Asphalt mixture performance and testing

Long lasting asphalt pavements with polymer modified bitumens

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Abstract

Over the years there has been increased interest in using polymer modified bitumens (PMBs) to ensure asphalt functional performance and long-term durability or to meet high requirements for certain special applications. To gain knowledge about various aspects of using PMBs (e.g. durability, relevance of lab tests, cost-effectiveness, etc.), between 2003 and 2006, a test road of several sections with PMBs was constructed along with reference conventional sections on the motorway E6 in Sweden. Performance follow up has been carried out regularly since then, and recent field measurements and inspections were made in October 2017. All the test sections were still in a good condition. Field asphalt cores were taken to study long-term performance differences between the different test sections, and the fatigue life of each section was predicted with regards to fatigue damage (bottom-up cracking) caused by traffic loading. It was found that the road base mix with the SBS modified bitumen produced significantly better fatigue cracking resistance. While the conventional reference sections were optimized with a design life of approximately 20 years, the sections with the SBS modified bitumen in the base mixes demonstrated more than 30 years' longer fatigue life, implying that they are long lasting asphalt pavements. Test results indicate that the SBS modified binders perform excellently in terms of rheology and resistance to aging. The high aging resistance of the SBS modified binders was further demonstrated by the stiffness measurement made on asphalt field samples. Furthermore, the different binders were evaluated by delta Tc (LST-LmT, measured by BBR and/or 4 mm DSR), a binder durability parameter which was reported to be associated with the aging-induced surface cracking of an asphalt pavement.

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1. INTRODUCTION

During the past decade, dramatically increasing traffic volume and traffic loading in combination with lowing maintenance cost has created high performance demands on asphalt pavements. To ensure a durable and quality pavement, it is of great importance to properly select bituminous materials, at the same time to optimize mix and pavement designs. Numerous laboratory investigations have shown advantages of using polymer modified bitumen (PMB) in asphalts [1-4]. Improvements in asphalt performance are found with respect to aging (durability), permanent deformation (rutting), fatigue, and low temperature cracking. The improvements are also verified by various full-scale tests and field projects. For example, it was shown by the American LTPP (Long Term Pavement Performance) program that, road sections with PMB mixes had much less fatigue cracking, thermal cracking and rutting compared to conventional companion sections; thus, the use of PMBs significantly extends pavement lifetime [5]. The long-term durability of PMB was also demonstrated in bridge application under high traffic loading and very tough environmental conditions such as a wide temperature span and large temperature fluctuation [6]. After more than 15 years in the bridge deck pavement, the PMB used was still very elastic and remained good low temperature and high temperature properties. Good example of PMB application was also reported in airfield runways [7].

As a result of those successful application cases and field trials, the use of PMB somehow has been increased, but still quite limited in many countries probably because of higher initial cost. In order to determine whether it is cost-effective to use PMB on heavy traffic roads under the Nordic conditions (long and cold winter time, use of studded tyres, etc.), a test road was built in Sweden during 2003 – 2006. The objective of constructing such a test road is also to investigate if functional properties of asphalt pavement can be predicted by binder tests. The test road, located in Geddeknippel – Kalsås, was built as part of highway E6 north of Uddevalla where the average daily traffic (ADT) was around ten thousand vehicles per day. The whole field trial consisted of five northbound and ten southbound sections, including two reference sections for each direction. The southbound sections used various PMBs in different asphalt layers, whereas the northbound ones were only tested in the wearing course. A research project was designed with focus on the southbound sections. Performance of the sections has been monitored since its opening to traffic, along with a lot of laboratory investigations. Long-term performance prediction was also made in terms of permanent deformation and fatigue cracking. Results and findings are presented and discussed in this paper.

2. MATERIALS AND PAVEMENT STRUCTURE OF TEST SECTIONS

The southbound sections of the test road are described in Table 1. They consist of two reference sections and eight sections with different binder combinations. Note that PMB grades of 50/70-53, 50/100-75 and 100/150-75 of that time are currently 45/80-55, 40/100-75, and 90/150-75, respectively. These sections were constructed in 2003/2004 by laying 100 mm base course (50 mm upper-layer and 50 mm lower-layer, both with hot-mix AG22) on 80 mm unbound sub-base, followed by 50 mm binder course of asphalt concrete ABb22. After about two years of traffic, 40 mm wearing course of stone mastic asphalt (SMA16) was applied to the binder course in September 2006.

Table 1. Description of test sections with various combinations of binders

<table>
<tr><th>Test section</th><th>Ref 1</th><th>1a</th><th>1b</th><th>2a</th><th>2b</th><th>3a</th><th>3b</th><th>4a</th><th>4b</th><th>Ref 2</th></tr>
<tr><td>Length (m)</td><td>400</td><td>275</td><td>275</td><td>124</td><td>226</td><td>128</td><td>292</td><td>398</td><td>102</td><td>260</td></tr>
<tr><td>Wearing course
40 mm SMA 16</td><td>70/100</td><td>70/100</td><td colspan="3">50/100-75 SBS</td><td colspan="4">70/100</td><td>70/100</td></tr>
<tr><td>Binder course
50 mm ABb 22</td><td>50/70</td><td>50/70</td><td colspan="5">50/70-53 EVA</td><td colspan="2">50/70-53 SBS</td><td>50/70</td></tr>
<tr><td>Upper base course
50 mm AG 22</td><td>100/150</td><td colspan="2">100/150-75 SBS</td><td colspan="6">100/150</td><td>100/150</td></tr>
<tr><td>Lower base course
50 mm AG 22</td><td>100/150</td><td colspan="2">100/150-75 SBS</td><td>100/150</td><td>160/220</td><td>160/220</td><td>100/150</td><td>160/220</td><td>100/150</td><td>100/150</td></tr>
</table>

* Currently, 50/70-53 = 45/80-55; 50/100-75 = 40/100-75; 100/150-75 = 90/150-75

The conventional properties of the binders selected for the test sections are shown in Table 2. The modified binders were produced using different polymers and different polymer concentrations. All the modified binders are storage-stable according to EN 13399. The selection of the binders was based on intensive laboratory investigations on binder properties, and on asphalt performance tests, including fatigue, permanent deformation, water sensitivity, and wear resistance [8, 9].

