Performance assessment of hot mix asphalt with chemically stabilized rubber bitumen

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ABSTRACT

The use of crumb rubber from vehicle tyres in hot mix asphalt production has been a very promising option in the field of waste recycling and sustainability. The disposal of used vehicle tyres has been a serious and difficult issue. Due to their indestructible nature the options are burning or disposal, none of these are desirable in our global environment.

The trials for using crumb rubber in hot mix asphalt started in the 1920s; these early applications used the so called dry method, where the rubber is considered as part of the aggregate instead of the binder. This method did not deliver the expected higher performance, and researchers have been looking into the so called wet process since the 1960s, where the rubber is added to the binder, modifying its properties. The modified binder is then added to the aggregate during asphalt production. Although many countries utilise the crumb rubber using the wet process, there is an ongoing problem with this technology, similarly to the application of polymer modified bitumens (PmBs): the storage stability of the product. This short-term segregation problem has been preventing the wide application of crumb rubber bitumen in road construction.

Additionally, the high viscosity of product may cause difficulties during manufacturing and paving which should be considered when selecting aggregate grading.

MOL Plc. developed and patented a procedure for producing chemically stabilized rubber bitumen (CSRB); the pilot scale production started in 2012 and the facilities are capable to produce 5000 tonnes of CSRB – equivalent of 150,000 tyres – in their Zala Refinery, Hungary.

This paper discusses an asphalt research program conducted at Budapest University of Technology on a 10mm nominal aggregate size wearing coarse hot mix asphalt. This study presents the comparative analysis of asphalts containing PmB and CSRB separately. Prepared samples were subjected to performance based and related mechanical testing. The findings summarised in this paper suggest that performance of asphalt mixes produced with CSRB binder are similar or equivalent to asphalt mixes produced with PmB with regard to moisture sensitivity, stiffness and wheel tracking, while the low temperature cracking test showed higher and superior performance.

Keywords: Low-Temperature, Mechanical Properties, Reclaimed asphalt pavement (RAP) Recycling, Rubber, Storage stability

1. INTRODUCTION

Pavement technology research focuses worldwide on the increased performance of different pavement layers, providing value-for-money solutions for the road agencies. Pavement technology research has delivered solutions, such as polymer modified bitumens (PmB), to the problem of ever-increasing traffic volumes and traffic loads; these products are increasingly utilised worldwide and they provide superior performance. The disadvantage of the PmB application is the high costs associated with the additives used in the manufacturing process; to address the need for lowering the costs, crumb rubber bitumen (CRM), also referred to as rubber modified bitumen (RmB), is used by many countries. The application of RmB, manufactured from used vehicle tyres, yields similar performance as provided by PmBs, however, at lower costs. In addition to the benefits, there is a sustainability aspect of the application. The disposal of used vehicle tyres has been a serious and difficult issue worldwide. Due to their indestructible nature, the treatment options are burning or disposal; these solutions are not desirable in our global environment. The application of RmB in high-performance road construction material could therefore contribute to eliminating this environmental problem.

The research work presented in this paper provides performance assessment of a chemically stabilised RmB, and comparison with control binders, such as a plain bitumen and a PmB. Following the performance assessment of the bitumens, the work was extended to asphalt mixes produced with these binders; mixes were subjected to performance-based asphalt tests.

1.1 Processing the crumb rubber - the dry and wet method

Trials for using crumb rubber in hot mix asphalt started in the 1920s; based on long-term observation it was found that by adding crumb rubber to the asphalt made it less prone to cracking and increased the in-service life of the asphalt pavement.

Crumb rubber can be added by using two different processes, the so-called dry and wet methods [1, 2]. Early applications used the dry method, where the rubber was considered as part of the aggregate instead of the binder. In this process the crumb rubber is added directly to the pug mill at the asphalt plant and the rubber is considered as part of the aggregate skeleton. Since the rubber is part of the filler/sand fraction, the performance benefits cannot be realised to a great extent [3]. The dry method did not deliver the expected higher performance, and researchers have been looking into the wet process since the 1960s, where the rubber is added to the binder by modifying its properties. The modified binder, preferably produced at a bitumen processing plant, is then delivered and added to the aggregate during asphalt production. In this process the rubber reacts with the base bitumen, swelling and partial dissolution of the rubber occurs and it absorbs the oils from the bitumen into the rubber matrix [2, 4].

1.2 Stability and segregation of the crumb rubber binder

Although many countries utilise the crumb rubber using the wet process, there is an ongoing problem with this technology, similar to the application of PmB, namely the storage stability of the product. This short-term segregation problem has been preventing the wide application of crumb rubber bitumen in road construction.

