**CETRA2026** 27-30 May 2026, Bol, Island Brač, Croatia
**9th International Conference on Road and Rail Infrastructure**

# EVALUATION OF THE METHODS FOR DETERMINING MIXING AND COMPACTION TEMPERATURES OF MODIFIED BITUMEN

**Lidija Ržek, Miomir Miljković**
*Slovenian National Building and Civil Engineering Institute, Slovenia*

## Abstract

Mixing and compaction temperatures are critical parameters in the production of asphalt mixtures, as they strongly influence bitumen viscosity, aggregate coating, asphalt workability, and the final mechanical performance of the pavement. For conventional paving-grade bitumens without additives, target values for these temperatures are typically defined as functions of universally adopted target viscosities and are referred to as equiviscous temperatures. Nevertheless, with the increasing use of bitumen modification, especially with polymers and temperature-reducing agents that exhibit non-linear viscosity–temperature relationships, the equiviscosity-based criteria are increasingly inadequate for controlling mixability and compactability. As a result, the equiviscosity method often produces unpredictable mixing and compaction temperatures, leading to excessive energy consumption or thermal degradation of the polymeric structure. The objective of this research was to compare three methods for determining the mixing and compaction temperatures for modified bitumen: based on equiviscosity, steady shear flow, and phase angle. The resulting temperatures depended strongly on the evaluation method. Thus, for base bitumens, the phase angle method produced the highest mixing and compaction temperatures, while the steady shear flow method produced the lowest. Due to the pronounced elastic response of polymer-modified bitumens, the phase angle method was inapplicable within the investigated temperature range. Different evaluation methods emphasize distinct rheological characteristics of bitumen. The results highlight the limitations of existing approaches for polymer-modified bitumens and the need for methods appropriate to bitumen type or a universally applicable alternative.

*Keywords: mixing temperature, compaction temperature, viscosity, steady shear flow, phase angle*

## 1 Introduction

Bitumen is a viscoelastic material, exhibiting both viscous and elastic behavior. At high temperatures, bitumen behaves as a viscous liquid and flows, while at low temperatures, it acts as an elastic solid. At intermediate temperatures, bitumen combines both viscous and elastic characteristics, potentially resulting in a complex rheological response. For asphalt mixture production, bitumen must be heated to achieve sufficient fluidity for uniform coating of the aggregate. After mixing, the mixture is compacted at the compaction temperature to achieve the optimum air void content, allowing the packing of aggregate particles' configuration into a stable dense skeleton. The temperatures at which asphalt is mixed and compacted are among the most important parameters for producing asphalt mixtures, as they are directly linked to workability and compactability, respectively. Since bitumen's internal resistance to shear, commonly expressed by viscosity, is a function of temperature, the mixing and compaction temperatures determine the resulting mesostructure of asphalt and, consequently, its ultimate macromechanical performance.

**DOI: https://doi.org/10.5592/CO/CETRA.2026.1968**

The most significant factors include the degree of aggregate coating, the quality of adhesion, heterogeneity, volume fraction and morphology of the pore space, and, ultimately, the mechanical performance and durability of the entire asphalt pavement. Based on existing research [1] characteristic examples of the influence of mixing and compaction temperature on the internal structure of the asphalt mixture are illustrated in figure 1.

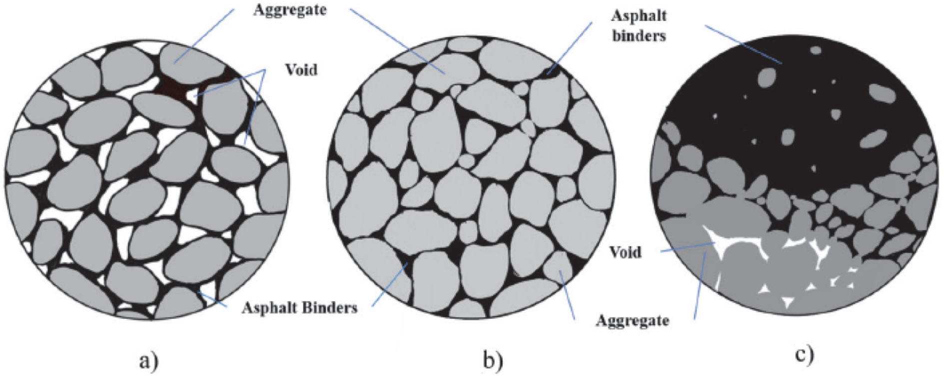

**Figure 1** Examples of the influence of mixing and compaction temperatures on the resulting structure of asphalt: (a) extremely low temperature leads to high viscosity of bitumen, which prevents satisfactory coating and the reduction of voids during compaction, (b) optimal temperature ensures even coating of aggregate and a homogeneous mesostructure of asphalt, and (c) extremely high temperature leads to low viscosity of bitumen, which may cause partial draining of bitumen from the mixture as well as excessive ageing as an especially destructive effect [1]

