

Article

Comparative Methodology of Viscosity-Based Classification and Measurement Techniques for High-Temperature Behaviour of Paving Grade Bitumen

Szabolcs Rosta ^{1,2} , Zita Szabó ²  and László Gáspár ^{3,4,*} 

¹ Multidisciplinary Technical Scientific Doctoral School, Széchenyi István University, 9026 Győr, Hungary; rosta.szabolcs@dunaaszfalt.hu

² Duna Group, 1126 Budapest, Hungary; szabo.zita@dunaaszfalt.hu

³ Hungarian Roads Non-Profit Ltd., 1024 Budapest, Hungary

⁴ Department of Transport Construction and Water Management, Széchenyi István University, 9026 Győr, Hungary

* Correspondence: gaspar.laszlo@kozut.hu; Tel.: +36-30-9401-288

Abstract

The accurate determination of the rheological properties of road bitumen types is essential for the reliable prediction of long-term pavement behaviour. At 60 °C, dynamic viscosity is a key rheological parameter characterising the shear-dependent viscoelastic behaviour of bitumen in the temperature range relevant to in-service pavement loading. This study aims to compare different viscosity determination methods—approximations, capillary viscosity, Brookfield measurement and complex viscosity determined by a dynamic shear rheometer (DSR)—and to analyse their relationships with each other in order to find the best method for bitumen classification. Furthermore, the European and Australian bitumen classification standards are compared in terms of dynamic viscosity and penetration, according to which Australian bitumen types show more stable results, as the CV% is less than 10 percent. The study is based on the testing of Hungarian paving-grade bitumens (B50/70, B70/100) and Australian viscosity-graded bitumens (C170, C320), with the comparison of a total of 191 samples obtained from industrial production. The statistical evaluation of the results obtained with the different methods was based on Pearson correlation analysis and relative deviation analysis. The results indicate that the DSR measurement at 1.6 Hz shows the closest agreement with capillary viscosity, with a linear correlation coefficient of 0.95, and exhibits the strongest overall correlation with the other measurement approaches, whereas the Heukelom equation tends to overestimate the dynamic viscosity. The Brookfield method yielded higher viscosity values in all tests. The study highlights that the results of different measurement methods can only be compared under specific shear conditions, and a DSR-based approach can be more suitable for the introduction of a new European bitumen classification system.



Academic Editors: Paulo Santos and Luís Picado Santos

Received: 5 January 2026

Revised: 3 February 2026

Accepted: 13 February 2026

Published: 25 February 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: dynamic viscosity; complex viscosity; DSR (dynamic shear rheometer); frequency sensitivity; paving grade bitumen

1. Introduction

The service life and performance of asphalt pavements are fundamentally determined by the mechanical behaviour of asphalt mixtures, which is closely related to the rheological properties of the binder (bitumen) [1]. Bitumen classification plays a key role not only

in material selection and quality control but also in performance-based pavement design. Classification systems define acceptance criteria across different markets and production sources and therefore directly affect the comparability, interchangeability and long-term performance expectations of binders used in pavement structures [2].

Traditional classification parameters, such as the penetration and softening point, provide only indirect indicators of in-service behaviour; consequently, their relationship with deformation resistance and long-term pavement performance is often limited. By contrast, viscosity-based parameters—particularly dynamic viscosity at higher temperatures—are more directly related to shear resistance after construction, thereby providing a stronger link between laboratory characterisation and pavement performance [3]. Due to the time-varying nature of traffic loads and the combined (synergistic) effect of temperature and aging, bitumen types behave as viscoelastic materials; therefore, a single test parameter is insufficient to characterise them. Laboratory methods that can describe the time- and frequency-dependent behaviour of the binder and the mixture are gaining increasing emphasis. Tests performed with a dynamic shear rheometer (DSR) can be used to determine complex viscosities and phase angles [3,4]. At the same time, traditional tests, such as penetration and softening point measurements—which form the basis of the European bitumen standardisation—remain widely used in practice. However, international practice, including Australian bitumen classification, places greater emphasis on dynamic viscosity measured at 60 °C using the vacuum capillary method. This parameter characterises the material's internal resistance to shear, allowing for a more detailed characterisation of the pavement's behaviour [4].

1.1. History and Limitations of the Vacuum Capillary Viscometer for Testing Road Bitumen

The vacuum capillary viscometer is the classic laboratory method for determining the dynamic viscosity of bitumen. The test is performed at 60 °C under a vacuum of approximately 300 mmHg (≈ 40 kPa), and an “apparent” viscosity is calculated from time–volume measurements based on the Hagen–Poiseuille law. The method became an industry standard through the use of Cannon–Manning, Asphalt Institute and Modified Koppers capillaries, which became widespread in the 1930s. Today, the ASTM D2171/D2171M-22 [5,6] and EN12596:2023 [7] standards specify the test procedure, including that for non-Newtonian binders; the result is an “apparent” value dependent on the shear rate [7]. Traditionally, viscosity at 60 °C has been used as an indicator of the temperature-dependent deformation resistance. This method remains widely applied, particularly in the research and formulation optimisation of elevated viscosity and high-elasticity binders (HVMA/HVE). Several recent studies characterise modified binders by the viscosity at 60 °C measured by the vacuum capillary method [8–10]. For high-viscosity binders prepared for two-layer, porous asphalts, the viscosity at 60 °C is a key indicator of adhesion and cohesion properties [11].

