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# Effect of bitumen characteristics obtained according to EN and Superpave specifications on asphalt mixture performance in low-temperature laboratory tests

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# Effect of bitumen characteristics obtained according to EN and Superpave specifications on asphalt mixture performance in low-temperature laboratory tests

The paper aims to identify those characteristics of bitumen which have the greatest impact on asphalt mixture low-temperature performance. It was observed that stiffness and m-value of bitumen from BBR test were moderately related to stiffness and m-value of asphalt mixture obtained from 3PB test. Simultaneously those rheological properties significantly impact on cryogenic stresses induced during TSRST test. The multiple regression model was developed and it implied that mixture failure temperature depends both on rheological properties, brittle fracture and content of bitumen, what means that only comprehensive assessment of bitumen properties enables reasonable assessment of its low-temperature performance.

Keywords: Bitumen, Performance Grade, TSRST, low-temperature cracking, thermal cracking, three-point bending, asphalt, transverse pavement cracking, cryogenic stresses, BBR, Fraass breaking point

## Introduction

### *Background*

Thermal cracking is one of the most common pavement distress types, beside rutting and fatigue cracking. At the same time, it is one of the most complex processes that occur in the pavement, as it is related to the properties of both bitumen and aggregate as well as the composition of asphalt mixture [1]. Depending whether the European or the US practice is followed, the low-temperature properties of bitumen are determined based on Fraass breaking point test performed according to the procedure given in the EN 12593 standard, or Bending Beam Rheometer (BBR) test in accordance with AASHTO standard method T313, which in some cases may be supplemented by Direct

Tension Test (AASTHO T314).

In the case of low-temperature evaluation of asphalt mixtures, different test methods relate to either mechanical or fracture properties. In the case of fracture properties, the most commonly used tests include: Thermal Stress Restrained Specimen Test (TSRST) [2,3], Semi-Circular Bending (SCB) [1,4,5], Disk-Shaped Compact Tension (DCT) [6], Asphalt Thermal Cracking Analyser (ATCA) [7] and Three Point Bending Test (3PB) [8]. Rheological properties can be obtained from bending tests such as BBR conducted for asphalt mixtures [9] and three point bending creep test [10]. The simple linear relationship between TSRST critical cracking temperature and BBR strength results was presented by Falchetto et al. [11]. In most analytical cases, prediction of an estimated cracking temperature or amount of thermal cracking requires both stiffness and fracture characteristics of the asphalt mixture. The first group of properties is utilised for calculation of thermal stresses build-up [2,12], while the second is used for the limiting condition, beyond which the analysed mixture cracks due to the effect of the decrease in temperature. A comprehensive and detailed characterisation of asphalt mixture low-temperature properties is time-consuming and expensive due to laboratory test procedures and required amounts of materials for sample production. One of the possible approaches to this problem is to limit the size of the asphalt mixture specimens [13,14]. Another way is to utilise selected bitumen properties as values correlated to asphalt mixture properties, in order to decrease the amount of laboratory efforts [15].

For many years many studies have been conducted which searched the correlation between bitumen properties (mechanical, rheological and chemical) and low-temperature properties of asphalt mixtures. In all cases it was simple single regression functions. Isacsson and Zheng [16] investigated to influence of composition of bitumen on fracture temperature of asphalt mixture determined using TSRST test. Correlation of fracture temperature with the percentage amount of respectively asphaltenes, aromatics and resins and their combination showed quite good correlation with fracture temperature ($R^2 \sim 0.71 \div 0.90$). In another study of the authors [17] tested the impact of bitumen rheology on fracture temperatures tested in TSRST test. G* modulus and phase angles determined in the temperature of -20°C and frequency of 1 Hz showed significant correlation with fracture temperature. Xu and Isacsson [18] and Xu, Isacsson and Ekblad [19] tested the influence of bitumen rheological properties on low temperature properties of asphalt mixtures. In their studies they found that fracture temperature of the mixtures correlates strongly with the BBR limiting temperatures ($R^2 > 0.80$), very weakly with Fraass breaking point ($R^2$ ~= 0.50) and not with other tested indices. Olard et al. [20] tested rheological properties of bitumen in lower temperatures. Study showed significant correlation of BBR limiting temperatures with binder glass transition temperatures. Study also presents the relation between the G* and E* moduli in the form of prediction equation. Tan, Zhang and Xu [21] tested bitumen bending tests for evaluation of asphalt mixture low-temperature properties. They found that bitumen bending strain energy density showed very good correlation with fracture temperature. Sheikhmotevali and Ameri [22] analysed which of the rheological parameters could be used for prediction of mixture cracking temperatures. Tests conducted on different XX-22 PG bitumen showed varied performance. Conventional bitumen properties such as Penetration, Ring and Ball temperature and kinematic viscosity showed low correlation coefficients with fracture temperatures of asphalt mixtures ($R^2 \sim 0.65 \div 0.73$). Also they showed that mixture fracture temperature does not match bitumen fracture temperature.

According to performance grade bitumen classification, the required resistance of the mixture to low-temperature cracking is ensured when the bitumen properties obtained from the BBR test meet the criteria for a given climatic region. In contrast, according to EN standardisation, bitumen low-temperature criteria do not depend on climatic region. The basic parameter used to assess the low-temperature properties of bitumen in EN standardisation is Fraass breaking point and the required values depend on the bitumen class determined on the basis of penetration and softening point. The analysis of performance grade climatic zones in Poland, performed in [23,24], showed that the majority of Polish territory lies in the zone of lower PG -22 (for wearing course and probability of 80%). The Polish requirements for asphalt mixtures WT-2 2014 allow to design wearing course mixtures using neat and modified bitumens, including: 50/70, 70/100, PMB 45/80-55 and PMB 45/80-80. Except the Fraass breaking point, no low-temperature properties of the bitumen are taken into account in selection of bitumen class for asphalt mixture. As studies [25] show, bitumens available on the Polish market meet the current requirements. However, when higher probability level P = 95% is assumed, the lower PG for wearing course drops to PG -28 for the major part of the Polish territory. Recent research [25] showed that most bituminous binders used for wearing courses in Poland, including neat, polymer-modified as well as highly modified bitumens, ensure performance grade PG -22 at most. Moreover, field observations given in [26,27] show that the problem of pavement low-temperature cracking is serious. It was also observed that among 30 field test sections described in the study [27], 75% of sections using high modulus asphalt concrete with neat bitumen exhibit low-temperature cracks, while the percentage of cracked sections with applied polymer-modified bitumen was lower and equalled 50%. This observation and also some other studies that included field observations [28,29] indicated that the requirements and methodology of assessment of low-temperature properties of bitumens correspond to pavement performance only to a small extent and need to be improved.

