Long-term durability of polymer modified bitumen in bridge deck pavements

Xiaohu Lu[1, a], Bengt Sandman[1], Henrik Arnerdal[1], Helene Odelius[1]

[1] *Nynas, Nynäshamn, Sweden*

[a] xiaohu.lu@nynas.com

Digital Object Identifier (DOI): dx.doi.org/10.14311/EE.2016.044

ABSTRACT

Polymer modified bitumen (PMB) has been successfully used for bridge deck application for a long time. In 1997, a large suspension bridge named the High Coast Bridge was built on the highway E4 over the Ångermanälven River in Northern Sweden. For this bridge, all asphalt layers were constructed using polymer modified binders, including asphalt concrete surface course. In spite of tough climatic condition (a wide temperature span from ca -40°C to 30°C and large temperature fluctuations) and a high traffic intensity, the asphalt pavement system on the steel deck has performed excellently. After almost 15 years of service, it was still in a good condition. To prevent the occurrence of potential stone loss which would subsequently damage the paint of the steel bridge, the Swedish Transport Administration decided to replace the top layer in 2012 with a very similar bituminous material. During the re-surfacing operation, asphalt samples were collected to study the durability of the modified binder. Extensive chemical and rheological tests were carried out on the recovered binder, as well as on the original PMB sample. For comparison, laboratory aging tests were also performed. The results demonstrate that, after a long time period of service, the modified binder is still very elastic and retains good low temperature and high temperature properties. Furthermore, the modified binder shows a great resistance to aging. It is evident that the durable PMB has contributed considerably to the high performance of the bridge asphalt pavement. Long lasting asphalt pavements with the same PMB are also seen on the Öresund Bridge, a heavily trafficked bridge between Sweden and Denmark which was inaugurated in 2000. Based on those good experiences with PMB, polymer modified binders especially designed for bridge applications have been developed further, and more examples are shown in this paper.

Keywords: Ageing, Durability, Modified Binders, Polymers

1. INTRODUCTION

Modern bridges can be categorized into two classes, those with steel decks and those with concrete decks. The use of asphalt on these types of bridge decks has been practiced for a long time [1-3]. Apart from the standard requirements for road paving, such as resistance to permanent deformation and resistance to cracking, asphalt pavement on bridge decks has to meet certain additional demands. First, asphalt layers must protect and seal the underlaying supporting structure to ensure a long service life for bridges [4]. They must protect bridge structure from surface water or moisture, especially salted water from de-icing agents or when bridges are over sea water, to avoid deterioration or corrosion. In case of a steel bridge of long suspension, large deflections due to dynamic traffic loadings are expected, suggesting deck pavements also need to tolerate large deformation and at the same time have to be exceptionally resistant to fatigue.

In general, bridge decks are covered by a pavement system that consists of four different layers: a sealing/bonding layer (primer), a waterproofing layer, a protecting asphalt layer, and a surface asphalt layer [4]. Different requirements are demanded for different layers; for a surface asphalt layer, those include sufficient resistance against deterioration, resistance against oil, water, less susceptibility to weather conditions, protection of the deck plate and the waterproofing layer, high stability, resistance to fatigue, resistance to permanent deformation, and possibility to spread traffic loading [4]. To meet all these requirements, it is rather difficult to use asphalts with conventional bitumens, especially in regions having a wide span of climatic temperatures. Thus, polymer modified bitumens (PMBs) are often the best choice for asphalt paving on bridge decks thanks to their recognized good performance.

In this paper, polymer modified bitumen used in the surface asphalt layer on the High Coast Bridge in Sweden is investigated with respect to its long-term durability. Pavement performance of the bridge was inspected after 15 years in-service. Samples of the modified binder (original, recovered from the bridge, and laboratory aged) are evaluated by different test methods, including various conventional and rheological tests, as well as chemical analyses. Applications of the modified bitumen to other bridges and its performance are also described in the paper.

2. HIGH COAST BRIDGE

2.1 Bridge construction

The High Coast Bridge (Högakustenbron in Swedish) is a suspension bridge over the Ångermanälven River and on the highway E4 in northern Sweden. It is one of the longest suspension bridges in Scandinavia with a total length of about 1800 meters. The bridge was constructed between 1993 and 1997 and was officially opened on 1 December 1997. Very extensive laboratory and field investigations were carried out on different waterproofing and pavement systems intended for the bridge [2]. The system finally selected is illustrated in Figure 1. It consists of two layers of epoxy, an SBS-modified bitumen sheet layer, a binder course of polymer modified mastic asphalt (PGJA 8), and a wearing course of polymer modified stone mastic asphalt (ABS 11). Normally, asphalt concrete ABS 11 contains about 6.5% binders (by weight) and 3.5% air voids (by volume). For the whole waterproofing and pavement system, the total thickness was set to 60 mm to avoid increasing the weight of the bridge more than necessary. In asphalt surface and binder layers, two different modified binders (PMB 20 and PMB 32) with styrene-butadiene-styrene (SBS) block copolymers were selected. Typical properties of the modified binders are shown in Table 1. When selecting the bituminous materials, special attention was paid to asphalt low temperature properties and fatigue performance, which were characterized by the Thermal Stress Restrained Specimen Test (TSRST) and the German fatigue test for steel bridges (ZTV-BEL ST-92), respectively [2].

