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Dynamic Viscosity Prediction of Blends of Paving Grade Bitumen with Reclaimed Bitumen

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Abstract

The recycling of reclaimed asphalt pavement is of significant economic and environmental benefits. In this case, however, the satisfactory performance of the final product needs scientific planning of the mixture and thorough quality control. Before its use, a number of tests must be performed to verify that the binder meets the relevant requirements and can be used in asphalt mixtures. The binder characteristics in the reclaimed asphalt pavement and the expected properties of the binder blend in the new asphalt mixture must be known. For its prediction and calculation, a European standard offers the calculation of the penetration or softening point of the binder blend in the mixture with reclaimed asphalt content. However, in some countries, the determination of paving grade bitumen types (categories) is based not on dynamic viscosity measured with DSR instrument, so other validated test and calculation methods are in force. A viscosity-based method has not yet been validated for paving grade bitumens standardized on a penetration basis, although this method is more advantageous in many aspects when monitoring daily production processes; it is much shorter and requires less material than measuring softening point or penetration. The article deals with the measurement of the dynamic viscosity of bitumen blends of asphalt mixtures made using reclaimed asphalts, determined with a dynamic shear rheometer at different frequencies (0.1–10.0 Hz sweep). Furthermore, the relationships between the different composition ratios of national paving grade bitumens classified on the bases of penetration level and bitumens from reclaimed asphalt pavement are examined.

Keywords

reclaimed binder, dynamic viscosity, bituminous binder blend, viscosity prediction of blends

1 Introduction

International literature describes several theories and calculation formulas are for the viscosity of material mixtures, emphasizing that viscosity (e.g. unlike mass) is not an additive quantity. In the following, the viscosity mixing (blending) formulae developed for bitumens found in the literature, as well as some of the results of our research on their applicability on mixtures of paving grade bitumen available in Hungary and bitumen recovered from RA will be presented. A statistical analysis of complex viscosity results measured at different frequencies are shown according to different prediction formulas, besides viscosity prediction formulae are compared, and their predicton results are related to the ones obtained in Hungarian asphalt laboratories.

2 Some viscosity prediction models for binder blends

Centeno et al. (2015) collected 26 viscosity blending formulae, then categorized them, and tested their suitability on different oil blends. Categories were designated for pure mixing rules, mixing rules with viscosity blending index, mixing rules with additional parameters determined by mathematical methods, mixing rules with a binary interaction parameter and mixing rules with an excess function. Since the latter three types of rules require other tests in addition to viscosity measurement to determine the necessary parameters and perform the calculations, these theories are pushed into the background when examining the rheological properties of bitumens. Some of the simpler viscosity mixing rules were also studied when researching the properties of bitumen, and were later used in the bitumen

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industry as studies and regulations (ASTM D4887-99, 2003; Austroads, 2006; Austroads, 2015a; Shu, 1984).

The application of viscosity mixing rules has spread mainly in the USA and Australia, and they are mainly used to determine the viscosity of paving grade bitumen, SBS modified bitumen, bitumen recovered from RAP and rejuvenating agent. In the case of bitumens, the biggest difference is that the calculation models are not only used at high temperatures (135-165 °C mixing and compaction temperature for asphalt mixtures) (Elkashef et al., 2019), where the binders (fresh bitumen or RAP bitumen) have properties similar to a Newtonian fluid, but also in the high (45–60 °C) behaviour temperature range usually established for asphalt mixtures, where viscoelastic properties characterize the binders (fresh bitumens, RA bitumens) and the rejuvenating agents are characterized by properties similar to a Newtonian fluid (Austroads, 2006).

When designing/manufacturing asphalt mixtures containing RAP, it is important to estimate the viscosity of the resulting binder blend, knowing the viscosity of the binder components. The calculation method according to the relevant standard (Austroads, 2015a) estimates the viscosity of the binder blend for designing a mixture containing binder from reclaimed asphalt, fresh binder and/or rejuvenator to a target viscosity. The viscosity of the appropriate binder blend can be validated by mixing the components in the laboratory and determining the viscosity of the mixture (Austroads, 2015b). The expected viscosity of the binder blend is calculated using Eqs. (1)–(3):

$$VBI_i = \frac{3 + \log \vartheta_i}{6 + \log \vartheta_i}, \quad (1)$$

$$VBI_\beta = \sum_{i=1}^{n} x_i \cdot VBI_i, \quad (2)$$

$$\mu = 10^{\left(\frac{3VBI_\beta}{1-VBI_\beta} - 3\right)}, \quad (3)$$

where:

- ϑ_i: viscosity of the ith component (in Pa·s),
- VBI_i: viscosity blending index of the ith component,
- VBI_β: viscosity blending index of the blend,
- x_i: volume fraction of the ith component,
- μ: viscosity of the blend (in Pa·s).