The studies of Pucci et al. [30] revealed that TSRST failure temperature is a promising parameter for assessing the low-temperature performance of asphalt layers. According to new visco-elastic method of calculation of low-temperature thermal stresses in asphalt mixtures, which was developed and verified by Judycki [12,31] stresses induced in TSRST fit well with theoretical calculations. The same method can be used to estimate cryogenic stresses in asphalt layer. The rheological properties of asphalt mixtures for this method are obtained from three-point bending beam test. In another studies [26] three point bending beam test was used to evaluate low-temperature properties of mixture drill out of newly constructed pavement and further to identify reasons of premature low-temperature cracks that appeared in the winter 2012 on several highways in Poland. Studies proved that decrease of asphalt layer homogeneity, measured by standard deviations in results of 3PB test (stiffness modulus) and 3PB flextural strength, was the main factor that contributed to low-temperature cracks occurrence.

### *Objectives and scope*

The main goal of the paper is to investigate how the characteristics of bitumens correspond to performance of asphalt mixtures in terms of low-temperature cracking. To this purpose, results obtained from a series of tests performed for ten bitumens and seventeen asphalt mixtures with those bitumens were analysed to provide simple and multiple regression. A new approach to assessment of low-temperature performance of bituminous binders, based on multiple regression functions, is proposed. The difference between this manuscript and related previous literature consist on the development of new approach in building relationships between bitumen and mixture low-temperature properties, which uses multiple regression function and combines both rheological and fracture behaviour. The new approach aims is to improve the method of bitumen low-temperature performance assessment.

## Materials

### *Bitumens*

Four neat and six polymer-modified (SBS) bitumens with various penetration grade and the different lower performance grade PG from -10 to -22 were selected for analysis. The low-temperature properties of bitumens are presented in Table 1 and include Fraass breaking point $T_{Fraass}$, stiffness modulus $S_{bin,60s}$ and m-value $m_{bin,60s}$ obtained after 60 s of loading in the Bending Beam Rheometer test, limit temperature LST for which $S_{bin,60s}$ = 300 MPa, and limit temperature LmT for which $m_{bin,60s}$ = 0.300 [-]. The binders were subjected to ageing in RTFOT or PAV, as marked in Table 1. The rheological low-temperature properties of binders are expressed by master curves obtained for S and m-value with the usage of Richards model [32–34]. They are given in Figure 1.

Table 1. Penetration and low-temperature properties of asphalt binders

| Bitumen type | | Pen (RTFOT) at 25°C | $T_{Fraass}$ (RTFOT) | $S_{bin,60s}$ (PAV) [-] at | | $m_{bin,60s}$ (PAV) [-] at | | LST (PAV) | LmT (PAV) |
|---|---|---|---|---|---|---|---|---|---|
| EN class | PG class | [1/mm] | [°C] | -12°C | -18°C | -12°C | -18°C | [°C] | [°C] |
| 20/30 | 76-10 | 21 | -6 | 273 | 547 | 0.260 | 0.209 | -12.0 | -2.5 |
| 35/50 | 70-22 | 34 | -5 | 238 | 440 | 0.304 | 0.219 | -13.8 | -12.2 |
| 50/70 | 64-22 | 40 | -12 | 168 | 361 | 0.309 | 0.263 | -16.1 | -13.2 |
| 70/100 | 58-22 | 48 | -10 | 149 | 331 | 0.342 | 0.267 | -17.0 | -15.4 |
| PMB 10/40-65 | 88-16 | 20 | -13 | 185 | 335 | 0.267 | 0.231 | -16,8 | -6.8 |
| PMB 25/55-60 | 88-16 | 26 | -13 | 169 | 338 | 0.284 | 0.246 | -16.9 | -9.5 |
| PMB 25/55-80 | 82-22 | 36 | -26 | 77.9 | 174.5 | 0.320 | 0.273 | -25.8 | -14.6 |
| PMB 45/80-55 A | 70-22 | 41 | -14 | 159 | 345 | 0.315 | 0.260 | -16.6 | -13.6 |
| PMB 45/80-55 B | 76-22 | 40 | -15 | 127 | 273 | 0.327 | 0.282 | -18.6 | -16.2 |
| PMB 45/80-80 | 82-22 | 40 | -20 | 119 | 256 | 0.305 | 0.267 | -19.9 | -12.8 |

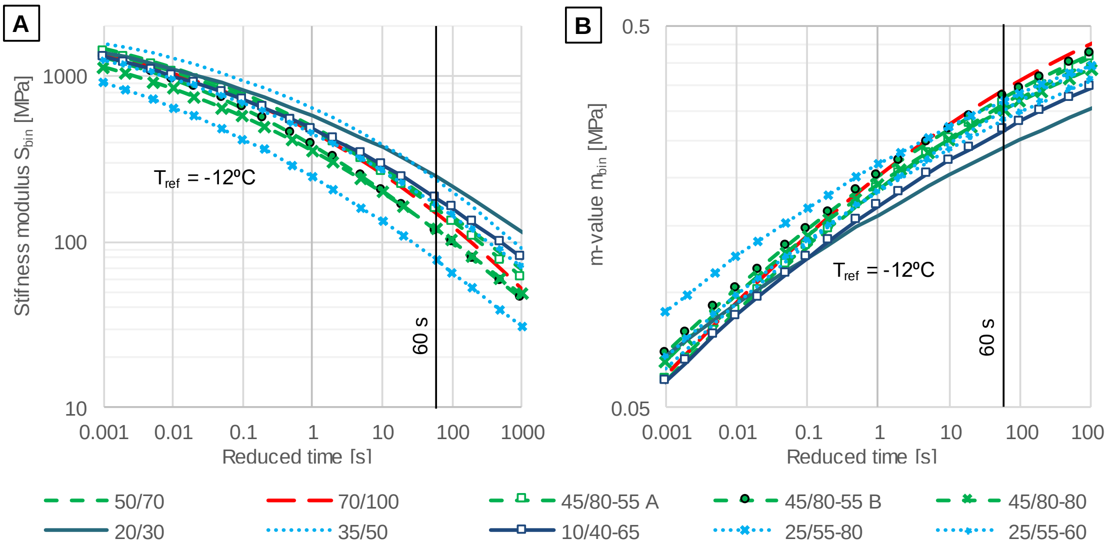

Figure 1. Master curves of: A) asphalt stiffness, B) asphalt m-value; obtained on the basis of BBR test for a reference temperature of -12°C

Wide range of Fraass breaking point values, equal to 20°C, indicates that the tested binders differ in terms of resistance to low-temperature cracking. Furthermore, master curves given in Figure 1 point to differences in rheological parameters between particular binders. They also suggest that limit temperatures LST and LmT are related to stiffness and m-value respectively, and provide separate indicators of rheological properties. It is not obvious which bitumen parameters have the greatest impact on low-temperature performance of the asphalt mixture.