MOL Hungarian Oil and Gas Plc. and the University of Pannonia developed a procedure [5, 6] for producing chemically stabilised rubber bitumen (CSRB). The process was patented in 2009 and the pilot large-scale production started in 2012 at MOL's Zala Refinery, in Hungary. The facilities are capable of producing 5 000 tonnes of chemically stabilised rubber bitumen – equivalent of 150 000 tyres. Following the research and development phase and road trials, a speciation framework was issued in September 2013 [7]. The stabilised rubber modified bitumen can be transported and, for limited time, stored in tanks at the asphalt plant. The RmB binder is specified by penetration and softening point, similar to PmBs [6, 7].

The maximum particle size of the rubber in this process is 1.25 mm; the rubber is extracted from used tyres at ambient temperature by mechanical processing. The RmB binder is produced then in a closed system, therefore degradation gases, developing during the process, are captured and cannot enter into the environment [6]. The manufacturing process of the RmB binder is discussed in detail by Geiger et al. [5, 6, 8]. It should be noted that the process applies an additive which promotes the dissolution of the rubber and decreases the segregation of undissolved particles. It also decreases the viscosity of the final product to a suitable level for asphalt mixing and paving operations.

In this paper the chemically stabilised rubber bitumen is referred to as RmB – a general product designation.

1.3 Objectives of the research work

In this study an asphalt research program was conducted on an 11 mm nominal aggregate size wearing course hot mix asphalt. Diurnal temperature variations in winter increases the risk of low temperature cracking in the top pavement layer (wearing course) under the Central European climate. Therefore this study primarily focused on the investigation of a wearing course type mix and further work is required to assess the benefit of RmB in structural asphalt layers.

The bitumen tests were conducted by MOL and asphalt tests were performed by the Asphalt Laboratory of the Budapest University of Technology and Economics. The test results were then jointly analysed by the authors of this paper.

In this research work performance-based tests were used for the comparison and assessment of the different binders. The volumetric properties of the different mixes were kept unaltered while the different binders were substituted; on this basis any difference in the mix performance can be attributed to the binder performance and not to the different volumetric properties. The mixes were as follows:

- AC 11 wearing course B50/70, control mix (conventional binder)
- AC 11 wearing course PmB 25/55-65, control mix (PmB binder)
- AC 11 wearing course RmB 45/80-55 mix.

The binder contents of all mixes were 5.1% (by total mass of the mix). The design mix was a proven heavy-duty asphalt, which was extensively used in large-scale productions.

Parallel to the asphalt performance tests the properties of the plain 50/70, RmB and PmB binders were assessed at in-service and handling temperatures; routine binder tests were also completed for conformance. The binders used in this study were sampled by MOL from large-scale production runs.

2. PERFORMANCE ASSESSMENT OF THE RUBBER MODIFIED BITUMEN

2.1 Binder test results - DSR test

DSR tests were performed according to the standard test method for determining the rheological properties of asphalt binder using a dynamic shear rheometer (DSR) [9]. Prior to the temperature-frequency sweep test the strain amplitude was selected at 0.2% strain and no strain sweep test was conducted. The temperature-frequency sweep was performed between 10 and 70 °C for unaged binders and between 20 and 70 °C for rolling thin film oven (RTFO) and pressure ageing vessel (PAV) aged samples. The RTFO and PAV tests were conducted according to EN 12607-1 [10] and EN 14769 [11] respectively. For the DSR test the following parameters were used:

- 10 °C temperature increments
- 16 different frequency values between 0.1 and 100 rad/s
- large diameter plate of 25 mm with 1 mm gap for all temperatures.

Only one set of the frequency-temperature sweep test was completed; based on previous experience it was found that there is negligible variability between duplicate DSR test results [12].

For comparison, the master curves were constructed using the time-temperature superposition principle [13]. The master curve is a continuous function, which can be illustrated as a non-linear S-shaped sigmoid model. The steps described by Petho and Toth [14] were used to develop the complex modulus master curves for the different binders; the results are presented in Figure 1 at the reference temperature of 60 °C. The parameters for each master curve are provided in Table 1.