Traditionally, the method for determining mixing and compaction temperatures was based on the equiviscosity of bitumen, as it assumes that the specified viscosity value represents the bitumen's ability to mix and compact properly. This method is well established for producing conventional paving-grade bitumens without additives and has been widely adopted by most asphalt specifications and guidelines [2]. Researchers [3] have shown that the viscosity–temperature relationship is not linear for modified bitumen and cannot adequately characterize its behavior during the production or compaction. Therefore, using the equiviscosity method may result in unrealistically high temperature requirements for mixtures with modified bitumens, leading to excessive energy consumption, increased greenhouse gas emissions, and the potential for thermal degradation of the polymeric networks in bitumen. In recent years, the growing trend towards the use of modified bitumen (especially polymer-modification) and various temperature-reducing agents has raised numerous questions about whether the equiviscosity method is still applicable to the production of modified bitumen [4]. In particular, a special type of bitumen with the LE-label was launched on the Slovenian market as a technological innovation, representing prefabricated bitumen with an additive that enables asphalt to be produced at lower temperatures. This bitumen is introduced in the same way as traditional types, without the need for any changes to the production process, but its behavior during production and compaction is still insufficiently understood. This research aimed to evaluate and compare the three most relevant methods for determining the mixing and compaction temperatures of modified bitumen based on the equiviscosity method, the steady shear flow (SSF) method, and the phase angle method. The main task was to improve understanding and interpretation of the relevance and domains of applicability of these methods, thereby contributing to the development of a universal methodological framework for determining these values. To this end, experimental results were analyzed for a wide range of bitumens, including paving-grade (base) bitumen, modified paving-grade bitumen (LE-modified), and polymer-modified bitumen products typically used in Slovenia.

# 2 Materials and methods

## 2.1 Materials

The experimental programme included two types of paving-grade bitumen, B50/70 and B70/100, as well as their temperature-reducing versions, B50/70 LE and B70/100 LE. The programme also included polymer-modified bitumen, PmB 45/80-65, and its temperature-reducing version, designated as PmB 45/80-65 LE. All bitumen specimens were subjected to conventional characterization tests, including the softening point by ring and ball, $T_{R\&B}$ [5], penetration, P [6], and Fraass breaking point, $T_{Fraass}$ [7], together with calculation of the penetration index, $I_p$, to provide basic insight into their properties. For the paving-grade bitumen, ductility, d [8] was additionally determined, while elastic recovery, $R_E$, was evaluated for the polymer-modified bitumen [9].

## 2.2 Methods for determining mixing and compaction temperatures

Mixing and compaction temperatures, $T_{mix}$ and $T_{comp}$, respectively, were determined using the previously mentioned methods based on equiviscosity, the steady shear flow (SSF-method), and the phase angle ($\delta$-method). In the equiviscosity method, the reference viscosities of bitumen corresponding to the mixing and compaction temperatures in this research were (0.17±0.03) Pa s and (0.28±0.03) Pa s, respectively [10, 11]. Bitumen viscosity was measured by rotational shear according to the European standard [12], with slight adjustments to the standard testing temperatures based on previous experience. To avoid unwanted thermal exposure, slightly lower temperatures were applied to the paving grade binders, while the polymer-modified bitumens (PmB) were heated to slightly higher temperatures to ensure stable flow behavior and obtain accurate viscosity measurements due to their high viscosity and polymeric network formation. Thus, for the paving-grade bitumens, measurements were performed at 60, 100, and 140°C, while for the polymer-modified bitumens, they were performed at 80, 100, and 160°C. At the lower temperatures, the rotation rate was 0.05 $s^{-1}$, at the intermediate temperatures, it was 5 $s^{-1}$, and at the upper temperatures, the rotation rate was 500 $s^{-1}$. The natural logarithms of the measured viscosities, *n*, were then plotted as functions of the reciprocal temperature, T, and modelled using linear regression to evaluate the overall dependency.