Table 2. Conventional properties of the binders used in the test road

Asphalt layer	Binder type	Penetration at 25°C, 1/mm	Softening point R&B, °C	Viscosity at 135°C, Poise	Fraass breaking point, °C
Wearing course	70/100	77	46	3.3	-13
	50/100-75 SBS	58	98	18.4	-20
Binder course	50/70	55	60	3.5	-11
	50/70-53 SBS	58	58	5.6	-13
	50/70-53 EVA	52	66	9.8	-13
Base course	100/150	127	43	2.6	-17
	160/220	190	38	1.9	-21
	100/150-75 SBS	123	90	12.1	-20

Testing program and performance follow-up of the test road are briefly shown in Figure 1. Laboratory aging was performed according to the Rolling Thin Film Oven Test (RTFOT, EN 12607-1) and the Pressure Aging Vessel (PAV, EN 14769). Asphalt concrete cores were taken in September 2010, and evaluated by various mechanical tests, as well as general analyses with respect to binder contents and air void contents. Binder extraction and recovery was performed in accordance with EN 12697-1 and EN 12697-3, using dichloromethane as solvent. Virgin, laboratory aged and recovered binders were characterized from several perspectives, and in this paper only the rheological part is presented.

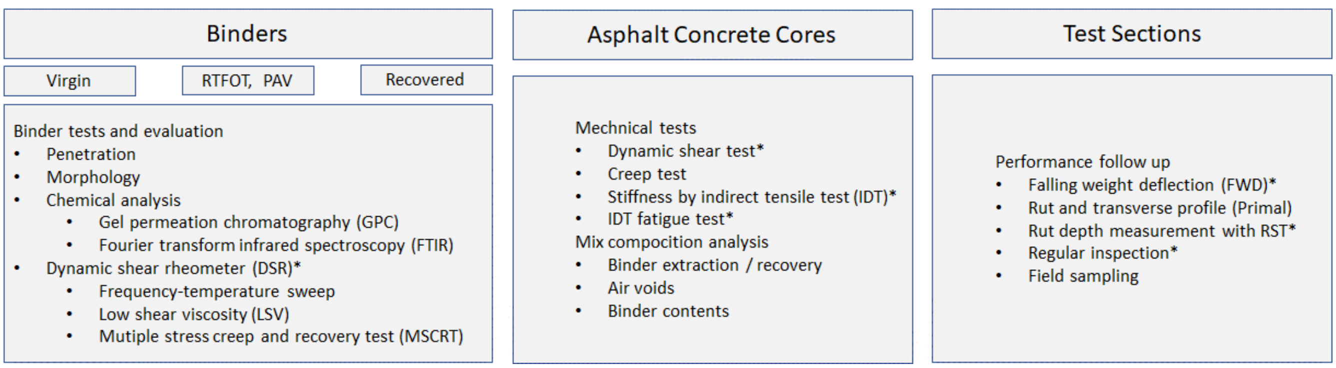

Figure 1: Testing program and pavement performance follow-up of the test road; the parts marked with * are presented in this paper.

3. RHEOLOGICAL CHARACTERIZATION OF BINDERS

3.1 Frequency-temperature sweeps

Using a dynamic shear rheometer (DSR), frequency sweeps (0.01 to 10 Hz) were performed at different temperatures ranging from 0 to 90°C. Depending on test temperature, parallel plates of 25 mm in diameter and 1 mm in gap or 8 mm in diameter and 2 mm in gap were used. From the DSR measurements, complex moduli are simply plotted against phase angles to obtain so-called black diagrams. As exemplified in Figure 2, for the SBS modified binder, higher elasticity (lower phase angle) is very evident even at low complex moduli (at high temperatures and/or low frequencies), which is beneficial when the resistance to permanent deformation is considered. The DSR results are also presented in master curves by applying the Time Temperature Superposition (TTS) principle and using a software available in the rheometer. Examples of the master curves are shown in Figure 2 for the two binders used in the wearing course. For both the modified and unmodified binders, the transition to the glassy state can be seen at high frequency. The differences between the binders, as well as the effect of aging, are more evident at low frequency range; the SBS modified binder exhibits significantly higher modulus than the pen bitumen, which is beneficial with respect to deformation resistance. For example, at a frequency of 1E-5 rad/s, the complex moduli of the modified binder are about 10 to 20 times higher than the unmodified bitumen, depending on if they are aged or not. In addition, the master curves of the recovered binders from the wearing course (4 years on the test road) lie between the virgin and RTFOT+PAV aged samples, implying the laboratory aging test predicts field aging quite well in this case.