In Australia, the Austroads Report AP-T66-06 (Austroads, 2006) formulated the requirements presented for the characterization of RAP bitumen, fresh bitumen and rejuvenating agent mixtures. The mass ratio of the binders can be calculated from the following relationship (Eq. (4)):

$$r = \frac{\log(V+3) - \log(T+3)}{\log(V+3) - \log(R+3)}, \quad (4)$$

where:

- r: the mass fraction of total binder in the mix that is rejuvenating agent or fresh bitumen,
- R, T, V: logarithms of viscosity (log Pa·s) at a single temperature that is usually 60 °C,
- R: logarithm of the viscosity of the rejuvenating agent,
- T: logarithm of the target viscosity of the final product,
- V: logarithm of the viscosity of the bitumen extracted from the RAP.

The formula is probably based on the work of Epps et al. (1980), in which the original unit of viscosity was – according to the American imperial system of units – centipoise. The three viscosities in the calculation formula were converted from centipoise to pascal-second (Pa·s) in accordance with the SI metric system when used in the early stages of Australian practice. (This is why the "+ 3" values are included in the formula.) The formula can also be found in the 1997 version of the Asphalt Recycling Guide, but an incorrect formula was included here, which was later corrected to the formula presented above (Austroads, 2013; Oliver, 2001; Oliver and Alderson, 2000).

The following formula developed by Kendall and Monroe (1917) can be used to determine the viscosity of bitumen mixtures and bitumen-rejuvenator mixtures (Eq. (5)):

$$\mu^{1/3} = w_A \mu_A^{1/3} + w_B \mu_B^{1/3}, \quad (5)$$

where:

- μ: viscosity of the blend (cP),
- μ_A: viscosity of component A (cP),
- μ_B: viscosity of component B (cP),
- w_A: weight fraction of component A,
- w_B: weight fraction of component B.

A relationship was originally established by Kendall and Monroe for liquid-phase, very low-viscosity materials, when they were looking for the ideal curve describing the viscosity of mixtures (Kendall and Monroe, 1917). The Asphalt Institute published a methodology for creating mixtures of RAP binder and fresh bitumen with the desired viscosity, using mixing diagrams (Asphalt Institute, 1981); this theory was also published in the form of standard in the USA (ASTM D4887-99, 2003). The origin of the formula can be linked to Arrhenius' dissertation about the dissociation of substances dissolved in water and measured the viscosity of water for different water-soluble substances (Arrhenius, 1887).

3 Materials and methods

3.1 Comparison of viscosity prediction formulae

The differences between the 4 viscosity prediction formulae outlined in Section 2 can be illustrated graphically in the simplest way (Fig. 1). Fig. 1 shows the viscosity values calculated based on the four models for road construction bitumen with a viscosity of 150 Pa·s and RA bitumen with a viscosity of 10,000 Pa·s in different application ratios.

The horizontal axis shows the mass percentage of RA bitumen in the blend, while the vertical axis shows the viscosity calculated based on the corresponding formula, on a log base 10 scale. It can be seen that when mixing fresh bitumen and RAP-bitumen, in the case of very low viscosity without rejuvenator, the differences between Austroads (2006), ASTM D4887-99 (2003) and AGPT-T193-15 (Austroads, 2015b) based viscosities are minimal, only in the range of 20-80% there is some difference. On the graph, the ASTM D4887-99 (2003) log linear graph appears straight. A greater difference can be observed in the case of the Kendall-Monroe equation, since in the 10–90% range it gives a much higher (up to 2 times) viscosity than the others.