In the SSF-method, the viscosity of the bitumen was first measured under controlled rotational shear stress conditions by logarithmically increasing the shear stress from 50 to 500 Pa at the temperatures of 72, 76, and 82°C until steady-state flow was reached [4]. The values of viscosity obtained at the maximum shear stress of 500 Pa were considered asymptotic and were used as representative for further analysis. As in the equiviscosity method, linear regression of logn as a function of logT was performed to extrapolate the mixing and compaction temperatures corresponding to the reference viscosities of (0.17±0.03) and (0.35±0.03) Pa s, respectively [3].

In contrast to the above methods, the phase angle method [4] is based on the oscillation frequency sweep of the phase angle, $\delta$, of bitumen. Measurements were performed at the frequencies ranging from 0.1 to 100 rad/s at temperatures between 40 and 80°C, in 10°C increments, with the shear strain amplitude fixed at 10%, which was sufficiently low to ensure the linear viscoelastic behavior of bitumen. The selected strain level was previously verified by an amplitude sweep test to confirm that it falls within the linear viscoelastic region. Phase angle master curves were then constructed using time–temperature superposition to determine the frequency, f, corresponding to the phase angle of 86°. This value of $\delta$ was adopted as a criterion since earlier research confirmed that the values between 85 and 90° indicate predominantly viscous behavior [3].

According to Casola [4], this critical frequency was used to calculate the target temperature from the following empirical equations:

$$T_{\mathrm{mix}} = 325\, f_{86^{\circ}}^{-0.0135} \tag{1}$$

$$T_{\mathrm{comp}} = 300\, f_{86^{\circ}}^{-0.012} \tag{2}$$

In addition to the approaches mentioned above, it should be noted that, according to the European standard for the preparation of asphalt mixtures in the laboratory [11], the compaction temperature for the paving-grade bitumen B50/70 is 150°C, and for B70/100 it is 145°C. The mixing temperature is not explicitly defined; however, it is recommended that it should not exceed the compaction temperature by more than 20°C. There are no requirements for the mixing and compaction temperatures for polymer-modified bitumen, and these are commonly specified by suppliers.

## 3 Results and discussion

The results of the conventional properties of the evaluated bitumens are provided in table 1. They show that the bitumens and their modified temperature-reducing versions exhibited quite similar properties. The values of penetration and softening point varied only minimally after the addition of the LE-additive. This was further supported by the penetration index values, which remained within a similar range. The Fraass breaking point and ductility results also confirm that low-temperature behavior and deformability were not adversely affected by the LE-modification. Recent research [13] has shown that the additive in the bitumen PmB 45/80-65 LE does not have a significant influence on viscosity and therefore cannot be categorized as bitumen with reduced viscosity. Nevertheless, this modification enabled the production at lower temperatures and ensured the quality of the mixture, which was comparable to conventional asphalts.

**Table 1** Results of the conventional properties of the evaluated bitumen

| Bitumen type | P [0.1 mm] | $T_{R\&B}$ [°C] | $T_{Fraass}$ [°C] | $I_p$ | d [cm] | $R_E$ [%] |
|---|---|---|---|---|---|---|
| B50/70 | 64 | 47.6 | −9 | −1.3 | > 150 | — |
| B50/70 LE | 67 | 48.6 | −12 | −0.9 | > 150 | — |
| B70/100 | 89 | 44.8 | −13 | −1.2 | > 150 | — |
| B70/100 LE | 92 | 46.2 | −13 | −0.7 | > 150 | — |
| PmB 45/80-65 | 53 | 78.6 | −18 | 4.3 | — | 94 |
| PmB 45/80-65 LE | 60 | 79.8 | −18 | 4.8 | — | 95 |

### 3.1 Equiviscosity method

The Arrhenius representation of these data is shown in figure 2, and the mixing (at the viscosity of 0.17 Pa s) and compaction (at the viscosity of 0.28 Pa s) temperatures determined for each bitumen according to the equiviscosity method are provided in table 2. The viscosity–temperature dependencies indicated a high degree of linearity for the paving-grade bitumens, whereas, as expected, the linearity is lower for polymer-modified bitumens. There were consistent differences in viscosity between the conventional bitumens and their LE-versions. The LE-bitumens showed lower viscosities, though the differences were quite small.