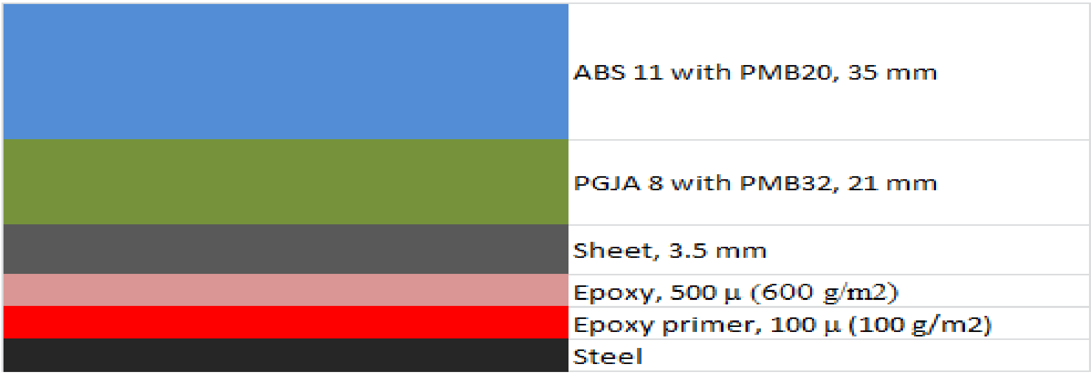


Figure 1: Waterproofing and paving system selected for the High Coast Bridge

Table 1: Typical properties of the PMBs selected for the asphalt layers on the High Coast Bridge deck

Properties	Method	PMB 20	PMB 32
Penetration at 25°C, mm/10	EN 1426	110	60
Softening point R&B, °C	EN 1427	80	85
Dynamic viscosity Brookfield at 180°C, cP	ASTM D 4402	250	200
Fraass breaking point, °C	EN 12593	-25	-12
Elastic recovery at 10°C, %	EN 13398	95	80

2.2 Pavement performance

The High Coast region is exposed to a wide temperature span and large temperature fluctuations. The average temperature in winter is around -20°C with the coldest weather down to -40°C, while in the summer temperature can be as high as 30°C. Moreover, as a part of the highway E4 in northern Sweden, high traffic density (ADT of about 3000 vehicles/day) and a high proportion of studded tyres are seen for the bridge. In spite of the tough climatic and traffic conditions, the asphalt pavement on the bridge has performed excellently since its opening to traffic in 1997. After almost 15 years in service, no cracks (fatigue cracking or low temperature cracking) were observed, and there was some very limited rutting (permanent deformation plus wearing). This was shown by a field inspection made in June 2012 (Figure 2), and was also confirmed by performance data recorded in the Swedish Pavement Management System (PMS) database [5]. In Figure 3, rutting is shown for the span part of the bridge (about 1200 meters). As can be seen, the rutting development over the years is rather insignificant.

Figure 2: The High Coast Bridge in November 1997 and its pavement surface conditions in June 2012

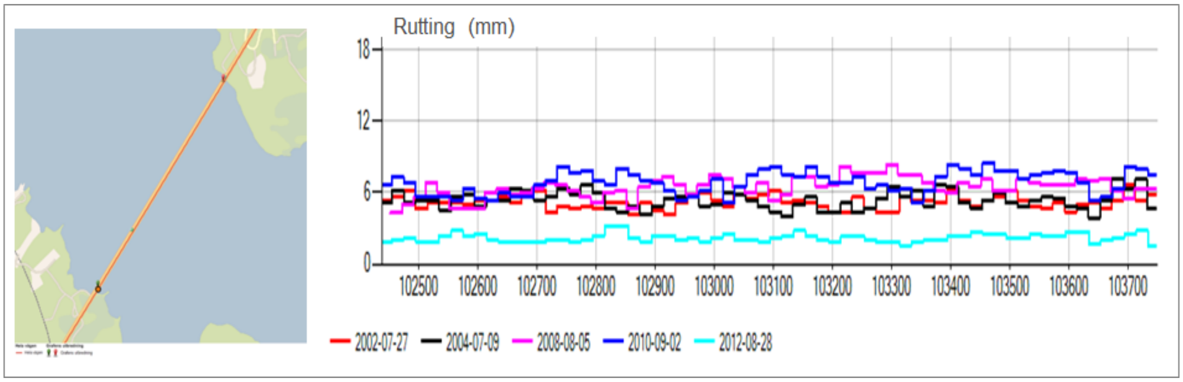


Figure 3: Rutting on the bridge (northbound) recorded in PMSv3 (Zero level on 2012-08-28 was after the re-surfacing of the bridge)

As a preventive measure for potential stone loss which would subsequently damage the paint of the steel bridge, the Swedish Transport Administration decided in 2012 to replace the top asphalt layer (ABS11 with PMB20) with a similar bituminous material (ABS11 with PMB Endura F2, Cf. Section 4) although the top layer was still in a very good condition. During the re-surfacing operation, asphalt samples were collected to study the durability of the modified binder. Test methods and test results are presented and discussed in the following sections.