In measurements using a vacuum capillary viscometer, bitumen is drawn into a capillary by applying a vacuum while the capillary is maintained in a thermostatically controlled bath at 60 ± 0.1 °C. The dynamic viscosity can be calculated from the transit time of the marked section and the capillary constant. The advantage of the method is the good repeatability for Newtonian (unmodified) binders and that it requires only simple equipment. However, for modified (SBS/CR, TPS, etc.) bitumen types, the measurement often only gives an “apparent” viscosity because the shear rate is not directly recorded and the sample may exhibit non-Newtonian behaviour [6,10]. These limitations are particularly important for comparative studies, as variations in shear conditions and the “apparent” nature of capillary viscosity can affect consistency across measurement methods. Although polymer-modified binders are especially sensitive to these effects, the present study focuses on conventional paving-grade bitumens; therefore, the identified limitations mainly provide

context for interpreting cross-method comparisons rather than assessing modified binder behaviour. In addition, calibration, the presence of impurities on the capillary wall and the vacuum stability significantly influence the measurement uncertainty [6,7]. As a result, other approximate methods are also used.

1.2. Viscosity Measurement Methods

Dynamic shear rheometer (DSR)

The determination of complex viscosity using a DSR (dynamic shear rheometer) is described in EN 14770:2023 standard [12]. The sample preparation required for the test is specified in the EN 12594:2025 standard [13]. The samples are poured into moulds and then placed between two preheated, parallel plates of the rheometer. The load is transferred to the sample by the upper plate, while the displacement occurring on the lower plate is recorded. The applied oscillating shear stress causes the resulting deformation to occur with a phase angle δ from the load [4]. The ratio of the applied shear stress (τ) to the amplitude of the deformation (γ) yields the complex shear modulus (G^*). Dividing G^* by the angular frequency (ω) gives the complex viscosity (η^*) [4]. The phase angle is suitable for characterising the viscoelastic behaviour of the mixture. If the phase angle (δ) is 0° , the material is elastic; if $\delta = 90^\circ$, it is viscous; and if it is between 0° and 90° , the material exhibits viscoelastic behaviour [14].

In 2010, Guericke, based on oscillation measurements and DSR studies, showed that at a low frequency ($f = 0.159$ Hz), the state of the material at the softening point temperature can be well characterised by the complex viscosity, with a value of $\eta^* = 1300$ Pa·s [15]. This value is used to estimate the viscosity at 60°C , calculated from the softening point temperature using the Heukelom equation.

Brookfield (rotational) viscometer

The EN 13302:2018 standard specifies the determination of the dynamic viscosity of various bitumen types using a rotational device (Brookfield-type viscometer) [16]. The principle of the method is that the dynamic viscosity can be calculated from the torque required to rotate a spindle immersed in the sample, which can be comparable only under identical shear conditions in the case of non-Newtonian materials. The rotational viscometer was previously criticised for limited accuracy; the measurement performance of modern devices is now equivalent to that of traditional methods [4]. The relationship between dynamic and complex viscosity is important for the interpretation of the measurement results. If the shear rate of the rotational measurement can be matched to the angular frequency of the oscillatory measurement, then the complex viscosity and dynamic viscosity are nearly equivalent within the linear viscoelastic range [17,18].

The measuring range of the Brookfield device is determined by the spring torque, spindle geometry and rotational speed. Thus, the measuring range can be determined as a function of the technical parameters of the rheometer and the type of spindle used [19]. By contrast, the dynamic shear rheometer (DSR), due to its stronger torque spring, provides a substantially wider measuring range [20], although it is significantly more expensive. To measure a certain viscosity range, the appropriate spindle of the Brookfield DV2T device must be selected.

1.3. Calculation of Viscosity from Other Parameters and Limitations

To predict the service life and deformation behaviour of pavement structures, it is necessary to determine the viscosity and stiffness of bitumen and asphalt mixtures. However, laboratory viscometer measurements are time-consuming and costly; therefore, numerous approximate equations have been proposed in the literature. These empirical and semi-empirical models seek to estimate viscosity and stiffness based on the penetration

value, temperature or dynamic modulus. Although these formulae are useful for practical estimation, their predictions may differ by one or two orders of magnitude compared to real data [21,22]. The following sections present the most commonly used approximate equations, together with their limitations and principal sources of error.

Heukelom's conversion (1973)

The relationship between viscosities measured at different temperatures is given by Heukelom's empirical equation [23]:

$$\log \eta = \log \eta_{\text{ref}} + (-C_1 \times (T - T_{\text{ref}})) / (C_2 + (T - T_{\text{ref}})), \quad (1)$$

where C_1 and C_2 are constants specific to the bitumen type, and T and T_{ref} are the temperature ($^{\circ}\text{C}$) and the reference temperature ($^{\circ}\text{C}$), respectively. This equation enables the conversion of viscosity between different temperatures [23].

The Heukelom equation has limitations because the parameters C_1 and C_2 were calibrated only for specific bitumen types; in other cases, it may underestimate the viscosity by up to one order of magnitude [21]. Although Heukelom originally proposed the values of C_1 and C_2 as 8.5 and 110, respectively, later studies reported different values as optimal; for instance, Anderson (1994) recommended $C_1 = 19$ and $C_2 = 92$, based on an analysis of SHRP asphalt data [2].