### *Asphalt mixtures*

Tests were performed on eight asphalt mixtures for wearing courses, eight for binder course and one for asphalt base course. Mixtures were designed in compliance with the Polish technical guidelines WT-2 2014 and all specimens were prepared in the laboratory. Detailed properties of asphalt mixtures are summarised in Table 2. Low-temperature performance of all mixtures were further evaluated in TSRST test. Additionally eight mixtures for wearing course were tested in two bending beam schemes [6,8] to obtain rheological properties and flexural strength at low temperatures.

Table 2. Properties of asphalt mixtures

| Asphalt mixture | AC 11 S | AC 11 S | SMA 11 S | AC 16 W | HMAC 16 W | AC22 P |
|---|---|---|---|---|---|---|
| Layer | Wearing course (S) | | | Binder course (W) | | Base course (P) |
| Type of traffic | Low (KR1÷2) | Medium (KR3÷4) | | Medium and high (KR3÷7) | | |
| Bitumen types | 70/100<br>50/70 | 50/70<br>45/80-55A<br>45/80-55B | 50/70<br>45/80-55A<br>45/80-80 | 35/50<br>50/70<br>25/55-60<br>25/55-80 | 20/30<br>25/55-60<br>10/40-65<br>25/55-80 | 35/50 |
| Binder content (% by mass) | 5.8 | 5.6 | 6.5 | 4.3 | 5.3 | 3.9 |
| Aggregate type | crushed aggregate | | | | | |
| Filler type | limestone | | | | | |
| Sieve size (mm) | % Passing (by mass) | | | | | |
| 22 | 100 | 100 | 100 | 100 | 100 | 100 |
| 16 | 100 | 100 | 100 | 98 | 99 | 79 |
| 11.2 | 97 | 98 | 95 | 77 | 77 | 68 |
| 8 | 83 | 77 | 55 | 65 | 63 | 42 |
| 5.6 | 71 | 62 | 39 | - | 54 | 51 |
| 4 | 60 | 52 | 32 | - | - | - |
| 2 | 40 | 39 | 24 | 32 | 37 | 30 |
| 0.125 | 11 | 11 | 13 | 8 | 9 | 7 |
| 0.063 | 8 | 7.2 | 9.6 | 5.7 | 7.7 | 5.0 |

### *Performance parameters obtained from the TSRST*

One of the most common laboratory methods to evaluate low-temperature properties of asphalt mixtures is the Thermal Stress Restrained Specimen Test (TSRST), presented for the first time in 1965 by [2] and then applied by other researchers such as [3,35]. The modified TSRST procedure using notched samples was later proposed by Mandal and Bahia [35]. A comparison of calculations and TSRST measurements of thermal stress was also presented [36,37]. The resistance of asphalt mixtures to low-temperature cracking was assessed by means of the TSRST method in accordance with the EN 12697-46 standard. In the TSRST procedure the specimen is held at a constant length, while temperature is decreased at a uniform rate. According to EN 12697-46, the thermal stress is defined as cryogenic stress induced during tension due to prohibited thermal shrinkage, at the temperature T. The test starts at the temperature of $T_0$ = +20°C. For the standard test method, the cooling rate is set to 10°C/h and three specimens are tested for each asphalt mixture. The precision of the conducted test was considered acceptable if the results of failure temperature for 3 specimens differed by no more than 2°C and the results of failure stress differed by no more than 0.5 MPa. TSRST results are presented in Table 3.

Table 3. TSRST results, mean values and coefficients of variation CV of asphalt mixtures

| Type of asphalt mixture | | Failure temperature $T_{failure}$, [°C] | Cryogenic stress at failure $\sigma_{cry, failure}$, [MPa] | stress at -20°C $\sigma_{cry, @-20°C}$, [MPa] |
|---|---|---|---|---|
| AC 11 S, KR1÷2, 70/100 | mean value | -26.4 | 4.56 | 2.72 |
| | CV, [%] | 0.57 | 5.03 | 6.41 |
| AC 11 S, KR1÷2, 50/70 | mean value | -24.6 | 4.13 | 2.95 |
| | CV, [%] | 5.45 | 4.84 | 6.50 |
| AC 11 S, KR3÷4, 50/70 | mean value | -25.7 | 4.69 | 3.11 |
| | CV, [%] | 0.97 | 1.06 | 1.27 |
| AC 11 S, KR3÷7, 45/80-55 A | mean value | -27.0 | 5.01 | 2.99 |
| | CV, [%] | 3.59 | 3.99 | 2.92 |
| AC 11 S, KR3÷7, 45/80-55 B | mean value | -29.5 | 4.95 | 2.32 |
| | CV, [%] | 4.10 | 4.65 | 1.24 |
| SMA 11, KR3÷4, 50/70 | mean value | -24.8 | 3.89 | 2.83 |
| | CV, [%] | 3.99 | 5.64 | 1.00 |
| SMA 11, KR3÷7, 45/80-55 A | mean value | -27.2 | 4.69 | 2.75 |
| | CV, [%] | 4.26 | 4.05 | 5.37 |
| SMA 11, KR3÷7, 45/80-80 | mean value | -30.3 | 4.68 | 2.19 |
| | CV, [%] | 6.30 | 3.20 | 6.82 |
| AC 16 W, KR3÷7, 35/50 | mean value | -22.8 | 3.10 | 2.60 |
| | CV, [%] | 4.84 | 6.42 | 10.8 |
| AC 16 W, KR3÷7, 50/70 | mean value | -24.4 | 3.20 | 2.10 |
| | CV, [%] | 4.85 | 6.17 | 5.07 |
| AC 16 W, KR3÷7, 25/55-60 | mean value | -23.7 | 3.70 | 2.80 |
| | CV, [%] | 7.02 | 13.92 | 9.67 |
| AC 16 W, KR3÷7, 25/55-80 | mean value | -33.8 | 4.70 | 1.70 |
| | CV, [%] | 1.46 | 2.95 | 5.57 |
| HMAC 16, KR3÷7, 20/30 | mean value | -19.5 | 4.10 | 4.20 |
| | CV, [%] | 2.59 | 2.78 | - |
| HMAC 16, KR3÷7, 25/55-60 | mean value | -25.2 | 4.90 | 3.30 |
| | CV, [%] | 3.00 | 3.66 | 3.26 |
| HMAC 16, KR3÷7, 10/40-65 | mean value | -24.7 | 4.90 | 2.30 |
| | CV, [%] | 2.83 | 5.55 | 4.18 |
| HMAC 16, KR3÷7, 25/55-80 | mean value | -31.6 | 5.70 | 2.30 |
| | CV, [%] | 2.84 | 2.79 | 4.58 |
| AC 22 P, KR3÷7, 35/50 | mean value | -20.6 | 3.10 | 2.70 |
| | CV, [%] | 2.78 | 4.85 | 8.38 |

