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Evaluation of test sections with Polymer Modified Bitumens

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ABSTRACT: It has been recognized that Polymer Modified Bitumens (PMB) have more potential for use in asphalt paving and can clearly demonstrate the value of their initial higher cost. To further assess sustainable benefits on heavy trafficked roads, test sections using various PMBs were built on highway E6 in Sweden during 2003–2006. The main objective of this paper is to study the aging and rheological properties of the binders used. A large number of cores were drilled and characterized with respect to stiffness, fatigue and permanent deformation. The binders (original, lab aged and recovered) were investigated extensively with rheological and chemical methods. It was found that PMBs, particularly SBS modified, demonstrate better rheological properties as compared to unmodified bitumens, even after several years in the field. These include higher strain recovery and lower non-recoverable compliance at high temperatures, and lower stiffness at low temperatures. For the SBS modified binders, good aging resistance was observed. The high resistance to aging for the SBS modified binders was also evident in the stiffness measurement made on asphalt field cores. Although significant differences have not yet been seen between the test sections (all the sections are in good condition after six years of traffic), the observed improvements for the modified binders are expected to be confirmed by a longer follow-up of the test road.

Keywords: test road; polymer modified bitumen; sustainability; aging; durability

1 INTRODUCTION

Over the years increased traffic volume and traffic loading along with a pressure of reducing material costs has created high performance requirement for asphalt pavements. In order to ensure pavement long-term durability, thus minimizing maintenance cost and conserving resources, proper selection of paving materials together with optimal mix and pavement design are of great importance. Numerous laboratory studies have shown beneficial effects of adding polymers to bitumen and using Polymer Modified Binders (PMB) in asphalt mixtures [1, 2]. Performance improvements are normally found with respect to permanent deformation (rutting), fatigue resistance and low temperature cracking, particularly for the modified binders with Styrene-Butadiene-Styrene copolymer (SBS). These improvements are also confirmed in full-scale tests using for example Heavy Vehicle Simulator (HVS) [3], and field trials, such as test sections in the Long Term Pavement Performance (LTPP) program in North America [4] and airfield runways [5]. The American LTPP study indicated that test sections with PMB mixtures had less fatigue cracking, thermal cracking and rutting compared to conventional companion sections. Thus, the use of PMBs extends the service life of flexible pavements and HMA overlays [4].

In spite of recognized good performance, the application of PMB to asphalt paving has been quite limited in many countries probably because of higher initial cost. To determine whether it is cost-effective to use PMB and to assess its sustainable benefits on heavy trafficked 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 validate if binder tests can quantity the functional properties of asphalt pavements. The test road is located in Geddeknippel—Kalsås, and 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. The northbound sections were only tested in the wearing course, whereas in the southbound sections various PMBs were tested in all asphalt layers, i.e. the wearing course, binder course and base course. The test road has been monitored continuously and a follow-up research was carried out. The research project includes field performance measurements, testing of asphalt cores, binder tests and evaluation, deterioration modeling, as well as Life Cycle Cost Analysis (LCCA). The present paper focuses on binder characterization with respect to aging and rheology. The binders used in the southbound test sections were studied.

2 MATERIALS, TEST SECTIONS AND FIELD SAMPLING

Table 1 shows the conventional properties of the binders selected for the test sections. The modified binders were produced using different polymers and different polymer concentrations. The 50/70-53 SBS, 50/100-75 SBS and 100/150-75 SBS contains 3, 4 and 6% SBS (by weight), respectively. In 50/70-53 EVA (ethylene vinyl acetate), the polymer content is 6%. All the modified binders are storage-stable according to the European standards EN 13399. Selection of the binders was based on intensive laboratory investigations on binder properties, and on asphalt mixture performance tests, including fatigue, permanent deformation (rutting), water sensitivity, and wear resistance, etc. [6, 7].

In the test road (southbound), two reference sections and eight sections with different binder combinations were built (Table 2). These sections were constructed in 2003/2004 by laying 100 mm base course (50 mm over-layer and 50 mm under-layer, both with hot-mix AG22) on a 80 mm unbound sub-base, and followed by 50 mm binder course of asphalt concrete ABb22. After about two years of traffic, 40 mm wearing course of stone mastic asphalt (ABS16) was applied to the binder course in September 2006. Detailed technical requirements for the used asphalt mixture types can be found in [8].