Mirza model and Witczak equation for viscosity

The relationship between viscosity (η , Poise) and penetration (Pen, dmm) measured at 25°C is described by the model developed at the University of Maryland [24]:

$$\log \eta = 10.5012 - 2.2601 \cdot \log(\text{Pen}) + 0.00389 \cdot [\log(\text{Pen})]^2 \quad (2)$$

This equation applies to penetration values between 3 and 300 dmm (tenths of a millimeter) and gives the dynamic viscosity at 25°C [24]. The Mirza equation [24] is valid only at 25°C and cannot be applied to modified bitumen types, because their non-Newtonian behaviour means that penetration is not proportional to viscosity [22].

A revised version of the Mirza model is the Witczak equation, which can estimate viscosity over a wider temperature range [22]:

$$\log \log \eta = A_i + \text{VTS}_i \log T_V, \quad (3)$$

where η is the viscosity value [$\text{mPa}\cdot\text{s}$], VTS_i is the viscosity–temperature susceptibility, T_V is the measurement temperature [$^{\circ}\text{R}$ —degree Rankine] and A_i is a constant [25]. However, for different asphalt mixture types and aging periods, the values of A_i and VTS_i vary, and even the units used for viscosity may differ. This issue was noted by Witczak and Fonseca [25], who subsequently proposed a nonlinear sigmoidal function, which, according to their research, can be applied to any unmodified asphalt type. Witczak-type models estimate the dynamic modulus (E^*) based on the viscosity of the binder and mixture characteristics. His equations have been revised several times over time, and Mirza also published approaches for approximating the dynamic modulus [24].

The Witczak–Fonseca model provides a particularly strong correlation value ($R^2 \approx 0.95$) with the measurement results, but only in the case of conventional bitumen types; however, significant differences appear in the case of polymer-modified, rubber-modified or additive-enriched bitumen types. According to Tóth's laboratory tests conducted in Hungary (2010), the Witczak–Hirsch models underestimate asphalt mixture stiffness by 20–30% at temperatures above 40°C , while they overestimate it at low temperatures [21].

Tex-535-C Approximate Formula

The Texas Department of Transportation also published an approximation for the relationship between penetration and viscosity [26]:

$$\mu = (1.559719 \times 10^9) \times \ln[0.0275 / (0.0005 - 0.0114488/P)] / P^2, \quad (4)$$

where μ is the viscosity (Poise) and P is penetration (0.1 mm).

The Tex-535-C equation is sensitive to measurement uncertainty: even a small error in penetration can result in an order-of-magnitude difference in the estimated viscosity [26].

Van der Poel model for stiffness modulus

The Van der Poel nomogram is suitable for determining the stiffness modulus (S) [27], which is a graphical solution of the following Maxwell-type viscoelastic model:

$$S = \eta \cdot \omega / \sqrt{1 + (\eta \cdot \omega / E)^2} \quad (5)$$

In the calculation, S is the desired stiffness modulus [Pa], ω is the angular frequency, E is the elastic modulus [Pa] and η is the binder viscosity [Pa·s]. If $\eta\omega$ is much smaller than E , then the product of viscosity and frequency is negligible compared to the elastic modulus, i.e., the material behaves predominantly elastically, and the stiffness modulus is approximately $S \approx \eta\omega$. If $\eta\omega$ is significantly larger than E , then viscous effects dominate, the material response becomes more viscous and the stiffness approaches the elastic modulus, i.e., $S \approx E$. The Van der Poel nomogram depicts these two extreme states—the purely elastic and purely viscous ranges—and the transitional range between the two, with viscoelastic behaviour, and connects them in a single graphical method [27].

In the Van der Poel model, errors are particularly evident at very low (below -10°C) and high (above 70°C) temperatures, as the linear viscoelastic assumption is no longer fulfilled. According to Gutarra's 2018 research in Peru, nomogram-based estimates of viscosity at 60°C showed a deviation of up to two times compared to experimental data [28].

Although the above formulae are widely used, they can only provide accurate results under specific conditions. Overall, classical penetration and temperature-based models are suitable for quick, engineering-level estimates, but they often give orders-of-magnitude differences in the values of viscosity and stiffness modulus. Modern neural networks and micromechanical approaches can reduce these errors to below 10–15% [29], but their data and computational requirements are significantly higher, and overly complex, data-specific approximations often appear in the background.

Overall, there is a clear lack of a modern and reliable method for viscosity determination, which is essential for implementing a viscosity-based bitumen classification system in Europe. In this study, different measurement approaches are compared in order to identify a suitable alternative to the outdated vacuum capillary method, thereby providing a basis for a classification framework that more accurately reflects aging effects induced by traffic loading and temperature conditions. Before comparing the different methods, we examine Australian and European classified bitumens' rheological properties to highlight the advantages of the viscosity-based bitumen types. After that, we search for the optimal currently existing method for determining bitumen viscosity.

2. Materials and Methods

A total of 191 industrially produced bitumen samples were analysed. Hungarian paving grade bitumens included 20 samples of B50/70 and 20 samples of B70/100, while Australian viscosity-graded bitumens comprised 16 samples of C170 and 135 samples of C320. The Hungarian bitumens were produced from Urals crude oil, and production samples were collected from a factory at intervals of approximately 100 tonnes to ensure

representative coverage of manufacturing variability. The Austral bitumens originate from Queensland state from a single factory. Table 1 summarises the performance indicators of the examined bitumens.

Table 1. Performance indicators of the examined data related to standard specifications.