2.3 Characterization of polymer modified bitumen

2.3.1 Test methods

The modified binder was extracted from the milled asphalt samples in accordance with the standard procedure EN 12697-3. This method uses dichloromethane as a solvent to extract bitumen from asphalts and uses a rotary evaporator to remove the solvent at the end. For laboratory aging, RTFOT (EN 12607-1) followed by PAV (EN 14769) at 100°C were conducted. RTFOT and PAV simulate binder's short- and long-term aging, respectively. The recovered and laboratory aged binders along with original PMB were tested by various conventional methods, such as penetration, softening point, elastic recovery and fracture toughness. Further evaluation was carried out using rheological measurements and chemical analyses.

In the rheological evaluation, temperature-frequency sweeps were performed from -30 to 100°C and from 0.1 to 100 rad/s using a dynamic shear rheometer (DSR, Physica MCR 501 from Anton Paar). Parallel plates of different geometries were employed at different temperature ranges: 25 mm in diameter (PP25) and 1 mm in gap for temperatures of 10 – 100°C, and 8 mm (PP08) diameter and 2 mm gap for -20 to 30°C. At low temperatures from 0°C down to -30°C, parallel plates of 4 mm in diameter (PP04 or so called 4-mm DSR) was also used [6]. Detailed descriptions of specimen preparation and the test procedure can be found in [7].

To further assess the properties at high temperatures, multiple stress creep and recovery (MSCR) [8, 9] tests with DSR were carried out with 25 mm plates at 60°C. In the MSCR tests, the sample is loaded at constant stress for 1 s, then allowed to recover for 9 s. Ten creep and recovery cycles are run at 100 Pa stress followed by ten more cycles at 3200 Pa stress. The measured parameters include strain recovery (R3200) and non-recoverable compliance (Jnr).

Moreover, binder low temperature properties were evaluated using a bending beam rheometer (BBR, Cannon Instrument). The BBR tests were conducted on the recovered and original binders at -18°C and -24°C.

As for chemical characterization, tests were performed by means of Fourier transform infrared spectroscopy with attenuated total reflectance (FTIR-ATR), as well as by gel permeation chromatography (GPC). In FTIR-ATR, a very small amount of bitumen sample (without preparing a solution) was directly placed on an ATR crystal and IR reflection from the sample was measured. Spectra were recorded at wavelengths ranging from 600 to 4000 cm^{-1}, which characterize bitumen functional groups (e.g. carbonyls at around 1700 cm^{-1} and aromaticity at 1600 cm^{-1}) and identify polymers in in the modified binders.

In GPC, an Alliance 2690 Separation Module (Waters) with a refractive index detector was employed. For the mobile phase, tetrahydrofuran (THF) was chosen. This solvent was also used to prepare sample solutions of 0.4% (by weight). Using GPC, the modified binders were fractionated generally based on molecular sizes.

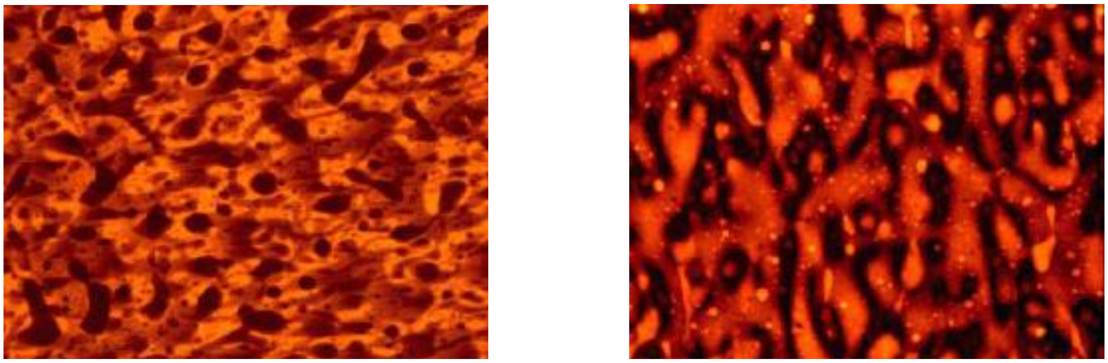
Additionally, samples of the modified binder were investigated by microscopy.

