Natural asphalt modified binders used for high stiffness modulus asphalt concrete

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Abstract. This paper presents a set of test results supporting the possibility of replacing, in Polish climate conditions, hard road 20/30 penetration grade bitumen used in the binder course and/or base course made of high stiffness modulus asphalt concrete with binders comprising of 35/50 or 50/70 penetration grade bitumens and additives in the form of natural Gilsonite or Trinidad Epuré asphalts. For the purpose of comparing the properties of the discussed asphalt binders, values of the Performance Grade have been determined according to the American Superpave system criteria.

1. Introduction

In the case of pavement repairs being undertaken in special load conditions such as slow traffic or parking of heavy vehicles, it is necessary to adopt special solutions with regard to materials and technology. A situation of this kind may involve e.g. intersections with traffic lights with high levels of traffic, roundabouts, or bus stops. In order to increase the resistance of pavement under repairs to permanent deformations in case of special load conditions, it is recommended (e.g. according to [1]) to apply a thin wearing course (e.g. made of BBTM or SMA mixtures) and a binder course and/or base course made of high stiffness modulus asphalt concrete. It is advised to use for the wearing and binder courses polymer modified asphalt binders or binders with special additives.

An alternative solution for hard road bitumens and multigrade bitumens used in high stiffness modulus asphalt concrete could be natural asphalt modified binders. The tests run on asphalt mixtures comprising of natural Gilsonite asphalt from the United States of America or extracted from Pitch Lake on the island of Trinidad (Trinidad Lake Asphalt), discussed by authors in [2, 3], indicate that the application of selected additives increases the stiffness of the pavement course, making it less susceptible to permanent deformations at high temperatures. Thanks to the application of modified asphalt binders, it is possible to achieve a binder course or base course characterised by a higher resistance to rutting, which is particularly essential in case of high level of heavy vehicle traffic. As the authors of [4] have remarked, there is a current trend for designers of asphalt mixtures to pay attention to resistance to rutting, whereas fatigue and thermally induced cracking are equally destructive factors contributing to pavement degradation. Premature pavement cracking is a severe problem, not appropriately accounted for by designers.

According to the Polish technical requirements, the use of 20/30 penetration grade bitumen in asphalt pavements on national roads [5] in the binder course and base course is only allowed on the territory of Poland in the climatic zones 1 and 2, as shown in Figure 1. This condition results from...
small resistance of 20/30 penetration grade bitumen to low temperature cracking. Moreover, it is not allowed to leave pavement courses made of 20/30 penetration grade bitumen uncovered with another layer for the winter season; the layer in question should compose of an asphalt mixture applying a binder softer than the 20/30 one. Figure 1 shows how, in line with Polish technical requirements, hard road 20/30 penetration grade bitumen may only be used in pavement structures of national roads in the area constituting one third of the country's territory, prevailingly in North-West and West regions of Poland.

2. Purpose of the study
Due to the limited scope of Poland's territory where hard road 20/30 penetration grade bitumen can be applied in high stiffness modulus asphalt concrete, the authors of the paper decided to establish whether selected bitumens could be replaced with binders manufactured on the basis of softer ones, e.g. 35/50 and 50/70 penetration grade bitumens, modified with natural Gilsonite or Trinidad Epuré asphalts. Furthermore, they considered the possibility of applying them on a larger area of the country. 35/50 and 50/70 penetration grade bitumens are characterised by higher resistance to cracking at low temperatures than 20/30 penetration grade bitumen, and lower stiffness at high temperatures. The authors of the paper believed that by use of appropriate amounts of natural asphalts, which produce a stiffening effect [6, 7], it is possible to achieve asphalt binders with good resistance to rutting at high temperatures and unimpaired low-temperature properties at the same time.

