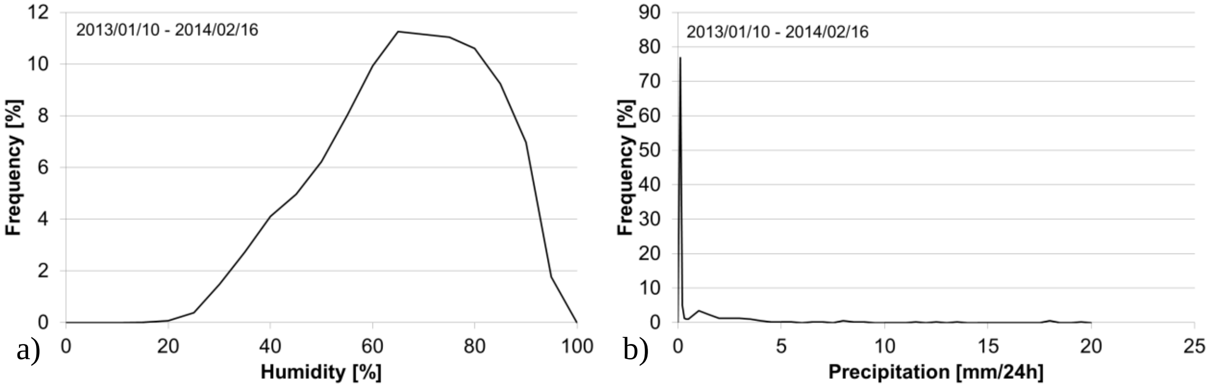


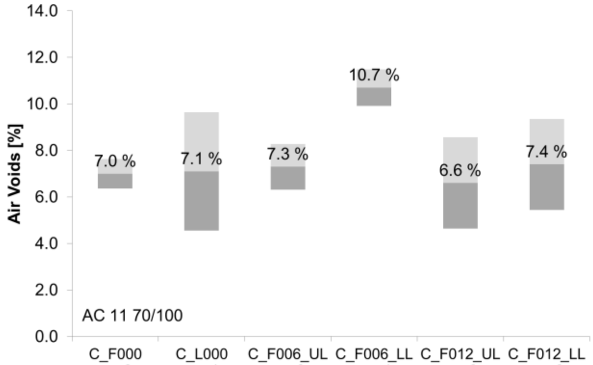
FIGURE 5 Humidity (a) and Precipitation (b) Distribution at the Test Field from 2013/01/10 to 2014/02/16

4.2 Tests on HMA Specimens

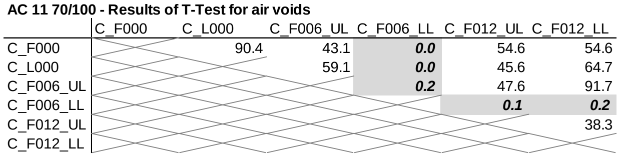
4.2.1 Cooling Tests (TSRST)

According to the test program for HMA (TABLE 2), specimens were tested in TSRST before ageing (C_F000), after 6 months of ageing (C_F006) (after the first winter) and after the first year of ageing (C_F012). Since all slabs for field ageing were heated twice for mixing in the plant and then for compaction in the lab, additional slabs with identical mix design were produced completely in the lab by mixing fresh binder and aggregates in the lab and compacting it subsequently in the roller compacter. Thus, the binder was only heated once for the lab-mixed slab (C_L000). Differences between non-field aged plant-mixed slabs (C_F000) and non-field aged lab-mixed slabs (C_L000) show the impact of double heating on the performance of the HMA.

FIGURE 6a shows the air void distribution of AC 11 70/100 specimens tested in TSRST. The value given in the diagram is the mean value (MV), the bars show the 95% confidence interval based on the standard deviation (SD). FIGURE 6b shows the results of the statistical analysis of air void distribution. The numbers in the table give the significance according to the t-test [29]. The significance level was set to 5%. For values below 5% it is considered that the air void content differs significantly for the compared set of specimens. As it can be seen from FIGURE 6b, the specimens after 6 months of field ageing from the lower layer (C_F006_LL) are significantly different from all other specimens. This is in accordance with the data shown in FIGURE 6a. Thus, any differences in results from C_F006_LL may be due to differences in the volumetric composition of the specimens and will not be taken into consideration.



a)



b)

AC 11 70/100 - Results of T-Test for air voids

	C_F000	C_L000	C_F006_UL	C_F006_LL	C_F012_UL	C_F012_LL
C_F000		90.4	43.1	***0.0***	54.6	54.6
C_L000			59.1	***0.0***	45.6	64.7
C_F006_UL				***0.2***	47.6	91.7
C_F006_LL					***0.1***	***0.2***
C_F012_UL						38.3
C_F012_LL						

FIGURE 6 Air Void Distribution of AC 11 70/100 Specimens for TSRST testing (a) and Statistical Analysis of significant Differences in Air Voids (b)