	B50/70		B70/100		C170		C320	
	Measured (Min–Max)	EN 12591 Thresholds	Measured (Min–Max)	EN 12591 Thresholds	Measured (Min–Max)	AS 2008 Thresholds	Measured (Min–Max)	AS 2008 Thresholds
Softening point [SP; °C]	49–53.4	46–54	43.5–48.5	43–51				
Penetration [0.1 mm]	52–69	50–70	73–93	70–100	62–86	>62	40–59	>40
Capillary viscosity at 60 °C [Pa*s]	169–414	145–175	87–178	90–145	166–238	140–200	219–422	260–380

The European system (EN 12591:2009) [30] is based on simple and rapid empirical tests such as penetration (EN 1426:2025) [31], ring & ball softening point and Fraass breaking point. Based on these, bitumen types are assigned penetration grades (e.g., B 50/70), which are also included in the product name. The Australian standard AS 2008-2013 [32] defines the classification of road construction bitumen types primarily based on dynamic viscosity measured at 60 °C, supplemented by tests of viscosity measured at 135 °C and needle penetration grade measured at 25 °C. The standard aims to ensure the proper processability and long-term performance of bitumen types in road construction. In the case of “C170”, “C” denotes conventional road construction bitumen, while “170” means the dynamic viscosity value (Pa s) measured at 60 °C. In Table 1, we summarise the performance indicators measured and reported in the standard.

Several empirical equations have been proposed in the literature to estimate bitumen viscosity from conventional test parameters. In the present study, only the Heukelom conversion based on softening point was used in the comparative analysis, as it provides a direct estimation of viscosity at 60 °C. The Mirza, Witczak, Tex-535-C and Van der Poel approaches were excluded from the quantitative comparison because their validity ranges, required input parameters or underlying assumptions are not fully compatible with the tested binder types or the applied measurement conditions. At the first approach, the Mirza equation and the Tex-535-C formula overestimated the measured viscosity values by orders of magnitude.

First, we compared European and Australian penetration and capillary viscosity data for different bitumen types. Then, we made a comparison of viscosity calculation/measurement methods for European paving grade bitumens. This comparison includes the results of the capillary viscometer, Brookfield and DSR measurement methods, as well as the viscosity calculated from the softening point using the Heukelom equation. Using the Mirza equation [24] to convert the penetration values to the viscosity measured at 25 °C and then converting this to 60 °C using the Heukelom equation [23], our results differed by orders of magnitude from the results of the other methods, so it was not part of the comparison. Similarly, the Tex-535-C approximation formula [26] produced large deviations, so these results were not used either.

In the Heukelom equation, the viscosities measured at the softening point, taken as 1300 Pa*s, were converted as a reference value to 60 °C viscosity values, knowing the softening point datasets (reference temperatures). The constants in the equation, based on the Heukelom approximation (1973), are as follows: $C_1 = 8.5$; $C_2 = 110$ [23].

Using the DSR method, the three most significant different frequency measurement results were selected from the frequency sweeps, based on the literature (Table 2). The selection of the three investigated frequencies is based on findings from previous studies. Australian research recommended frequency sweeps in the range of approximately

0.1–10 Hz and identified 0.16 Hz as a representative frequency for characterising viscosity at 60 °C [33], while European practice and the American SHRP (Strategic Highway Research Program) research finds a 1.6 Hz frequency more appropriate [3]. However, on roads designed for higher operating speeds (130–150 km/h), traffic-induced effects may be characterised by a higher frequency, around 10 Hz [3].

Table 2. Selected frequency values corresponding to the results measured using the DSR method.

Low Frequency	0.16 Hz $\approx$ 1 rad/s
Average frequency	1.6 Hz $\approx$ 10 rad/s
High frequency	10 Hz $\approx$ 62.9 rad/s

In the case of the Brookfield type rotational viscometer RV DV2T, the shear rate was set to a value close to the range specified in the Australian guideline. In the RV (medium) spring torque range, using the SC4-27 spindle and at a speed of 0.5 RPM, a viscosity range of 50–500 Pa*s was measurable. With these settings, the shear frequency was 0.17 Hz, which is almost the same as the 0.16 Hz frequency used in the DSR tests.

3. Results and Discussion

3.1. Comparison of European and Australian Penetration and Viscosity Results with International Classification Systems

The study aimed to compare the penetration and capillary viscosity measured at 60 °C of different bitumen types (B50/70, B70/100, C170, C320) (Figure 1). Based on the results obtained, with the increase in penetration—i.e., moving towards softer binders—a definite decrease in viscosity can be observed, which is in line with classical rheological expectations. The data dispersions belonging to each bitumen type are clearly visible on the graph, which allows for the comparison of the different quality classes with the standard specifications.