3. Methodology of the studies
In order to verify the theory outlined above, the authors of the paper used a classification of bitumens conforming with the AASHTO M320-17 Standard Specification for Performance-Graded Asphalt Binder, which has been designed based on the premise that asphalt paving mixtures are resistant to rutting, as well as fatigue and low-temperature cracking, in given pavement temperature ranges. Performance Grade (PG) is a method of categorising asphalt binders used in road pavements according to their properties in working temperatures from -46°C to 82°C. The advantage of the PG classification is that bitumens are categorised on account of their functional features, which makes it possible to determine a temperature range for a given pavement and simultaneously retain its resistance to wheel loads. Bitumen type is selected basing on climate conditions and traffic speed and

Figure 1. Poland divided into climatic zones - as per [5].
volume. The functional type of asphalt binder is marked as PG x − y (e.g. PG 58−28), where x means the maximum pavement temperature, and y the minimum one. Based on the archival climate data, the average 7-day maximum air temperature and the minimum temperature measured in the area of the planned asphalt pavement are estimated. While determining the PG value, the probability of occurrence of the maximum and minimum temperatures is assumed as 50% or 98%. The maximum pavement temperature is assumed on the basis of calculations, while the minimum is assumed according to the lowest air temperature, then attributed to the existing PG value ranges. Whenever the predicted traffic volume exceeds 10 or 30 million ESAL (Equivalent Single Axle Load), which is a standard single axle load of 80 kN, the maximum pavement temperature should be increased by 6°C or 12°C accordingly. An analogous action should be taken in the case of slow traffic (velocity from 20 km/h to 70 km/h) or parking (velocity up to 20 km/h) on the designed road, by increasing the temperature by 6°C in the former case, and by 12°C in the latter. For example, when traffic volume ranges from 10 to 30 million ESAL and there is slow traffic involved, the maximum pavement temperature should be increased by 12°C [8, 9].

For the purposes of determining the Performance Grade (PG) (Table 1) for asphalt binders discussed in the paper, in line with the premises of the American Superpave system (SUperior PERforming Asphalt PAVEments), the tested materials have been submitted to ageing processes simulated in laboratory conditions: in case of short-term ageing by use of RTFOT method according to standard EN 12607-1:2015-01 Bitumen and bituminous binders - Determination of the resistance to hardening under influence of heat and air - RTFOT method, and in case of long-term ageing by use of PAV method, according to standard EN 14769:2012 Bitumen and bituminous binders - Accelerated long-term ageing conditioning by a Pressure Ageing Vessel (PAV).

| average 7-day max pavement design temp. °C | < 46 | < 52 | < 58 | < 64 | < 70 | < 76 | < 82 |
|------------------------------------------|------|------|------|------|------|------|------|
|                                          | -10  | -16  | -16  | -10  | -10  | -10  | -10  |
|                                          | -16  | -16  | -16  | -16  | -16  | -16  | -16  |
|                                          | -34  | -22  | -22  | -22  | -22  | -22  | -22  |
|                                          | -40  | -28  | -28  | -28  | -28  | -28  | -28  |
| min 1-day pavement design temp. °C       | -10  | -16  | -16  | -16  | -16  | -16  | -16  |
|                                          | -22  | -22  | -22  | -22  | -22  | -22  | -22  |
|                                          | -28  | -28  | -28  | -28  | -28  | -28  | -28  |
|                                          | -34  | -34  | -34  | -34  | -34  | -34  | -34  |
|                                          | -40  | -40  | -40  | -40  | -40  | -40  | -40  |
|                                          | -46  | -46  | -46  | -46  | -46  | -46  | -46  |

The next step was to conduct tests on original and aged asphalt binders by use of a bending beam rheometer (BBR), according to standard EN 14771:2012 Bitumen and bituminous binders - Determination of the flexural creep stiffness - Bending Beam Rheometer (BBR), as well as the dynamic shear rheometer (DSR), according to standard EN 14770:2012 Bitumen and bituminous binders - Determination of complex shear modulus and phase angle - Dynamic Shear Rheometer (DSR).

The change in the bitumen mass resulting from short-term ageing simulated by the RTOFT method according to AASHTO M320 should not exceed 1.0%. In case of long-term ageing of binders in the PAV chamber following the AASHTO M320 recommendations, the temperature of 100°C was applied, as advised in case of asphalt binders used in road pavements produced and exploited in the temperate climate.