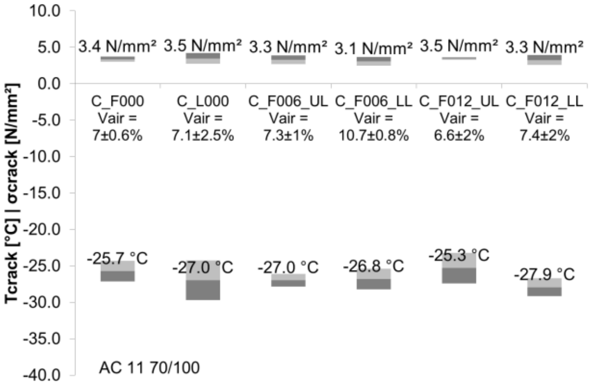


FIGURE 7 Results of TSRST of AC 11 70/100 for non-field aged Slabs from Plant Mix (C_F000) and from Lab Mix (C_L000) and after 6 and 12 Months of Field Ageing for Upper Layer (C_F006_UL, C_F012_UL) and Lower Layer (C_F006_LL, C_F012_LL)

FIGURE 7 gives the results of TSRST for AC 11 70/100 specimens. The diagram shows the temperature at which the specimens fail due to cryogenic stress (T_{crack}) and the stress at cracking (σ_{crack}). Again, the given values represent the MV and the bars indicate the 95% confidence interval. As expected, the lab-mix (C_L000) produced better low-temperature behaviour than the plant-mix (C_F000) in terms of a 1.3°C lower T_{crack}. The results from 6-month field-aged specimens do not show large differences to the non-aged specimens. After 12 months of field ageing, the upper layer (C_F012_UL) seems to be affected stronger by ageing than the lower layer (C_F012_LL). The crack temperature on the UL is 2.6°C higher than on the LL. Interestingly enough, most of the field-aged specimens produce better low-temperature behaviour than the non-aged specimens from the plant-mix.

TABLE 4 presents results for the statistical analysis of TSRST results of AC 11 70/100. Again a significance level for the t-test of 5% is taken into consideration. TABLE 4a gives data for T_{crack}, TABLE 4b for σ_{crack}. The only significant difference can be found for T_{crack} between 12-month field aged specimens at the lower layer (C_F012_LL) and non-aged specimens (C_F000), as well as at the upper layer (C_F012_UL). It can be concluded from these results, that ageing starts to affect the low-temperature behavior significantly after a year of ageing. At this time, significant differences in terms of ageing time and distance of the material to the surface can be found. No significant differences were detected for σ_{crack}.

TABLE 4 Statistical Analysis of Results of TSRST of AC 11 70/100 for T_{crack} (a) and σ_{crack} (b) - Statistically significant differences marked in grey (significance level: 5%)

AC 11 70/100 - Results of T-Test for T_crack

	C_F000	C_L000	C_F006_UL	C_F006_LL	C_F012_UL	C_F012_LL
C_F000		22.4	6.4	11.4	59.1	***1.7***
C_L000			99.8	82.3	14.5	32.3
C_F006_UL				72.0	6.7	9.5
C_F006_LL					7.7	8.1
C_F012_UL						***2.1***
C_F012_LL						

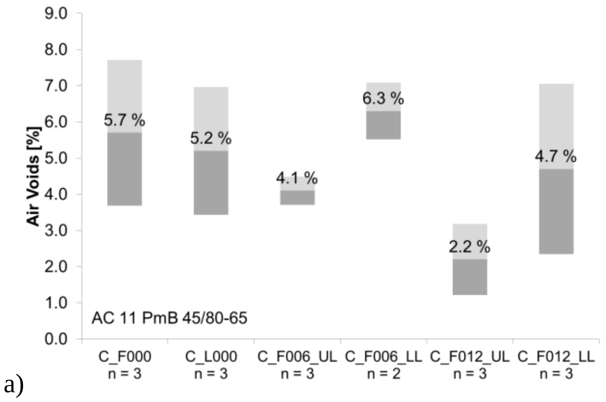
a)

AC 11 70/100 - Results of T-Test for sig_crack

	C_F000	C_L000	C_F006_UL	C_F006_LL	C_F012_UL	C_F012_LL
C_F000		68.1	73.8	18.2	49.8	64.3
C_L000			53.7	14.2	92.7	47.2
C_F006_UL				35.9	43.2	88.3
C_F006_LL					8.3	47.8
C_F012_UL						39.6
C_F012_LL						

b)

The same analysis as for the unmodified mix AC 11 70/100 is shown in the following for AC 11 PmB 45/80-65. FIGURE 8 shows data for the air void distribution of specimens for TSRST testing. As it can be seen from FIGURE 8b, the specimens after 12 months of field ageing from the upper layer (C_F012_UL) show significantly different air void distribution compared to all other specimens. Any differences found for these specimens will not be considered as significant since an influence of the air void content is possible.



