ACTA TECHNICA JAURINENSIS
Vol. 16, No. 2, pp. 62-74, 2023
10.14513/actatechjaur.00694

Research Article

Rheological characterisation of bituminous binder blends for the design of asphalt mixes with high recycled asphalt content

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Submitted: 29/04/2023 Accepted: 14/05/2023 Published online: 31/05/2023

Abstract: Reclaimed asphalt pavement (RAP) is gained from road reconstructions; however, its usage is less optimised in Hungary and neighbouring regions, since on the project level the proportion of RAP in the asphalt mixes is only 10-15%. This is less than the recommended level in other EU countries. The higher usage of RAP provides economic and environmental advantages, decreasing the need for new materials, the transport cost, and the carbon footprint. The composition of the resultant bituminous binder blend is a critical element in the asphalt mix design with high RA content. This paper discusses the design of the resultant bituminous binder blend to provide performance and compliance characterisation. This paper also presents the complex rheological analysis of the base bitumen, the bitumen extracted from the RA and the bituminous binder blend, applying the dynamic shear rheometer (DSR) device. It was shown that for paving grade bitumen (B), polymer modified bitumen (PmB) and rubber modified bitumen (GmB), the addition of higher proportions of RA content is possible without compromising on the performance of the binder blend. With a carefully chosen paving grade bitumen it is possible to utilise up to 40% RA content. For the polymer modified bitumen, the limit of the RA content is 20%. For the rubber modified bitumen, the various proportions of RA contents showed no or negligible changes in the characteristics of the bitumen and the RA content can reach 30% in this case.

Keywords: recycled asphalt pavement; dynamic shear rheometer; binder blend characterisation; Black diagram

I. INTRODUCTION

Reclaimed asphalt pavement (RAP) is gained from road reconstructions; however, its usage is less optimised in Hungary and neighbouring regions, since on project level the proportion of RAP in the asphalt mixes is only 10-15%, that is less, than the recommended level in other EU countries [1]. The higher usage of RAP provides economic and environmental advantages, decreasing the need for new materials, the transport cost, and the carbon footprint, moreover, promoting ecological issues. For example, in the reconstruction of Motorway M1 (Budapest – Vienna) the usage of RAP will be a real challenge. The authors have analysed the possibilities for producing asphalt mixes of high RAP content through the development of the production plant in a recent research and development project. However, there was still a need for dealing with the problems of the asphalt mix design and stockpile management in the production of asphalt with high RAP content. Previous studies [2, 3] have demonstrated that RAP may exhibit variability, therefore the characterisation of RA is necessary, especially for high RAP asphalt mixes.

The volumetric design of an asphalt mix of high recycled asphalt (RA) content is the same as the mix design procedure of any other asphalt mix [4, 5]. However, there is a critical element in the mix design, the composition of the resultant bituminous binder blend should be considered when designing a mix with a high RA content as part of the volumetric mix design [6]. Because of the ageing of the binder of the RA, there may be a need for the „rejuvenation" or „regeneration" of the binder of the RA by adding fresh bitumen and/or rejuvenator additives. This fact can be extremely important in case of a RA originating from older, intensely aged pavements or in case of adding a higher proportion of RA into the mix. Words like „rejuvenation” or „regeneration” can be misleading, since these additives can serve two goals; either the modification of the chemical content of the bitumen, or the modification of the performance and the compliance of the bitumen. This paper deals with the design of the resultant bituminous binder blend to provide the performance and the compliance and does not deal with the modification of the chemical content.

The predictive calculations of the performance and the compliance of the resultant bituminous binder blend are performed based on penetration [7], softening point [8], elastic recovery [9], or dynamic shear rheometer (DSR) viscosity. These tests are valid for a certain temperature or loading (frequency) point, and not necessarily consider the complex rheological characteristics of the bituminous binder blend, which is influenced by the required base bitumen and the bitumen extracted from the RA.

This paper presents therefore the complex rheological analysis of the base bitumen, the bitumen extracted from the RA and the bituminous binder blend, using the DSR device. Performing the provided test series and analysis may not be practical for the daily routine in the factory production control at an asphalt production plant, nevertheless, the scientific results presented are critical for understanding the overall performance of the bituminous binder blends.

II. Preparation of bituminous binder blends

For the analysis described in this paper, normal paving grade bitumens, polymer modified bitumens and rubber modified bitumens have been mixed with the aged binder extracted from RA in different mass proportions, based on a special procedural order. The extraction of the RA binder was performed according to standard test method MSZ EN 12697-3 [10]. The analysis of these blends in the present work has not included the traditionally required softening point and penetration tests, rather the values of the complex shear modulus, the phase angle and the complex viscosity have been determined applying the DSR device, representing the results on Black diagrams as described later. The procedural order was as follows:

- The approximately required quantity is cut from the bitumen and measured on a precision scale in a jar. After the measurement, the quantity of the bitumen in the jar is increased or decreased until the required amount of the prescribed blending proportion is reached with the required accuracy. This step is performed for both bitumens (the recycled and the fresh).
- The jar with the measured bitumen quantities is put into an oven at 170°C temperature for about 15 minutes.
- In the oven the blend is thoroughly remixed for 2 minutes using a spatula or an equivalent tool.
- The remixed bitumen is stored in the oven for a further 5-10 minutes to reach again 170°C temperature (the spatula may remain in the bituminous blend).
- The specimen is remixed again (no time required, a thorough 10-30 seconds mixing is recommended though) and in the oven the bitumen is poured into the specimen template forms. Two pieces of samples are made from each blend.
- The templates are heated to 170°C temperature as well to let the specimen extend properly, then they are removed from the oven to let cool down.
- After cooling, the surplus amount of bitumen is cleared away, entirely to the plane of the template form.
- The completed specimens are put into a refrigerator at 10°C temperature until the DSR measurements are performed.

III. Rheological characteristics determined by the dynamic shear rheometer (DSR)

1. The DSR device

The dynamic shear rheometer (DSR) is suitable for the testing of asphalt binders (**Fig. 1**). During the test, rheological parameters, like the complex shear modulus (G*) and the phase angle (δ) can be measured at a wide frequency and temperature range. These parameters are used for characterising

Figure 1. *Dynamic shear rheometer (DSR), Rheotest 4.3*

the viscous and elastic behaviour of the asphalt binder.