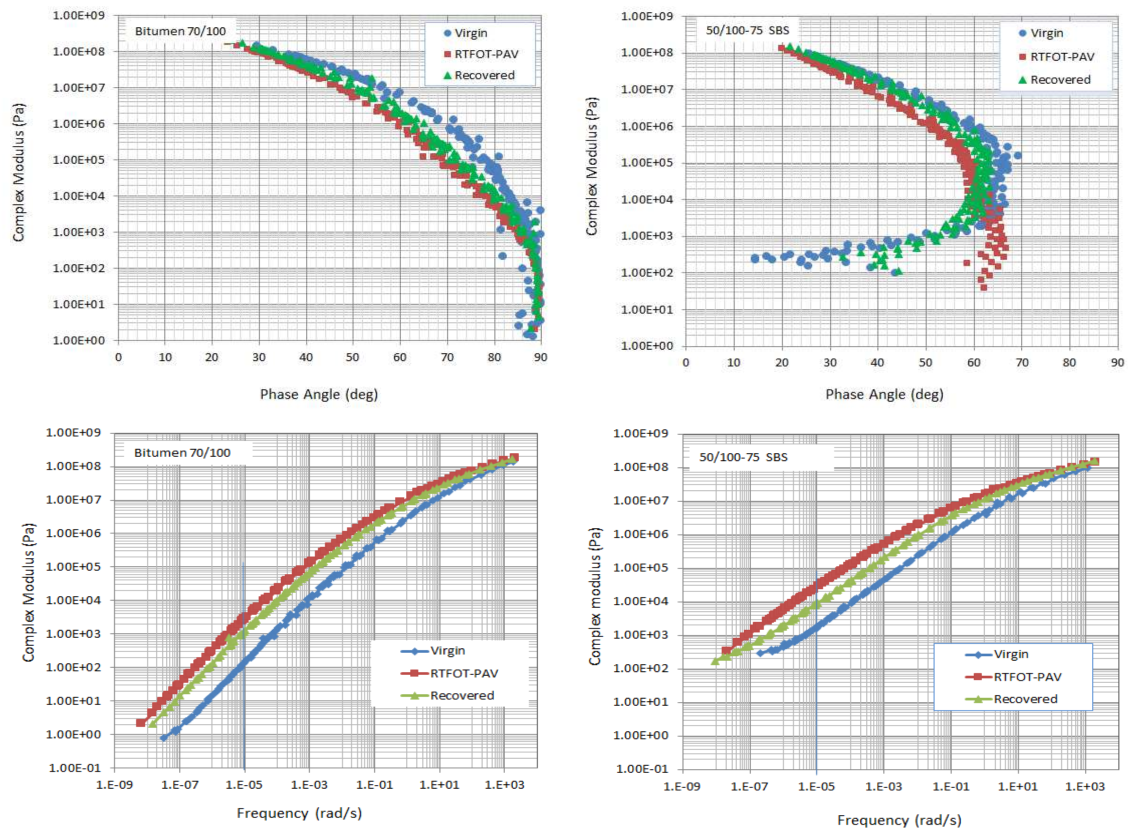

Figure 2: Black diagrams (upper row) and master curves of complex modulus (lower row)

Based on the DSR measurement, several parameters have used (or proposed) to evaluate binder performance in terms of rutting resistance, including G*/sinδ and zero-shear viscosity (ZSV). It is known that, for polymer modified binders, a zero-shear state is not always achieved; instead, low shear viscosity (LSV) measured at a low frequency (e.g. 0.001 Hz) is used. Figure 3 shows the results of LSV and G*/sinδ measured at 60°C for the binders aged in laboratory and those extracted from the different test sections. Accordingly, the rutting resistance of the binders can be ranked as: 50/100-75 SBS > 70/100 in the wearing course, and 50/70-53 EVA > 50/70-53 SBS > 50/70 in the binder course. The same ranking was seen when LSV and G*/sinδ were compared at 40°C (figure not shown).

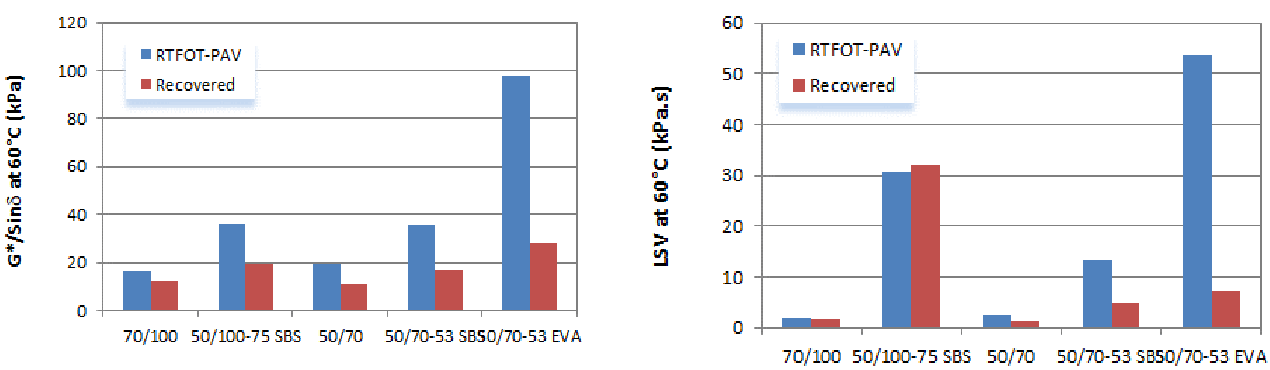

Figure 3: Comparison of binders by G*/sinδ and LSV, both at 60°C

3.2 Multiple stress creep and recovery test (MSCRT)

The MSCRT was performed at 60°C on all the samples, including virgin (unaged), laboratory aged, and those extracted from the test road. A procedure according to ASTM D 7405 was followed. Typical examples of the MSCR curves are shown in Figure 4, and the obtained strain recovery (R) and non-recoverable compliance (Jnr) are shown in Figure 5. Obviously, the polymer modified binders show much higher strain recovery and lower non-recoverable compliance as compared to the unmodified bitumen, suggesting strong structural networks and high rutting resistance for the modified binders.