AC 11 PmB 45/80-65 - Results of T-Test for air voids

	C_F000	C_L000	C_F006_UL	C_F006_LL	C_F012_UL	C_F012_LL
C_F000		56.0	5.7	50.5	***0.6***	33.4
C_L000			14.3	26.0	***1.0***	61.3
C_F006_UL				5.2	***3.3***	52.7
C_F006_LL					***0.2***	18.0
C_F012_UL						***2.9***
C_F012_LL						

b)

FIGURE 8 Air Void Distribution of AC 11 PmB 45/80-65 Specimens for TSRST testing (a) and Statistical Analysis of significant Differences in Air Voids (b)

FIGURE 9 shows results for the TSRST at specimens from the modified mix AC 11 PmB 45/80-65. Again, a small difference between lab- and plant-mix can be detected in terms of T_{crack}. The lab mix results in a 0.3°C lower crack temperature. All field-aged specimens show similar low-temperature behaviour compared to the non-aged specimens from the plant mix.

When the results for the polymer-modified mix (FIGURE 9) are compared to the results of the non-modified mix (FIGURE 7), the positive effect of the SBS modification on the low temperature behaviour becomes obvious. Since the SBS-modified binder can bear higher tensile stresses, the cracking temperature of the modified mix is about 8°C lower than of the non-modified mix.

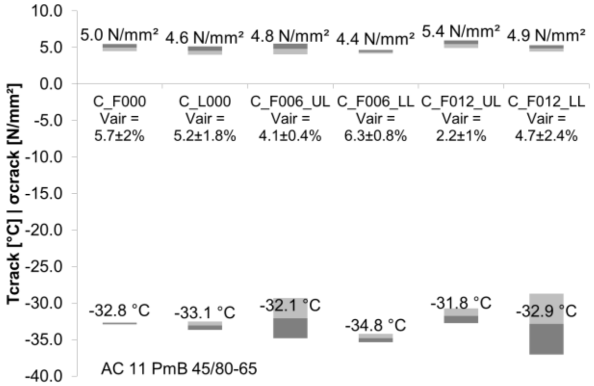


FIGURE 9 Results of TSRST of AC 11 PmB 45/80-65 for non-field aged Slabs from Plant Mix (C_F000) and from Lab Mix (C_L000) and after 6 and 12 Months of Field Ageing for Upper Layer (C_F006_UL, C_F012_UL) and Lower Layer (C_F006_LL, C_F012_LL)

TABLE 5 provides information on the significance of differences between the mixes for T_{crack} (a) and σ_{crack} (b). The statistically significant differences for 12-months field-aged specimens from the upper layer (C_F012_UL) cannot be taken into account since they also differ in their air-void content significantly from all other mixes. Specimens from the lower layer after 6 months of ageing (C_F006_LL) show a significantly better low-temperature performance than the non-field aged mix. Material that is further away from the surface is therefore not affected from ageing as much as material closer to the surface. The same can be said about the lower layer after 12 months of ageing (C_F012_LL).

TABLE 5 Statistical Analysis of Results of TSRST of AC 11 PmB 45/80-65 for T_{crack} (a) and σ_{crack} (b) - Statistically significant differences marked in grey (significance level: 5%)

AC 11 PmB 45/80-65 - Results of T-Test for T_crack

	C_F000	C_L000	C_F006_UL	C_F006_LL	C_F012_UL	C_F012_LL
C_F000		14.1	43.8	***0.1***	***2.6***	94.3
C_L000			28.8	***0.7***	***1.7***	86.6
C_F006_UL				8.2	73.6	61.8
C_F006_LL					***0.5***	30.9
C_F012_UL						42.9
C_F012_LL						

a)

AC 11 PmB 45/80-65 - Results of T-Test for sig_crack

	C_F000	C_L000	C_F006_UL	C_F006_LL	C_F012_UL	C_F012_LL
C_F000		13.4	55.1	6.1	8.9	65.1
C_L000			42.9	49.6	***1.7***	19.9
C_F006_UL				25.1	7.3	77.6
C_F006_LL					***1.5***	6.8
C_F012_UL						***4.6***
C_F012_LL						

b)