The complex shear modulus characterises the resistance to deformation of the material, in case of a sinusoidal shear stress loading as expressed by equation (1), where τ is the stress and γ is the strain.

$$G^* = \frac{\tau_{max} - \tau_{min}}{\gamma_{max} - \gamma_{min}} \tag{1}$$

The complex shear modulus as a rheological attribute consists of an elastic (recoverable) and a viscous (non-recoverable) component. The phase angle shows the relative quantities of viscous and elastic components, from a measurement point of view it is the phase difference between the applied stress and the resulted strain. Values of these two parameters for bituminous binders largely depends on the test temperature and the loading frequency. At high temperatures and low loading frequency binders behave as a viscous liquid with small recovery ability. On the contrary, at very low temperatures these binders behave as an elastic solid material, totally recovering from deformation. At normal pavement temperatures and traffic loading bitumens present both attributes (viscous liquid and elastic solid material), that is why they are rightly called viscoelastic materials.

The DSR test provides information on the behaviour of the bitumen by determining the complex modulus and the phase angle at a wide frequency and temperature range, relevant to the in-service pavement behaviour. **Fig. 2** demonstrates the relation of the two components of the viscoelastic behaviour.

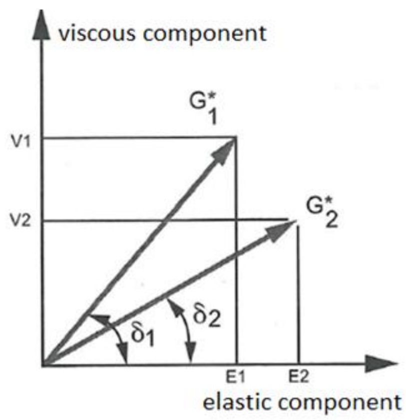

Figure 2. *The relation between the viscous and the elastic components of the viscoelastic behaviour [11]*

In case of only viscous behaviour (G* has got no elastic component, coincidence with ordinate axis), δ = 90°. In case of only elastic behaviour (G* has got no viscous component, coincidence with abscissa axis), δ = 0°. The two complex modulus values on **Fig. 2** (G^*_1 and G^*_2) have the same absolute value representing the viscoelastic characteristics of two different bitumens. **Fig. 2.** indicates that only one parameter is not enough for describing the rheological characteristics of the bitumen, since the two bitumens are different, despite of their identical G* value. Bitumen marked „2" has a higher elastic component; therefore, the measured phase angle value is smaller [11].

Operation of the dynamic shear rheometer device is a rather simple task, there is no need for a serious professional education. The bitumen specimen for the test is prepared in a cylindrical shape using a silicone template form, although in certain cases putting the bitumen directly onto the plate is also permitted. The diameter of the template form can be 8 mm or 25 mm, depending on the test temperature and the expected value of the complex modulus or viscosity. Standard test method MSZ EN 14770 [12] recommends using 25 mm specimen diameter for measuring stiffnesses 1 kPa – 100 kPa (reached above about 40-50°C), and 8 mm specimen diameter for measuring stiffnesses 100 kPa – 10 MPa (reached at about 0-50°C). An advantage of the DSR test is that only a small amount of representative bitumen is required, in case of the 25 mm specimen, about 0,49 cm^3, and in case of the 8 mm specimen, about 0,1 cm^3. This is better than the material requirement of a penetration test or of a softening point test, since the DSR test can be performed when obtaining a very small amount of representative bitumen sample. The prepared specimen is placed between the parallel measurement plates of the rheometer (**Fig. 3**).

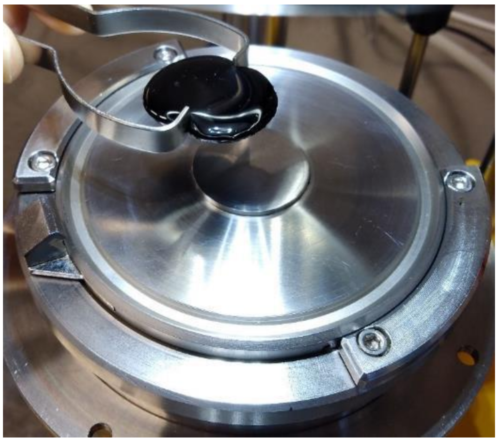

Figure 3. *Putting a 25 mm diameter specimen onto the DSR plate*

The lower plate is fixed, the other plate can be rotated for the oscillation loading. The proper gap distance shall be adjusted (in case of a 25 mm specimen it is 1,000 mm + 0,025-0,050 mm); the surplus bitumen pressed out shall be trimmed by a suitable tool like a metal spatula. During the measurement, the specimen is in a closed space that can be heated and cooled by a casing, and is loaded by a sinusoidal cyclic deformation, the so-called oscillation shear, at a controlled temperature, and the reaction stress is measured. It is worth performing strain-controlled measurements, since that guarantees a properly small deformation, so the bitumen can be tested under its viscoelastic domain. This is important because in this domain the connection between the stress and the strain is linear, the characteristics of the bitumen depend only on the time and temperature and does not depend on the magnitudes of the stress and strain. Performing this test, a lot of information about the bitumen can be acquired, since applying the DSR it is possible to perform measurements at different temperatures and at various frequencies.

2. DSR test parameters

DSR tests may be performed by existing standards MSZ EN 14770 [12], AASHTO T 315 [13] or AGPT-T192 [14]. For the temperature-frequency-sweep analysis an important step is to determine the shear strain amplitude. Former studies have proven that at 5% strain value the results are within the linear domain both in case of normal bitumen and in case of modified bitumen [15], therefore for the DSR tests presented in this paper 5% strain value was chosen.