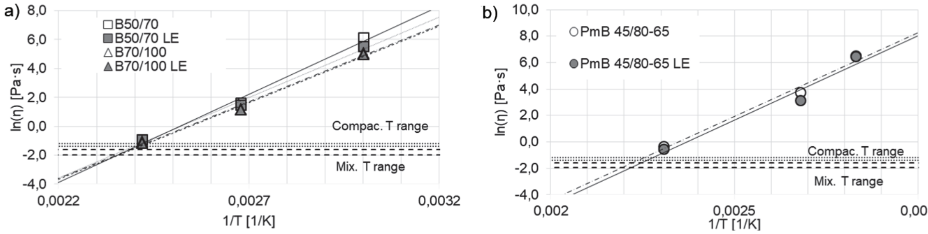

**Figure 2** Determination of the mixing and compaction temperatures by the equiviscosity method: a) paving-grade bitumen, b) polymer-modified bitumen

**Table 2** Mixing and compaction temperatures by the equiviscosity method

| Bitumen type | $T_{mix}$ [°C] | $T_{comp}$ [°C] |
|---|---|---|
| B50/70 | 148.6 | 141.4 |
| B50/70 LE | 150.2 | 142.3 |
| B70/100 | 148.4 | 140.3 |
| B70/100 LE | 147.3 | 139.2 |
| PmB 45/80-65 | 179.9 | 171.9 |

Although the bitumen B50/70 LE had lower viscosity, the resulting mixing and compaction temperatures were higher than those of the reference bitumen B50/70. The observed increase in calculated temperatures could be explained by differences in the viscosity–temperature dependency, as reflected in the Arrhenius fit (figure 2a). Consequently, extrapolation to the target viscosities for temperature determination produced higher temperatures for the L-bitumen. This finding implied that the temperature calculations based on viscosity were more influenced by the overall shape of the viscosity–temperature curve than by the absolute viscosity values at specific temperatures. For B70/100 and B70/100 LE, a slight reduction in the required temperatures was observed. This suggests that the LE-bitumen allows similar processing conditions while offering potential technological or environmental advantages. The LE-polymer-modified bitumen consistently exhibited lower viscosities across the tested temperature range, resulting in reduced mixing and compaction temperatures compared with the reference PmB. As shown in figure 2b, both bitumens displayed similar temperature dependency.

## 3.2 Steady shear flow method

Results of the steady shear flow method are shown in figures 3 and 4. Figure 3 clearly indicated Newtonian behavior of the paving-grade bitumen B70/100, as its viscosity was independent from the shear stress. In contrast, the polymer-modified bitumen showed a pronounced dependence of viscosity on both temperature and the shear stress. The viscosity of the PmB decreased with the shear stress, indicating shear thinning behavior and suggesting degradation of the original polymeric structure during the shear stress sweep. This response reflected the sensitivity of the polymer-modified system to applied deformation, with the internal polymer structure being the key reason for the non-Newtonian flow behavior. Therefore, the viscosities of PmB are more significantly influenced by changes in shear conditions than those of conventional paving-grade bitumens. The mixing and compaction temperatures are provided in table 3. In general, the equiviscosity method produced higher temperatures than the SSF-method for all bitumen types, with the largest difference observed for polymer-modified bitumen, where the equiviscosity method resulted in much higher temperatures than the SSF-method. This substantial difference originated from the distinct rheological principles of each testing method: the equiviscosity method relied on viscosity criteria, while the SSF-method is based on steady shear flow behavior, which more accurately reflects the actual shear environment during mixing and compaction.