4.2.2 Combined Analysis of Cooling Tests (TSRST) and Uniaxial Tensile Strength Tests (UTST)

To explain the concept of combined analysis of TSRST and UTST, FIGURE 10 shows results of both tests for the plant-mixed (C_F000) AC 11 70/100 (a) and AC 11 PmB 45/80-65 (b). The diagrams contain data of the three single TSRST (light grey) and the MV of the TSRST (long dashed black line). The TSRST results give the thermally induced (cryogenic) stress versus temperature. In addition the single results (tensile strength) from UTST at different temperatures are shown by diamonds. The UTST results versus temperature are approximated by a quadratic function. The difference between UTST (tensile strength) and TSRST (cryogenic stress) is the tensile strength reserve ($\Delta\beta_t$), which is given by the small dashed black line. The higher the reserve is, the more stress additional to thermal stress can be applied to the pavement (e.g. by traffic) before it fails due to cracking. The maximum strength reserve for the AC 11 70/100 occurs at -8.7°C and 3.0 N/mm² and at -13.2°C and 5.2 N/mm² for the AC 11 PmB 45/80-65 respectively. Thus, the modified mix shows a more than 70% higher maximum strength reserve. As another parameter to assess the resistance to thermal cracking the area between the x-axis and the tensile strength reserve curve from 0°C to the interception of the tensile strength reserve curve with the x-axis is introduced. This sums up the tensile strength reserve for the critical temperature range (< 0°C) to one single value. This Cumulative Tensile Strength Reserve (CTSR) is defined as follows:

$$CTSR = \int_{\tau=I_{\Delta\beta t|x}}^{0°C} \Delta\beta_t \, d\tau = \int_{\tau=I_{\Delta\beta t|x}}^{0°C} \left(\beta_t(\tau) - \sigma_{cry}(\tau)\right) d\tau \tag{1}$$

where

$I_{\Delta\beta t|x}$	left interception of $\Delta\beta_t$ with the x-axis ($\Delta\beta_t$=0) in °C
$\beta_t(\tau)$	tensile strength from UTST as a function of temperature τ in N/mm²
$\sigma_{cry}(\tau)$	cryogenic stress from TSRST as a function of temperature τ in N/mm².

For the unmodified mix, CTSR comes to 59.8 N/mm²*°C and to 113.7 N/mm²*°C for the modified mix, which means a 90% higher resistance to thermal cracking for the modified mix. Since the mix design of both materials is the same, the higher resistance is due to the SBS-modification of the bitumen.

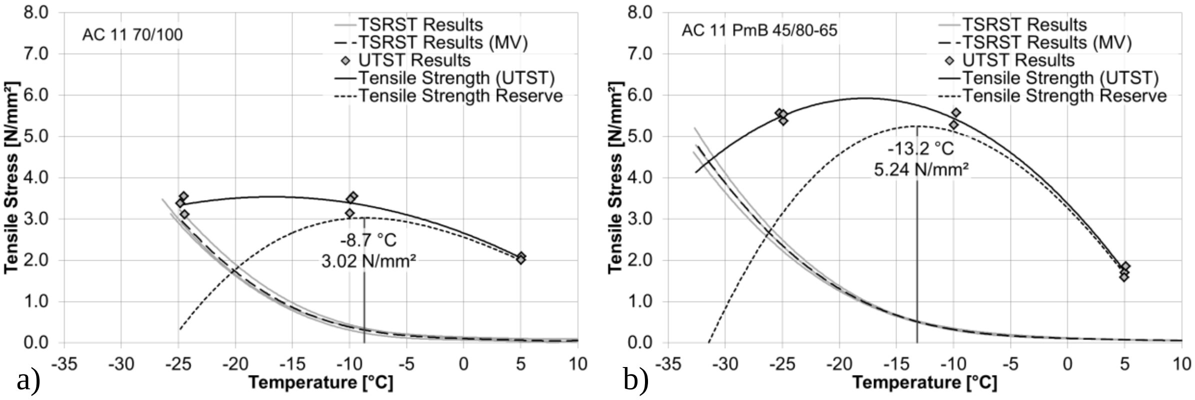


FIGURE 10 Combined Results of TSRST and UTST for non-field aged (C_F000) AC 11 70/100 (a) and AC 11 PmB 45/80-65 (b)

UTST were also carried out on specimens from the lab-mix (C_L000) to see differences between lab- and plant-mix (C_F000). In addition, UTST were run on specimens from slabs after 12 months of field ageing for upper and lower layers. FIGURE 11 presents results for the unmodified AC 11 70/100. Maximum tensile strength reserve and the temperature at which this maximum strength occurs are given in FIGURE 11a. The lab-mix indicates a 27% higher strength reserve at a 2.2°C lower temperature than the unaged plant-mix. Both values show that the low-temperature behavior is more favorable for the lab-mix. The results after 12 months of field ageing show only slight changes, the maximum strength reserve is around 10% higher for upper and lower layers compared to the unaged plant-mix.

FIGURE 11b compares the CTSR. Results are analogue to the maximum strength reserve. The lab-mix shows 31% better results than the plant mix. The 12-month field-aged specimens have a 10% higher CTSR.