The temperature-frequency-sweep analysis between 0°C and 70°C has been performed at the following parameters:

between 50-70°C

- 5% strain
- 50-60-70°C
- frequency values 0.1 - 0.1668 - 0.2783 - 0.4642 - 0.7743 - 1.292 - 2.154 - 3.594 - 5.995 - 10 Hz
- specimen diameter 25 mm
- specimen thickness 1.0 mm

between 0-50°C

- 5% strain
- 0-10-20-30-40°C (some measurements were possible only at the 30-40°C domain because of the stiffness of the bitumen)
- frequency values 0.1 - 0.1668 - 0.2783 - 0.4642 - 0.7743 - 1.292 - 2.154 - 3.594 - 5.995 – 10 Hz
- specimen diameter 8 mm
- specimen thickness 2.0 mm.

3. Presenting rheological data

The resulting data from the DSR tests shall be presented for the studies of rheological characteristics of road paving binders (both normal bitumens and polymer modified bitumens) in a useful and easily understandable way, providing a possibility for a simple comparison. Since the DSR test provides a large amount of data, their presentation is not necessarily an easy task.

A simple graphical presentation is the isochrone diagram or the isochrone curve. Such a graph shows the behaviour of the binder at a constant frequency or loading time. Isochrones are presented when plotting curves of a complex modulus (G*) or other viscoelastic functions obtained from a DSR test as a function of the temperature [16].

The isothermal plot or isotherm is a curve that presents the complex behaviour of the bitumen at a constant temperature. Isotherms are presented when plotting curves of a complex modulus (G*) obtained from a DSR test as a function of the frequency [16].

The Cole-Cole diagram presents the loss (viscous) modulus (G″) as a function of the stored (elastic) modulus (G′), containing the values of the complex modulus and the phase angle in an indirect way. The Cole-Cole diagram provides the possibility for presenting the viscoelastic characteristics of the bitumen without using the frequency and/or the temperature as a variable.

A Black diagram presents the absolute value of the complex modulus (G*) as a function of the phase angle (°). Similarly, to the Cole-Cole diagram, the Black diagram does not contain the frequency and the temperature, which makes possible to present all dynamic data on one diagram, without any time-temperature superposition calculation of the raw data (constructing a master curve). When the Black diagram shows a continuously decreasing curve, that means a useful indication of the equivalency of the time and the temperature. A not continuously decreasing curve suggests the lack of time-temperature superposition and is suitable for identifying polymer modified bitumens beside other deviations or changes in the composition of the bitumen [16].

The effect of the SBS modification (or any other modification) on the rheological parameters (the complex modulus and the phase angle) are presented on the Black diagram, eliminating the temperature and frequency dependency. Typical curves of bitumens with different SBS content are presented on **Fig. 4** [17].

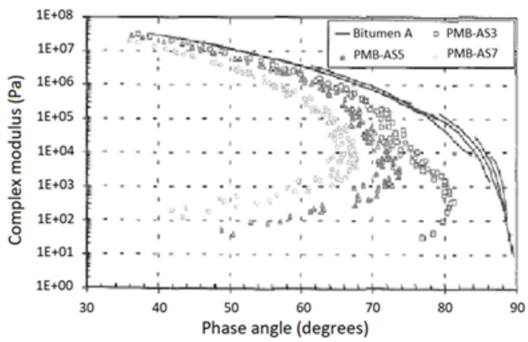

Figure 4. *Black diagram depending on the SBS modification*

For a lower polymer content (3%) the behaviour of the modified binder is rather resembles the behaviour of the base binder since the phase angle remains near to the value of 90° at high temperature low frequency. In case of a higher polymer content (5 and 7%) the characteristics of the base binder changes considerably since the phase angle significantly decreases and remains usually below the value of 70°.

The DSR may be utilised to run the binder fast characterization (BTSV) test and it was developed for fast characterization of bitumen and it could be used as a replacement to the softening point test [18]. The DSR can be used to perform the Grower-Rowe test, which is a method developed to characterize the susceptibility of a binder to cracking [19, 20]. The Multiple Stress Creep Recovery Test (MSCRT) is developed to determine the creep performance of asphalt binders using the DSR [21].

The BTSV, Glover-Rowe and MSCRT tests are developed to describe specific binder behaviour, such as high temperature creep or cracking potential. While they provide useful description of the binder for specific application, the overall complex behaviour of the binder can be assessed by the Black diagram. Therefore, this paper utilises this methodology to describe various binder blends.

4. Measuring complex viscosity and estimating complex viscosity of the bituminous binder blend

Test method AGPT-T193 [22] includes the design process of the viscosity of binder blends. A study by Austroads [23] recommended if the RA proportion of an asphalt mix is above 15%, the properties of the binder blend (consisting of RA binder, base binder and possibly rejuvenator additive) shall be determined as follows:

- Collect a representative sample of the RA
- Determine the binder content of the RA
- Extract the binder from a representative sample of the RA
- Determine the complex viscosity of the RA binder, the virgin binder and rejuvenator (where applicable) by using the DSR at 60°C and 1 rad/s
- Predict the viscosity of the binder blend according to AGPT-T193 [22]
- If the predicted viscosity is outside of the desired range for the design, adjust the proportion of the binder blend components iteratively to achieve the desired viscosity range of the final product.

The method has already been validated for Hungarian conditions [24].

The viscosity of virgin bitumens and bitumens extracted from RA were measured according to the method described before at 60°C, 1 rad/s, and the viscosity of the binder blends were estimated applying the calculation method. Following these steps, the blending process was validated by preparing bitumen blends in the laboratory and measuring their viscosity at the Budapest University of Technology and Economics, Department of Highway and Railway Engineering, Laboratory for Pavement Structures. The difference between the tested and calculated viscosity was calculated according to equation (2), where Δ is the difference and ν is the viscosity.

$$\Delta = \frac{|\nu_{tested} - \nu_{calculated}|}{\nu_{calculated}} \times 100 \qquad (2)$$

The results are presented in the next chapter.