As shown in Table 3, mixtures with modified binders provide lower failure temperatures in the TSRST procedure. The stress at failure is higher in the case of mixtures with modified bitumens, while the cryogenic stress at -20°C is similar across all types of mixtures. It suggests that mixtures with modified bitumens are able to carry higher stresses until fracture failure occurs. Another observation is that asphalt mixtures that contain bitumens classified in the same group 45/80-55 can show significantly different failure temperatures.

### *Performance parameters obtained from bending beam tests*

The bending beam test with constant displacement rate was conducted using the methodology developed at the Gdansk University of Technology [8]. At each of the two temperatures: +10°C and -20°C, five beam specimens are subjected to bending with the constant rate of displacement equal to 1.25 mm/min. To evaluate low-temperature properties, four different parameters are determined: stiffness modulus, strength, critical displacement and stiffening ratio. The last parameter describes how fast the stiffness modulus increases with the decrease in temperature. In this study only two parameters are used and presented (Table 3): stiffness modulus and strength at the temperature of -20°C.

The bending beam test at a constant load was also conducted according to the methodology developed at the Gdansk University of Technology [8,10]. At each test temperature (usually +10°C, 0°C, -10°C and -20°C) five specimens are subjected to constant load equal to around 30% of the ultimate strength at the specific temperature. The time of loading differs from 3600 to 10800 seconds, depending on the test temperature. The specimen deformation is measured every 0.1 second. In this study, data was obtained using the above laboratory procedure, and the S and m values were calculated in accordance with the BBR protocol for the time of loading of 60 seconds. Results of both tests (constant displacement and constant load) performed in the scheme of bending beam are presented in Table 4.

Table 4. Results of asphalt mixture tests performed in the scheme of bending beam

| Mixture type | | *Bending beam test with constant load* | | | | *Bending beam test with constant displacement rate* | |
|---|---|---|---|---|---|---|---|
| | | $S_{mix,60s}$ *[MPa]* | | $m_{mix,60s}$ *[-]* | | $R_{zg}$ *[MPa]* | $S_{zg}$ *[GPa]* |
| | | -10°C | -20°C | -10°C | -20°C | -20°C | -20°C |
| AC 11 S KR1÷2 50/70 | mean value | 8 729 | 14 425 | 0.281 | 0.275 | 7.63 | 10.17 |
| | CV, [%] | 7.27 | 8.43 | 3.99 | 18.99 | 7.08 | 18.00 |
| AC 11 S KR1÷2 70/100 | mean value | 8 401 | 15 973 | 0.293 | 0.237 | 7.35 | 9.73 |
| | CV, [%] | 6.90 | 11.23 | 5.48 | 11.71 | 11.02 | 14.59 |
| AC 11 S KR3÷4 50/70 | mean value | 9 453 | 15 368 | 0.287 | 0.297 | 7.57 | 9.82 |
| | CV, [%] | 6.85 | 5.18 | 6.92 | 14.02 | 7.93 | 17.82 |
| AC 11 S KR3÷4 45/80-55 A | mean value | 8 761 | 15 669 | 0.287 | 0.277 | 9.19 | 11.25 |
| | CV, [%] | 8.02 | 11.44 | 3.06 | 17.80 | 3.81 | 8.89 |
| AC 11 S KR3÷4 45/80-55 B | mean value | 7 787 | 13 700 | 0.295 | 0.284 | 9.13 | 9.39 |
| | CV, [%] | 4.47 | 9.75 | 2.62 | 6.46 | 5.91 | 15.12 |
| SMA 11 S KR3÷7 50/70 | mean value | 8 429 | 15 942 | 0.265 | 0.238 | 7.29 | 8.78 |
| | CV, [%] | 7.31 | 15.35 | 5.09 | 17.43 | 8.64 | 15.83 |
| SMA 11 S KR3÷7 45/80-55 A | mean value | 6 836 | 12 813 | 0.285 | 0.215 | 8.05 | 10.86 |
| | CV, [%] | 11.36 | 5.51 | 1.74 | 20.15 | 10.43 | 24.86 |
| SMA 11 S KR3÷7 45/80-80 | mean value | 5 998 | 11 709 | 0.271 | 0.229 | 9.55 | 7.47 |
| | CV, [%] | 11.76 | 10.03 | 4.68 | 19.11 | 13.09 | 16.06 |

Based on Table 4, it can be stated that SMA mixtures provided lower values of stiffness moduli than asphalt concretes. Similarly, application of polymer-modified bitumens resulted in lowering of stiffness moduli of asphalt mixtures. It is difficult to identify the impact of mixture type and bitumen type on m-value of asphalt mixture. Flexural strength reaches higher values in the case of polymer-modified bitumens than in the case of neat bitumens. It is noteworthy that flexural strength obtained from the bending beam test with constant displacement rate (Table 4) reaches higher values than the maximum cryogenic stress at failure in the TSRST (Table 3). The main cause is probably the difference in the schemes and characters of both tests, what was wider described in [38].