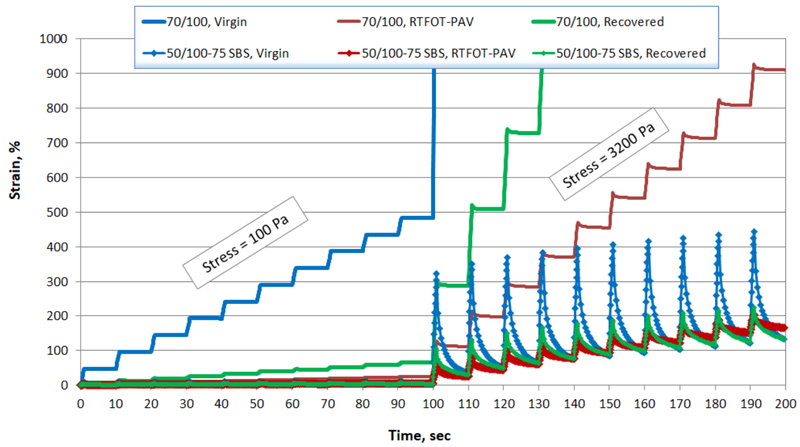

Figure 4: MSCR tests at 60°C for unmodified and polymer modified binders

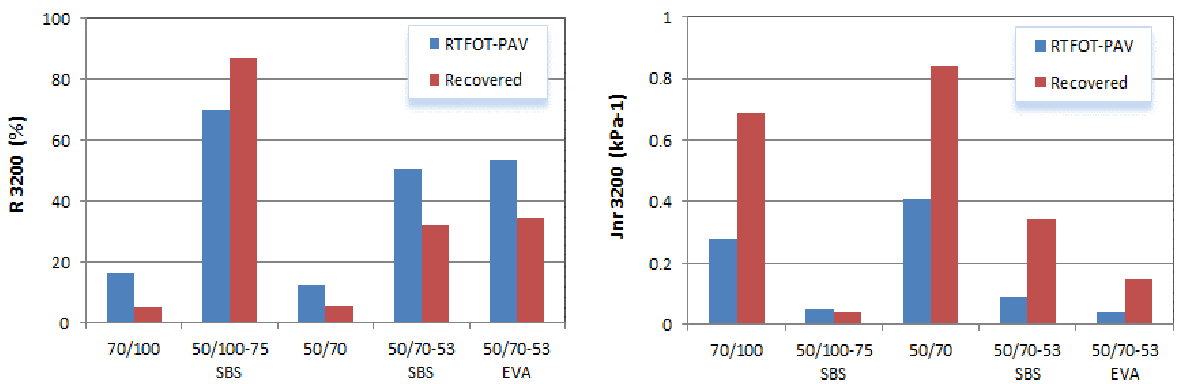

Figure 5: MSCRT results at 60°C for unmodified and polymer modified binders

Figure 4 also shows that the binders show less deformation after the aging due to the increased binder stiffness. For the unmodified bitumen, as well as for the EVA modified, aging also increases strain recovery and decreases the non-recoverable compliance (Figure 5). This is due to the oxidation of bitumen that makes the binders more elastic. Such aging effects are positive with respect to rutting performance. In the case of the SBS modified binders, inconsistent changes may be observed in the MSCR parameters, depending on a combined effect of bitumen oxidation and polymer changes. Nevertheless, the SBS modified binders, especially the one used in the wearing course (50/100-75 SBS), show significantly improvement by the MSCR parameters. The MSCRT was also performed at 40°C. Similar trends were observed with advantages for the modified binders, but differences between the binders became smaller compared to the results at 60°C.

3.3 Durability

To assess the aging sensitivity of the different binders in the test road, viscosity aging index is calculated using LSV at 60°C, i.e. LSV of the extracted binders divided by that of the virgin ones. The averaged aging indices are: 6.8 for bitumen 70/100, 4.3 for bitumen 50/70, 5.1 for 50/70-53 EVA, 1.0 for 50/70-53 SBS, and 0.90 for 50/100-75 SBS. These results indicate that, of the binders used in the test road, the SBS modified binders are the most resistant to aging. The improved resistance to in-service aging of the SBS modified binders is also verified by a small change in asphalt stiffness in the field, which will be shown later. Less aging is good against cracking. It keeps binder's cracking resistance better with time compared to other bitumen types. On the other hand, high aging characteristics could be good in terms of rutting resistance.

In literature, ΔTc has been shown as a binder durability parameter [10, 11]. It is related to the oxidative aging and relaxation properties of bitumen and is defined as the difference between the critical low temperatures, i.e. LST (temperature at 300 MPa stiffness) minus LmT (temperature at 0.300 m-value), measured by a beading beam rheometer (BBR). ΔTc has also been measured using a DSR with 4 mm plates (4-mm DSR). A more positive value of ΔTc means a higher durability.

In this paper, 4-mm DSR was used to determine ΔTc for several binders recovered from the surface courses of the test road, including three north-bound sections which were only tested on the wearing course (SMA 16). From the master curves of $G^*(\omega)$ and using Rhea software, $G(t)$ data were generated to determine $G(60s)$ and $m(60s)$ at temperature intervals of 6°C. LST and LmT were then determined following a procedure described in ASTM D 7643, LST as the temperature where $G(t)$ is 143 MPa and LmT as the temperature where $m = 0.275$ [11]. The results obtained are shown in Table 2. For a simple overview of the field aged binders, penetration values are also listed in Table 2. Unexpectedly, by ΔTc, the polymer modified binders tested do not demonstrate advantages over the unmodified bitumen, and trends are rather opposite. It is, however, worthwhile to note that higher elastic component in the modified binders may make ΔTc more negative [12]. Also aging characteristics of the base bitumen used in the PMBs may have an effect. Thus, caution is necessary when using such a parameter to draw any conclusion in this case.

Table 2. Critical temperatures and ΔTc determined by 4-mm DSR for recovered binders

Test section	Binder	Penetration, 1/10 mm	LST, °C	LmT, °C	ΔTc, °C
1b	50/100-75 SBS	23	-12.8	-11.3	-1.5
Ref 1	70/100	26	-12.7	-13.6	0.9
N2-North	50/70-53 EVA	19	-11.6	-9.3	-2.3
N3-North	50/100-75 SBS	26	-16.0	-12.8	-3.2
R1-North	70/100	23	-15.3	-15.4	0.1

4. ASPHALT TESTS AND PERFORMANCE PREDICTION

4.1 Stiffness

Stiffness measurements were conducted on asphalt mixes at different temperatures using indirect tensile test (IDT) according to EN 12697-26 annex C. Based on the results at 10°C, aging indices of the asphalt cores, defined as relative increase in stiffness modulus per year in percentage, are calculated. As shown in Figure 6, in both wearing course and binder course, the asphalt mixes made of the SBS modified binders are less aged as compared to those with other binders. This is in agreement with the observation on the binders (Cf. Section 3.3). In the case of the base course, the mix with the SBS modified binder displays a slightly higher aging index than the unmodified one. This mix was found to

Figure 6 also shows that the aging of the base course mix is much higher than the wearing course and binder course mixes. It was found that, in addition to a low binder content in the base course mix, the air voids content of the mix was about 5%, while in the wearing course and binder course, the air voids content was less than 2%. An easier access to oxygen due to higher air voids combined with thinner binder layer (lower binder content) may have caused a higher degree of aging for the base course mix.