2.3.2 Results of conventional tests

The results obtained with conventional methods are shown in Table 2. As indicated, after a long service time (15 years) on the bridge, the polymer modified bitumen has little change in softening point. The modified binder also retains very good low temperature properties as indicated by fracture toughness test and Fraass breaking point. In addition, a very small change is observed in the elastic recovery, both the original and recovered binders are highly elastic. This is attributed to strong polymer networks built within the binder, as illustrated by micro-photos in Figure 4. Even after the short- and long-term aging (RTFOT+PAV), continuous polymer phases are seen in the binder. Microscopies were also taken on the recovered binder, but not shown in this paper as they may be not so relevant due to possible solvent effects from the extraction and recovery processes.

Table 2: Results of conventional tests

Analysis	Method	Original PMB	Recovered PMB
Penetration at 25C, 1/10 mm	EN 1426	109	54
Softening point R&B, °C	EN 1427	83.5	81.0
Fraass breaking,° C	EN 12593	-25	-20
Elastic recovery at 10°C, %	EN 13398	98	80
Fracture toughness temp, °C	CEN/TS 15963	< -30	-23



Original

After RTFOT-PAV

Figure 4: Micro-photos taken by transmitted white light for the modified bitumen before and after aging (magnification 100x)

2.3.3 Rheological measurements

It is known that the viscoelastic properties of bituminous binders have significant impacts on asphalt mix properties and field performance. A binder may exhibit either elastic or viscous behavior, or a combination of these (viscoelastic), depending on testing temperature and observation time. Viscoelasticity may be assessed by the phase angle, where 90 and 0° are measured for purely viscous liquids and ideal elastic solids, respectively. In Figure 5, the phase angle as a function of temperature is shown for the modified binder at 10 rad/s over a temperature range from -30 to 100°C. For comparison, an unmodified bitumen of 70/100 pen is also shown. The rheological measurements were carried out using parallel plates of different diameters, 4 mm (PP04), 8 mm (PP08) or 25 mm (PP25), depending on temperature ranges (Cf. Section 2.3.1). As can be seen from Figure 5, the polymer modified bitumen displays much higher elasticity (lower phase angles) at temperatures of about 20 to 90°C than the unmodified bitumen. The modified binder also retains considerable elasticity after laboratory aging and 15 years in the field. This is believed to be beneficial to the deformation resistance of the asphalt on the bridge. Moreover, at low temperatures (< -10°C), the modified binder shows higher phase angles than 70/100 bitumen, implying higher flexibility for the modified binder.

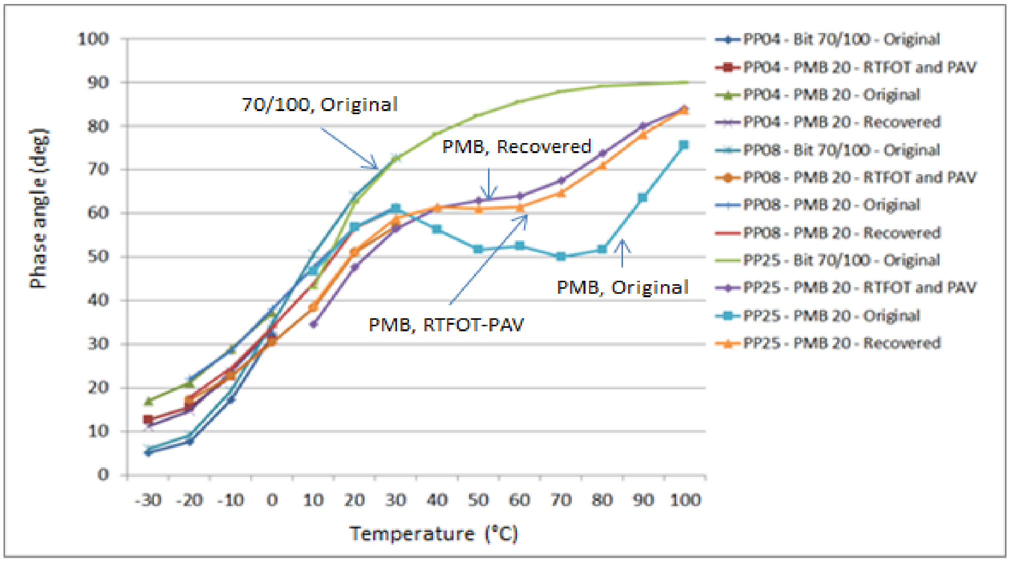


Figure 5: Phase angle as a function of temperature at 10 rad/s

In Figure 6, the data generated by temperature-frequency sweeps are plotted in Black diagrams. In these diagrams, the complex moduli are plotted *versus* the phase angles. The Black diagrams provide information on structural or chemical changes during the rheological tests. As shown in Figure 6, at binder stiffness levels of importance to asphalt rutting, high elasticity (low phase angles) is observed for the modified bitumen. For example, at the complex modulus of 10 kPa, the modified binder displays phase angles of 20° to 30° lower than that of the pen bitumen. The modified binder with enhanced elasticity should also be beneficial in terms of resistance to fatigue, especially for a relatively thin asphalt layer on the bridge where fatigue may be more strain-controlled.