## Effect of bitumen characteristics on asphalt mixture performance

### *Simple linear regressions*

In the first step, simple linear regressions were performed between bitumen properties (variable X) and asphalt mixture properties (variable Y) to assess how a given bitumen characteristic corresponds to low-temperature performance of asphalt mixture. Models were fitted with the use of least squares method and coefficient of determination was used to estimate how well the observed outcomes are described by linear function. All the considered combinations of relationships between bitumen and asphalt mixture properties are summarised in Table 5. Some of the combinations listed in Table 5, however, have doubtful physical meaning. For example, Fraass breaking point correlates fairly well with stiffness modulus of asphalt mixtures, but the Fraass test implies brittle fracture temperature, which depends rather on integral cohesion and ductility of bitumen at low temperatures than on bitumen stiffness. Analogously, bitumen stiffness should not be compared with asphalt mixture flexural strength. All relationships which should be treated with reserve due to their physical meaning have been marked in Table 5. Consideration of physical meaning led also to the conclusion that for the TSRST failure temperature it is better to consider its relationships with the limit temperature LST than with the stiffness modulus of bitumen. Limit temperature LST and stiffness of bitumen describe the same properties of the bitumen, but in different terms.  LST and $S_{bin}$ are related with each other, so it is sufficient to choose one of those two parameters for consideration of correlations with asphalt mixture properties. Analogous observation is valid in the case of LmT and m-value of bitumen. Due to this fact, only one from each pair of related bitumen characteristics ($S_{bin}$ or LST, $m_{bin}$ or LmT) was recommended by the authors for the analysis of the impact on a given mixture property. The recommended relationships are described in Table 5 and further shown in Figures 2-6.

The temperatures at failure in the TSRST as well as the temperatures of bending beam test with constant load performed for asphalt mixtures differ from the test temperatures assumed in the BBR test. For this reason, values of bitumen stiffness and m-values were calculated on the basis of master curves given in Figure 1.

It should be noted that several other characteristics can be used to describe the bitumen, including: penetration index, softening point, characteristics of the ageing process etc. While all of them can correlate with mixture low-temperature performance, only those characteristics that are commonly used and directly describe the properties of bitumen at low temperatures were chosen for this study.

Table 5. Summary of simple linear regression between bitumen and asphalt mixture low-temperature properties

| Bitumen properties (variable X) | *Asphalt mixture low-temperature properties (variable Y)* | | | | | | |
|---|---|---|---|---|---|---|---|
| | TSRST test | | | Bending beam test with constant load | | *Bending beam test with constant displacement rate* | |
| | $T_{failure}$, [°C] | $\sigma_{cry,\ failure}$, [MPa] | $\sigma_{cry,\ -20°C}$, [MPa] | $S_{mix,60s\ ,-10°C}$ / $S_{mix,60s\ ,-20°C}$ [MPa] | $m_{mix,60s,-10°C}$ $m_{mix,60s,-20°C}$ [-] | $R_{zq}$ *[MPa]* | $S_{zq}$ *[GPa]* |
| | *Coefficient of determination $R^2$ of linear regression function* | | | | | | |
| $T_{fraass}$ | 0.86 | 0.47 1) | 0.35 1) | 0.70 1) | 0.05 1) | 0.73 | 0.28 1) |
| LST | 0.85 | 0.38 3) | 0.45 3) | 0.58 3) | 0.52 1) | 0.00 1) | 0.05 3) |
| LmT | 0.39 | 0.03 3) | 0.38 3) | 0.00 1) | 0.02 3) | 0.54 1) | 0.03 3) |
| $S_{bin,60s,\ @°C}$ | 0.50 2) | 0.17 | 0.33 | 0.55 | 0.06 1) | 0.51 1) | 0.61 |
| $m_{bin,60s,\ @°C}$ | 0.06 2) | 0.34 | 0.59 | 0.17 1) | 0.48 | 0.21 1) | 0.30 |
| | *Slope of linear regression A* | | | | | | |
| $T_{fraass}$ | 0.57 | -0.085 1) | 0.055 1) | 439 1) | 0.00 1) | -0.262 | 0.207 1) |
| LST | 0.94 | -0.127 3) | 0.103 3) | 616 3) | 818 1) | 0.000 1) | 0.005 3) |
| LmT | 0.69 | -0.037 3) | 0.102 3) | -58 1) | -195 3) | -0.006 1) | -0.004 3) |
| $S_{bin,60s,\ @°C}$ | -0.02 2) | 0.003 | 0.003 | 13 | 0.00 1) | -0.008 1) | 0.01 |
| $m_{bin,60s,\ @°C}$ | 51 2) | -24 | -19 | -77058 1) | 0.45 | 50 1) | -78 |
| | *Constant of linear regression B* | | | | | | |
| $T_{fraass}$ | -18.33 | 3.2 1) | 3.4 1) | 20434 1) | 0.286 1) | 4.656 | 12.499 1) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| LST | -9.7 | 2.2 $^{3)}$ | 4.5 $^{3)}$ | 18610 $^{3)}$ | 28467 $^{1)}$ | 0.288 $^{1)}$ | 0.337 $^{3)}$ |
| LmT | -17.6 | 3.9 $^{3)}$ | 3.9 $^{3)}$ | 7237 $^{1)}$ | 11736 $^{3)}$ | 0.196 $^{1)}$ | 0.200 $^{3)}$ |
| $S_{bin,60s,\,@°C}$ | -9.0 $^{2)}$ | 2.4 | 1.4 | 9081 | 0.223 $^{1)}$ | 11.205 $^{1)}$ | 5.479 |
| $m_{bin,60s,\,@°C}$ | -36 $^{2)}$ | 9.3 | 7.4 | 33655 $^{1)}$ | 0.136 | -4.388 $^{1)}$ | 29.144 |

1) excluded from the analysis due to doubtful physical meaning of the relationship
2) an alternative relationship with limit temperatures LST or LmT is further considered
3) an alternative relationship with bitumen stiffness $S_{bin}$ or m-value is further considered