3.2 Terminology and materials

In our research work, three RAP-bitumen types (coming from the wearing and base courses of a secondary main road, and the wearing course of a municipality road using the relevant EN standard (SIST EN 12697-3:2013+A1:2019, 2019) were utilized. The idea was to test RAP-bitumens at different aging levels blending them with B 70/100 and

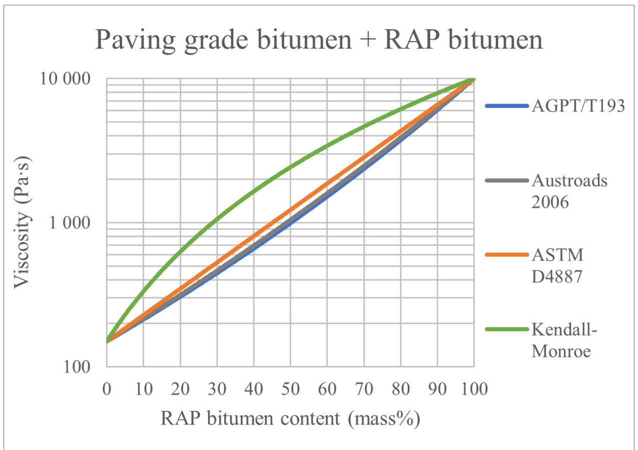

Fig. 1 Viscosity of a blend of paving grade and RA-bitumen with different ratios using the four predictive models, plotted on log scale

B 100/150 paving grade bitumens in various (10-20-30-40-50 m%) mass ratios in four blends.

The prepared binder blends were tested using a dynamic shear rheometer on samples with a diameter of 25 mm. The complex viscosities measured at 60 °C were compared with those calculated by formulae for calculating the viscosity of different mixtures. For the analysis, in addition to the 1 rad/s (0.159 Hz) angular frequency, ω included in the relevant Australian standard, complex viscosities for 4 different estimating formulae were determined, at 10 different frequencies (0.1–10 Hz), and then error analysis was also performed.

The measurements at higher frequencies were justified by the fact that studies indicating the high-temperature rutting tendency of asphalt mixtures are also modelled at higher frequencies. For example, the researchers of the SHARP model considered the stiffness of the viscous component ($G^*/\sin\delta$) at a loading time of 0.1 s as a critical value for the rutting resistance when compiling the specification. The loading time of 0.1 s was chosen according to the real loading time, which is derived from the passage of car tyres at a speed of 80 km/h. For a sinusoidal load, 0.1 s corresponds to 10 rad/s (1.6 Hz) (Tóth and Perlaki, 2006).

As a first step, in accordance with European regulations (EN 1426:2016, 2016; EN 1427:2016, 2016), the softening point and the penetration of the binders were measured. In order to find out the viscosity of domestic bitumens, the complex viscosity of road construction bitumens (B 20/30, B 35/50, B 50/70) standardized on a penetration basis with a DSR device at 60 °C at a frequency of 1 rad/sec were also determined. The basic properties of the paving grade bitumens and the recovered asphalt bitumens used can be found in Table 1.

We have developed our own procedure for mixing bitumens in the laboratory, making sure that the bitumens are heated for the shortest possible time, but that the mixing is as efficient as possible. The homogeneity of the mixtures is ensured by mixing twice; its success is supported by the results of parallel measurements of the mixture (Rosta and Gáspár, 2023). In Australia, bitumens are mixed under a heating lamp, ensuring that the bitumen does not cool down during mixing and resulting in a well-mixable, homogeneous mixture (Austroads, 2013). In the domestic bitumen testing laboratories, the heating lamp did not spread, so the bitumens were heated using a drying cabinet and tempered at the mixing temperature.

The components of the bituminous blends in appropriate proportions were heated and then thoroughly mixed

Table 1 Main statistical parameters of binder types used in the analysis

Paving grade/RAP bitumen		B 20/30	B 35/50	B 50/70 (1)	B 50/70 (2)	B 70/100 (1)	B 70/100 (2)	B 100/150	RAP Surf 1	RAP Surf 2	RAP Bind 1
Complex viscosity 60 °C 1 rad/s (Pa·s)	Mean value	2 445	517	261	305	129	164	93	8 264	1 685	33 556
	Range	814	133	16	45	21	24	6	1133	113	3344
	Standard deviation	361.6	54.8	5.13	16.1	9.95	10	2.71	489.2	45.3	1455.2
	Covariance	0.15	0.11	0.02	0.05	0.08	0.06	0.03	0.06	0.03	0.04
	No. of measurements	3	3	7	5	4	3	3	3	3	3
Penetration (0.1 mm)	Mean value	26	45	55	52	81	76	109	27	42	12
Softening point (°C)	Mean value	62.8	54.4	49.4	50.9	46.5	47.0	42.9	64.8	60.4	77.2

while maintaining the heating. After mixing, the mixture was repeatedly tempered, and after a repeated, shorter period of mixing in a heated medium, the sample molds were filled. The samples were kept at a temperature of 10 °C until the DSR measurement. Table 2 shows the composition of the tested bitumen blends and the complex viscosity determined at 60 °C and 0.159 Hz (1 rad/s).