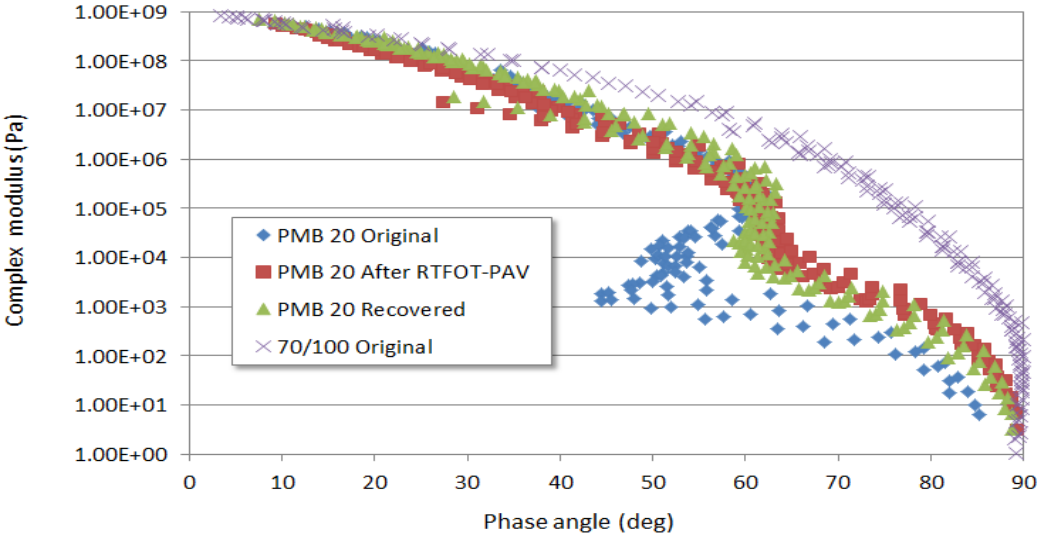


Figure 6: Complex modulus *versus* phase angle for the polymer modified bitumen (unaged and aged) as well as for a penetration bitumen

To quantitatively evaluate the rutting properties of the modified binder, MSCR tests were performed at 60°C. Values of strain recovery (R3200) and non-recoverable compliance (Jnr) are shown in Figure 7. It is evident that, after 15 years in-service on the bridge, the modified binder still retains higher strain recovery and also lower non-recoverable compliance. According to [9], for heavy traffic (> 3 million ESAL's) and very heavy traffic (> 10 million ESAL's), the maximum values of Jnr 3200 are specified to be 2.0 kPa^{-1} and 1.0 kPa^{-1}, respectively. This would suggest that the modified binder performs according to the heaviest class with respect to deformation resistance, and as described in Section 2.2, high resistance to permanent deformation had been observed for the asphalt layer.

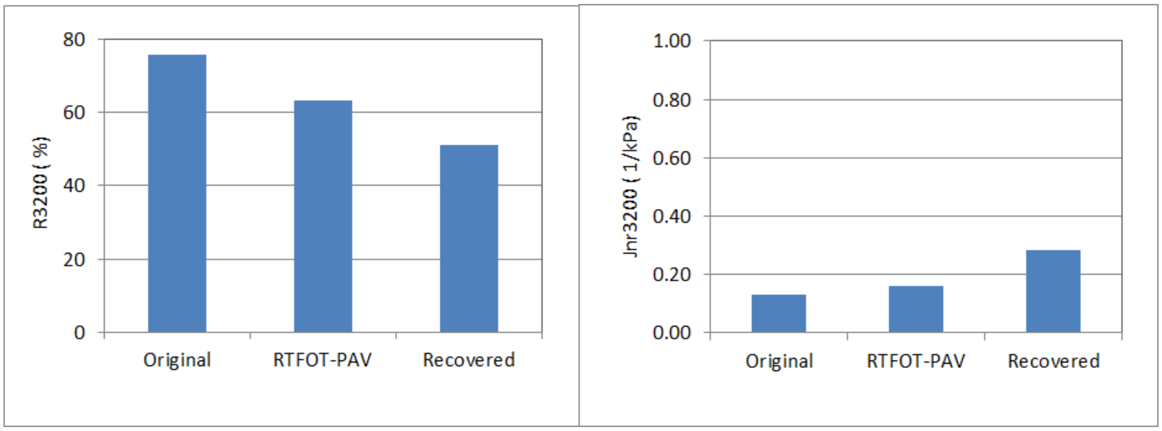


Figure 7: Strain recovery (R3200) and non-recoverable compliance (Jnr) at 60°C

In Figure 8, BBR test results are shown for the original PMB and for the binder recovered from the bridge. At a temperature as low as -24°C, even after 15 years in the field, the modified binder far exceeds the low temperature requirement as specified in the American SuperPave binder specification (maximum stiffness at 300 MPa and minimum m-value at 0.300). On the asphalt layer on the High Coast Bridge, no cracks were observed.