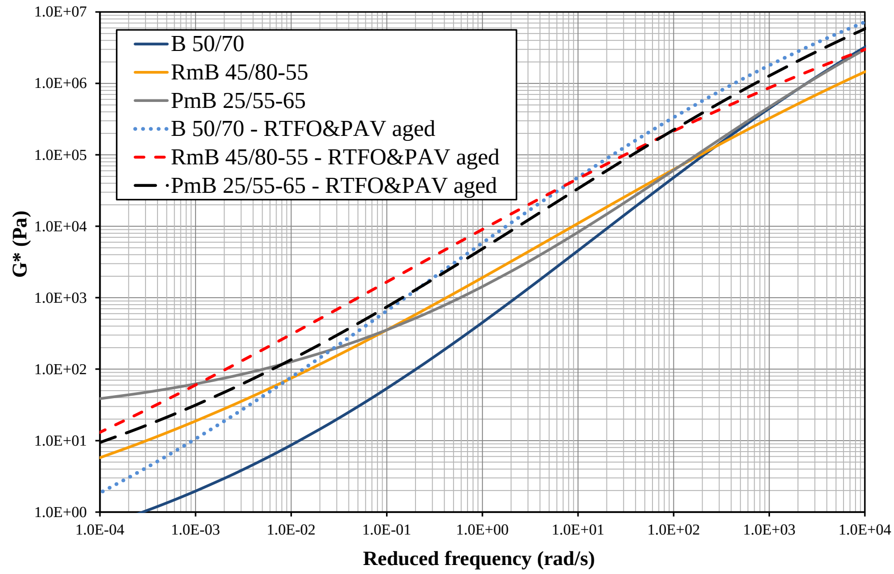

Figure 1: Master curves of different binders at 60 °C

The distinctive difference between the 50/70 plain binder and the modified binders (PmB and RmB) can be seen in Figure 1. It shows that the PmB has the best temperature susceptibility for unaged binders, followed by the RmB and the plain 50/70 bitumen; however, for aged binder the RmB shows the highest stiffness at low frequencies (high temperatures) and the lowest stiffness at high frequencies (low temperatures). For climatic conditions where the summer is hot and the winter is cold, such a characteristic is the most desirable to develop a balanced and high-performing asphalt mix.

Table 1: Master curve parameters

Parameters	B 50/70	B 50/70 - RTFO&PAV aged	PmB 25/55-65	PmB 25/55-65 - RTFO&PAV aged	RmB 45/80-55	RmB 45/80-55 - RTFO&PAV aged
δ	-1.50	-2.44	1.23	-0.62	-1.16	-2.41
α	10.79	11.23	7.42	9.60	10.14	11.31
β	0.47	-0.21	1.05	0.21	0.25	-0.25
γ	0.38	0.34	0.48	0.35	0.30	0.26
C	8292.45	8765.23	8508.65	8534.09	8411.35	8767.58

The rheological parameters of complex modulus and phase angle were combined in Figure 2; it is evident that the RmB binder shows similar characteristics to the PmB binder for both pre- and post-aged conditions.

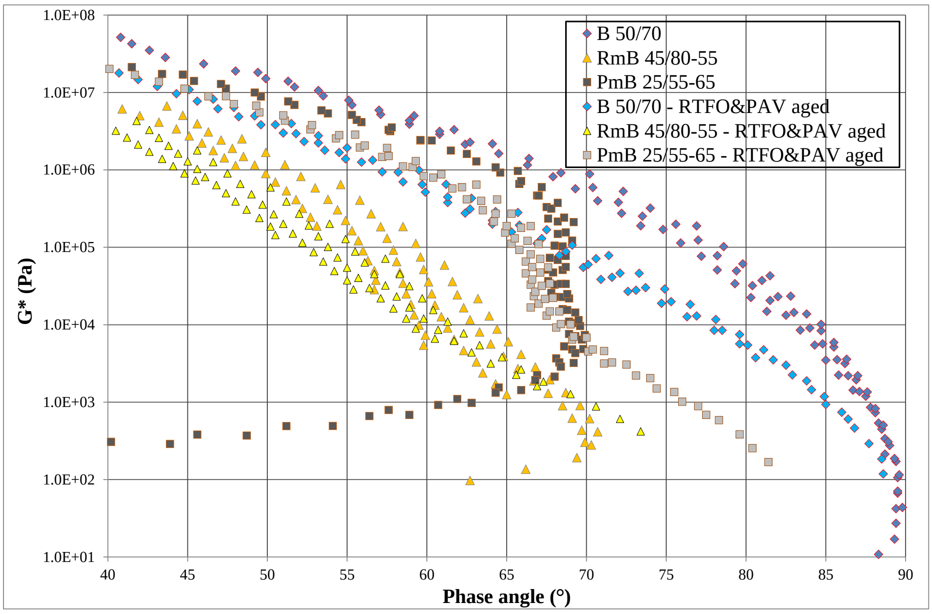

Figure 2: Black diagram of the different binders

For PmB 25/55-65 (modified by 4-5% of linear SBS) and for RmB 45/80-55 (modified by 14-17% rubber) there is a significant increase in G* at low frequencies compared to the conventional bitumen 50/70. The hardening of each binder is indicted by the shifting towards lower phase angle regions as described by Airey [15].