Field sampling was made in September 2010 when asphalt cores were drilled from two different positions—the wheel path (or under track) and between the tracks, denoted as UT and

Table 1. Binders used in the test road and their conventional properties.

Asphalt layers	Binder types*	Polymer % wt	Penetration, 1/mm	Softening point, °C
Wearing course	70/100	0	77	46
	50/100-75 SBS	4	58	98
Binder course	50/70	0	55	50
	50/70-53 SBS	3	58	58
	50/70-53 EVA	6	52	66
Base course	100/150	0	127	43
	160/220	0	190	38
	100/150-75 SBS	6	123	90

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

Table 2. Test sections with various combinations of binders.*

Test sections	Ref 1	1a	1b	2a	2b	3a	3b	4a	4b	Ref 2
Wearing course	70/100	70/100	50/100-75 SBS			70/100				70/100
Binder course	50/70	50/70	50/70-53 EVA					50/70-53 SBS		50/70
Base course—over	100/150	100/150-75 SBS		100/150						100/150
Base course—under	100/150	100/150-75 SBS		100/150	160/220	160/220	100/150	160/220	100/150	100/150

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

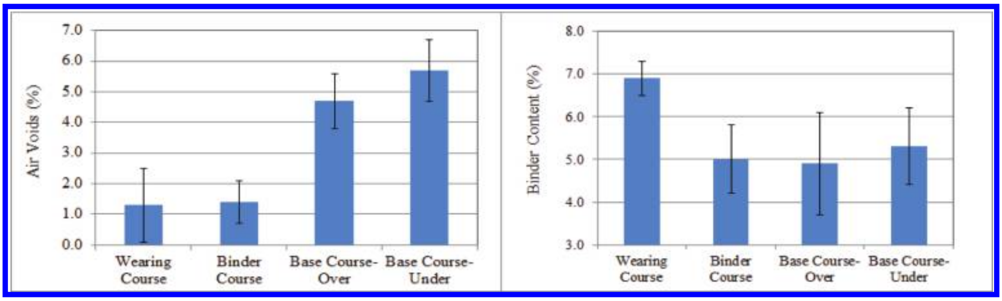

Figure 1. Binder contents and air void contents averaged for different asphalt layers.

BT, respectively. General analyses were conducted on the field cores with respect to binder contents and air void contents. The data averaged for different asphalt layers are compared in Figure 1.

3 CHARACTERIZATION OF BINDERS

Comprehensive tests were carried out on original binders, lab aged samples according to the Rolling Thin Film Oven Test (RTFOT, EN 12607-1) and the Pressure Aging Vessel (PAV, EN 14769), and recovered binders from the test sections. For binder extraction and recovery, the European standards EN 12697-1 and EN 12697-3 were followed. The solvent used was dichloromethane. Binder tests include penetration, fluorescence microscope (morphology), Gel Permeation Chromatography (GPC), Fourier Transform Infrared spectroscopy with Attenuated Total Reflectance (FTIR-ATR), and rheology with a Dynamic Shear Rheometer (DSR).

In the microscopic test, specimens were prepared by taking a drop of sample at 180°C on a glass plate, and morphologies measured at room temperature. The microscope used was Carl Zeiss Axioskop 40F1 equipped with a digital camera DP200.

GPC is a technique to determine molecular weights and molecular weight distribution. In this study, an Alliance 2690 Separation Module (Waters) with UV or refractive index detector was employed. Sample solutions of 0.4% were prepared using Tetrahydrofuran (THF). This solvent was also used as mobile phase.

In FTIR-ATR, a very small amount of bitumen sample was directly placed on an ATR crystal and IR reflection from the sample was detected. Spectra were recorded at wavelengths ranging from 500 to 4000 cm^{-1}. The compositional information was measured for polymers, e.g. SBS at 966 cm^{-1} (butadiene) and 699 cm^{-1} (styrene), and for bitumen functional groups, such as carbonyl compounds at around 1700 cm^{-1} and aromaticity at about 1600 cm^{-1}.

With DSR, frequency sweeps (0.01 to 10 Hz) were performed at different temperatures ranging from 0 to 90°C, and Multiple Stress Creep and Recovery test (MSCR) according to ASTM D7405. 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.