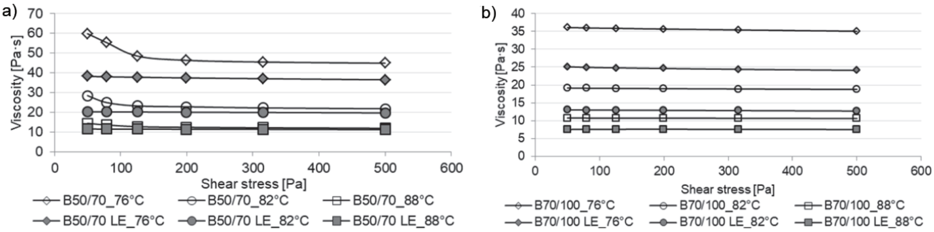

**Figure 3** Viscosity as a function of the shear stress for paving-grade bitumen: a) B50/70, b) B70/100

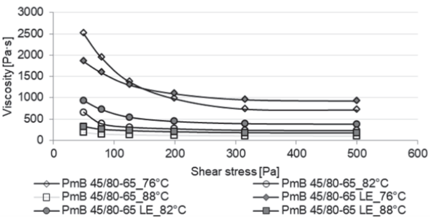

**Figure 4** Viscosity as a function of the shear stress for polymer-modified bitumen

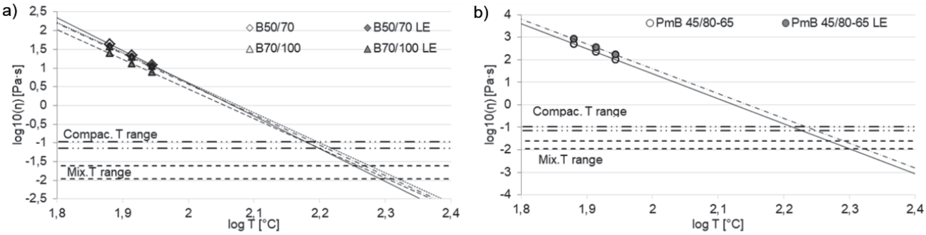

**Figure 5** Determination of the mixing and compaction temperatures by the SSF-method: a) paving-grade bitumen, b) polymer-modified bitumen

**Table 3** Mixing and compaction temperatures by the SSF-method

| Bitumen type | $T_{mix}$ [°C] | $T_{comp}$ [°C] |
|---|---|---|
| B50/70 | 143.1 | 131.8 |
| B50/70 LE | 148.3 | 135.5 |
| B70/100 | 146.2 | 133.8 |
| B70/100 LE | 141.8 | 129.4 |
| PmB 45/80-65 | 155.9 | 146.0 |

## 3.3 Phase angle method

Master curves of the phase angle are shown in figures 6 and 7, while the temperatures determined by the phase angle method are provided in table 4. For polymer-modified bitumens, the phase angle did not reach the reference value proposed by Casola because of the persistently elastic response, with values well below 70°. Consequently, the phase angle method was inapplicable for determining the mixing and compaction temperatures for these bitumens.

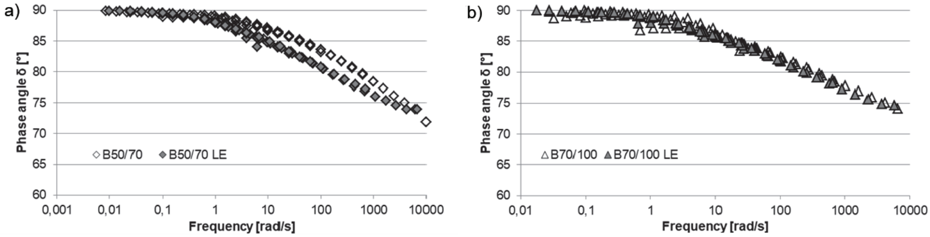

**Figure 6** Master curves of the phase angle of the paving-grade bitumen: () Bitumen B50/70, b) Bitumen B70/100

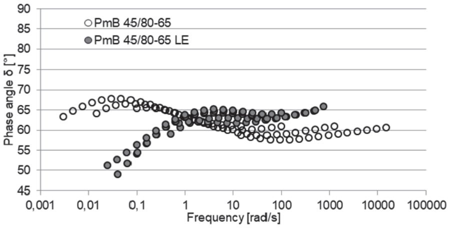

**Figure 7** Master curves of the phase angle of the polymer-modified bitumen

**Table 4** Mixing and compaction temperature by the δ-method

| Bitumen type | $T_{mix}$ [°C] | $T_{comp}$ [°C] |
|---|---|---|
| B50/70 | 155.3 | 142.7 |
| B50/70 LE | 159.1 | 145.9 |
| B70/100 | 157.3 | 144.4 |
| B70/100 LE | 157.5 | 144.5 |

On the other hand, the determined temperature ranges for the paving-grade bitumens were found to be fairly close, suggesting a similar viscoelastic character at high temperature. This was supported by comparable penetration index values for each bitumen type, indicating that their temperature susceptibility remains the main factor determining the viscous–elastic transition, rather than relying solely on the penetration index. Minor differences were observed in the LE-bitumens compared to the conventional ones, indicating that the LE-modification had only a slight impact on the temperature at which viscous-dominated behaviour occurs.