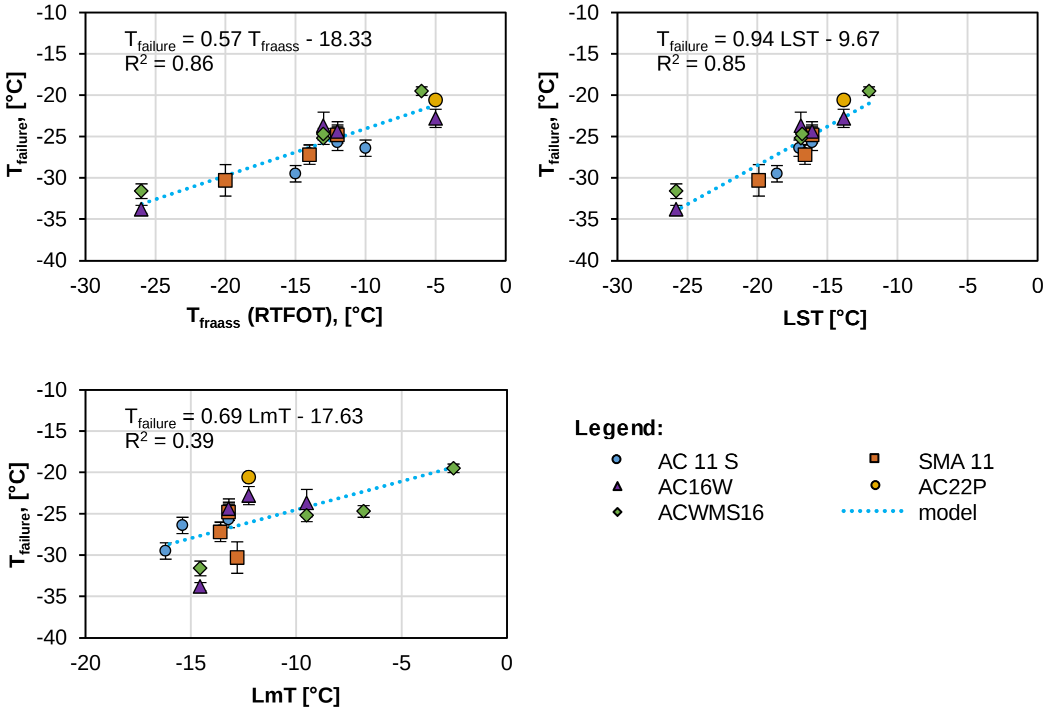

Figure 2. Relationships between mixture failure temperature from the TSRST and the following values: bitumen temperature of brittle cracking (Fraass), limit temperature at bitumen stiffness 300 MPa (LST) and limit temperature at m-value of 0.300 (LmT).

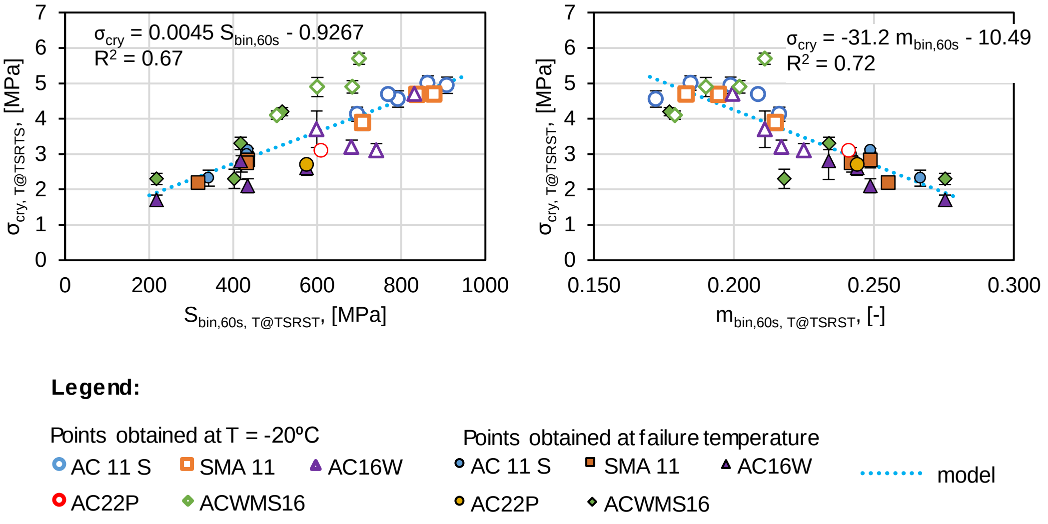

Figure 3. Relationships between stiffness and m-value of bitumens and cryogenic stress of mixture at T=- 20$^{o}$C and at failure in the TSRST

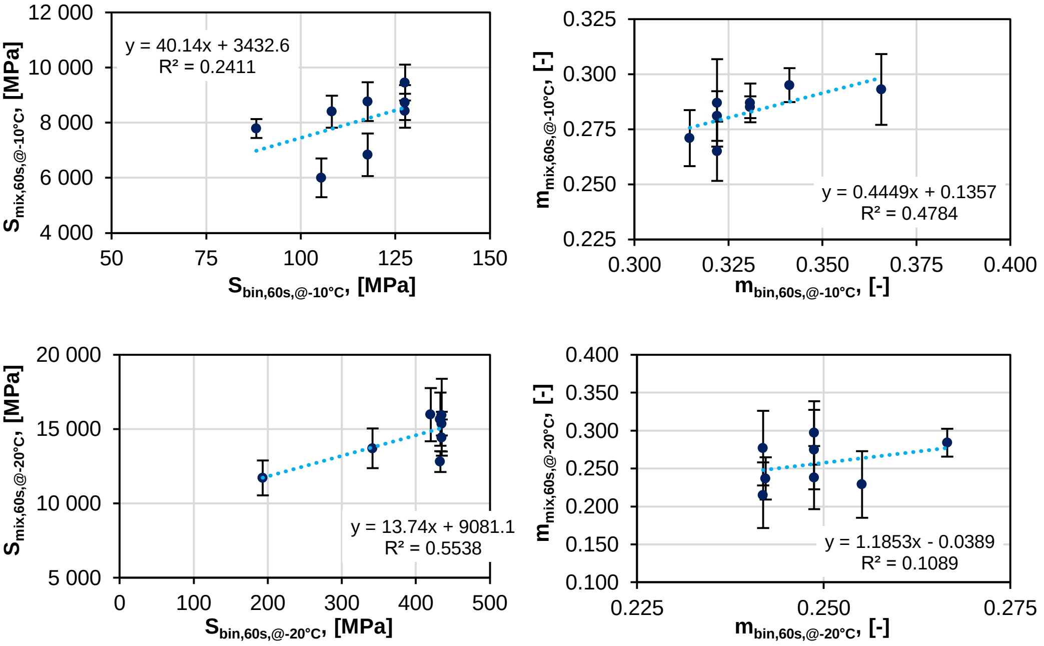

Figure 4. Relationships between stiffness and m-value obtained for bitumens and asphalt mixtures at temperatures of -10°C and -20°C