Following the ageing process, the 50/70 and PmB binders show an increase of G* at low and medium temperatures; however, for the PmB there is a decrease of G* at higher temperatures (Figure 1). This can be attributed to the degradation of the SBS copolymer as previously reported by Airey [15]. The changes in the phase angle after RTFO and PAV ageing are negligible for the unmodified binder (50/70) and significant for the PmB binder; at elevated test temperatures there is an increase in the phase angle after ageing.

This phenomenon is, however, not evident for the RmB binder and can be attributed to the high bitumen production temperatures (>200 °C) of the RmB; as explained earlier, the binders are sampled from large-scale production runs. At such a high production temperature the degradation of the RmB occurs, and therefore additional ageing in the RTFO and PAV process at 163 °C and 100 °C does not alter the properties significantly. It should be noted that for PmB the production temperatures are lower compared to the RmB and RTFO and PAV ageing has greater influence on the properties. Figure 2 shows that the effect of ageing is less severe for the RmB binder as the pre-aged and post-aged phase angles are very similar.

2.2 Binder test results - dynamic viscosity test

Dynamic viscosity tests were performed according to EN 13302 [16] in order to establish the viscosity of the different binders at handling temperatures; the test results are summarised in Figure 3. As expected, the RmB has slightly higher viscosities compared to the PmB. This property should be considered in establishing the laboratory mixing and compaction temperatures and the production and paving conditions.

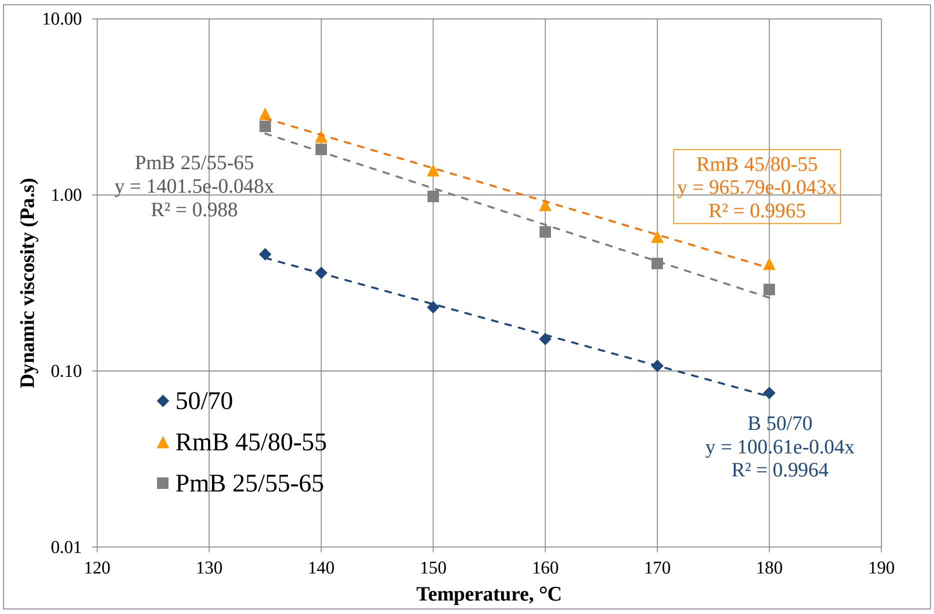

Figure 3: Dynamic viscosity test results

2.3 Binder test results - conventional bitumen tests

The conventional binder tests, i.e. softening point [17], penetration [18] and Fraas breaking point [19] were performed for each binder; the test results are summarised in Table 2.

Table 2: Conventional binder test results

Property	50/70	RmB 45/80-55	PmB 25/55-65
Softening point (°C)	50.2	62	78
Penetration (0.1 mm)	55	47	32
Fraas breaking point (°C)	-17	-21	-20

3. ASPHALT MIX PERFORMANCE ASSESSMENT

3.1 Mix constituents and volumetric properties

Performance-based asphalt tests were used for the comparison and assessment of the different binders. The volumetric properties of the different mixes were kept unaltered; the binder contents of all mixes were 5.1% (by total mass of the mix). Constituent materials were transported directly from the asphalt plant to the laboratory where the asphalt was mixed in batches. Table 3 summarises the particle size distribution (PSD) for the mix.