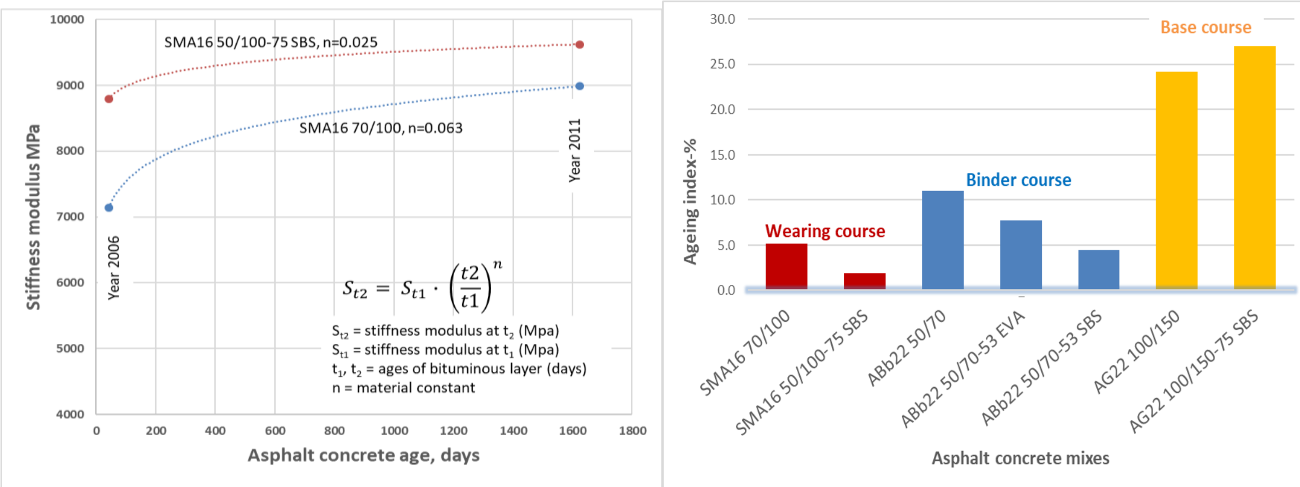

Figure 6: Aging sensitivity of asphalt mixes as evaluated by stiffness at 10°C

4.2 Permanent deformation

On asphalt pavements, one of the major potential distresses is permanent deformation (or flow rutting). Permanent deformation is largely influenced by the properties of asphalt mixes, especially at high temperatures and under relatively long loading duration when the mix properties are dominated by the viscous character of the material. In this study, the permanent deformation of asphalt mixes is assessed by different tests, including dynamic shear modulus tests and wheel tracking test. The dynamic shear tests were carried out using a procedure reported previously [13]. Specimens (150 mm in diameter, and 35 to 40 mm in thickness) taken from the test road were measured by frequency sweeps from 0.05 to 16 Hz at different temperatures of -5, 5, 20, 35 and 50°C. Then master curves were constructed for dynamic shear modulus, as well as for phase angle. As exemplified in Figure 7, the surface course mixes (SMA 16) with the modified and unmodified binders behave quite similarly over a broader frequency and/or temperature range. However, in terms of phase angle, the SBS-modified surface mix displays a lower value than the unmodified mix, indicating a better elastic property, which should be beneficial for the resistance to permanent deformation, as well as fatigue cracking.

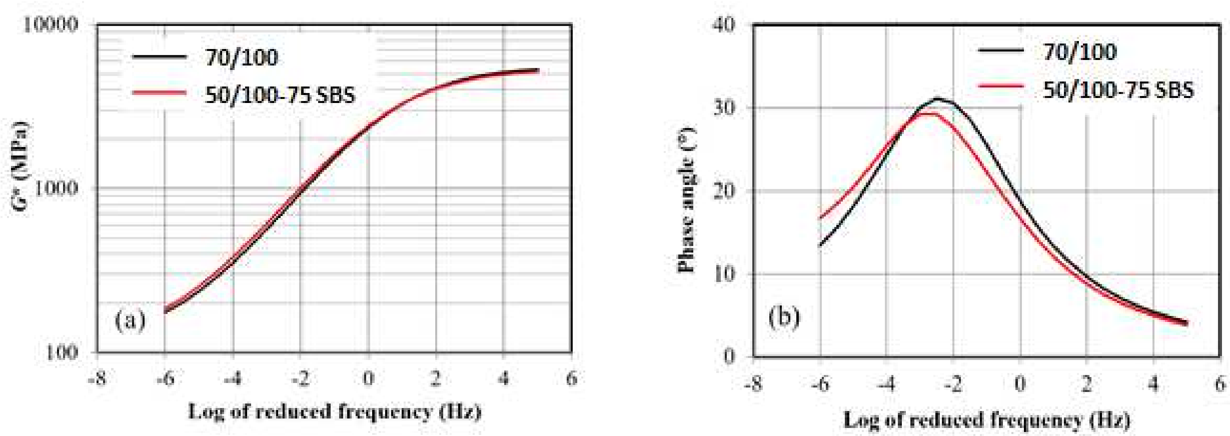

Figure 7: Master curves of (a) Dynamic shear modulus, (b) Phase angle of the surface course mixes SMA 16 at a reference temperature of 10°C

A limited investigation was carried out on asphalt mixes of ABT11 (a Swedish dense grade) prepared at laboratory with a reference bitumen (70/100 pen) and PMB 40/100-75 which is identical to the one used in the test road (50/100-75 SBS). The rutting performance of the asphalt mixes first was evaluated by the wheel tracking tests (WTT) at 60°C in air. As demonstrated in Figure 8, the asphalt mix with the polymer modified binder performs almost 10 times better than the one with the reference bitumen with respect to rutting resistance.