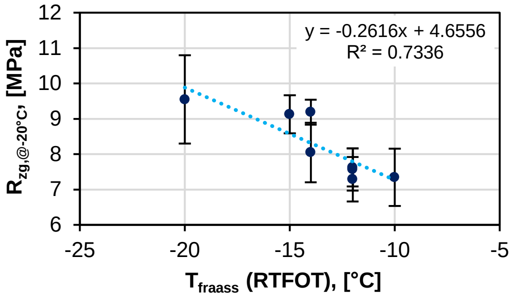

Figure 5. Effect of Fraass breaking point of bitumen on flexural strength of asphalt mixtures

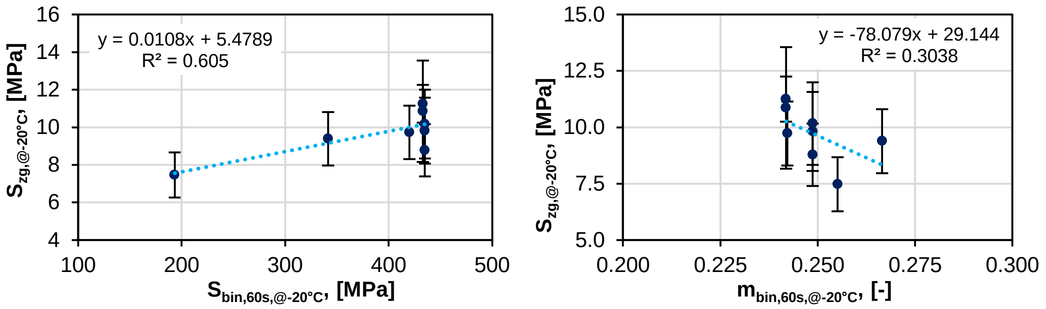

Figure 6. Effect of bitumen stiffness and m-value obtained from the BBR (constant load) on mixture stiffness delivered from bending beam test (constant displacement rate)

Figures 2-6 include selected combinations of relationships between bitumen characteristics and mixture performance. The linear tendencies are clearly visible in all cases. It is visible that Fraass breaking point corresponds quite well to mixture flexural strength (Figure 5) and failure temperature in the TSRST (Figure 2), which results partially from mixture strength. As shown in Figure 4, while bitumen stiffness and m-value have an effect on mixture stiffness and m-value respectively, the relationships are not strong, which implies that other factors (including ageing of bitumen) have significant impact on the behaviour of asphalt mixtures. Figure 6 shows that stiffness modulus of asphalt mixture measured in the bending beam test with constant displacement rate has a tendency to increase with an increase in stiffness modulus of bitumen and with a decrease in the m-value of bitumen obtained from the BBR test (where the scheme is bending beam with constant load).

### *Multi-parametric approach*

In the case of TSRST, it can be concluded from the relationships given in Figures 2 and 3 that complex characteristics of bitumen, including both rheological properties and resistance to brittle fracture, affect the performance of asphalt mixture, as expressed by failure temperature. Therefore, the multi-parameter linear regression model was proposed. It is given in Table 6.

The cryogenic stress measured in the TSRST depends both on stiffness modulus of the bitumen and its ability of stress relaxation (described by m-value), as clearly visible in Figure 3. The estimation of cryogenic stress on the basis of bitumen rheological properties can be a convenient approach to assessment of impact of both bitumen stiffness and stress relaxation. The regression formula for calculation of mixture cryogenic stresses obtained on the basis of the bitumen test data is given in Table 6.

Table 6. Multiple linear regression between bitumen properties and the TSRST results obtained for asphalt mixtures

| Multiple regression model | Regression adjusted $R^2$ | Standard error |
|---|---|---|
| $T_{failure} = 0.310\, T_{Fraass} + 0.315\, LST + 0.284\, LmT - 0.545\, B - 4.7$ | 0.924 | 1.023 |
| $\sigma_{cry,T} = 0.00238\, S_{bin,60s,T} - 18.271\, m_{bin,60s,T} + 0.155\, B + 5.261$ | 0.780 | 0.497 |

Designations in regression models given in table 6 are as follows:

$T_{failure}$ – failure temperature of asphalt mixture according to TSRST test,

$T_{fraass}$ – Fraass breaking point of bitumen [°C],

LST – limit temperature for bitumen stiffness S = 300 MPa [°C],

LmT - limit temperature for m-value m = 0.300 [°C], B – binder content, percentage in mass [%],

$\sigma_{cry,T}$ – cryogenic stress induce in asphalt mixture at given temperature T [MPa] in TSRST test,

$S_{bin,60s,T}$ – stiffness modulus of bitumen at 60 s and temperature T,

$m_{bin,60s,T}$ – m-value of bitumen at 60 s and temperature T.

To obtain values of LST, LmT, $S_{bin,60s,T}$ and $m_{bin,60s,T}$ the master curves obtained from results of BBR test of bitumen are required. LST, LmT, $S_{bin,60s,T}$ and $m_{bin,60s,T}$ correspond to rheological properties of bitumen while $T_{frasss}$ temperature correspond to resistance to brittle fracture of bitumen.

In the case of failure temperature $T_{failure}$ in the TSRST, the regression was built for three temperatures characteristic for bitumens: Fraass breaking point, the limit temperature for bitumen stiffness S = 300 MPa (LST) and the limit temperature for m-value m = 0.300 (LmT). Use of the same physical quantity (temperature) in the model enables the use of regression coefficients in assessment of the impact of brittle fracture and rheological properties of bitumen on the failure temperature of asphalt mixture. Based on the coefficients that appear next to particular temperatures in the equation, it can be concluded that failure temperature is most susceptible to changes in the m-value of bitumen, then to changes in Fraass breaking point and lastly, to the smallest degree, to changes in bitumen stiffness.