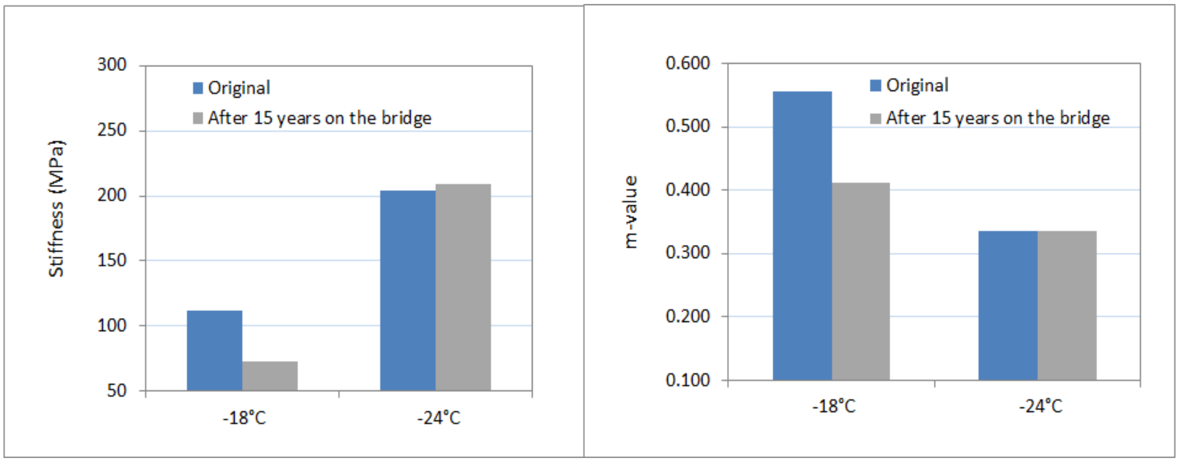


Figure 8: Stiffness and m-value measured at different low temperatures

2.3.4 Chemical tests

It is well-known that oxidation causes hardening and embrittlement of bitumen, and consequently contributes to the deterioration of an asphalt pavement. By using a polymer modification, the oxidative age-hardening of the bituminous binders can be slowed down. This is partly because polymer modified binders allow the use of softer base bitumen, and at the same time, aging induced chemical and structural changes of polymers may further balance the consistency of the modified binders [14].

As shown by GPC measurements in Table 3, for the modified binder (PMB20) studied in this paper, laboratory aging and many years in-service increase the molecular weight for the bitumen part, while for the SBS polymer, an opposite change is observed. The decrease in polymer sizes is believed to compensate for the oxidative age-hardening of the bitumen components. The well-retained desirable properties for the modified binder as shown in previous sections are mainly attributed to a strong presence of the polymer and/or fragments of the polymer, as illustrated by FTIR in Figure 9, for the polybutadiene blocks at a wavelength of about 966 cm^{-1} and for the polystyrene blocks at about 699 cm^{-1}.

Table 3: Molecular weights (weight average) measured by GPC for the modified binder

Samples	Bitumen part	Polymer part
Original	2170	202000
RTFOT-PAV	3600	139000
Recovered	3900	184000