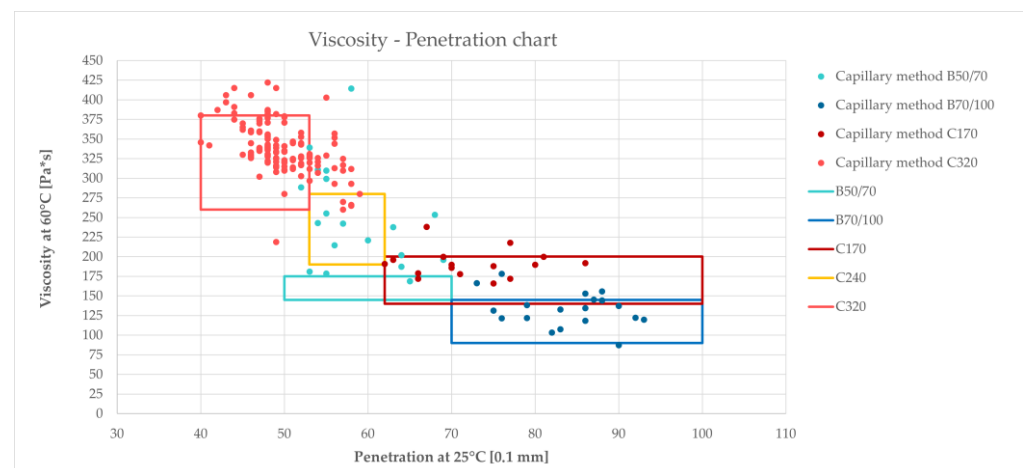


Figure 1. Viscosity–penetration graph.

Figure 1 shows the viscosity [Pa*s] and penetration [0.1 mm] values for different coloured bitumen types, with a frame indicating their corresponding standard limit values. The y-axis shows the dynamic viscosity [Pa*s], and the x-axis illustrates the penetration [0.1 mm] measured at 25 °C. The results of four different bitumen types are presented, and the corresponding Australian and European bitumen class limits are also indicated (frames). The penetration maximum of the Australian bitumen class C170 was taken as 100 based on Australian practice.

The test points reflect the categorisation: the B50/70 samples are located in the penetration band between 50 and 60, while the B70/100 data are located around the 75–95 range; their viscosity follows the expected hardness trend, with lower penetration corresponding to higher viscosity.

The obtained measurement values—particularly for C170 and C320—closely follow these ranges. In the graph, the data for the C-class binders are concentrated within the standard viscosity bands with a low standard deviation, with CV% is being less than 10% for both types, indicating that these products are more homogeneous from a rheological point of view and have a better controlled manufacturing quality (confirmed also in Table 3). By contrast, the European B-grade bitumens show greater variability, with a significantly higher (16% and 26%) coefficient of variation, but do not provide a noticeably better approximation to penetration.

Table 3. Statistical characteristics of the measured viscosity and penetration measurements of the bitumen types and their deviations from the average calculated values based on the standards.

	P B50/70 [0.1 mm]	η B50/70 [Pa*s]	P B70/100 [0.1 mm]	η B70/100 [Pa*s]	P C170 [0.1 mm]	η C170 [Pa*s]	P C320 [0.1 mm]	η C320 [Pa*s]
Average	58.15	253.61	84.00	133.25	72.19	191.00	50.70	325.85
Standard deviation	5.40	64.81	5.95	21.66	6.85	17.93	3.87	32.49
Coefficient of variation (CV, %)	9.29	25.55	7.08	16.26	9.49	9.38	7.63	9.97
Mean deviation from standard mean values	−1.85	93.61	−1.00	15.75	−8.81	21.00	4.20	5.85
Mean deviation from standard mean values in %	−3.08	58.51	−1.18	13.4	−10.88	12.35	9.03	1.83

The results of C-type (Australian) bitumen types are much more concentrated, and the measured points almost entirely remain within the specified viscosity class. This is because the Australian system is specifically viscosity-based, so production control also strives for greater viscosity stability. The smallest standard deviation observed for the C320 type indicates that this product range is the most homogeneous and stable, which may also provide useful feedback for European bitumen manufacturers. It is also important to note that penetration-based European binders exhibit substantially greater relative variation in viscosity than viscosity-based Australian grades, with respect to penetration. The highest coefficient of variation (CV% = 25.55%) was observed for the B50/70 bitumen class, which also shows the largest percentage deviation from the standard mean (58.51%).

The examined data confirm that the viscosity-based classification system better reflects rheological stability, whereas the European binders with penetration systems exhibit greater variability. The narrow spread observed for C-type binders suggests that these products show a more predictable viscosity-temperature response, which is particularly beneficial for performance in warm climates, such as Australia.

3.2. Statistical Analysis and Comparison of Test Results Obtained with Different Measurement Methods

Figure 2 presents viscosity data obtained using the following methods/conditions: DSR (dynamic shear rheometer) at 0.16 Hz, DSR at 1.6 Hz and DSR at 10 Hz; the Heukelom equation (viscosity converted from the softening point, SP); the vacuum capillary method; and the Brookfield rotational viscometer.