3.1 *Morphology*

The morphologies of the modified binders measured at room temperature are presented in Figure 2. As expected, at a low concentration (3 or 4% by weight), the polymer exhibits dispersed phase in the binder. At a sufficiently high concentration of 6%, a continuous polymer phase is formed. The morphologies are also affected by aging. Apparently, in the studied binders of dispersed polymers, finer structures can be seen after the RTFOT-PAV. The polymer morphology may significantly influence the rheological properties of the binder [9, 10]. But for mixture performance, it is probably more important to know polymer structures in the mixture or mastics and to determine its structural impact. Further research on this aspect is needed.

3.2 *Retained penetration*

In assessing the age-hardening of bitumen or PMB over the time, an empirical parameter is retained penetration. It was found that after several years in the field, the modified binders used in the wearing course and base course generally showed higher retained penetration (i.e. less age-hardening) than the unmodified. The results are exemplified in Figure 3 for the binders extracted from the base course (AG22) which has been in the field for six years. On average, the degree of the age-hardening of 100/150-75 (SBS) is about half of that of bitumen 100/150 pen. This is probably due to polymer modification starting with soft bitumen and/or aged SBS acting as a softener in the bitumen. In the binder course, this effect was not seen for the binders modified by EVA or with a low concentration of SBS (3% by weight).

3.3 *Rheological properties*

From DSR frequency sweeps at different temperatures, complex moduli are plotted against phase angles. The so called black diagrams provide a method to check for the Time Temperature Superposition (TTS) principle and give information about chemical or structural changes during the rheological measurements. As exemplified in Figure 4, for the unmodified bitumens, no matter if aged or unaged, these curves are quite smooth, suggesting no structural changes during the rheological tests. On the other hand, it was not possible for the EVA

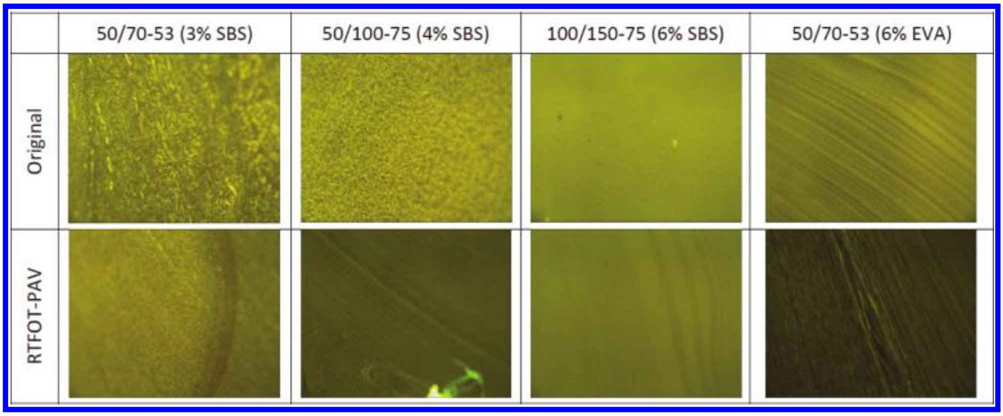

Figure 2. Morphologies of polymer modified binders (magnification 200×).

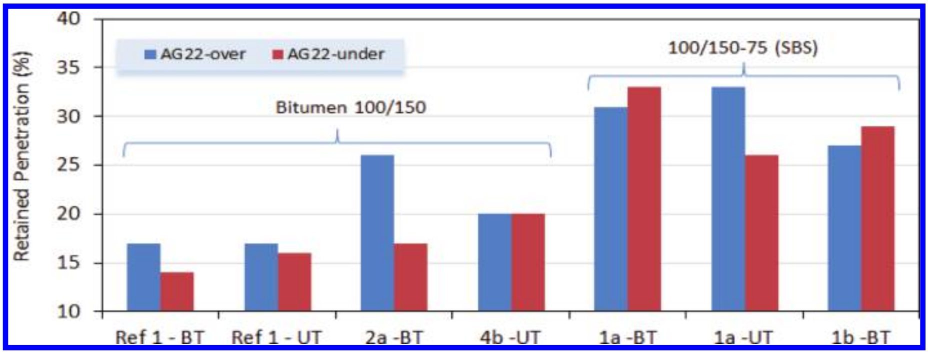

Figure 3. Retained penetration for the binders used in the base course (AG22).