In the case of cryogenic stress, both stresses delivered from the TSRST at failure temperature and at -20°C were used to build the model. The assessment of the impact of bitumen stiffness and m-value of bitumen on cryogenic stresses is not as obvious as in the case of failure temperature model. If the Superpave limit values of bitumen parameters $S_{bin}$ = 300 MPa and $m_{bin}$ = 0.300 were assumed, the regression formula (Table 6) would provide cryogenic stress $\sigma_{cry}$ = 2.14 MPa. An adverse increase in bitumen stiffness by 10% to $S_{bin}$ = 330 MPa at constant m = 0.300 causes an increase in cryogenic stress by 5%. Analogously, an adverse decrease in m-value by 10% to $m_{bin}$ = 0.270 causes an increase in cryogenic stress by 7%. These calculations lead to the conclusion that m-value of bitumen has a slightly more significant impact on development of stress in asphalt mixture during its cooling than bitumen stiffness.

It was found that binder content has a significant effect both on of failure temperature and cryogenic stresses, but on failure temperature is much stronger. Higher binder content from the one side causes a slight increase in cryogenic stresses and on the other side contribute to positive effect of crucial decrease in failure temperature, what result from increase in strength of the mixture.

The quality of the model for failure temperature was assessed based on the bitumen and low temperature data sets obtain from the literature [19,39–42]. The obtained data consisted of: type of mixture, type of bitumen, binder content, TSRST fracture temperature, Fraass breaking point and temperatures for limiting values of stiffness modulus and m-value obtained from BBR test. Where it was possible [40,41] all related properties were derived or interpolated from presented results. In some research [19,39] it was necessary to assume some of the values. In the case of research made by Hase and Oelkers [39] values of Fraass breaking point and binder content were assumed on the basis that both bitumen requirements and type of asphalt mixtures are very similar in Germany and Poland. In the case of research made by Olard et al. [42] only Fraass breaking point values were assumed. The comparison between predicted fracture temperature and fracture temperature determined on the basis of TSRST test is presented in figure 7. As was expected when full data set was available the model for TSRST fracture temperature presents very good accuracy with mean value of error of -0.88°C (for 80% of results error was in range from -1.58°C to -0.28°C). When in the data set assumptions were used the accuracy of the model is a bit worse with mean value of error of -0.50°C (for 80% of results error was in range from -3.88°C to +2.15°C). Nevertheless the prediction of the model for the whole data set is quite good and fits in most cases in the range of the scatter of TSRST test results, which equals to 2°C

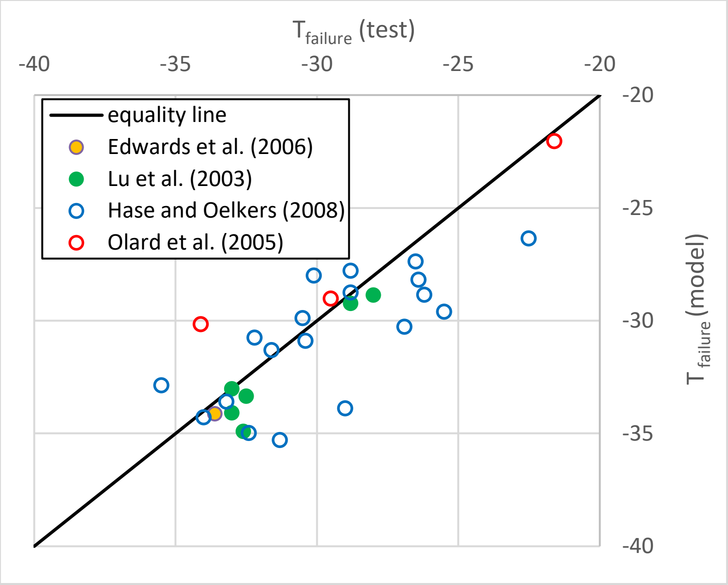

Figure 7. Evaluation of the empirical equation of failure temperature on the basis of experimental data collected from literature

Nevertheless, an extension of the database with further values of tested properties of both bitumens and mixtures may lead to a more precise model, which would be useful for complex performance analysis of asphalt binders. The use of multi-parametric regression model for complex evaluation of bitumen properties has some advantages in comparison to current approach, which is based on limit value requirements. The new approach would make it possible to assess how an adverse change in one of bitumen characteristics may be compensated by a positive change in another. Moreover, it would enable the choice of the best bitumen among all that meet the performance grade requirements.

## Summary

Recent research carried out in Poland indicated that commonly used bitumens ensure lower performance grade from PG -10 to PG -22, it meets the requirements resulting from Polish climatic conditions only at an 80% probability level. Field observations of road sections in Poland also revealed that problem of low-temperature cracks is serious and current requirements for bitumens in this respect are definitely insufficient.

The group of tested binders included four neat bitumens with different penetrations, four polymer-modified bitumens as well as two highly polymer-modified bitumen. Low-temperature performance properties of six different mixture types designed with those binders varied significantly. The comparison of laboratory tests performed on bitumens and asphalt mixtures indicated that the requirements and methodology of assessment of low-temperature properties of bitumens correspond to mixture performance to a limited extent and need to be improved.

Analysis of the laboratory test results indicated that Fraass breaking point corresponds quite well to mixture flexural strength and failure temperature in the TSRST, which depends partially on mixture strength. While bitumen stiffness and m-value have an effect on mixture stiffness and its m-value respectively, the relationships are not very strong, which implies that other factors (including ageing of bitumen) have significant impact on rheological behaviour of asphalt mixtures. Also binder content has a significant effect both on of failure temperature and cryogenic stresses. Higher binder content from the one side causes increase in cryogenic stresses and on the other side contribute to positive effect of decrease in failure temperature, what result from increase in strength of the mixture.

Only a comprehensive assessment of both rheological and fracture properties of bitumen enables prediction of asphalt mixture performance. To this purpose, the multi-parameter linear regression models were developed and analysed. Models predict the mixture performance characteristics relatively well, as expressed by failure temperature and cryogenic stresses of asphalt mixture. The investigation of the model suggested that m-value of bitumen is the factor that has the greatest impact both on the temperature of failure and the cryogenic stress development in asphalt mixture in the TSRST.

Models presented in the study were developed for a quite wide but still limited set of bitumen types and mixtures. Validation using independent data sets from literature provided quite accurate prediction of the TSRST fracture temperature.. Nevertheless, there new data describing bitumen and mixture properties should still be added to the proposed multiparameter model, what will contribute to further increase in its precision. The proposed approach may supplement the current requirements set for bitumens in the EN standards and in the Superpave, which are based only on limit values of particular bitumen characteristics.

## Acknowledgement

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