Table 3: Particle size distribution of the AC11 wearing course asphalt mix

Sieve size (mm)	Percentage passing (%)
16	100
11.2	98
8	71
5.6	56
4	46
2	36
1	24
0.5	18
0.25	14
0.125	11
0.063	8.0

3.2 Determination of the compaction temperature

According to Figure 3, the viscosities of the PmB and RmB binder are higher than the conventional bitumen. The Asphalt Institute mix design manual [20] recommends viscosities for the determination of mixing and compaction temperatures; the asphalt should be heated to 0.17 ± 0.02 Pa.s for mixing and to 0.28 ± 0.03 Pa.s for compaction. Based on the research conducted at the Asphalt Institute, these viscosity ranges can require heating of modified binders to unrealistically high temperatures, causing degradation and oxidation of the binder. There are several different methods developed for the establishment of mixing and compaction temperatures of modified binders; however, these methods usually ignore the asphalt characteristics and only consider the binder properties. A straightforward and simple application was developed by the Japan Modified Asphalt Association [21]. According to the method, for laboratory mix designs the optimum mixing and compaction temperatures are determined by using the equi-viscous principle.
The compaction temperature of the 50/70 plain binder was selected in line with the EN specifications and it corresponds well with the viscosity recommendations by the Asphalt Institute (Figure 3). For the PmB and RmB binders three specimens were compacted at temperatures of 165-175-185 °C and the bulk density was determined. It was found that for the RmB binder the maximum density, compared to the 50/70 reference mix, can be achieved at 175 °C (Figure 4). For the PmB no maximum point was found; however, considering normal asphalt production temperatures, recommended by the binder supplier, 175 °C compaction temperature was selected for the PmB. The above temperatures were used throughout the study for preparing laboratory specimens.

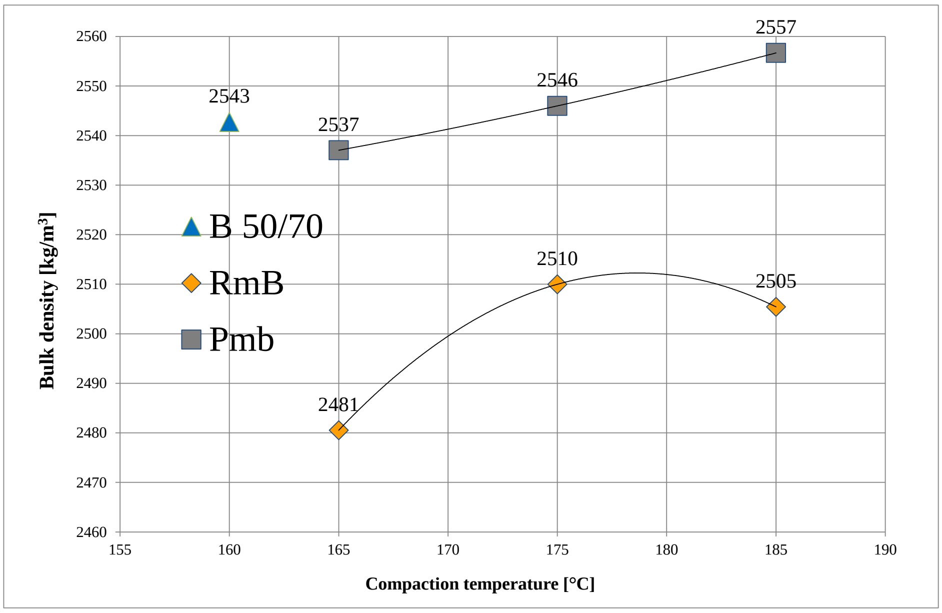

Figure 4: Determination of the laboratory compaction temperatures by using the equi-viscous method

3.3 Assessment of the workability

Laboratory-prepared mixes were compacted according to EN 12697-31 [22] to assess the workability of the mix with different binders. The results are summarised in Figure 5, where the air voids contents relate to mensuration air voids obtained directly from the change of the specimen height during compaction. Based on Figure 3 it was expected that the RmB had slightly higher resistance to compaction compared to the PmB. This is confirmed in Figure 5; at 100 cycles the air voids contents are the highest amongst the mixes tested.