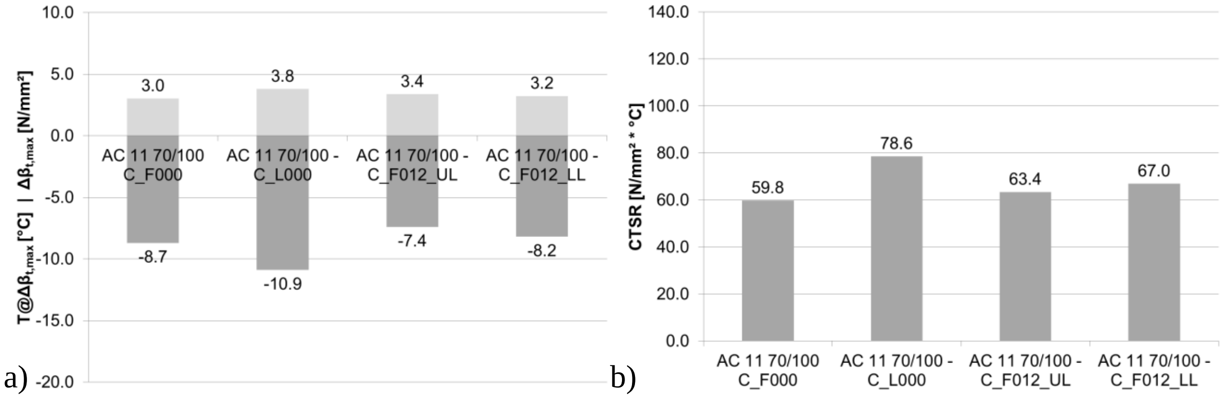


FIGURE 11 Combined Results of TSRST and UTST of AC 11 70/100 for non-field aged Slabs from Plant Mix (C_F000) and Lab Mix (C_L000) and after 12 Months of Field Ageing for Upper Layer (C_F012_UL) and Lower Layer (C_F012_LL)

FIGURE 12 shows the combined results of TSRST and UTST for the SBS-modified AC 11 PmB 45/80-65. The lab-mix shows a slightly better (+13%) performance in terms of maximum strength reserve (FIGURE 12a) than the plant-mix. The 12-month field aged samples show a similar or slightly better performance than the non-aged mix as well. In terms of the CTSR (FIGURE 12b), again, lab-mix and field-aged plant-mix show better results than the non-aged plant mix.

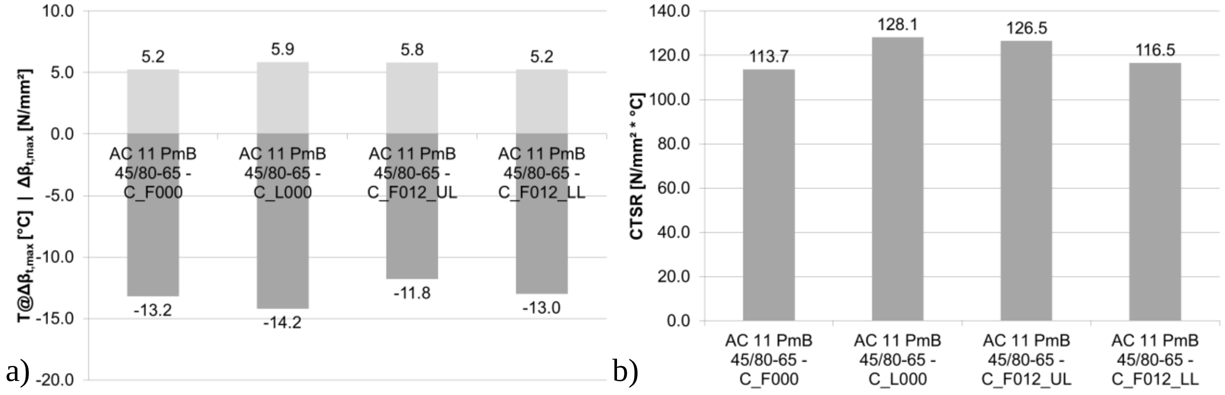


FIGURE 12 Combined Results of TSRST and UTST of AC 11 PmB 45/80-65 for non-field aged Slabs from Plant Mix (C_F000) and Lab Mix (C_L000) and after 12 Months of Field Ageing for Upper Layer (C_F012_UL) and Lower Layer (C_F012_LL)

4.3 Tests on Binder Samples

To compare performance of the mixes to the performance of the binders, exact lower PGs were derived from bending beam rheometer (BBR) testing according to the SHRP procedure. Therefore, the stiffness and the m-value of the binder were investigated after 60 s of testing versus test temperature. The temperature where the stiffness exceeds 300 MPa and the m-value falls below 0.3 was determined. The higher of both temperature values is taken to derive the lower PG by subtracting 10°C from the determined temperature value. The results are given in FIGURE 13a for the non-modified 70/100 and in FIGURE 13b for the SBS-modified

PmB 45/80-65. The left three bars show the lower PG for the fresh, the RTFOT and the RTFOT+PAV aged binder, the middle four bars for the 6- and 12-month field-aged binders and the right three bars for binder samples extracted from different mix sources to compare lab- versus plant-mix. The results for the fresh and lab-aged samples are given as a reference.