The designations of low-temperature properties in the BBR rheometer at the temperatures of -8°C, -16°C, -24°C and -32°C for asphalt binders, discussed in this paper, submitted to the short-term and long-term ageing processes, were made on the basis of four independent samples of bitumen beams. The designation results for the $S(60s)$ stiffness modulus and $m(60s)$ m-value arrived at by use of a BBR rheometer were applied to calculations of the $T_{cr}$ critical temperature value of the tested asphalt binders, using the formula [7]:

$$T_{cr} = \max (T_{S=300MPa, m=0.3}) - 10 \, °C$$  (1)
where:

- \( T_c \) – critical temperature, °C,
- \( T_{300 \text{ MPa}} \) – temperature in which the value of stiffness modulus indicated in the BBR rheometer after loading time \( t = 60 \text{s} \) reaches value equal to 300 MPa, °C,
- \( T_{m=0.37} \) – temperature in which the m-value indicated in the BBR rheometer after loading time \( t = 60 \text{s} \) reaches value equal to 0.3, °C.

According to the American Superpave system, the critical temperature marks the resistance of pavement to low-temperature cracking depending on the properties of the asphalt binder applied.

The values of the dynamic shear modulus \(|G'| \) is an absolute value of complex shear modulus \( G' \) and the phase angle \( \delta \) have been determined by use of the DSR rheometer for all asphalt binders studied in this paper within the range of temperatures from -40°C to 82°C. The conducted tests used a measuring plate with an 8 mm diameter, and an aperture of the height of 1.5 mm. The test temperatures ranged between -40°C and 82°C, with measurements beginning with the highest temperature and subsequent determination being made every 60 s at a temperature lower by (1.0±0.1)°C than the preceding one. The tests were conducted at the constant angular frequency of oscillation equal to \( \omega = 10 \text{ rad/s} \) (≈ 1.59 Hz). The values for the oscillation amplitude (deflection angle) were changing on a logarithmic scale in the range of 10 mrad for temperature of 82°C to 0.1 mrad for the temperature of -40°C. Using determined values of a dynamic shear modulus \(|G'| \) and phase angle \( \delta \), it was possible to determine the values of equivalent temperature relating to rutting of pavement (designated in this paper as \( ET_R \)). For this purpose, the highest temperature meeting the conditions for asphalt binders not submitted to ageing – \(|G'|/\sin(\delta) \geq 1.0 \text{kPa} \) and asphalt binders submitted to ageing in accordance with the RTFOT method – \(|G'|/\sin(\delta) \geq 2.2 \text{kPa} \) [11].

The values of equivalent temperature relating to pavement resistance to fatigue cracking (designated in the paper as \( ET_F \)) were determined at the lowest temperature satisfying the conditions for asphalt binders submitted to short-term and then long-term ageing – \(|G'| \cdot \sin(\delta) \leq 5000 \text{kPa} \).

The PG value relating to the minimum 1-day pavement temperature was assumed as \( T_{\alpha} \) given in Table 2, which is equal to or greater than the value achieved from Formula 1 for the selected asphalt binder. Determining the PG value related to the average 7-day maximum pavement temperature consists in assuming \( ET_R \) value given in Table 2, which is equal to or less than the value presented in Figures 4 and 5 (the lower of temperatures pertains to conditions \(|G'|/\sin(\delta) = 1.0 \text{kPa} \) and \(|G'/\sin(\delta) = 2.2 \text{kPa} \) for the selected asphalt binder. The next step is to verify the \( ET_R \) value by checking if the value \( ET_F \) is equal to or greater than the value presented in Figures 4 or 5 (\(|G'| \cdot \sin(\delta) = 5000 \text{kPa} \) condition) for the selected asphalt binder. Where \( ET_F \) is lesser, \( ET_R \) needs to be decreased to the level in which \( ET_F \) value is equal to or greater than the value presented in Figures 4 or 5 for a selected asphalt binder.

| \( ET_F \), °C | 46 | 52 | 58 |
|----------------|-----|-----|-----|
| \( ET_R \), °C |     |     |     |
| \( T_{\alpha} \), °C | -34 | -40 | -46 |

| \( ET_F \), °C | 64 | 70 |
|----------------|----|----|
| \( ET_R \), °C |    |    |
| \( T_{\alpha} \), °C | -10 | -16 |

| \( ET_F \), °C | 76 | 82 |
|----------------|----|----|
| \( ET_R \), °C |    |    |
| \( T_{\alpha} \), °C | -10 | -16 |