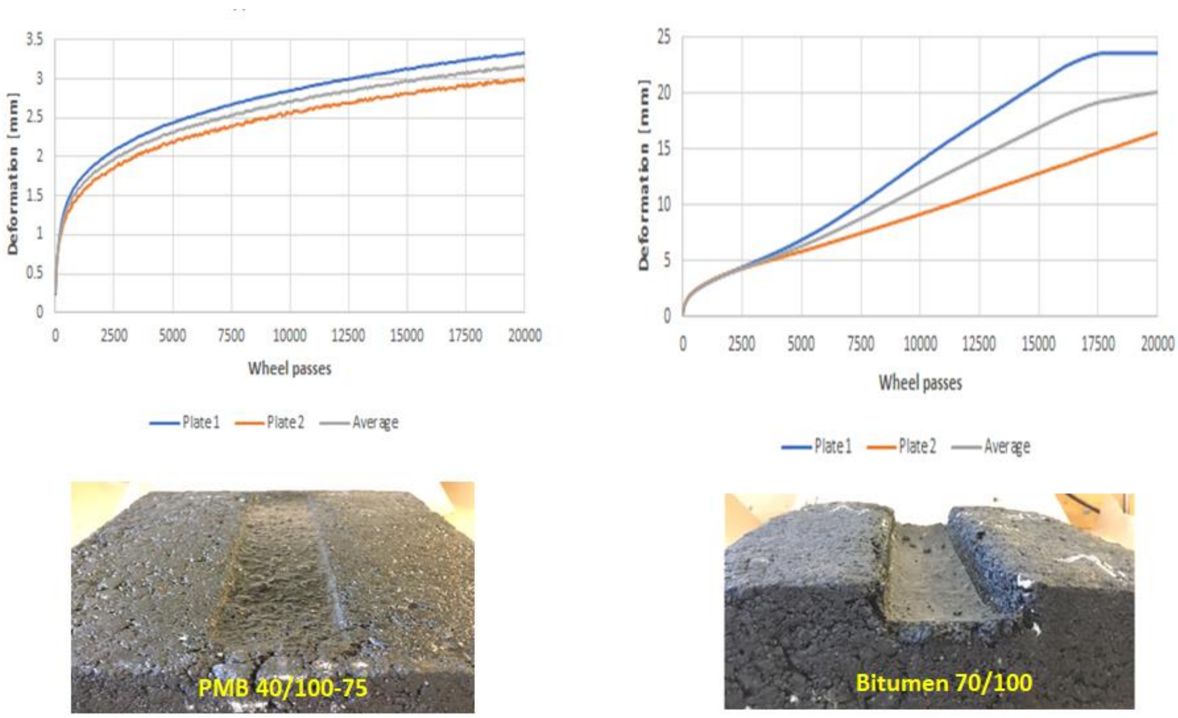

Figure 8: Wheel tracking tests at 60°C on the dense grade asphalts (ABT 11) made with a polymer modified bitumen as compared to reference bitumen

The same asphalt mixes were further investigated by the dynamic shear modulus test. From the master curves obtained on one sample per mix (Figure 9), viscosities of the asphalt mixes ($|\eta^*| = |G^*|/\omega$) were determined at the maximum phase angles, and then used as material property inputs to predict the rutting performance of the asphalt concrete layers using a linear viscoelastic approach called PEDRO (PErmanent Deformation of asphalt concrete layer for Roads) [14]. It was observed that the asphalt made with the polymer modified binder displays a higher (> 20%) viscosity than the unmodified one. A road section with such PMB was predicted to show about 20% less deformation as compared to a section with the reference bitumen. This means that if PMB section needs maintenance in 20 years, then the reference section would be in 16 years, or 4 years earlier than the PMB section.

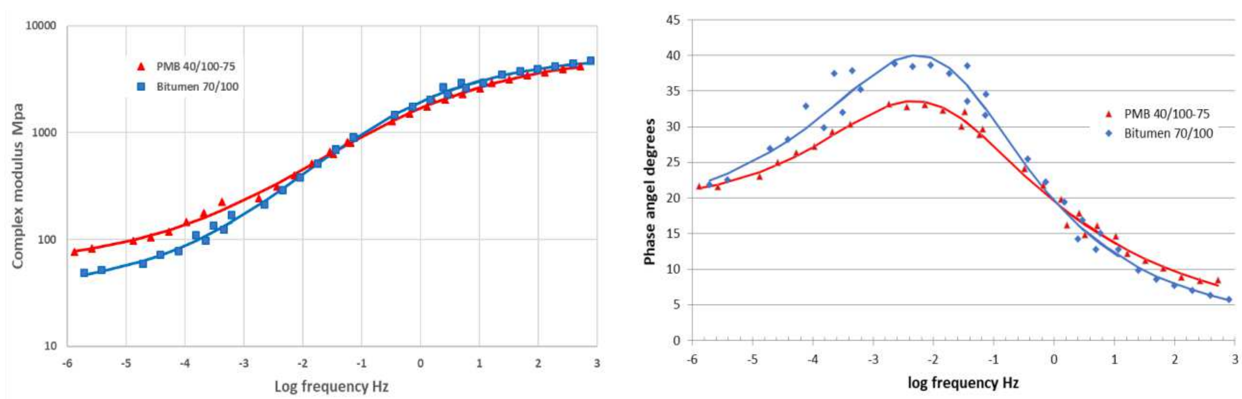

Figure 9: Master curves of dynamic shear modulus and phase angle at a reference temperature of 10°C for dense grade asphalts (ABT 11) made with a polymer modified bitumen as compared to reference bitumen