When the non-aged binder from the plant mix (C_F000) is compared to the field-aged samples, it can be seen from both binder types, that the field-aged sample show only slightly worse lower PGs. In any case they cannot be seen as significant showing, that the first year of field ageing does not seem to have a crucial impact on the binder performance. Also, the differences between upper and lower layers of field aged samples do not differ strongly.

Different from the mix performance, where the benefit from SBS modification reflected in better low-temperature behavior, this cannot be stated for the binder performance to the same extent. In terms of lower PG, the SBS-modified binder results in only around 5% better values than the non-modified binder.

A better low-temperature binder performance can be found for the binder extracted from the once heated lab mix compared to binder extracted from the double heated plant mix for the non-modified 70/100 (FIGURE 13a) where the lower PG is 2.3°C lower, as well as for the SBS-modified PmB 45/80-65 with a 1.6°C lower lower PG.

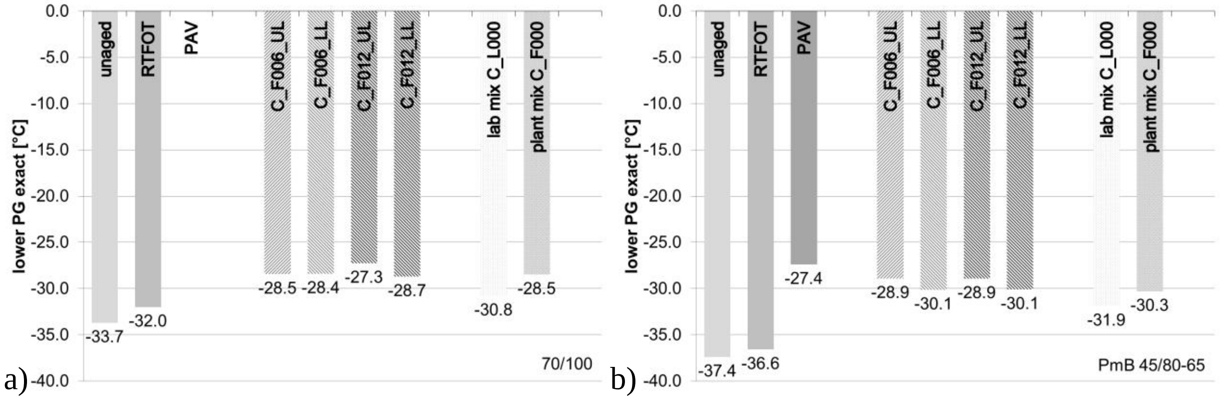


FIGURE 13 Exact Lower PGs derived from BBR testing of binder samples from non-modified mix (AC 11 70/100) (a) and SBS-modified mix (AC 11 PmB 45/80-65) (b)

5. SUMMARY AND OUTLOOK

This paper contains first investigations on a test field to monitor field ageing of bitumen and HMA. The test field consists of 72 slabs (50x26x10 cm) from plant-mixed, lab-compacted HMA. Thermo couples and a weather station monitor pavement temperatures in various depths and most important climatic parameters. Two mixes (AC 11) are investigated: One mix is made from unmodified bitumen 70/100 pen, the other mix from PmB 45/80-65. The test field was constructed in September 2012. Thus, the material will have been aged for 21 months in June 2014. The focus of this paper is the low-temperature performance of field-aged mix and extracted binder after the first 12 months of field ageing in terms of cooling tests (TSRST) and tensile strength tests (UTST) for the mix and BBR tests for the binders.

All slabs for the test field were heated twice: once in the plant for mixing and another time in the lab for compacting (C_F000). To analyze the impact of double heating on ageing, slabs with lab-mixing and -compaction were produced for which the mix was only heated once (C_L000):

- Double-heated mixes (C_F000) resulted in a slightly worse low-temperature performance than lab-produced mixes made in the lab (C_L000). The non-modified mix showed a 1.3°C higher cracking temperature, the SBS-modified mix in a 0.3°C higher T_{crack}. These differences were not found to be significant.
- Combined analysis of TSRST and UTST in terms of maximum tensile strength reserve ($\Delta\beta_{t,max}$) and cumulative tensile strength reserve (CTSR) showed that the non-modified mix performed around 30% and the SBS-modified mix around 13% better when heated only once compared to double heating.
- The lower PG determined from BBR testing on the extracted binder from lab- and plant-mix confirmed the trends seen for the mix. Both binders show a better low-temperature performance, for the non-modified 70/100 the lower PG is 2.3°C lower when lab-mix is compared to plant-mix, for the SBS-modified PmB 45/80-65 it is 1.6°C lower.
- All analyzed data show that the effect of double heating is harsher on the non-modified binder with smaller impact on the SBS-modified binder.