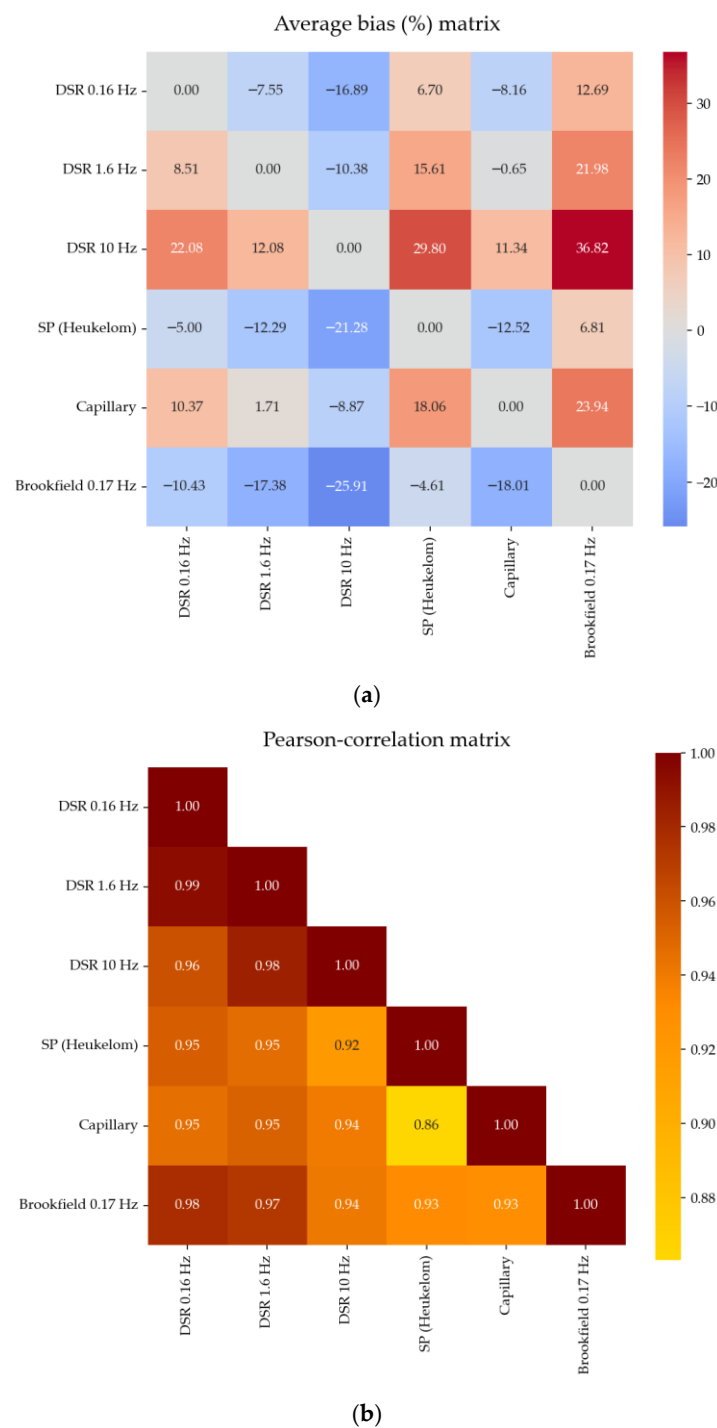


Figure 2. Comparison of viscosities obtained by different measurement methods and approximations. Matrix (a): Average sign differences between measurements in [%]. Matrix (b): Pearson correlations characterising linear approximation.

Figure 2 presents two complementary matrix-based evaluations of the viscosity determination methods. The Average bias (%) matrix (Figure 2a) quantifies the average differences between each pair of methods by expressing the mean signed relative deviation, thereby highlighting consistent over- or underestimation tendencies attributable to differ-

ences in the loading mode and shear conditions. For the average bias matrix, with method A and B for n number of samples, the following formula was used:

$$\bar{\Delta}_{A \rightarrow B}(\%) = \frac{100}{n} \sum_{i=1}^n \frac{B_i - A_i}{A_i} \quad (6)$$

Figure 2b shows the Pearson-correlation matrix, giving the consistency of relative trends across binders by measuring the linear correlation between methods. While the bias matrix reflects systematic magnitude differences, the correlation matrix indicates how similarly the methods rank the investigated bitumens. Together, these matrices provide a comprehensive basis for evaluating both agreement and methodological consistency among the applied viscosity determination techniques. Equation (7) shows the calculating method.

$$r_{A,B} = \frac{\sum_{i=1}^n (A_i - \bar{A})(B_i - \bar{B})}{\sqrt{\sum_{i=1}^n (A_i - \bar{A})^2} \sqrt{\sum_{i=1}^n (B_i - \bar{B})^2}} \quad (7)$$

Based on the Pearson correlation matrix, most methods exhibit an extremely strong linear relationship ($r = 0.86\text{--}0.99$), suggesting that the relative behaviour of bitumen types is ranked similarly by the system, regardless of the testing method. The DSR test at 1.6 Hz gives the highest correlation values, showing a correlation of over 0.95 with all other methods. This suggests that the 1.6 Hz oscillatory shear test best reproduces the viscosity behaviour of bitumen types, even in the measurement range of other devices.

The capillary viscometer results also show high correlations ($r = 0.86\text{--}0.95$), but these are lower than the correlations between the DSR measurements. This indicates that although the capillary method reliably reproduces the magnitude of the bitumen viscosity, systematic deviations may appear compared to other techniques due to differences in the shear rate and temperature dependence. The average signed deviation matrix confirms this. Compared to the capillary method, the DSR 1.6 Hz shows an average deviation of only +1.71%, which is the smallest average deviation among the methods examined. This result corresponds to the main European and American practice [3], while Australian practice offered the frequency of 0.16 Hz before [33]. Thus, the results obtained with the capillary viscometer are reproduced most accurately by the DSR 1.6 Hz. The high correlation observed is not only statistical but also supported by rheological considerations. Although the complex viscosity measured by DSR is frequency-dependent for non-Newtonian binders, the selected frequency of 1.6 Hz (10 rad/s) corresponds to an intermediate loading regime that is commonly used to approximate steady shear conditions relevant to conventional viscosity measurements. The same frequency was used by Sheidaei [14], which demonstrated good performance as well. At this frequency, the measured complex viscosity shows limited sensitivity to small frequency variations and provides a stable representation of the material's shear resistance at 60 °C.