IV. Analysis of binder blends of bitumens and RA originated bitumens

The bitumen samples were extracted (MSZ EN 12697-3) from asphalt samples collected from two RA sources as described later and the bituminous binder blends have been prepared according to the procedure mentioned above. Following this, the DSR temperature-frequency-sweep testing has been performed, bituminous binder blends of different RA content, characteristically 10-20-30-40%, has been prepared in the laboratory. The temperature-frequency-sweep testing of the base bitumen, the RA bitumen and the blend of these has been performed at the University of Győr, Laboratory for Road Construction and then Black diagrams have been created from the results. The next part of the paper summarises these results.

Three types of base bitumen have been used, an SBS modified bitumen PmB, a rubber modified bitumen GmB and the normal paving grade bitumen B, keeping these abbreviations in the paper. Two sources of RA binder were used in this study:

- Zsámbék 0/11 RA 0/8 T002 – denoted as Zs RA T002. The orignal asphalt mix was probably manufactured using polymer modified binder, which is based on anecdotal evidence. According to verbal information, this RA has been originated from a reconstruction of a high-speed road, therefore it can be reasonably assumed that the original asphalt mix had been produced using PmB.
- Körmend 0/11 RA 0/8 – denoted as K RA. The RA was obtained from the demolition of a temporary road used for the construction of a bridge structure. The in-service life of the road was two years.

1. MOL PmB 25/55-65 + MOL B 50/70 blends

To ensure a controlled check (validation) of the calculation method of the binder blend viscosity for the PmB type binder, first a MOL PmB 25/55-65 bitumen has been mixed at 10-20-30-40%

proportions with a MOL B 50/70 road paving bitumen. Analysis of these blends helped in mapping the magnitude of the „thinning” effect of the road paving bitumen on the PmB. Based on the results in **Table 1**., it was established, that the above described viscosity calculation method is valid for the PmB type binder, since the difference between the calculated and the measured viscosity values have been very small, remaining under 10%.

Table 1. *Summary of tested and calculated viscosities for MOL PmB 25/55-65 + MOL B 50/70 bitumen blends*

B 50/70 % (in blend)	***Tested viscosity (Pa.s)***	***Calculated viscosity (Pa.s)***	***Difference (%)***
10	1 466	1 368	7
20	1 161	1 122	3
30	1 008	924	9
40	838	763	10
100% MOL B 50/70	261		
100% MOL PmB 25/55-65	1 674		

The temperature-frequency-sweep has been performed by the DSR device for the base bitumens as well as for binder blends with 10-20-30-40% proportions of MOL B 50/70 content, and their Black diagrams have been plotted as on **Fig. 5**. The Black diagram – as mentioned above – describes the behaviour of the bitumen or the blend at a wide temperature and frequency range, showing the connection between the complex modulus and the phase angle.

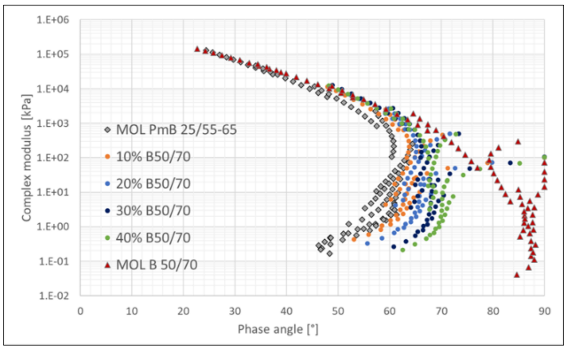

Figure 5. *Black diagrams of MOL PmB 25/55-65 + MOL B 50/70 blends*

As it has been described in the earlier sections, the PmB has got a low phase angle value at high temperature and low frequency values, that is clearly visible on **Fig. 5**. For blends with 10% and 20% B 50/70 content, it was observed that the characteristics of the basic PmB have not changed significantly from the point of view of the phase angle, although the curves have been slightly shifted downwards because of the lower complex modulus of the B 50/70. In case of blends with 30% and 40% B 50/70 content, the curves have been shifted further downwards, the complex modulus has decreased, and the phase angle has increased, indicating the increasing effect of the B 50/70. It is worth mentioning, that the characteristic PmB feature, the low phase angle, have remained dominant even for the 40% B 50/70 blending, which should have a significant „thinning” effect on the PmB.

2. Zs RA T002 + MOL B 70/100 blends

A relatively good agreement can be observed between the calculated and the measured viscosities when analysing the blends of an RA extracted bitumen originated from Zsámbék and the MOL B 70/100 base bitumen (**Table 2.**). Comparing to the analysis results in the previous chapter, here the difference between the calculated and the measured viscosities are higher, because of the presence of the bitumen extracted from the RA.

Table 2. *Summary of tested and calculated viscosities for Zs RA T002 + MOL B 70/100 bitumen blends*

RA % (in blend)	***Tested viscosity (Pa.s)***	***Calculated viscosity (Pa.s)***	***Difference (%)***
10	276	205	35
20	464	334	39
30	881	558	58
40	1 575	958	64
100% Zs RA T002	16 748		
100% MOL B 70/100	129		

In this section the authors have tried to analyse the changes in the characteristics of a relatively soft bitumen, the B 70/100, when blended with a stiffer bitumen extracted from RA. The viscosity of the B 50/70 bitumen was 261 Pa.s, and this value has been used for comparison. According to **Table 2.**, this viscosity value is close to the viscosity of the blend with the B 70/100 bitumen and 10-20% RA. This fact means that the viscosity of the harder RA bitumen can be decreased by adding a softer base bitumen to the blend, or the viscosity of a softer road paving bitumen can be increased by adding RA to the blend. These two statements have the same engineering meaning, although the aim of their utilisation is different. The Hungarian paving industry characteristically applies the B 50/70 bitumen, and a similar product can be created with the blend of the B 70/100 and the bitumen extracted from the RA.

Likewise in the previous section, the total temperature-frequency-sweep has been performed by the DSR device for the base bitumen (B 70/100) and the RA originated bitumen, as well as for binder blends with 10-20-30-40% proportions of RA bitumen content. Black diagrams are shown on **Fig. 6.**, including the curve of the B 50/70 bitumen for comparison. The observations have been the same as for the viscosities, the characteristics of blends with the B 70/100 and 10% RA as well as 20% RA bitumens are in good agreement with characteristics of the B 50/70 bitumen. It is worth mentioning that in these Black diagrams the typical shape of the PmB curves cannot be observed for the RA binder. A probable cause of this is the ageing and the degradation of the PmB during its life cycle.