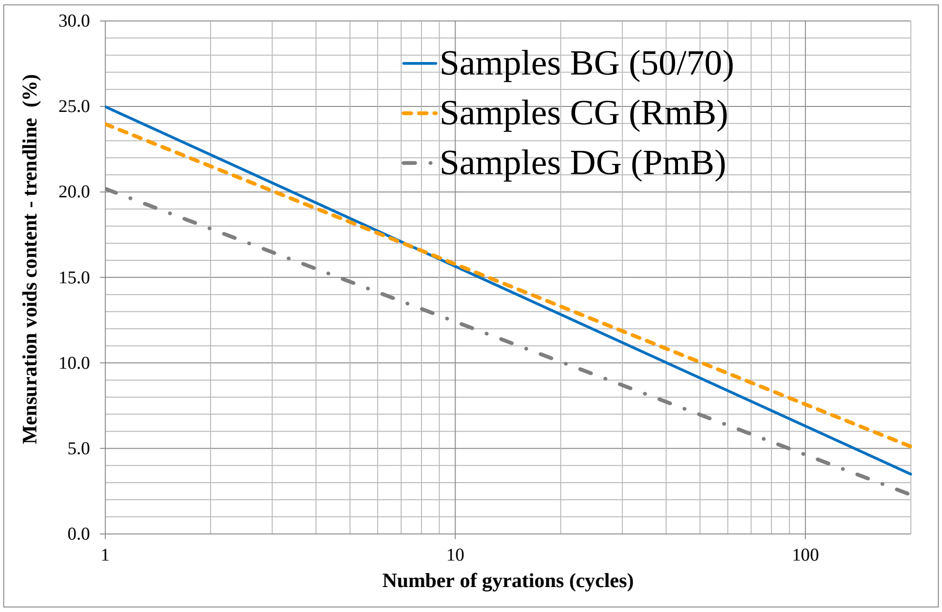

Figure 5: Workability test results of the asphalt mix with different binders

3.4 Stiffness test

The stiffness of the mixes was tested according to EN 12697-26, Annex C, indirect tension to cylindrical specimens (IT-CY) at 20 °C [23]. At this temperature the stiffness of the RmB and PmB mixes is higher compared to the 50/70 control mix and the RmB stiffness is lower compared to the PmB (Figure 6). However, Figure 1 indicates that it is not possible to assess the overall performance of the different mixes at one single temperature, therefore the dynamic modulus temperature-frequency sweep test was conducted (Section 3.7).

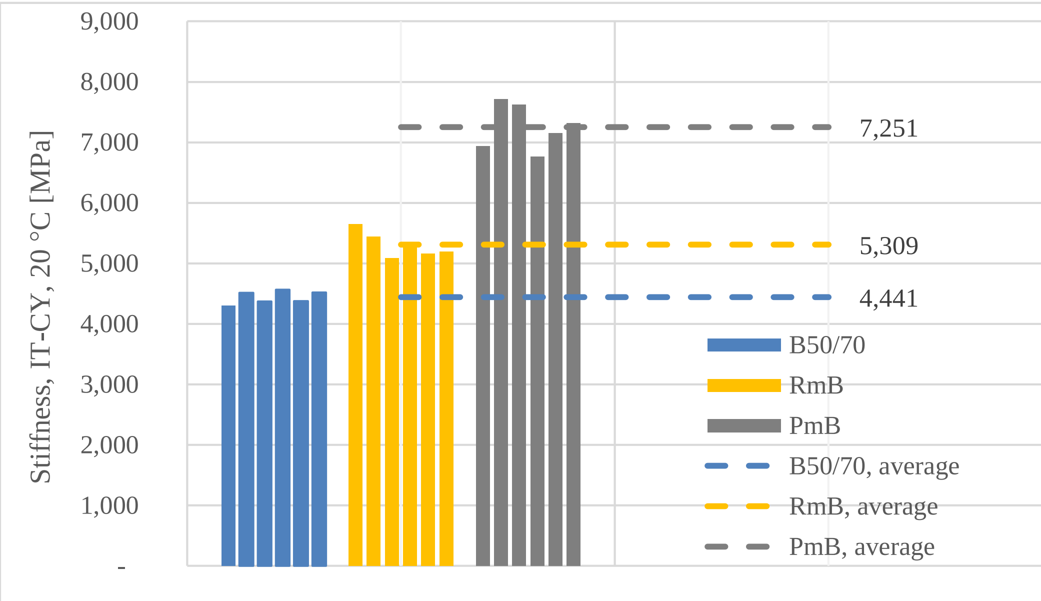

Figure 6: IT-CY stiffness test results at 20 °C

3.5 Wheel-tracking test

A wheel-tracking test was conducted according to EN 12697-22, small size device, procedure B, in air [24]. Figure 7 shows that the RmB binder has superior resistance to wheel-tracking at 60 °C compared to the PmB and the control 50/70 binder; for each mix four samples were tested and the figure shows each individual result and the average values. The test results correspond well with the low frequency (high temperature) characteristics of the binders as is shown in Figure 1.