The impact of field-ageing on the mix- and binder-performance was tested after 6 and 12 months of ageing:

- Regarding the cooling tests and resulting cracking temperatures, no significant difference were found after 6 months of field-ageing compared to non-aged samples for both mixes. Also, no difference between upper and lower layer was found after this period of ageing.
- After 12 months of field ageing, the difference in cracking temperature between upper and lower level is significantly different for the non-modified mix, the lower layer showing a 2.6°C lower (i.e. better) T_{crack}. Also, the difference between non-aged and 12-month field-aged lower layer results is significant for the non-modified mix. Interestingly enough, the lower layer after a year of ageing shows a better performance than the non-aged sample.
- Regarding the tensile strength reserve derived from combined analysis of TSRST and UTST only slight changes can be observed between non-aged and field-aged mixes with both binders. Interestingly enough, the low-temperature performance is 6% to 12% better for field-aged mixes. This is contradictory to the common understanding that the low-temperature performance decreases with increasing field ageing. Since the differences are rather small, no certain conclusions can be drawn from the results at this time. A better performance after one year of ageing could be linked to a stress relaxation phenomenon that occurs if the HMA slabs have time to rest after compaction. This is not the case for non-aged samples since they were tested around 5 days after production. Further investigation into this field have to be carried out to analysis this phenomenon in more details.

A direct comparison between non-modified and SBS-modified mix is sensible in this case since the mix design is the same for both mixes and the SBS-modified binder was produced from the same crude oil source as the non-modified binder. The benefit of SBS modification is obvious. The cracking temperature in TSRST is 8°C lower for the SBS-modified mix, the tensile strength reserve is 70% (maximum strength reserve) to 90% (cumulative strength reserve) higher.

Interestingly enough, no significant differences can be seen in binder performance when comparing the lower PG derived from BBR testing.

Further results from direct-tension and compression testing (DTC) on the mix and from traditional testing as well as DSR testing on the binder are still being analyzed. In addition, testing of specimens after 24, 36 and 60 months of field ageing is planned. Together with an in-depth analysis of bitumen samples extracted from the field-aged slabs, which will be analyzed by chemical methods, a better understanding of field aging is expected. Since winter maintenance is simulated on parts of the test field, the influence of de-icing by thawing salt will be investigated more closely in the further course of the study. The outcomes of this long-term study will help to optimize existing lab ageing methods for binder and mixes to simulate short- and long-term ageing in a more realistic way.

REFERENCES

[1] Nicholls C. (editor). Analysis of Available Data for Validation of Bitumen Tests, Report on Phase 1 on of the BitVal Projekt, 2005.

[2] Corbett, L. W., and R. E. Merz. Asphalt Binder Hardening in the Michigan Test Road After 18 Years of Service, Transportation Research Record 544, Washington DC, 1975.

[3] Martin, K. L., R. R. Davidson, C. J. Glover, and J. A. Bullin. Asphalt Aging in Texas Roads and Test Section, Transportation Research Record 1269, Washington DC, 1990.

[4] Kliewer, J., Zeng, H., and Vinson, T. Aging and Low-Temperature Cracking of Asphalt Concrete Mixture, Journal of Cold Regions Engineering, 10(3), 134–148, 1996.

[5] Teshale E. Z., Moon K.-H., Turos M., and Marasteanu M. Pressure Aging Vessel and Low-Temperature Properties of Asphalt Binders; Transport Research Record, Washington DC, 2011.

[6] Petersen J. C. A Review of the Fundamentals of Asphalt Oxidation - chemical, Physicochemical, Phycial Property, and Durability Relationships, Transport Research Circulare E-C140, Washington DC, 2009.

[7] Herrington, P. R., J. E. Patrick, and G. F. A. Ball. Oxidation of Roading Asphalts, Industrial and Engineering Chemistry Research, Vol. 33, 1994.

[8] Mirza, M. W., and M. W. Witczak. Development of a Global Aging System for Short- and Long-Term Aging of Asphalt Cements, Journal of the Association of Asphalt Paving Technologists, Vol. 64, 1995.

[9] Dickinson, E. J. Prediction of the Hardening of the Bitumen in Pavement Surfacing by Reaction with Atmospheric Oxygen, Road Materials and Pavement Design, Vol. 1, No. 3, 2000.

[10] Ruan Y., Davison R. R., and Glover C. J. The Effect of Long-Term Oxidation on the Rheological Properties of Polymer Modified Asphalts, Fuel, 82, 1763-1773, 2003.

[11] Petersen J.C. Asphalt Oxidation - an overview including a new model for oxidation proposing that physicochemical factors dominate the oxidation kinetics, Fuel, 11, 1993.

[12] Lesueur D. The colloidal structure of bitumen: Consequences on the rheology and on the mechanisms of bitumen modification, Advances in Colloid and Interface Science, 145, 2009.