4 Results and discussion

The complex viscosity (η^*) determined by oscillatory test is defined as the ratio between the complex shear modulus (G^*) and the angular frequency (ω). By increasing the angular frequency, complex shear modulus of bitumen decreases, however, the change in the ratio of the two parameters can no longer be clearly defined. In the case of very soft bitumens, the complex viscosity decreases much less than in the case of reclaimed asphalt bitumens of higher viscosity. This phenomenon is well illustrated in Table 3. While in the case of soft paving grade bitumens,

Table 2 Complex viscosities of various bituminous blend types as a function of RAP bitumen content

Blend type	RAP Surf 1 + B 70/100	RAP Surf 1 + B 100/150	RAP Bind 1 + B 70/100	RAP Surf 2 + B 70/100
RAP bitumen content (mass%)	Complex viscosity 60 °C 1 rad/s (Pa·s)			
0%	164	93	164	164
10%	252	140	309	265
20%	305	187	524	273
30%	402	241	742	315
40%	592	398	1 366	402
50%	965	648	2 353	496
100%	8 264	8 264	33 556	1 685

Table 3 Complex viscosity of various binder types as a function of angular frequency

Frequency		B 70/100	B 100/150	Surf 2	Surf 1	Bind 1
rad/s	Hz	Complex viscosity (η^*) 60 °C (Pa·s)				
0.63	0.10	96	177	1 745	8 692	37 630
1.05	0.17	96	177	1 690	8 241	33 840
1.75	0.28	96	176	1 630	7 743	30 130
2.92	0.46	95	174	1 560	7 183	26 640
4.86	0.77	94	171	1 481	6 594	23 340
8.11	1.29	93	169	1 396	6 006	20 310
13.53	2.15	92	165	1 305	5 418	17 530
22.57	3.59	90	161	1 215	4 836	15 060
37.65	6.00	89	156	1 121	4 286	12 840
62.80	10.00	87	151	1 027	3 770	10 910
Difference between 0.17 and 1.29 Hz (%)		96.8%	95.6%	82.6%	72.9%	60.0%
Difference between 0.17 and 10 Hz (%)		90.2%	85.5%	60.8%	45.7%	32.2%

the complex viscosity ratio for 0.1 Hz and 10 Hz is 0.85-0.90, while for RAP bitumens, this ratio is between 0.3-0.6. As the complex viscosity increases, this ratio decreases. However, it is important to emphasize that viscosity itself is a property with a logarithmic scale.

Figs. 2–5 show the change of the measured and calculated complex viscosities for the frequencies of 0.17 Hz, 1.29 Hz and 10.00 Hz, on a logarithmic scale, as a function of the ratios of paving grade bitumen and RAP bitumen in the blend. It can be seen that the complex viscosity increases exponentially with the RAP bitumen content. This increase is larger at lower frequencies. It can be

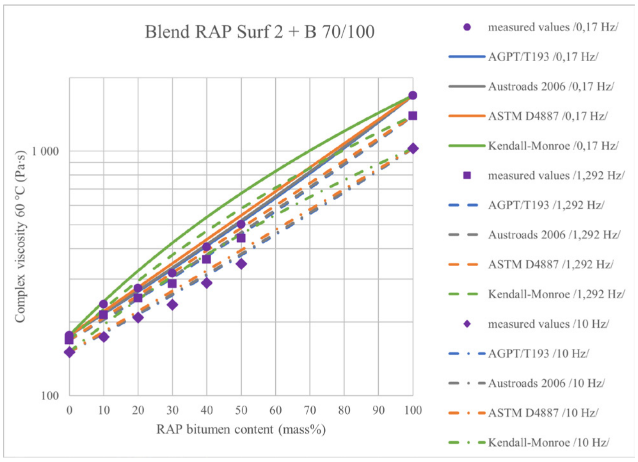

Fig. 2 Complex viscosity as a function of RAP bitumen content (%) at various angular frequencies (blends of RAP Surf 2 and B 70/100)