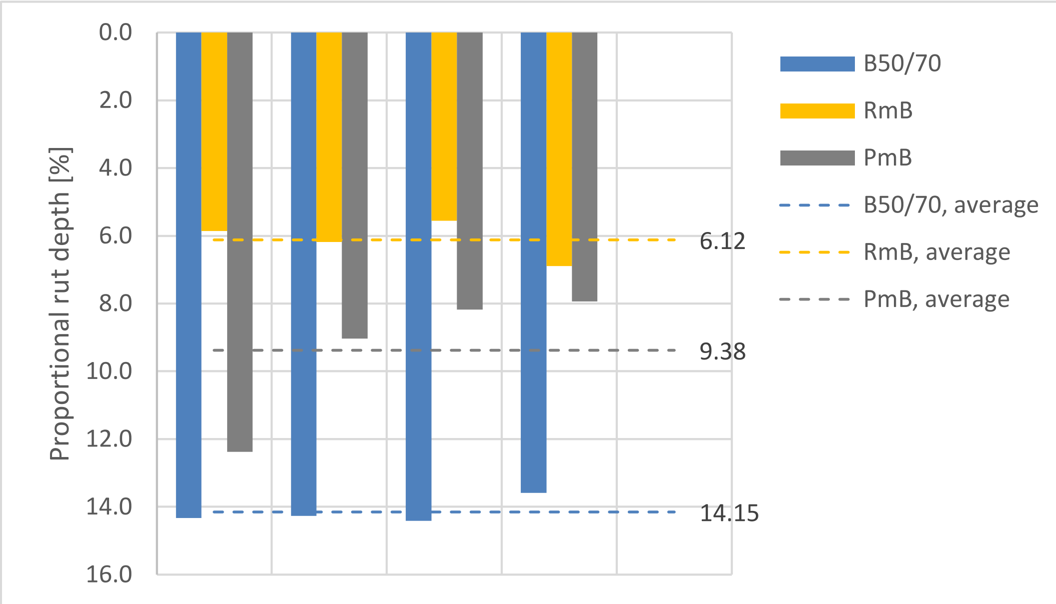

Figure 7: Wheel-tracking test results (proportional rut depth)

3.6 Resistance to cracking at low temperatures

According to Figure 7 the RmB has superior rut resistance at high in-service temperatures of 60 °C. Mixes with good resistance to plastic deformation are normally expected to have less resistance to cracking at low temperatures, due to the high stiffness of the material. PmB binders, due to the characteristics of the material, balance this behaviour and have good rutting resistance without compromising the low-temperature cracking resistance. Figure 8 shows that RmB has better performance compared to PmB as the cracking temperature is lower; lower cracking temperature indicates better cracking resistance. The resistance to low-temperature cracking was tested according to EN 12697-46 [25], thermal stress restrained specimen test (TSRST). It should be noted that the width and height of the prismatic specimens were 50 mm instead of 40 mm required by the test method; the length of the specimens was 250 mm, complying with the standard.
The tests results indicate that superior rutting resistance combined with good low-temperature cracking resistance can be achieved when RmB is used. The findings correspond well with the improved temperature susceptibility of the RmB as indicated in Figure 1.