4. The subject of the tests

The tests were conducted on three different penetration grade road bitumens - 20/30, 35/50 and 50/70, produced in a Polish refinery from Russian petroleum and natural asphalts - Gilsonite in powdered form and Trinidad Epuré as 0/8 mm aggregate. Their basic properties, that is penetration values...
determined at 25°C and at the softening point for asphalt binders studied in this paper have been presented in Table 3. The content of Gilsonite and Trinidad Epuré natural asphalt additives in 35/50 and 50/70 road bitumens was calculated to produce upon modification an asphalt binder with similar penetration grade, that is, it was assumed that the differences between the determined penetration grade will not exceed 2 mm/10. After conducting a series of trial determinations of penetration at 25°C for asphalt binders containing natural asphalts of varying composition, the following samples were selected for further research, with the corresponding content of natural asphalt (in relation to the mass of modified asphalt binders): 3%, 5%, 7% for Gilsonite and 15%, 25%, 35% for Trinidad Epuré. The produced asphalt binders were marked, first, with the type of road bitumen, second, with the type and content of the applied additive. Gilsonite was described as GIL for short, and Trinidad Epuré as TE. For example, a 35/50 penetration grade bitumen with a 15% Trinidad Epuré additive would be – 35/50+15% TE.

| Asphalt binder | Penetration at 25°C mm/10 | Softening Point °C | Asphalt binder | Penetration at 25°C mm/10 | Softening Point °C |
|----------------|---------------------------|-------------------|----------------|---------------------------|-------------------|
| 20/30          | 25.6±0.5                  | 63.6±0.2          | 50/70          | 55.9±0.7                  | 51.6±0.2          |
| 35/50+3% GIL   | 27.2±0.3                  | 61.1±0.2          | 50/70+3% GIL   | 38.6±0.3                  | 55.8±0.4          |
| 35/50+5% GIL   | 24.4±0.5                  | 62.9±0.3          | 50/70+5% GIL   | 32.6±0.4                  | 57.2±0.3          |
| 35/50+7% GIL   | 19.8±0.3                  | 65.3±0.2          | 50/70+7% GIL   | 26.6±0.7                  | 60.4±0.4          |
| 35/50+15% TE   | 28.6±0.7                  | 57.5±0.3          | 50/70+15% TE   | 39.7±0.6                  | 53.3±0.3          |
| 35/50+25% TE   | 24.8±0.3                  | 59.5±0.2          | 50/70+25% TE   | 32.0±0.6                  | 55.7±0.3          |
| 35/50+35% TE   | 19.2±0.5                  | 62.0±0.2          | 50/70+35% TE   | 25.8±0.6                  | 58.6±0.4          |

Gilsonite is an asphaltite extracted from deposits in North-East part of the Utah state (USA). This material is a natural mixture of (per product mass) coal - 85%, hydrogen - 10%, nitrogen - 3% and oxygen, sulphur and other components in an amount of about 2% [12]. Gilsonite resembles bituminous coal in appearance, and is usually sold after having been granulated in the form of 0/2 mm aggregate or powdered.

Trinidad Epuré is a natural asphalt submitted to the refinery process, loosened from the surface of the lake (Pitch Lake) in the vicinity of the town of La Brea in the island of Trinidad. The process consists in i.a. heating the acquired material in order to soften it, evaporate free water and chemical compounds dissolved in it, as well as to separate mineral and organic impurities, e.g. in the form of stones or wood [14].