It was found that viscosities calculated using the Heukelom equation usually overestimate capillary measurement results (the average deviation is around +18.06%), likely due to the choice of empirical constants or the indirect estimation of viscosity at the softening point. In the case of the Brookfield viscometer, this tendency is even more typical, with significant overestimations compared to other methods (e.g., +36.82% compared to DSR at 10 Hz). Such systematic overestimation could be the result of the empirical nature of the test methods. The results of the Brookfield viscometer correlate best with the results of the DSR method taken at 0.16 Hz, which is also justified by the instrument settings detailed earlier.

4. Conclusions

According to existing literature, the results of Australian and European vacuum capillary viscosity measurements were compared for the first time, considering the classification categories. Australian C-type bitumen types show higher rheological stability, which is due to the viscosity-based classification according to the Australian standard AS2008-2013 [32] and the quality requirements of bitumen manufacturers.

In addition to the traditional capillary measurement method, among the formulae approximating viscosity, the Heukelom equation was used to determine the viscosity value at 60 °C from the softening point, and, as additional methods, the Brookfield rotational instrument and the DSR shear rheometer were used at three different (0.16, 1.6, 10 Hz) frequencies. The results show that the differences between the test methods can also arise from differences in the shear rate and loading frequency. The use of empirical conversion equations can only be considered reliable if their validity range and the associated test conditions are clearly defined. As a result, the approximate formulae can be wrong by orders of magnitude.

Among the investigated techniques, DSR measurements at 1.6 Hz showed the closest agreement with capillary viscosity, providing the highest overall correlation and representing a reliable dynamic rheological alternative for binder characterisation. Brookfield measurements consistently yielded higher viscosity values, while the Heukelom equation provided a reasonable approximation at 60 °C when derived from softening point data.

As a summary, the presented results contribute to a more accurate interpretation of the relationships between the different test methods and to the development of a more uniform, rheology-based approach. The DSR test at 1.6 frequency can well represent real-life road conditions as well. With further experimental data and an extended range of binder types, the presented approach may support the development of a European bitumen classification framework based on complex viscosity, which can better reflect the effects of traffic loading and temperature on pavement performance. This rheology-based classification would represent a meaningful step toward performance-oriented binder standardisation in European practice.

The main limitation of this study is the restricted range of investigated binder types. Further research incorporating additional grades and production sources is required to strengthen the proposed rheology-based classification approach.

Author Contributions: Conceptualisation, S.R. and L.G.; methodology, S.R. and L.G.; validation, Z.S.; formal analysis, Z.S.; investigation, S.R.; resources, S.R.; data curation, S.R.; writing—original draft preparation, S.R. and Z.S.; writing—review and editing, L.G.; visualisation, Z.S.; supervision, L.G. and S.R.; project administration, L.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be available on request from the corresponding author.

Conflicts of Interest: Authors Szabolcs Rosta and Zita Szabó were employed by the company Duna Group and László Gáspár was employed by the company Hungarian Roads Non-Profit Ltd. All authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

DSR	Dynamic Shear Rheometer
SBS	Styrene–Butadiene–Styrene
CR	Crumb Rubber
TPS	Thermoplastic Starch
AS	Standards Australia
EN	European Norm
ASTM	American Society for Testing and Materials