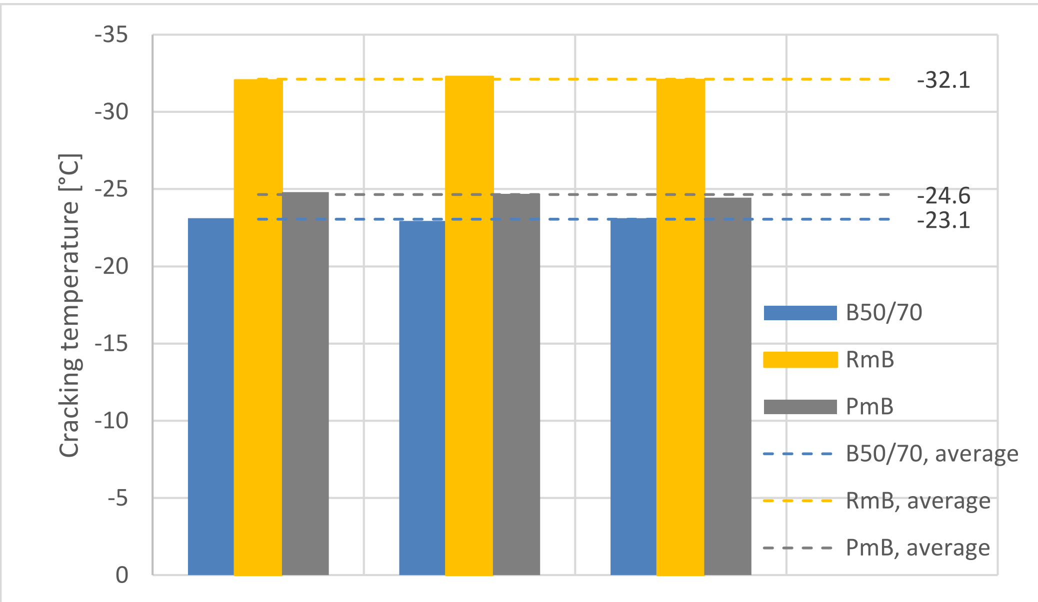

Figure 8: Low-temperature cracking test results

3.7 Dynamic modulus master curves

In order to cross-check the performance of the test results collected for the mixes produced with different binders, a dynamic modulus temperature-frequency sweep test was conducted according to AASHTO TP-62 [26] with a target axial stress of 100 kPa; the 100 mm diameter specimens were prepared in the gyratory compactor according to EN 12697-31 [22]. The master curves of the different mixes were constructed and the results are summarised in Figure 9. The figure indicates similar characteristics as found in Figure 1; the asphalt mix with RmB provides a superior performance for climatic conditions where both hot and cold in-service temperatures can be expected.

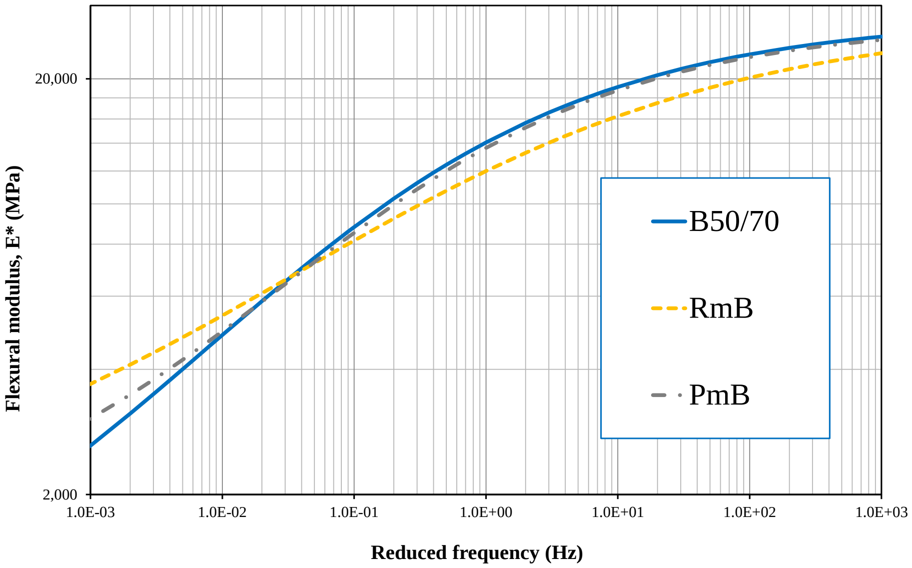

Figure 9: Dynamic modulus master curves of the asphalt mix with different binders

4. SUMMARY

The paper summarises the performance assessment of an asphalt mix with rubber modified bitumen (RmB). The binder is chemically stabilised to ensure the well-known problem with RmB, which is the storage stability. Performance-based bitumen tests showed that the characteristics of the RmB are similar to the PmB; however, the RmB shows better temperature susceptibility.

A reference mix, a heavy duty AC 11 wearing course was mixed with an RmB 45/80-55 binder and the properties were compared to control mixes manufactured with plain 50/70 penetration grade bitumen and a PmB 25/55-65. The findings indicate that the performance of the asphalt mix produced with RmB is higher compared to the asphalt mixes produced with plain binder and PmB; the asphalt mix with RmB showed superior performance with regard to wheel-tracking and resistance to low-temperature cracking.

Laboratory and field data collected to date indicate that asphalt produced with RmB is expected to be a very high performing mix and provide a value-for-money solution; the environmental benefits of the technology are also significant. It must be noted however, that further testing is required to achieve statistically convincing results on the mixes presented in the paper, as well as on other mix types.

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