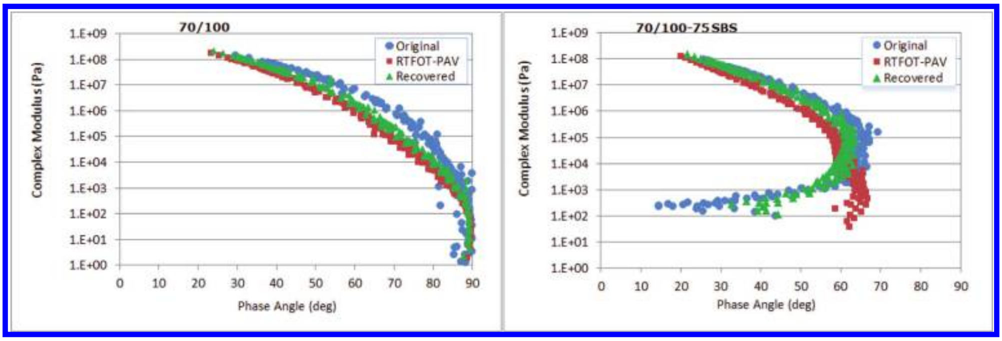

Figure 4. Complex modulus *vs* phase angle for different binders before and after aging.

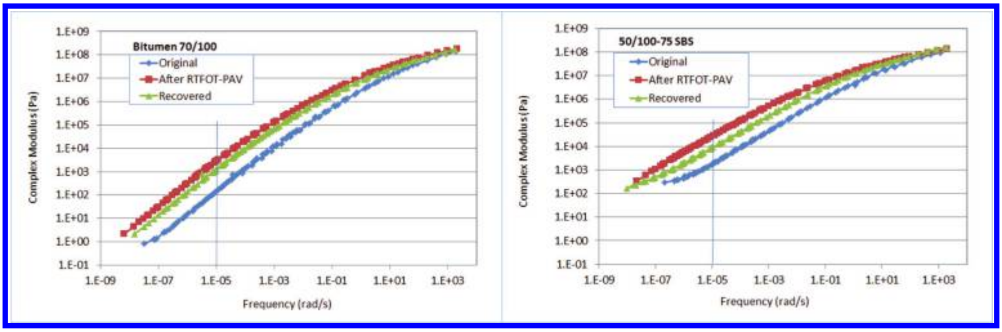

Figure 5. Complex modulus master curves at reference temperature 10°C.

modified binder to get a single smooth plot (figures are not shown). This is attributed to a phase change induced by the melting of the polymer. In the case of SBS modification, higher elasticity (lower phase angle) is very evident even at low complex moduli (at high temperatures and/or low frequencies), as well as after laboratory aging or several years in the field. This is beneficial when the resistance to permanent deformation is considered.

The DSR frequency—temperature sweeps are also used to construct master curves by applying the TTS principle [11]. Using master curves, bitumen rheological behavior and the effect of aging may be characterized over wider ranges of time or frequency at a specified temperature. Examples of the master curves of complex modulus are shown in Figure 5 for the 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 original and RTFOT-PAV aged samples, implying the laboratory aging test predicts field aging quite well in this case.

To quantify the aging sensitivity of the different binders in the test road, it was intended to use aging index based on Zero Shear Viscosity (ZSV) measurements. Unfortunately it was not possible to precisely define ZSV for most of the modified binders. Instead, the complex viscosities measured at a low frequency of 0.001 Hz and at 60°C (LSV) are used to calculate the aging index (LSV of the extracted binders divided by that of the virgin samples). The averaged aging indices are: 6.77 for bitumen 70/100, 4.29 for bitumen 50/70, 5.05 for 50/70-53 EVA, 1.02 for 50/70-53 SBS, and 0.90 for 50/100-75 SBS. These data indicate that, of the binders used in the test sections, the SBS modified binders are the most resistant to aging. The high resistance to aging of the SBS modified binders is also confirmed by stiffness measurements on asphalt field cores; this will be shown later.