4.3 Fatigue

To study the differences between the test sections with conventional and polymer-modified base mixes, the fatigue life of each section was predicted with regard to damage caused by traffic loading [15]. The reference sections Ref 1 and Ref 2 with conventional base mixes and sections 1a and 1b with SBS-modified bitumen base mixes were investigated in respect of bottom-up fatigue cracking. Indirect tensile (IDT) fatigue tests were performed at 10°C. Based on the developed fatigue lines and the strain calculated from the measurements made by the falling weight deflectometer (FWD) in September 2012, the estimated allowable number of ESALs to fatigue cracking of the base courses were determined. As shown by the fatigue lines in Figure 10 (left), the resistance to fatigue cracking of the reference sections and the sections with SBS-modified base mixes is on average 0.6E6 and 3.5E6 loading repetitions, respectively. The SBS-modified base mix demonstrates significantly better fatigue cracking resistance. Based on traffic monitoring between 2005 and 2009 and using an equivalent axle load factor of 1.3, the accumulated 100 kN ESALs were extrapolated, as shown in Figure 10 (right). Then the conventional structures were estimated to withstand the traffic loading until around 2024, while the structures with the polymer modified bitumen were estimated to withstand the traffic loading until between 2058 and 2071, which is more than 30 years longer than the reference.

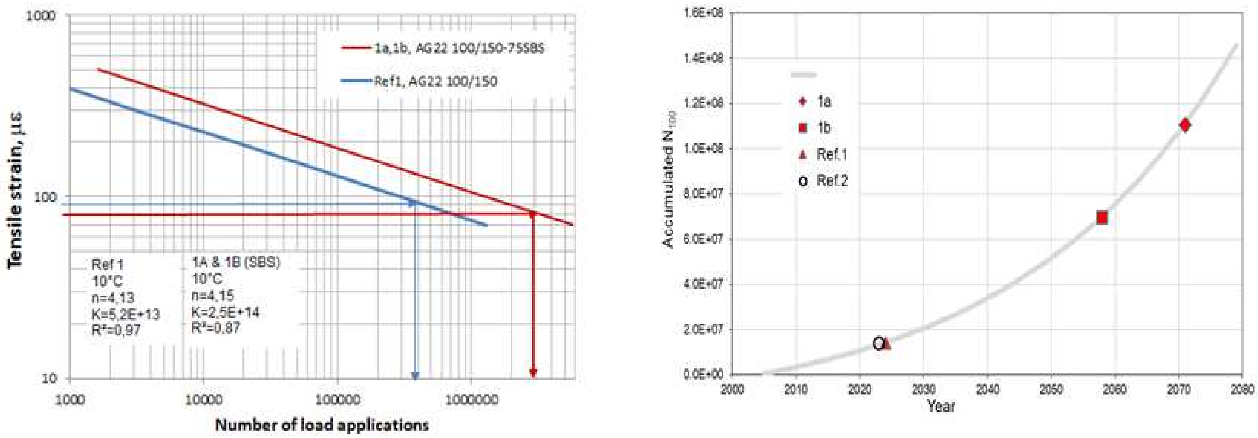

Figure 10: Laboratory-determined fatigue lines (left) and prediction of pavement service life of test sections (right)

5. FIELD PERFORMANCE

The test road has been monitored since its opening to traffic. To follow up the deterioration in the pavement sections, measurements of deflection using a Falling Weight Deflectometer (FWD), rut depth measurements using a high-speed Road Surface Tester (RST) are performed periodically. As example, the total rut development on the test sections measured using RST is shown in Figure 11 by the normalized surface rut depth at the first measurement of the test sections in 2006 until 2017. A rut depth development of approximately 4 mm was measured after a 10-year in-service and rather small differences (< 1 mm) were observed between the different sections. The differences could be below the marginal error of the measurement.

The rut developments on the asphalt layers of the test road during the past years were also evaluated using the PEDRO model, and permanent deformation over an analysis period of 20 years was further predicted [15]. In general, all the sections, including reference ones, were predicted to show small rutting (< 5 mm), suggesting over-designed strong structures for the test road. But certain differences do exist between the polymer modified sections and the reference sections, with lower rut for the polymer modified ones, as illustrated in Figure 12. Accordingly, the section 1a with the SBS base course mix show less measured and predicted rutting compared to the reference section with conventional binder in all bituminous layers (See Table 1) and the section 2a with PMB in all bituminous layers shows least rutting.

Moreover, field inspection has been carried out regularly. All the sections remain in good condition; no distresses, such as stripping and low temperature cracking, were observed in a recent inspection in October 2017.