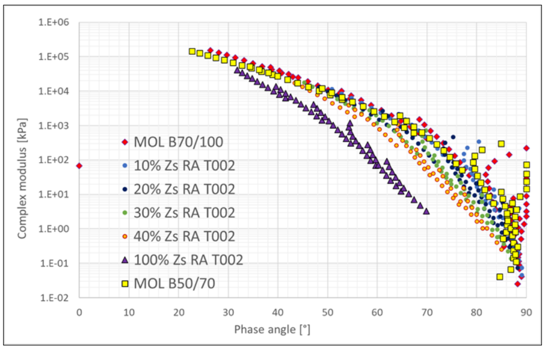

Figure 6. *Black diagrams of Zs RA T002 + MOL B 70/100 blends*

3. Zs RA T002 + MOL PmB 25/55-65 blends

In this series of analysis, the MOL PmB 25/55-65 has been blended by 10-20-30-40% proportion of the Zsámbék RA originated bitumen. Based on **Table 3**, there have been minimal differences between the calculated and the measured viscosities. For this blending series the temperature-frequency sweep has been performed as well, the relevant Black diagrams are shown on **Fig. 7**.

Table 3. *Summary of tested and calculated viscosities for Zs RA T002 + MOL PmB 25/55-65 bitumen blends*

RA % (in blend)	***Tested viscosity (Pa.s)***	***Calculated viscosity (Pa.s)***	***Difference (%)***
10	2 360	2 142	10
20	3 178	2 757	15
30	4 112	3 569	15
40	5 597	4 649	20
100% Zs RA T002	16 748		
100% MOL PmB 25/55-65	1 674		

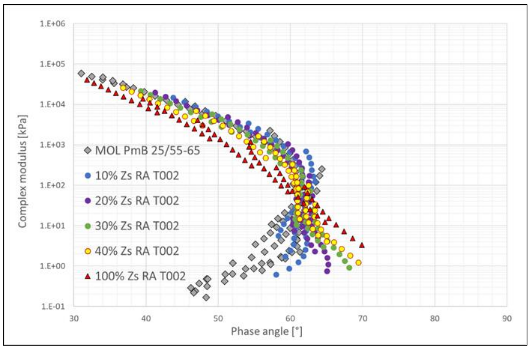

Figure 7. *Black diagrams of Zs RA T002 + MOL PmB 25/55-65 blends*

It can be observed, that in case of 30% and 40% RA contents, phase angles have started to increase at the high temperature and low frequency domain, although the phase angle values have remained still in the rather lower domain characterising PmB types, not exceeding the 70° value. This observation is valuable for the practical utilisation, since the 10% and 20% RA proportion in the PmB based blend has not indicated any significant changes. While in the domain of the 30% and 40% RA content the original characteristics of the PmB have not fully remained, the dilution into a normal paving bitumen still has not occurred.

To prove this statement, **Fig. 8.** has been plotted including the Black diagram of the OMV B 20/30 bitumen, that is one of the hardest road paving bitumen types available on the market nowadays. **Fig. 8.** proves the validity of the statement; however, there is a need for further research in this field when the practical utilisation requires more than 20% RA content in the blend when applying a PmB base bitumen.

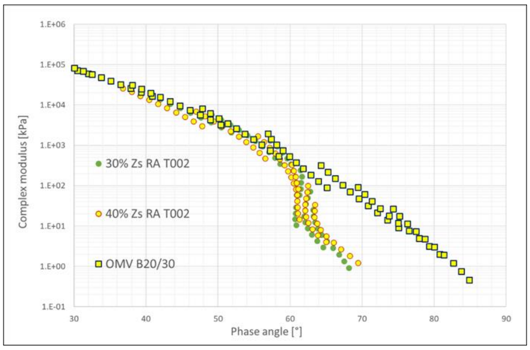

Figure 8. *Black diagrams of Zs RA T002 + MOL PmB 25/55-65 with 30% and 40% RA content blends, including the OMV B 20/30 blends*

4. Zs RA T002 + MOL PmB 45/80-65 blends

In this series of analysis, the MOL PmB 45/80-65 bitumen has been used instead of the MOL PmB 25/55-65 bitumen that is currently widely used in Hungary. The Hungarian practice has less utilised the MOL PmB 45/80-65 bitumen, nevertheless, the aim of this part of research has been whether it is possible to reach a performance similar to the blends of the MOL PmB 25/55-65 base bitumen containing bitumen extracted from RA. The proportion of the Zs RA T002 bitumen has been 10-20-30-40%, similarly to the previous series. The comparison table of the calculated and the measured viscosities shows a rather good agreement between the values, similarly to the case of the PmB 25/55-65 bitumen (**Table 4.**).

Table 4. *Summary of tested and calculated viscosities for Zs RA T002 + MOL PmB 45/80-65 bitumen blends*

RA % (in blend)	***Tested viscosity (Pa.s)***	***Calculated viscosity (Pa.s)***	***Difference (%)***
10	2 440	1 901	28
20	2 973	2 479	20
30	4 216	3 255	30
40	5 590	4 303	30
100% Zs RA T002	16 748		
100% MOL PmB 45/80-65	1 467		

For this blending series the relevant Black diagrams based on the temperature-frequency sweep are shown on **Fig. 9**.

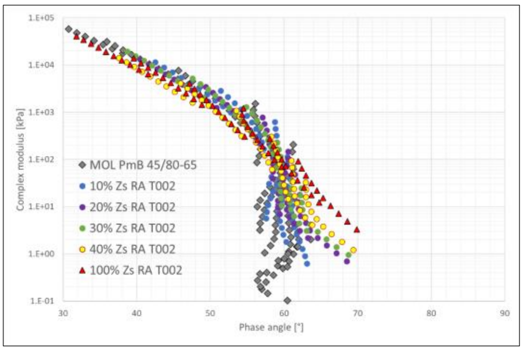

Figure 9. *Black diagrams of Zs RA T002 + MOL 45/80-65 bitumen blends*

It can be observed that even the 40% RA content has not significantly changed the features of the PmB 45/80-65 bitumen, regarding both the complex modulus and the phase angle. On **Fig. 10**. the Black diagram of the PmB 25/55-65 bitumen has been plotted as well; based on **Fig. 10** it can be stated, that both the PmB 45/80-65 bitumen and its 40% RA content blend have got significantly different curves compared to the PmB 25/55-65 bitumen.