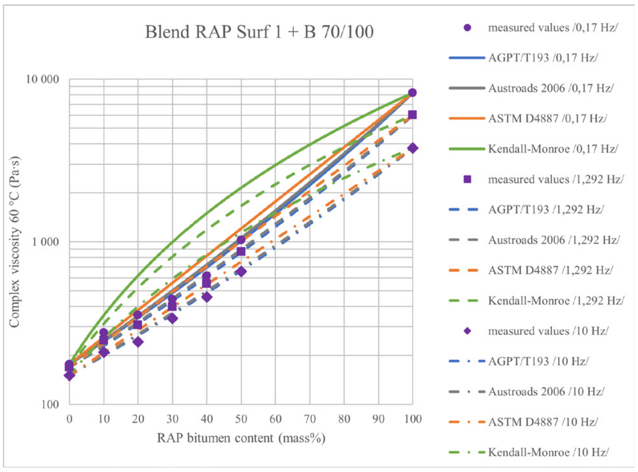

Fig. 3 Complex viscosity as a function of RAP bitumen content (%) at various angular frequencies (blends of RAP Surf 1 and B 70/100)

concluded that in the case of each mixture, at low, medium and high shear frequencies, it closely approximates the values of AGPT-T193-15 (Austroads, 2015b), Austroads (2006) and ASTM D4887-99 (2003) models, but at the same time, it does not provide an acceptable degree of correlation with the Kendal-Monroe equation.

A statistical error analysis was carried out on the measured and the calculated values, examining how accurate a predictive formula describes the measured results in the case of a given blend. For this purpose, for each mixing ratio (10–50%) and each frequency (0.1–10 Hz), the signed differences between the measured and calculated value using the corresponding empirical formula (absolute error) were taken. Then the absolute error as a percentage of the measured values (relative error), was calculated. Finally, the arithmetic mean value of the relative errors for each predictive formula was determined. The obtained results are shown in Tables 4 and 5.

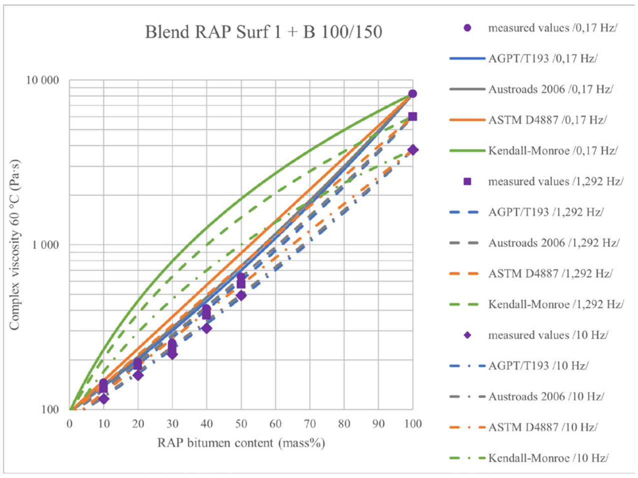

Fig. 4 Complex viscosity as a function of RAP bitumen content (%) at various angular frequencies (blends of RAP Surf 1 and B 100/150)

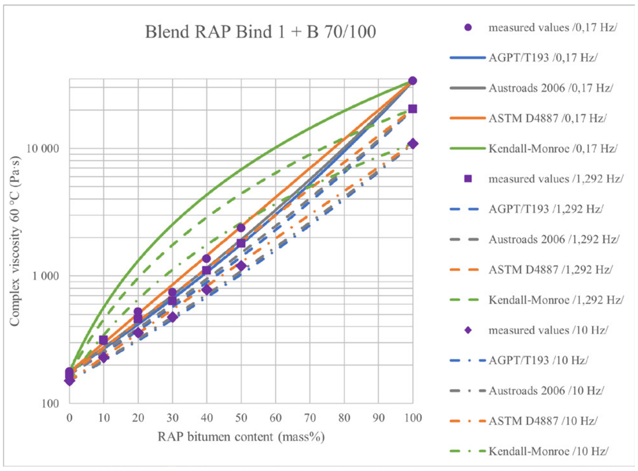

Fig. 5 Complex viscosity as a function of RAP bitumen content (%) at various angular frequencies (blends of RAP Bind 1 and B 70/100)

To establish the final order, the average of the relative errors of all four mixtures were calculated with the following results these: Austroads (2006): +1.8%; ASTM D4887-99 (2003): +12.4%; AGPT-T193-15 (Austroads, 2015b): −1.3%; Kendall and Monroe (1917): +95.4%.

5 Conclusions

The following conclusions can be drawn from the comparison of the measured and predicted viscosity values of the blends of reclaimed bitumens at three different aging levels and paving grade bitumens B70/100 and B100/150 that were measured at 60 °C and at a frequency of 0.1-10.0 Hz (four predictive formulae were tested):

- There is no significant difference between the results of AGPT-T193-15 (Austroads, 2015b) and Austroads (2006) models.