In the literature, several rheological parameters are used to assess binder rutting resistance. One test which can distinguish differences in the rutting potential is Multiple Stress Creep and Recovery test (MSCR) [12]. The measured parameters include strain recovery and non-recoverable compliance (Jnr). Typical examples of binder response to repeated loading are shown in Figure 6. Differences in strain recovery at 3.2 kPa and 60°C between the binders and the effect of aging are compared in Table 3. Obviously, the SBS modified binders show much higher strain recovery compared to others. Considering the effect of aging, the unmodified and EVA modified binders follow the same trend; the increased strain recovery for the aged and recovered samples is due to bitumen oxidation that makes the binders more elastic. In the case of SBS modification, aging may reduce binder strain recovery probably due to oxidation of the polymer. However, even after laboratory or field aging, the SBS modified binders still retain a higher level of strain recovery as compared to other binders.

Differences between the binders, as well as the effect of aging, are also evident when the non-recoverable compliances, Jnr 3200, are compared (see Table 3). Regardless of sample state (original, laboratory aged, or extracted from the test road), the polymer modified binders always show lower values of Jnr 3200 than the reference, suggesting higher rutting resistance for the modified binders.

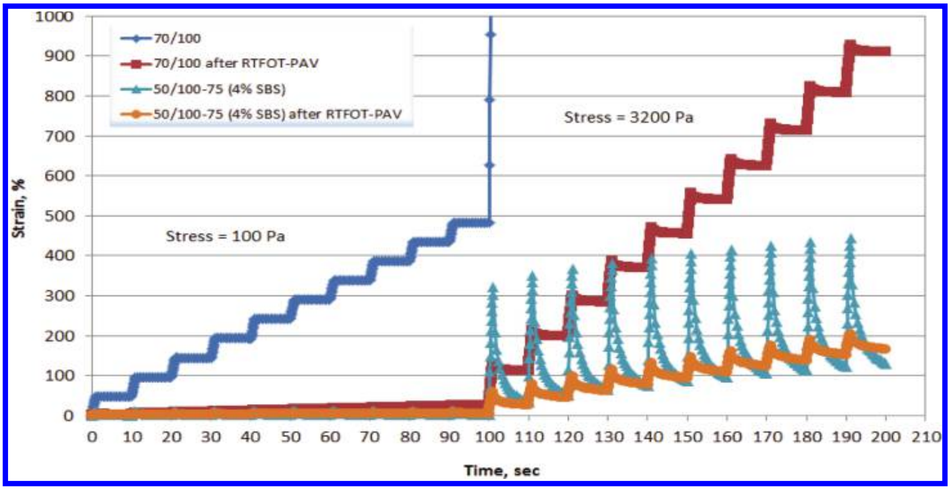

Figure 6. Strain response to repeated loading at 60°C for unmodified and SBS binders.

Table 3. Strain recovery and non-recoverable compliances (Jnr) measured at 60°C.

Asphalt layers	Binder types	Strain recovery, %			Jnr 3200, kPa^{-1}		
		Original	RTFOT-PAV	Recovered	Original	RTFOT-PAV	Recovered
Wearing course	70/100	0	16	5	5.16	0.28	0.69
	50/100-75 SBS	96	70	87	0.04	0.05	0.04
Binder course	50/70	0	13	6	3.55	0.41	0.84
	50/70-53 EVA	6	54	34	1.76	0.04	0.15
	50/70-53 SBS	47	51	32	1.00	0.09	0.34
Base course	100/150-75 SBS	99	90	78	0.01	0.08	0.34

MSCR tests were also carried out at 40°C for some test sections. Not surprisingly, differences between the binders became smaller as compared to the measurements at 60°C. For the unmodified and EVA modified binders, the strain recoveries increased to about 40 and 60%, respectively, while for the SBS modified binders, strain recoveries were more than 70%. In all cases, low values of Jnr were seen at 40°C (<0.03 kPa^{-1} at stress level of 3.2 kPa).

So far the above observation on binder rutting properties has not been validated by field measurement. All the test sections are in good conditions and very little rutting was observed.

Another aspect of particular importance to the Nordic countries is low temperature cracking. For the binders used in the surface layer, low temperature tests were performed according to Performance Grading (PG). It was found that 70/100 bitumen and 50/100-75 SBS were in a similar low temperature range of −22°C to −28°C. In addition, the critical cracking temperatures were determined in accordance with AASHTO PP42, and 70/100 bitumen and 50/100-75 SBS had −28.6°C and −29.1°C, respectively. The critical cracking temperatures are far below the lowest pavement temperature which is about −10°C.