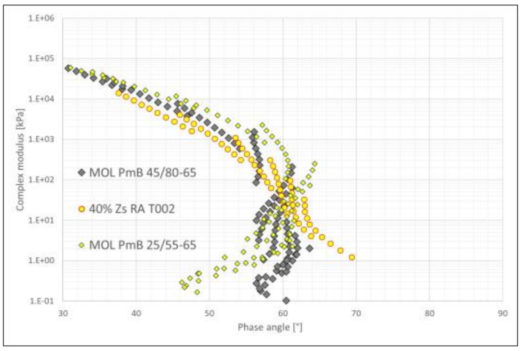

Figure 10. *Black diagrams of MOL PmB 45/80-65 + 40% RA blend, as well as of the MOL PmB 45/80-65 and the MOL PmB 25/55-65 bitumens*

5. Zs RA T002 + MOL GmB 45/80-55 blends

The rubber modified bitumen is interesting for the Hungarian road paving, therefore the next series of analysis has dealt with the blends of the rubber modified bitumen and the bitumen extracted from RA. The base bitumen used has been the MOL GmB 45/80-55, blended with the Zsámbék RA T002 extracted bitumen in 10-20-30-40% proportions. Rubber modified bitumens are normally characterised by their penetration and softening point similarly to the PmB grade. Although the rubber modified bitumens show similar characteristics to the PmB (as per the EN product standard), the rubber particles form a blend with its base bitumen in a different way. That may be the explanation of the weak correlation between the measured and the calculated viscosities (**Table 5**).

Table 5. *Summary of tested and calculated viscosities for Zs RA T002 + GmB 45/80-55 bitumen blends*

RA % (in blend)	***Tested viscosity (Pa.s)***	***Calculated viscosity (Pa.s)***	***Difference (%)***
10	3 045	2 079	46
20	4 321	2 685	61
30	6 031	3 488	73
40	7 411	4 561	62
100% Zs RA T002	16 748		
100% MOL GmB 45/80-55	1 333		

Interestingly, Black diagrams show a far better agreement than the viscosities. Based on **Fig. 11**, it can be observed, that the RA content has practically no effect on rheological characteristics of the base GmB 45/80-55, as their Black diagrams are almost fully overlapped. It can also be observed that the characteristics of the GmB 45/80-55 are not similar to the PmB bitumens described before. Although at the range of high temperature and low frequency, phase angles have remained under 80°, this still differs from the characteristics of the PmB 25/55-65, where phase angles have only slightly exceeded the 60° value. Another figure (**Fig. 12.**) has been plotted including the Black diagram of the OMV PmB 10/40-65 bitumen, since the characteristics of the GmB 45/80-65 has been found to be similar to this bitumen type.

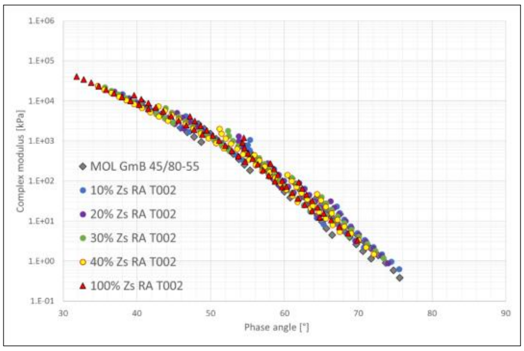

Figure 11. *Black diagrams of Zs RA T002 + GmB 45/80-55 blends*

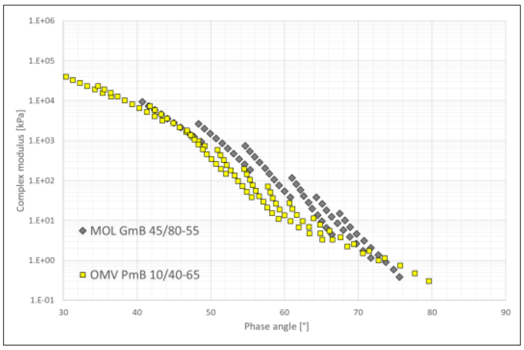

Figure 12. *Black diagrams of the GmB 45/80-55 and the OMV PmB 10/40-65 bitumens*

Table 6. *Summary of tested and calculated viscosities for Zs RA T002 + GmB 45/80-55 bitumen blends – repeated analysis*

RA % (in blend)	***Tested viscosity (Pa.s)***	***Calculated viscosity (Pa.s)***	***Difference (%)***
10	3 863	2 079	86
20	4 828	2 685	80
30	6 435	3 488	84
40	8 116	4 561	78
100% Zs RA T002	16 748		
100% MOL GmB 45/80-55	1 620		

Since there are only limited experiences in the Hungarian practice concerning the GmB 45/80-55 bitumen, it was intended to validate the first set of results presented beforehand. The test regime and analysis for the GmB have been repeated regarding both the viscosity (**Table 6.**) and the temperature-frequency sweep with its resulting Black diagram (**Fig. 13.**).

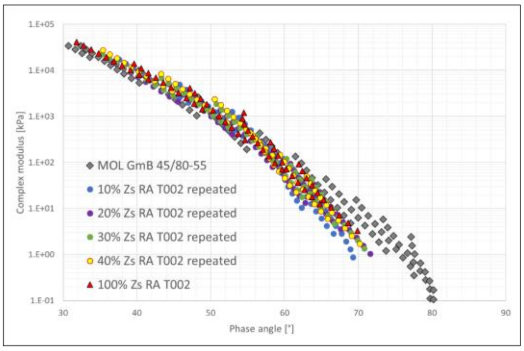

Figure 13. *Black diagrams of Zs RA T002 + GmB 45/80-55 blends – repeated analysis*

It has been observed that the results of the original and the repeated analyses present equivalent tendencies, consequently, it can be stated, that the behaviour of the GmB really differs from the behaviour of PmBs.