# 4 Conclusion

As expected, different methods produced different results for the mixing and compaction temperatures of the evaluated bitumen types, and the observed incomparability arises because each method is based on different intrinsic material properties (determined under varying conditions). For example, when measuring the phase angle of a sample using the phase angle method, the viscosity of the bitumen does not directly influence the phase angle result. The relatively small differences observed between the penetrations of the paving-grade bitumens indicated that temperature susceptibility, rather than penetration grade alone, governed the rheological response relevant to the processing temperatures.

The LE-bitumens showed only minor deviations from the conventional ones, which was in complete contrast to the polymer-modified bitumen. This suggested that the polymeric structure (and its degradation during the experiment) had the predominant influence, while the influence of LE on bitumen rheology within the investigated temperature range was limited. The phase angle method could not determine the mixing and compaction temperatures of the polymer-modified bitumens, as the selected viscous-dominated condition was not reached across the tested temperature range. Polymer-modification increased the elastic nature and microstructural stability of the systems, demonstrating that the phase angle method has limitations as an analytical approach for predominantly elastic bitumens.

Overall, the findings of this study confirm that different evaluation methods capture distinct aspects of bitumen behavior, leading to varying temperature estimates. For conventional paving-grade bitumens, all methods give similar results. In contrast, for polymer-modified binders, discrepancies can be significant: overestimation (e.g., by the equiviscosity method) may cause excessive energy use and polymer degradation, while underestimation can reduce aggregate coating and mixture workability. These findings highlight the need to select evaluation methods according to bitumen type to ensure optimal mixture performance, energy efficiency, and pavement durability. This study provides a comparative framework for conventional, LE-modified, and polymer-modified bitumen, highlighting limitations of current methods and the need for a universally applicable approach. Future research should focus on developing methods that reliably determine mixing and compaction temperatures for all bitumen types while minimizing energy use and avoiding thermal degradation.

## References

[1] Luo, H., Huang, X., Rongyan, T., Ding, H., Huang, J., Wang, D., Liu, Y., Hong, Z.: Advanced method for measuring asphalt viscosity: Rotational plate viscosity method and its application to asphalt construction temperature prediction, Construction and Building Materials, 301 (2021), 124129

[2] Yildirim, Y., Solaimanian, M., Kennedy, T.W.: Mixing and compaction temperatures for hot mix asphalt concrete, Texas Department of Transportation, Austin, TX, USA, 2000.

[3] Almusawi, A., Sengoz, B., Topal, A.: Investigation of Mixing and Compaction Temperatures of Modified Hot Asphalt and Warm Mix Asphalt, Periodica Polytechnica Civil Engineering, 65 (2021) 1, pp. 72–83

[4] West, R.C., Watson, D.E., Turner, P.A., Casola, J.R.: Mixing and compaction temperatures of asphalt binders in hot-mix asphalt, National Cooperative Highway Research Program, Washington DC, USA, 2010.

[5] SIST EN 1427: Bitumen and bituminous binders - Determination of softening point - Ring and Ball method, 2015.

[6] SIST EN 1426: Bitumen and bituminous binders - Determination of needle penetration, 2025.

[7] SIST EN 12593: Bitumen and bituminous binders - Determination of the Fraass breaking point, 2015.

[8] DIN 52013: Bitumen und bitumenhaltige Bindemittel - Bestimmung der Duktilität, 2007.

[9] SIST EN 13398: Bitumen and bituminous binders - Determination of the elastic recovery of modified bitumen, 2018.

[10] ASTM D2493/D2493M-16: Standard Practice for Viscosity-Temperature Chart for Asphalt Binders, 2016.

[11] SIST EN 12697-35: Bituminous mixtures - Test methods - Part 35: Laboratory mixing, 2016.

[12] SIST EN 13702: Bitumen and bituminous binders - Determination of dynamic viscosity of bitumen and bituminous binders by the cone and plate method, 2018.

[13] Šobak, K., Pavšič, P., Ržek, L.: Uporaba bitumna »PmB 45/80-65 LE« v proizvodnji toplih asfaltnih zmesi, 2025.