Table 4 Average differences from measured values (10-20-30-40-50 m% RAP) in a given frequency for 2 binder blends

Frequency (Hz)	RAP Surf 1 + B 70/100				RAP Surf 1 + B 100/150			
	Austroads (2006)	ASTM D4887-99 (2003)	AGPT-T193-15 (Austroads, 2015b)	Kendall and Monroe (1917)	Austroads (2006)	ASTM D4887-99 (2003)	AGPT-T193-15 (Austroads, 2015b)	Kendall and Monroe (1917)
0.10	0.022	0.134	−0.012	0.951	0.129	0.302	0.082	1.696
0.17	0.045	0.157	0.012	0.961	0.130	0.300	0.084	1.647
0.28	0.064	0.175	0.032	0.955	0.126	0.291	0.081	1.578
0.46	0.064	0.171	0.033	0.915	0.126	0.285	0.082	1.509
0.77	0.062	0.165	0.032	0.868	0.111	0.262	0.070	1.404
1.29	0.053	0.151	0.025	0.809	0.104	0.248	0.064	1.319
2.15	0.056	0.149	0.029	0.766	0.103	0.242	0.066	1.244
3.59	0.056	0.145	0.030	0.720	0.087	0.217	0.052	1.136
6.00	0.062	0.146	0.037	0.683	0.076	0.198	0.043	1.040
10.00	0.058	0.138	0.035	0.637	0.066	0.181	0.036	0.949
Average	0.054	0.153	0.025	0.827	0.106	0.253	0.066	1.352

Table 5 Average differences from measured values (10-20-30-40-50 m% RAP) in a given frequency for other 2 binder blends

Frequency (Hz)	RAP Bind 1 + B 70/100				RAP Surf 2 + B 70/100			
	Austroads (2006)	ASTM D4887-99 (2003)	AGPT-T193-15 (Austroads, 2015b)	Kendall and Monroe (1917)	Austroads (2006)	ASTM D4887-99 (2003)	AGPT-T193-15 (Austroads, 2015b)	Kendall and Monroe (1917)
0.10	−0.131	0.044	−0.181	1.901	0.004	0.043	−0.007	0.248
0.17	−0.132	0.036	−0.180	1.767	0.004	0.042	−0.007	0.242
0.28	−0.131	0.031	−0.177	1.640	0.010	0.047	−0.001	0.242
0.46	−0.129	0.026	−0.173	1.523	−0.044	−0.009	−0.054	0.174
0.77	−0.124	0.025	−0.166	1.417	0.019	0.054	0.009	0.236
1.29	−0.137	0.004	−0.178	1.279	0.027	0.061	0.017	0.236
2.15	−0.108	0.030	−0.147	1.226	0.036	0.069	0.026	0.237
3.59	−0.094	0.038	−0.132	1.153	0.047	0.079	0.038	0.240
6.00	−0.081	0.046	−0.117	1.081	0.059	0.090	0.050	0.244
10.00	−0.065	0.058	−0.100	1.021	0.072	0.101	0.063	0.248
Average	−0.113	0.034	−0.155	1.401	0.023	0.058	0.013	0.235

- AGPT-T193-15 (Austroads, 2015b) slightly underestimates and Austroads (2006) and ASTM D4887-99 (2003) slightly overestimate the viscosities measured at 60 °C; AGPT-T193-15 (Austroads, 2015b) and Austroads (2006) are the most accurate ones.
- The complex viscosity of RAP bitumen measured at 60 °C increases with increasing load frequency.
- Similar values occur in the low and medium categories of 0.1-2.0 Hz, and lower ones at high frequency.
- The complex viscosities of RAP bitumens at low and medium aging levels were more accurately approximated by AGPT-T193-15 (Austroads, 2015b) and Austroads (2006) formula, while bitumen blends at a high aging level were more accurately approximated by ASTM D4887-99 (2003) formula.
- The viscosity values predicted by Kendall-formula were very far from the measured values.
- The research of following related topics is planned in the near future: correlation between T_{BTSV} and σ_{BTSV} values, for polymer and rubber modified bitumens; determination of the influence of SBS and rubber in the blends containing bitumen from recycled asphalt; performance assessment of hot mix asphalt with chemically stabilized rubber bitumen (Petho and Toth, 2012; Toth et al., 2016).

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