6. K RA + OMV 45/80 RC blends

In this series of analysis, an RA bitumen originated from Körmend has been used. The viscosity values showed that in the short in-service life the normal paving grade bitumen has not been aged or degraded to a large extent. The base bitumen used for preparing blends has been an OMV 45/80 RC bitumen. According to the manufacturer, this PmB bitumen type has been particularly developed for recycling with a high RA content, when the „thinning" effect of the RA bitumen has been considered intentionally in the production process of this base bitumen.

There have been small differences between the measured and the calculated viscosities according to **Table 7**. The changes in Black diagrams at 10-20-30-40% RA bitumen contents are presented in **Fig.14**. As it has been previously observed, in case of different blends of PmB and RA, though the RA bitumen changes the characteristics of the PmB, at the 10% to 20% RA proportion in the range of high temperature and low frequency, phase angles still have remained typically low. **Fig. 15**. shows that there has been no significant difference between the characteristics of the 45/80 RC bitumen and the PmB 25/55-65 bitumen.

Table 7. *Summary of tested and calculated viscosities for K RA + OMV 45/80 RC bitumen blends*

RA % (in blend)	***Tested viscosity (Pa.s)***	***Calculated viscosity (Pa.s)***	***Difference (%)***
10	1 811	1 790	1
20	1 307	1 420	-8
30	1 292	1 132	14
40	1 076	907	19
100% K RA	339		
100% OMV 45/80 RC	2 269		

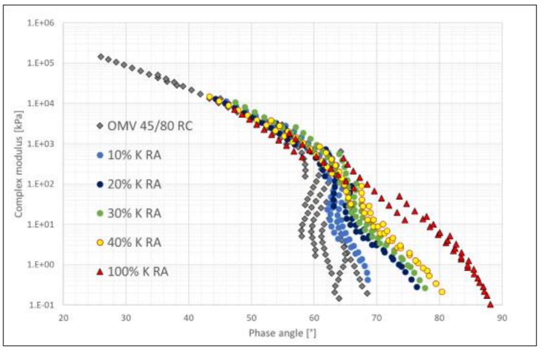

Figure 14. *Black diagrams of K RA + OMV 45/80*

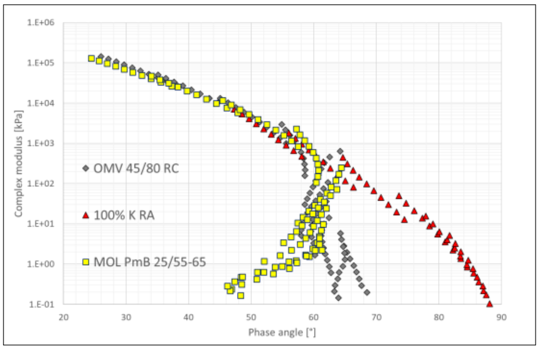

Figure 15. *Black diagrams of the K RA, the OMV 45/80 RC and the MOL PmB 25/55-65 bitumens*

7. OMV B35/50 + MOL GmB 45/80-55 blends

As it has been presented beforehand, the Körmend originated RA bitumen has not been aged or degraded to a large extent, therefore it can be assumed, that its behaviour is similar to a harder grade road paving bitumen. It has also been presented that the behaviour of the MOL GmB 45/80-55 is not similar to the SBS modified PmBs, even though they are characterised similarly by penetration and softening point in the EN product standard. In the next series of analysis, an effort has been made to map the effect of a harder grade road paving bitumen (or a less aged non-PmB RA bitumen) on the GmB characteristics. Therefore, blends of the OMV B 35/50 and the MOL GmB 45/80-55 bitumens have been prepared with 10-20-30-40% proportions. Results of this analysis are summarised in **Table 8.** and on **Fig. 16.**

Table 8. *Summary of tested and calculated viscosities for OMV B 35/50 + MOL GmB 45/80-55 bitumen blends*

B 35/50 % (in blend)	***Tested viscosity (Pa.s)***	***Calculated viscosity (Pa.s)***	***Difference (%)***
10	2 186	1 386	58
20	1 981	1 209	64
30	1 681	1 056	59
40	1 592	925	72
OMV B 35/50	517		
MOL GmB 45/80-55	1 591		

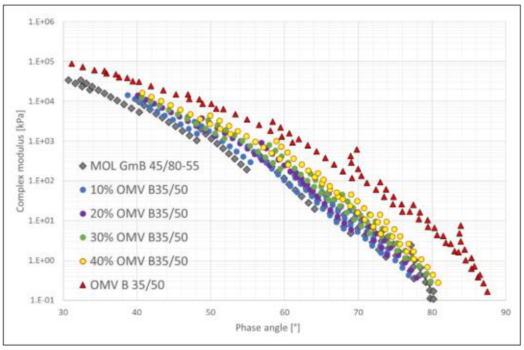

Figure 16. *Black diagrams of OMV B 35/50 + MOL GmB 45/80-55 blends*

The characteristics of the blend of the GmB 45/80-55 bitumen with higher B 35/50 content increasingly have approached the characteristics of the plain B 35/50. As it has been already presented it was found again in this series that the measured and the calculated viscosity values are fairly different for the GmB and its blends.

8. Zs RA T002 + OMV 45/80RC blends

Finally, the OMV 45/80 RC base bitumen has been blended with 10-20-30-40% proportions of RA, using the harder RA binder extracted from the Zsámbék sample. According to **Table 9**, as already experienced in case of the harder RA, there has been a large difference between measured and calculated viscosities. **Fig. 17.** shows the Black diagrams, where results are in accordance with previous experiences, indicating that the 10% and 20% RA contents have not significantly changed the characteristics of the PmB. There has also been a possibility to plot together the Black diagrams of the Zsámbék and the Körmend originated RA bitumens as well as of the MOL PmB 25/55-65 bitumen (**Fig. 18.**), showing a significant difference between two types of RA bitumens originated from different sources.