5. Results
The requirements of Superpave specifications relating to changes in mass following the induction of ageing process by use of the RTFOT method (mass decrease ≤ 1.0%) have been fulfilled by all asphalt binders discussed in the paper except for asphalt binders containing the Trinidad Epuré additive in the amount of 35%. As far as such high-modified asphalt binders are concerned, and considering the value of expanded uncertainty, the mean mass decrease equals the boundary value of 1.0%. Figure 2 shows mean values for mass decrease in ageing processes induced by the RTFOT method. It is to be assumed that the 35% content of the Trinidad Epuré additive in road asphalt binder is the absolute maximum, considering the excessive change in mass of the binder as a result of short-term ageing. For bitumens modified with the Trinidad Epuré additive, submitting them to the ageing process by use of the RTFOT method results in a significant decrease of mass, which intensifies, the higher the content of that additive in the modified asphalt binder. This is the consequence of the Trinidad Epuré's chemical composition, which includes water trapped in crystalline structure and volatile substances that are released only at temperatures exceeding 150 °C [14].
Figure 2. Weight loss of the asphalt binders as a result of short-term ageing induced with the RTFOT method.

The values of the critical temperature determined for asphalt binders submitted to both short-term and long-term ageing are presented in Figure 3. It has been observed that critical temperatures of 35/50 and 50/70 penetration grade road bitumens with and without the natural Gilsonite additive in the amount of 3% and 7%, as well as with the Trinidad Epuré additive, in the amount of 15% exclusively, are lower than that of 20/30 penetration grade bitumen. The application of Gilsonite reflects on a substantially lesser increase of critical temperature as a result of 35/50 or 50/70 penetration grade bitumen modification than in the case of Trinidad Epuré.

Figure 3. The values of critical temperatures of road bitumens and modified binders as well as the Performance Grade values determined on the basis of $T_{cr}$, as per Table 2.

The values of the equivalent temperature corresponding to pavement resistance to rutting ($|G'|/\sin(\delta) = 1.0$ kPa values in the case of unaged asphalt binders and $|G'|/\sin(\delta) = 2.2$ kPa in the case of asphalt binders aged by use of the RTFOT method) and fatigue cracking ($G^* \cdot \sin(\delta) = 5000$ kPa in the case of binders aged by short-term and then long-term ageing) have been presented in Figures 4 and 5.
Figure 4. The values of equivalent temperature determined in the case of 20/30 bitumen and modified binders containing 35/50 bitumen, as well as the Performance Grade values determined on the basis of $E_{TR}$ and $E_{TF}$ as per Table 2.

Figure 5. The values of equivalent temperature determined in the case of 50/70 bitumen and modified binders containing 50/70 bitumen, as well as the Performance Grade values determined on the basis of $E_{TR}$ and $E_{TF}$ as per Table 2.

It has been observed that 20/30 penetration grade bitumen is characterised by a higher equivalent temperature in relation to resistance to fatigue cracking ($|G^*| \cdot \sin(\delta) = 5000$ kPa) than binders containing additives of natural asphalts with comparable resistance to rutting ($|G^*| / \sin(\delta) = 1.0$ kPa and $|G^*| / \sin(\delta) = 2.2$ kPa). The exception to this is 35/50 penetration grade bitumen with at least 25% Trinidad Epuré additive content, which shows greater susceptibility to fatigue cracking than 20/30 penetration grade bitumen (higher values of equivalent temperature).
By use of the data presented in Figures 3, 4, and 5, as well as Table 2, values of the Performance Grade have been determined for all asphalt binders studied in this paper, and shown in Table 4.

### Table 4. The PG values of asphalt binders studied in the paper.

| Asphalt binder | PG   | Asphalt binder | PG   |
|----------------|------|----------------|------|
| 20/30          | 82-16| 50/70          | 70-22|
| 35/50          | 70-22| 50/70+3% GIL   | 76-22|
| 35/50+5% GIL   | 82-16| 50/70+5% GIL   | 76-22|
| 35/50+7% GIL   | 82-16| 50/70+7% GIL   | 82-22|
| 35/50+15% TE   | 82-16| 50/70+15% TE   | 76-22|
| 35/50+25% TE   | 82-16| 50/70+25% TE   | 82-16|
| 35/50+35% TE   | 82-16| 50/70+35% TE   | 82-16|

The analysis of the Performance Grade values presented in Table 4 has yielded conclusions that binders with a percentage of the natural Gilsonite or Trinidad Epuré asphalt discussed in this paper in most cases bear identical PG values to 20/30 penetration grade bitumen. Applying an even softer 50/70 penetration grade bitumen produces binders characterised by an even greater resistance to low-temperature cracking than the 20/30 penetration grade bitumen.