[13] Durrieu F., Farca F., and Mouillet V. The Influence of UV Aging of an SBS Modified Bitumen: Comparison between Laboratory and on Site Aging, Fuel, 86, 1446-1451, 2007.

[14] Woo W. J., Chowdhury A. and Glover C. J. Field Aging of Unmodified Asphalt Binder in Three Long-Term Performance Pavements, Transport Research Record, Washington DC, 2008.

[15] Xiang L., Tu J., Cheng J., and Que G. Outdoor Aging of Road Asphalt and SBS modified Asphalt, Frontiers of Chemical Science Engineering, 5, 35-42, 2011.

[16] Huang S. C., Tia M., and Ruth B. E. Laboratory Aging Methods for Simulation of Field Aging of Asphalts, Materials in Civil Engineering, 1996.

[17] Kandhal P. S., and Sanjoy C. Effect of Asphalt Film Thickness on Short and Long Term Ageing of Asphalt Paving Mixtures, Transport Research Record 1535, Washington DC, 1996.

[18] Pierard N., and Vanelstraete A. Developing a Test Method for Accelerated Ageing of Bituminous Mixtures in the Laboratory, Advanced Testing and Characterization of Bituminous Materials, 2009.

[19] Mollenhauer K., Pierard N., Tusar M., Moulliet V., Gabet T.: Development and Validation of a Laboratory Ageing Method for the Accelerated Simulation of Reclaimed Asphalt, Journal of Wuhan University of Technology, 2010.

[20] van de Ven M. F. C., Voskuilen J. L. M. and Jacobs M. M. J. Practical Laboratory Ageing Method for Porous Asphalt, Proceedings of the 5th E&E Congress, Istanbul, Turkey, 2012.

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

[22] Moulliet V., Farcas F., and Besson S. Ageing by UV-Radiation of an Elastomer Modified Bitumen, Fuel, 87, 2408-2419, 2008.

[23] EN 12697-6. Bituminous mixtures - Test methods for hot mix asphalt - Part 6: Determination of bulk density of bituminous specimens, European Standardization Committee, 2012.

[24] EN 12697-8. Bituminous mixtures - Test methods for hot mix asphalt - Part 8: Determination of void characteristics of bituminous specimens, European Standardization Committee, 2003.

[25] EN 12697-46. Bituminous mixtures - Test methods for hot mix asphalt - Part 46: Low-temperature cracking and properties by uniaxial tension tests, European Standardization Committee, 2012.

[26] Arand W., Steinhoff G., Eulitz J., and Milbradt H.: Verhalten von Asphalten bei tiefen Temperaturen; Entwicklung und Erprobung eines Prüfverfahrens (in German). Forschung Straßenbau und Straßenverkehrstechnik des Bundesministers für Verkehr, Abteilung Straßenbau, Heft 407, 1984.

[27] EN 12697-26: Bituminous mixtures - Test methods for hot mix asphalt - Part 26: Stiffness, European Standardization Committee, 2012.

[28] DiBenedetto H., Partl M. N., Francken L., and De La Roche C. Stiffness testing for bituminous mixtures, Materials and Structures, 34, 2001.

[29] Bamberg G., Baur F., and Krapp M. Statistik (in German), Oldenburger Wissenschaftsverlag, 2011.

[30] Findley, W. N., Lai, J. S. Y., and Onaran, K. Creep and Relaxation of Nonlinear Viscoelastic Materials, Mineola, US: Dover Publications Inc., 1989.

[31] Hofko B., Blab R., and Mader M. Impact of Air Void Content on the Viscoelastic Behavior of Hot Mix Asphalt, Four-Point Bending, Taylor & Francis Group, London, ISBN 978-0-415-64331-3, 2012.

[32] EN 12697-3. Bituminous mixtures – Test methods for hot mix asphalt – Part 3: Bitumen recovery: Rotary evaporator, European Standardization Committee, 2013.

[33] EN 1426. Bitumen and bituminous binders. Determination of needle penetration, European Standardization Committee, 2007.

[34] EN 1427. Bitumen and bituminous binders - Determination of the softening point - Ring and Ball method, European Standardization Committee, 2007.

[35] EN 14770. Bitumen and bituminous binders. Determination of complex shear modulus and phase angle. Dynamic Shear Rheometer (DSR), European Standardization Committee, 2012.

[36] EN 14771. Bitumen and bituminous binders - Determination of the flexural creep stiffness - Bending Beam Rheometer (BBR), European Standardization Committee, 2012.

[37] EN 12607-1. Bitumen and bituminous binders. Determination of the resistance to hardening under influence of heat and air. Part 1. RTFOT method, European Standardization Committee, 2013.

[38] EN 14796. Bitumen and bituminous binders. Accelerated long-term ageing. Pressure Ageing Vessel (PAV), European Standardization Committee, 2012.