Table 9. *Summary of tested and calculated viscosities for Zs RA T002 + OMV 45/80 RC bitumen blends*

RA % (in blend)	***Tested viscosity (Pa.s)***	***Calculated viscosity (Pa.s)***	***Difference (%)***
10	1 862	2 818	-34
20	2 397	3 515	-32
30	3 138	4 404	-29
40	4 496	5 545	-19
100% Zs RA T002	16 748		
100% OMV 45/80 RC	2 269		

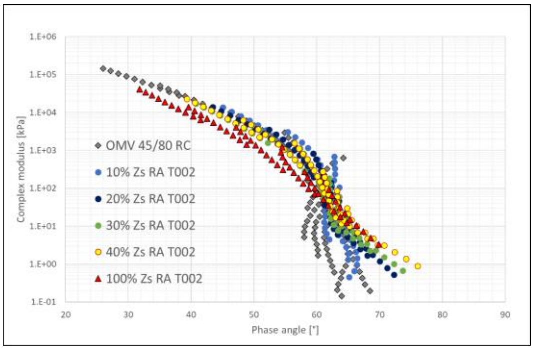

Figure 17. *Black diagrams of Zs RA T002 + OMV 45/80 RC blends*

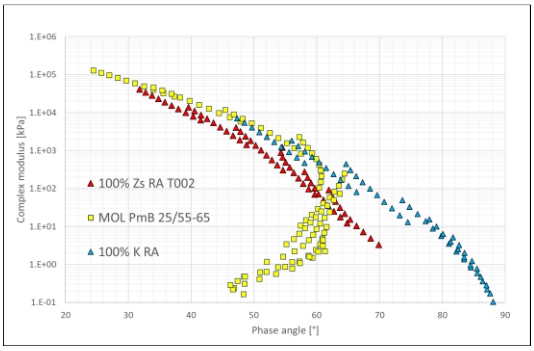

Figure 18. *Black diagrams of Zs RA T002, the K RA and the MOL PmB 25/55-65 bitumens*

V. CONCLUSIONS

Designing and manufacturing hot mix asphalt (HMA) with high recycled asphalt (RA) content have economic and environmental benefits, due to the reduction of primary raw materials, such as crushed stone, bitumen and additives, resulting in the reduction of the overall carbon footprint of the asphalt industry. Incorporating high proportion RA into the manufacturing of new HMA is still at a very low level in Hungary, despite the obvious economic advantages. This paper provides learnings and details with regard to the design and management of the binder blend in the HMA containing high proportions of RA.

Studies of bituminous materials of aged pavement layers found on the Hungarian road network is difficult by applying traditional and mainly empirical test methods, because their bitumen must be extracted in laboratories using a solvent in large quantities when preparing for these tests. Also, the traditional tests are not adequate for describing the total behaviour of bituminous binder blends. Instead, an analysis method has been found and presented in this paper, which makes possible the preparation and testing of a smaller amount of bitumen specimens in the laboratory, characterising base binders, binders extracted from the RA or their blends. There are emerging technologies available in civil engineering, such as digital image correlation method (DICM) to predict behaviours in structures [25]; similarly, the dynamic shear rheometer (DSR) device and the data derived from the DSR test is considered emerging technology and it was found suitable for this purpose.

Samples from different recycled asphalt (RA) sources have been collected and their bitumen has been extracted. Their viscosity has been analysed by a procedural order established by the authors. Based on the test results, the viscosities of blends of different RA content (characteristically 10-20-30-40%) have been calculated as well. Similar blends have been prepared in the laboratory and their viscosity has been measured. Based on the resulting data, it is possible estimating the performance of the binder blend (that is the base binder and the binder extracted from the RA), and consequently the performance of the asphalt mix. This was based on the characteristics of the bitumen extracted from the RA and the base bitumen, and the methodology has been validated.

The results of the analysis of the bituminous binder blends have proved, that in all cases of paving grade bitumen (B), polymer modified bitumen (PmB) and rubber modified bitumen (GmB), the utilisation of a higher proportion of RA content is possible without compromising on the overall characteristics of the virgin binder. In case of the paving grade bitumen, the maximum proportion of RA is determined by the softer bitumen applied. Based on the data presented in this paper, a properly chosen paving grade bitumen makes it possible to utilise up to 40% RA content. Based on large scale asphalt production the methodology of utilising softer bitumen grade has been validated up to 50% RA [26].

For the polymer modified bitumen, the limit of the RA content is 20%, but substituting an RC type bitumen, the RA content may be increased to 30%. For the rubber modified bitumen, the various proportions of RA contents showed no or negligible changes in characteristics of the bitumen. The RA content can reach 30% for this binder type, even without changing the base rubber modified bitumen.

Such rheological characterisation of various bituminous binders, including base binders, binders extracted from the RA and their blends has not been provided for Hungarian conditions before. Based on the DSR characterisation it was possible to evaluate the complex behaviour of the various binder types – B, PmB and GmB. A reliable methodology was also developed for laboratory prepared binder blends and the complex rheological characterisation of these binder blends provided a tool for establishing the risk profile of binder blend performance when incorporating various percentages of recycled binder extracted from recycled asphalt pavement.

The need for future research was identified to ensure reliable use of more than 30% RA in mixes containing PmB; for such application a highly modified PmB binder would be required to compensate for the polymer content in the binder blend containing RA bitumen. Also, further work needs to be completed on the effect of rejuvenator agents when added to mixes containing paving grade bitumen.

Acknowledgement

The research work outlined in this paper was completed as part of project 2020-1.1.2-PIACI-KFI-2020-00060, supported by the National Research, Development and Innovation Office of the Ministry of Innovation and Technology - National Research, Development and Innovation Fund.

AUTHOR CONTRIBUTIONS

Cs. Toth: Conceptualization, laboratory testing, review.

L. Petho: Conceptualization, analysis, writing and editing.

Sz. Rosta: Sample collection, laboratory testing, review.

Disclosure statement

The authors have no known conflict of interest to declare.

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