For the binders recovered from the test sections, BBR tests were not performed due to limited amounts of samples. Instead, DSR with 8 mm parallel plate geometry was applied to measure binder stiffness (complex modulus) at −25°C. It was observed that at this low temperature and at 10 rad/s, the stiffness of the SBS modified binder was about 25% lower than that of the unmodified bitumen.

3.4 *Chemical analyses*

Using FTIR-ATR, the compositional information can be obtained directly on the binders without preparing a sample solution. Examples of the IR spectra are shown in Figure 7. To evaluate bitumen oxidation, IR absorbances are measured for oxygen-containing functional groups—carbonyl compounds at 1700 cm^{-1}, as well as aromaticity at 1600 cm^{-1}. As expected, the amount of the carbonyl compounds and aromaticity increase after laboratory aging (Fig. 8). However, for some test sections, the aromaticity and the carbonyl compounds measured for the recovered binders are lower compared to the original and lab aged samples. This could suggest that the functional groups are probably not completely extracted from asphalts, or there might be strong interactions between the bitumen and aggregates or fillers.

FTIR also showed that aging did not change EVA as reflected by more or less unchanged absorbance at 1241 cm^{-1} for the polymer. For the SBS modified binders, the butadiene signal at 966 cm^{-1} decreased slightly while the styrene at 699 cm^{-1} remained unchanged after aging (Fig. 7). Although the SBS polymers take part in chemical reactions and degradation of the polymers may occur during aging, the fragments formed are still kinds of polymer which are large enough to affect the binders in a beneficial way. It was shown by GPC that there were no significant changes in the contents of SBS polymer (and its fragments) after the laboratory aging or field aging.

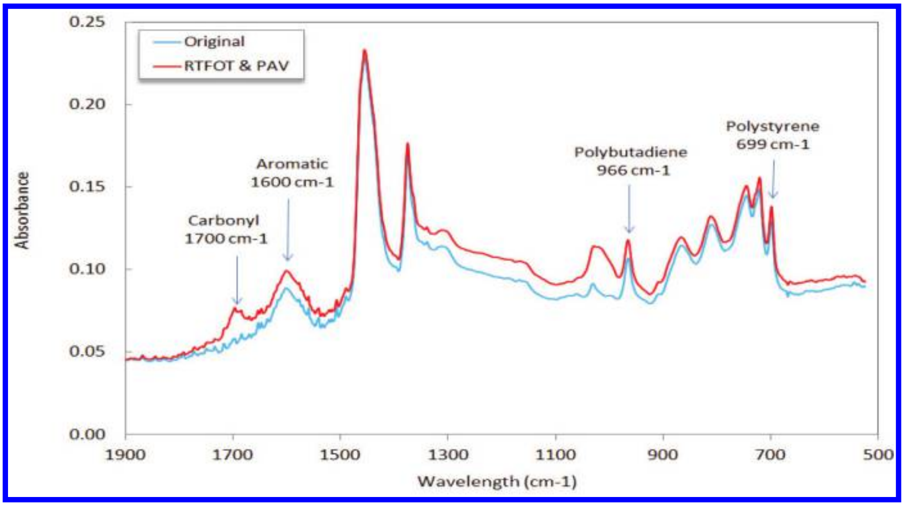

Figure 7. FTIR spectra of 50/100-75 SBS before and after aging.

Figure 8. Carbonyl compounds and aromaticity measured by FTIR-ATR.

4 MECHANICAL TESTS ON ASPHALT FIELD CORES

Several types of tests were performed on asphalt field cores, including stiffness measurement and repeated creep test. Based on stiffness results at 10°C, aging indices of the asphalt mixtures, defined as relative increase in stiffness modulus per year in percentage, are calculated. As shown in Figure 9, in both wearing course and binder course, the asphalt concretes made of the SBS-binders are less aged than those with other binders. This is in agreement with binder test results. Unexpectedly, in the base course, the mix with the SBS modified binder display a slightly higher aging index than the unmodified one. However, in spite of that, the SBS modified base course has shown better fatigue