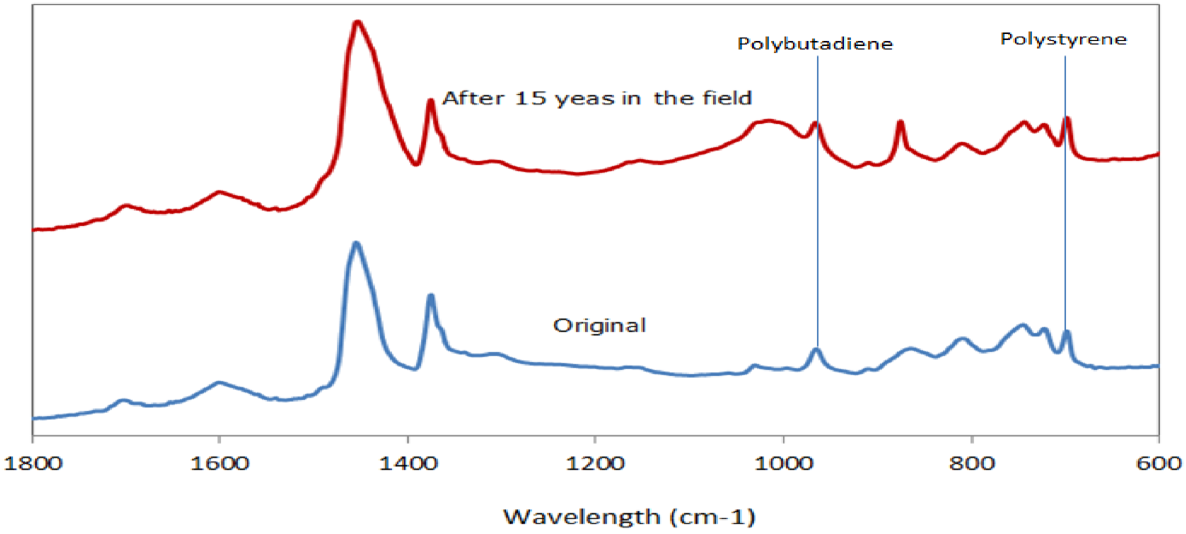


Figure 9: FTIR spectra of the SBS polymer modified binder

3. ÖRESUND BRIDGE

The Öresund or Øresund Bridge (Swedish: Öresundsbron, Danish: Øresundsbron,) is a double-track railway and motorway bridge on highway E20 across the Öresund strait between southernmost Sweden and Denmark (Figure 10). The bridge is about 8 km long and was inaugurated on the 1st of July 2000 [10]. The waterproofing and paving system used on this concrete bridge deck consisted of two layers of epoxy primer, 5 mm polymer modified bituminous sheet, 30 mm polymer modified mastic asphalt (PGJA 11), and 45 mm wearing course made with polymer modified stone mastic asphalt (ABS 16) [11]. The polymer modified binders used in the asphalt wearing course and binder course were the same as on the High Coast Bridge.

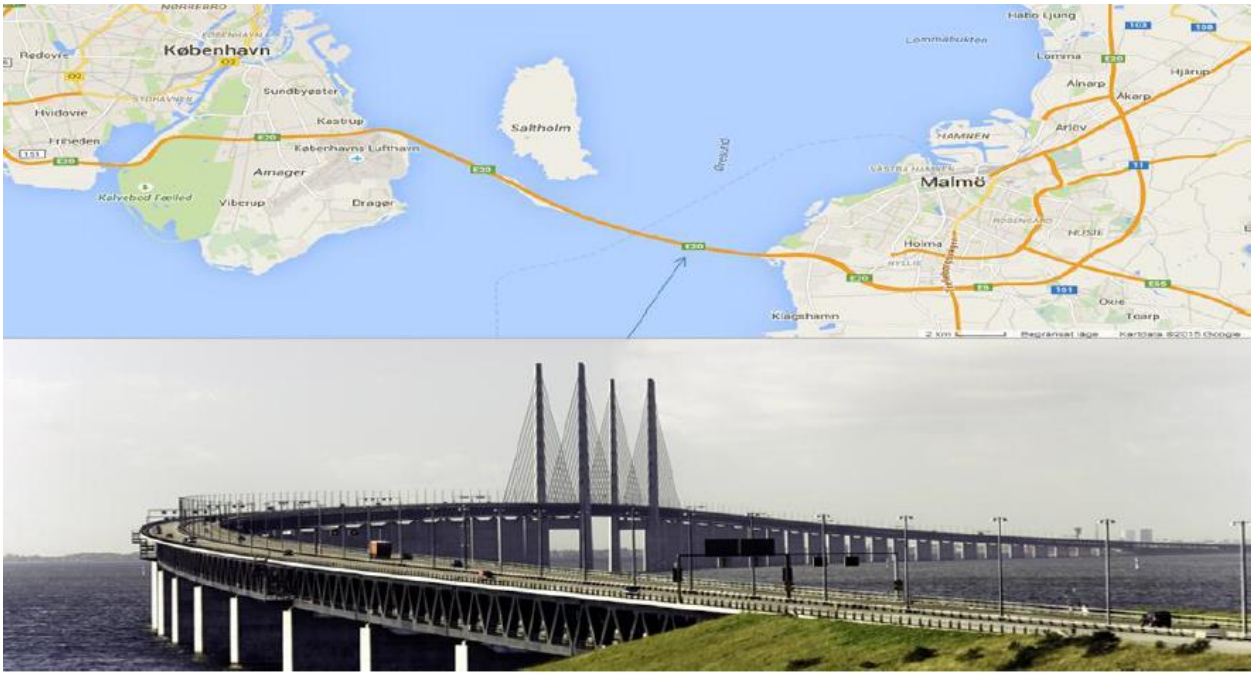


Figure 10: The Öresund Bridge between Sweden and Denmark

The bridge has been heavily trafficked since its opening in 2000. An estimation based on [12] shows that over 85 million vehicles had travelled through the bridge during the past 15 years (ADT > 15000 vehicles/day). In spite of such high traffic loading for such a long time, the asphalt pavement with polymer modified bitumen continues to perform well.