### 6. Discussion

Based on the analysis of the achieved results it has been concluded that the 20/30 penetration grade bitumen can be effectively replaced with 35/50 and 50/70 penetration grade bitumens containing from 3% up to 7% of the natural Gilsonite asphalt, as binders modified in this manner are characterised by greater resistance to low-temperature cracking - the values of the critical temperatures (Figure 3) are lower by 1°C to up to 6°C, with unimpaired resistance to rutting (Figure 4 and 5) in the case of climate conditions prevailing on the territory of Poland. Moreover, asphalt binders including Gilsonite in their composition have greater resistance to fatigue cracking (Figures 4 and 5) compared to 20/30 penetration grade bitumen. The effect of modifying 35/50 and 50/70 penetration grade bitumens with the Trinidad Epuré additive is not as favourable as in the case of Gilsonite. The only asphalt binders with properties even better than 20/30 penetration grade bitumen are exclusively the ones with the 15% percentage of additive in the examined samples. In the case of 25% or 35% content of the Trinidad Epuré additive, the asphalt binders discussed in this paper have higher values of the critical temperature, ranging from 1°C to 3°C (Figure 3), and lower resistance to fatigue cracking (Figure 4) in the case of modifications of 35/50 penetration grade bitumen.

The analysis of the determined values of the Performance Grade (Table 4) demonstrates that asphalt binders containing the natural Gisonite or Trinidad Epuré additive are characterised in most cases by and identical PG to that of 20/30 penetration grade bitumen, whereas the application of the softer 50/70 penetration grade bitumen produces binders with even higher resistance to low-temperature cracking than the 20/30 penetration grade bitumen, with unimpaired resistance to rutting in the climate conditions prevalent on the territory of Poland.

In papers [15, 16], the authors have attempted to apply the Superpave requirements regarding classifying bitumens according to the Performance Grade to Polish conditions. The results for the binder course and base course are presented in Figures 6 and 7. The analysis of Figures 6 and 7 has demonstrated that the 20/30 penetration grade bitumen does not fulfil the Performance Grade requirements at all, when used in the binder course or base course of roads constructed on the territory of Poland. In conformity with the PG values presented in Figures 6 and 7, these requirements are met by 35/50 penetration grade bitumen containing 3% of Gilsonite and 50/70 penetration grade bitumen with the Gilsonite additive of 3% and 5% or Trinidad Epuré additive of 15%. On account of an extremely high PG value connected with the average 7-day maximum air temperature for the 20/30 penetration grade bitumen and asphalt binders containing natural asphalts (in most cases these are higher than the maximum PG value of 82°C).
Figure 6. The values of the Performance Grade of the asphalt binders recommended to use in Poland for the binder course and base course as per [15].

Figure 7. The values of the Performance Grade of the asphalt binders recommended to use in Poland for the binder course and base course of motorways and expressways as per [16].

In reference to the results from papers [15, 16] it is reasonable to use softer bitumens as binders for the basic substance for modifications using natural asphalts (assuming most unfavourable conditions, the maximum PG value connected with the average 7-day maximum air temperature is 64°C) due to better low-temperature properties. Notably, the requirements conforming with the Performance Grade are fulfilled by the 35/50 and 50/70 penetration grade road bitumens not submitted to modifications, which are not included in technical requirements for asphalt pavements on national roads [5] for high stiffness modulus asphalt concrete.

7. Conclusions

- The 20/30 penetration grade road bitumen used in mixtures such as high stiffness modulus asphalt concrete can be effectively replaced with 35/50 and 50/70 penetration grade bitumens with the natural Gilsonite asphalt additive of 3% to 7% and Trinidad Epuré additive of 15%.
Asphalt binders containing the natural Gilsonite or Trinidad Epuré additive are characterised in most cases by identical PG to that of 20/30 penetration grade bitumen, whereas the application of the softer 50/70 penetration grade bitumen produces binders with even higher resistance to low-temperature cracking than the 20/30 bitumen, with unimpaired resistance to rutting in the climate conditions prevalent on the territory of Poland.

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