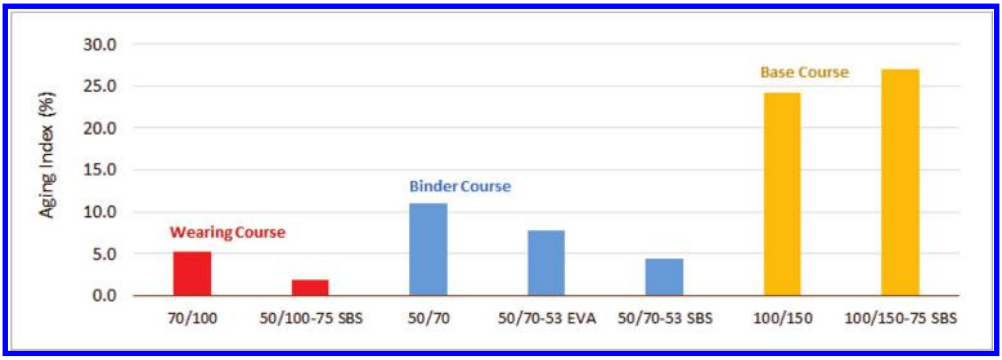

Figure 9. Aging indices of asphalt mixes at 10°C.

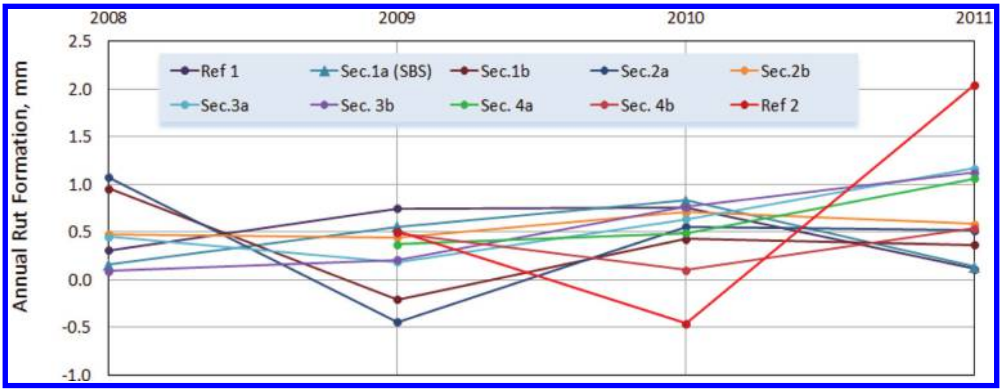

Figure 10. Annual rut formation of different test sections.

resistance than the conventional mix based on laboratory fatigue testing on field cores (data not shown).

Figure 9 also reveals that the aging of the base course mix is much higher than the wearing course and binder course mixes. Notice that in addition to the low binder content in the base course mix, the air voids content of the mix is about 5%; however in the wearing course and binder course, the air voids content is less than 2% (Fig. 1). An easier access to oxygen due to higher air voids combined with thinner binder layer (lower binder content) has caused a higher degree of aging for the base course mix.

5 FIELD PERFORMANCE OF THE TEST ROAD

The performance of the test road has been monitored since its opening to traffic. Annual field measurements and inspection show that all the sections are in good conditions. After 6 years traffic (2012), the rut depth measured on the wearing course was less than 7 mm, and rather small differences (about 2 mm) were found between the different sections. In Figure 10, the annual rutting in asphalt concrete layers estimated with Road Surface Tester (RST) between 2008 and 2011 is compared for different sections. In the estimation, wear rutting caused by studded tires is excluded. In addition to rutting, other deteriorations, such as stripping and low temperature cracking, have not been seen on the test road. To make definite comparisons on performance, a longer time of follow-up of the test road is obviously needed.

6 CONCLUSIONS

The polymer modified binders studied in this paper demonstrate better rheological properties than the unmodified bitumens, even after several years in the test road. These include higher strain recovery and lower non-recoverable compliance (Jnr) at high temperatures, and lower stiffness at low temperatures. For the SBS modified binders, good aging resistance is found. The high resistance to aging for the SBS modified binders is confirmed by stiffness measurements on asphalt field cores. The variation on binder rutting parameters (MSCR) has not yet been validated by the field performance of the test sections. So far, all the test sections are in good conditions and differences in rut depth are small. It is, however, believed that the improved binder properties should be beneficial to pavement performance. This is expected to be confirmed by a longer time of follow-up of the test road.

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