4. SUNDSVALL BRIDGE

Based on the good experience and excellent field performance of the modified binder on the bridges described above, a similar PMB product (Endura F2) was further developed especially for bridge applications. It is a highly polymer modified binder with SBS. As indicated in Table 4, this PMB has a high elasticity and exceptional flexibility, suggesting it can sustain large strains / stresses at a wide range of temperatures. Also, an excellent aging resistance is shown, as assessed by RTFOT. The modified bitumen has been used in the re-surfacing of the High Coast Bridge (Cf. Section 2.2), and also in a new bridge built on highway E4 in Sundsvall in 2014 (Figure 11). The total length of the Sundsvall Bridge is about 2100 meters, of which 1420 meters is over water. According to an estimation made by the Swedish Transport Administration, approximately 17 000 vehicles per day will drive on the bridge [13]. To evaluate the modified binder used, regular follow-up on asphalt performance of the bridge will be carried out by using the Swedish PMSv3 [5].

Table 4: Typical properties of PMB developed for bridge application

Original			
Penetration at 25°C, mm/10, EN 1426	100	Force ductility at 5°C, J/cm^2, EN 13703 /EN13589	2
Softening point R&B, °C, EN 1427	90	Fraass breaking, °C, EN 12593	-25
Elastic recovery at 10°C, %, EN 13398	95	Fracture toughness, °C, CEN/TS 15963	-30
After RTFOT			
Penetration at 25°C, EN 1426	80	Elastic recovery at 10°C, %, EN 13398	85
Softening point R&B, °C, EN 1427	85	Fraass breaking, °C, EN 12593	-25

Figure 11: Sundsvall Bridge [15]

5. CONCLUSIONS

It is well recognized that performance demands for bituminous materials used on bridge decks are normally higher than those for road paving. In this paper, an SBS polymer modified bitumen used for such applications has been studied. Field observations show that asphalt pavements with the polymer modified bitumen on bridge decks perform excellently over a long time. Despite high traffic loading and tough environmental conditions such as a wide temperature span and large temperature fluctuations, no cracks (fatigue or low temperature) and only very limited rutting were observed on the asphalt layer after 15 years. Laboratory tests have shown that, even after this long time in service, the polymer modified bitumen is still very elastic and also retains good low temperature and high temperature properties. The well retained desirable properties for the modified binder are attributed to a strong presence of the polymer and/or polymer fragments in the binder. Furthermore, the modified binder displays a great resistance to aging, as assessed by changes in its mechanical and rheological properties. Evidently, the long-term durability of the modified bitumen has provided higher performance to the bridge deck asphalt pavements. With the successful application cases, the sustainable benefits of using polymer modified bitumen in bridge deck pavements are demonstrated.

ACKNOWLEDGMENTS

The authors would like to acknowledge Kenneth Olsson (Skanska) for supporting this study. Lena Strand (Stockholm City) is acknowledged for her initial involvement in the project. The authors also wish to thank their own technical staffs for providing laboratory assistance.

REFERENCES

[1] Surfacing of concrete bridges, V. Wegan, Danish Road Institute, Report 106, 2000.
[2] Polymer modified waterproofing and pavement system for the high coast bridge in Sweden, Y. Edwards, Westergren P., VTI Rapport 430A, 2001.
[3] Waterproofing membranes for concrete bridge decks - A synthesis of highway practice, NCHRP Synthesis 425, Transportation Research Board, 2012
[4] Asphalt pavements on bridge decks, EAPA position paper, June 2013.
[5] The Swedish Transport Administration, https://pmsv3.trafikverket.se/
[6] A new low-temperature performance-grading method using 4-mm parallel plates on a dynamic shear rheometer, C. Sui, M.J. Farrar, P.M. Harnsberger, W.H. Tuminello, T.F. Turner T F, TRB Annual Meeting 2011.
[7] Rheological testing of bitumen at low temperatures with 4-mm DSR, X. Lu, P. Uhlback, H. Soenen, The 8th International RILEM Symposium, Ancona, Italy, 7-9 October 2015.
[8] Standard test method for multiple stress creep and recovery (MSCR) of asphalt binder using a dynamic shear rheometer, ASTM Standard D7405-10a.
[9] Performance-graded asphalt binder using multiple stress creep recovery (MSCR) test, AASHTO MP19, 2010.
[10] Vägen över öresund, Øresundsbro Konsortiet, Jan 2005.
[11] Erfarenheeter från Øresundsbron, L. Emanuelsson, http://www.vegvesen.no/, accessed 2015-07-09
[12] Traffic data, http://se.oresundsbron.com/
[13] www.trafikverket.se/e4sundsvall
[14] Chemical and rheological evaluation of ageing properties of SBS polymer modified bitumens, X. Lu, U. Isacsson, Fuel, Vol. 77, 1998, p.961-972.
[15] A sustainable bridge project, Stopp & Belägg, No. 3, 2014, in Swedish.