References

1. Anderson, D.A.; Christensen, D.W. Strategic Highway Research Program Binder Rheological Parameters: Background and Comparison with Conventional Properties. *Transp. Res. Rec.* **1995**, *1488*, 32–39.
2. Anderson, D.A.; Christensen, D.W.; Bahia, H.U.; Dongre, R.; Sharma, M.G.; Antle, C.E.; Button, J. *Binder Characterization and Evaluation*; Volume 3: Physical Characterization; SHRP-A-369; Strategic Highway Research Program, National Research Council: Washington, DC, USA, 1994; ISBN 0-309-05767-1.
3. Tóth, S.; Puskás, A. Rheological Basis of the Requirement Systems of Bitumen and Asphalt Standards. *Az Aszfalt* **2006**, *2*, 4–49.
4. Rosta, S.; Gáspár, L. Útépítési bitumen és visszanyert bitumen elegyének dinamikai viszkozitás számítása és előrebecslési lehetősége. *Közlekedéstudományi Szle.* **2023**, *73*, 21–37. (In Hungarian) [[CrossRef](#)]
5. *ASTM D2171*; Standard Test Method for Viscosity of Asphalts by Vacuum Capillary Viscometer. ASTM International: West Conshohocken, PA, USA, 2010.
6. *ASTM D2171M-22*; Standard Test Method for Viscosity of Asphalts by Vacuum Capillary Viscometer (SI Units). ASTM International: West Conshohocken, PA, USA, 2022.
7. *EN 12596:2023*; Bitumen and Bituminous Binders. Determination of Dynamic Viscosity by Vacuum Capillary. European Committee for Standardization: Brussels, Belgium, 2023.
8. Wang, D.; Feng, D.; Chen, Z.; Liu, Z.; Zhang, W.; Lei, J.; Yao, D.; Yi, J.; Pei, Z. Research on TPS–SBS composite-modified asphalt with high viscosity and high elasticity in cold regions. *Coatings* **2025**, *15*, 108. [[CrossRef](#)]
9. Chen, Z.; Wang, W.; Abdulkadir, A.; Lei, J.; Yi, J.; Pei, Z. C9 petroleum resin and polyethylene-based high-viscosity modified asphalt binder: Proportioning optimization and performance study. *Coatings* **2025**, *15*, 343. [[CrossRef](#)]
10. Wang, W.; Chen, B.; Shen, J. Zero shear viscosity of hybrid modified asphalts and its gray correlation with other properties. *Materials* **2022**, *15*, 7056. [[CrossRef](#)] [[PubMed](#)]
11. Hu, J.; Ma, T.; Zhu, Y.; Huang, X.; Xu, J.; Chen, L. High-viscosity modified asphalt mixtures for double-layer porous asphalt pavement: Design optimization and evaluation metrics. *Constr. Build. Mater.* **2021**, *270*, 121893. [[CrossRef](#)]
12. *EN 14770:2023*; Bitumen and Bituminous Binders. Determination of Complex Shear Modulus and Phase Angle. Dynamic Shear Rheometer (DSR). European Committee for Standardization: Brussels, Belgium, 2023.
13. *EN 12594:2025*; Bitumens and Bituminous Binders. Preparation of Test Samples. European Committee for Standardization: Brussels, Belgium, 2025.
14. Sheidaei, M. Dynamic Shear Rheometer for Rheological Investigation of Bitumen in Road Applications: The Impact of Measurement Technique. Ph.D. Thesis, Lund University, Lund, Sweden, 2025.
15. Guericke, R. 100 Jahre Erweichungspunkt Ring und Kugel: Was kommt danach? *Straße Autob.* **2010**, *61*, 481–491. (In German)
16. *EN 13302:2018*; Bitumen and Bituminous Binders. Determination of Dynamic Viscosity of Bituminous Binder Using a Rotating Spindle Apparatus. European Committee for Standardization: Brussels, Belgium, 2018.
17. Remisová, E.; Zatkaliková, V.; Schlosser, F. Study of rheological properties of bituminous binders in middle and high temperatures. *Civ. Environ. Eng.* **2016**, *12*, 13–20. [[CrossRef](#)]
18. Cox, W.P.; Merz, E.H. Correlation of dynamic and steady flow viscosities. *J. Polym. Sci.* **1958**, *28*, 619–622. [[CrossRef](#)]
19. Brookfield Engineering Laboratories. *More Solutions for Sticky Problems: A Guide to Getting More from Your Brookfield Viscometer and Rheometer*; Brookfield Engineering Laboratories: Middleboro, MA, USA, 2014; p. 55.
20. Parhamifar, E.; Tyllgren, P. Assessment of asphalt binder viscosities with a new approach. In Proceedings of the 6th Eurasphalt & Eurobitume Congress, Prague, Czech Republic, 1–3 June 2016.
21. Tóth, C. Aszfaltkeverékek Merevsége a Terhelési idő, Hőmérséklet és Szemeloszlás Függvényében. Ph.D. Thesis, Budapest University of Technology and Economics, Budapest, Hungary, 2010. (In Hungarian)
22. Bíró, S. Kémiaiilag Stabilizált Gumibitumenek Előállítás és Vizsgálata. Ph.D. Thesis, University of Veszprém, Veszprém, Hungary, 2005. (In Hungarian)

23. Heukelom, W. *Bitumen and Bituminous Mixtures*; Koninklijke/Shell-Laboratorium: Amsterdam, The Netherlands, 1973.
24. Mirza, M.W.; Witczak, M.W. Predicting asphalt viscosity from penetration. In Proceedings of the Association of Asphalt Paving Technologists (AAPT), Portland, OR, USA, 27–29 March 1995.
25. Witczak, M.W.; Fonseca, O.A. Revised predictive model for dynamic (complex) modulus of asphalt mixtures. *Transp. Res. Rec.* **1996**, *1540*, 15–23. [[CrossRef](#)]
26. Texas Department of Transportation. *Tex-535-C: Calculating Viscosity from Penetration*; TxDOT: Austin, TX, USA, 1999.
27. Van der Poel, C. A general system describing the visco-elastic properties of bitumens and its relation to routine test data. *J. Appl. Chem.* **1954**, *4*, 221–236. [[CrossRef](#)]
28. Gutarra Lara, L. Influencia de las Fibras Acrílicas en Mezclas Asfálticas en Caliente. Master's Thesis, Universidad Continental, Huancayo, Peru, 2018. (In Spanish)
29. Karki, P.; Kim, Y.R.; Little, D.N. Dynamic modulus prediction of asphalt concrete mixtures through computational micromechanics. *Transp. Res. Rec.* **2015**, *2507*, 1–9. [[CrossRef](#)]
30. *EN 12591:2009*; Bitumen and Bituminous Binders. Specifications for Paving Grade Bitumens. European Committee for Standardization: Brussels, Belgium, 2009.
31. *EN 1426:2025*; Bitumens and Bituminous Binders. Determination of Needle Penetration. European Committee for Standardization: Brussels, Belgium, 2025.
32. *AS 2008-2013*; Bitumen and Bituminous Binders. Standards Australia: Sydney, NSW, Australia, 2013.
33. Denneman, E.; Dias, M.; Malone, S.; Choi, Y.; Woodall, E.; Urquhart, R. *Maximising the Re-Use of Reclaimed Asphalt Pavement: Binder Blend Characterisation*; Austroads Publication No. AP-T245-13; Austroads Project No. TT1817; Austroads Ltd.: Sydney, NSW, Australia, 2013; ISBN 978-1-925037-18-0.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.