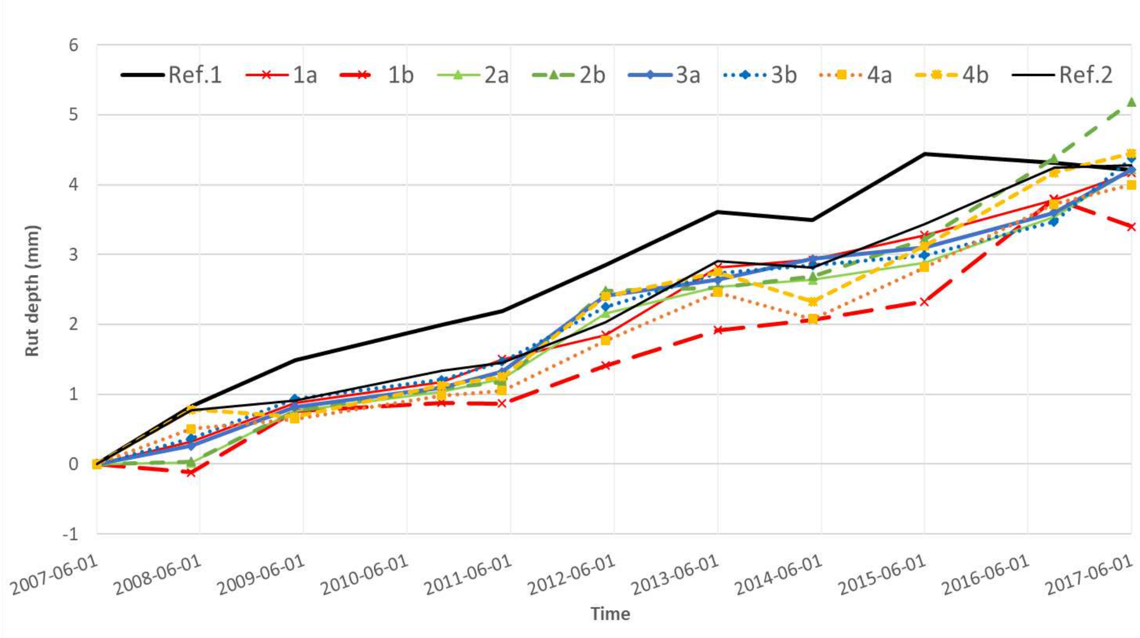

Figure 11: Rut development on the test sections measured by RST

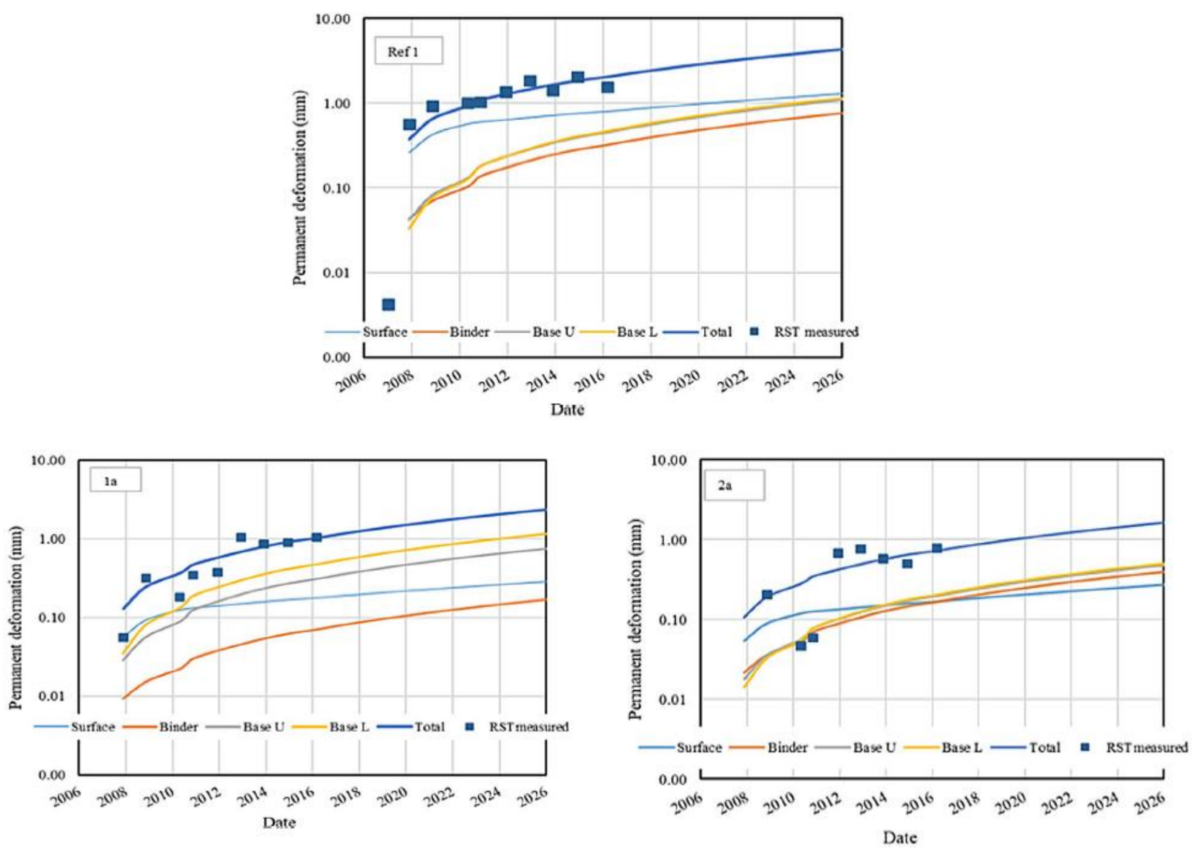

Figure 12: Measurement and prediction of the permanent deformation of the test section with conventional binder (Ref 1) compared to the sections 1a (PMB in base course) and 2a (PMB in surface and base courses)

6. CONCLUSIONS

The polymer modified binders, particularly with SBS polymers, show enhanced properties, including good aging resistance and high resistance to permanent deformation. The high resistance to aging for the modified binders is also evident when stiffness measurements are made on asphalt field cores. The SBS modified binders significantly enhance the fatigue life of the asphalt mixes. When the reference sections are optimized with a design life of approximately 20 years, the sections with the SBS modified binder in the base course mix are predicted to last more than 30 years longer, implying that they are long-life asphalt pavements. Longer service time for the SBS modified binder is also demonstrated in terms of resistance to permanent deformation, based on mechanical tests and modelling on the asphalt slabs prepared at laboratory. Regarding field performance, after 11 years in-service all the sections are still in good condition; differences in rut depth are rather small, other distresses, such as stripping and cracking, are not observed. As for binder performance indicators, at this moment, variations on the binders reflected by e.g. MSCRT have not yet been validated by the field performance of the test road. In addition, no conclusion can be drawn on ΔTc as a durability parameter for PMBs due to the available data are very limited, at the same time no surface cracks had appeared on the test sections.

7. ACKNOWLEDGEMENTS

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