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Determination of modifier contents in polymer-modified bitumens and in samples collected from the roads using high performance gel permeation/size exclusion chromatography

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Determination of modifier contents in polymer- modified bitumens and in samples collected from the roads using high performance gel permeation/size exclusion chromatography

Abstract

This paper describes application of high performance gel permeation/size exclusion chromatography (HP-GPC/SEC) for the determination of content of polymer modifiers in modified road bitumens. The obtained results were compared with the measurements based on the procedure recommended by the American Association of State Highway and Transportation Officials, which employs Fourier transform mid-infrared spectroscopy (mid-IR FTIR). Two most commonly used modifiers of paving bitumens, namely styrene-butadiene-styrene (SBS) and styrene-butadiene (SB) copolymers as well as modified bitumens sampled from various streets in the city of Gdansk (Poland) were investigated. This work confirmed the ability of GPC/SEC to distinguish modified road bitumens from unmodified ones. The developed methodology is particularly important in quality control of modified bitumens, as well as in arbitration analysis when there is a suspicion that the amount of modifier added to bitumen was lowered or that the material does not meet the specifications concerning the modifier content.

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Keywords: polymer modifiers; styrene-butadiene-styrene (SBS); road bitumen; size exclusion chromatography (GPC/SEC); Fourier transform infrared spectroscopy (FTIR); thin layer chromatography coupled with flame ionization detection (TLC-FID)

11 **1. Introduction**

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Bitumens belong to the group of thermoplastic and viscoelastic materials. Heated bitumens become soft and undergo a gradual transition from a solid to a liquid, while cooling turns them into a brittle-elastic solid. At intermediate temperatures bitumens exhibit the properties of both a viscous liquid and an elastic solid. The properties of road pavements called asphalts (a mixture of bitumen and aggregates) vary as a function of temperature and duration of use. Therefore, the range of viscoelastic properties of a given bitumen type should be properly matched with the expected temperatures of the bitumen in order to retain its rheological characteristics (Loeber, Muller, Morel & Sutton, 1998).

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The climate of Poland has a negative impact on paved surfaces. Traditional asphalts do not fulfill all the expectations of road users. Ruts caused by slowly moving trucks during hot summer months and transverse cracks formed as a result of abrupt temperature drops in winter are a real issue for drivers. Furthermore, asphalt undergoes aging processes when exposed to oxygen, heat and ultraviolet light, resulting in changes of physical properties and chemical structure of asphalts (Lamontagne, Dumas, Mouillet & Kister, 2001; Lu & Isacson, 1998; Ruan, Davison & Glover, 2003; Fernandes, Forte & Leite, 2008; Wang, Razaqpur, Xing & Chen, 2015), as well as, polymer-modifiers added to bitumen (Zhang, Jia, Yu & Xue, 2013; Polacco, Biondi, Stastna, Vlachovicova & Zanzotto, 2004; Airey, 2004). Consequently, the ideal bitumen should possess both a high relative stiffness at high temperatures (summer) to reduce rutting and shoving and an

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3 increased adhesion between bitumen and aggregates in the presence of moisture to reduce
4 stripping (Roberts et al.,1996).
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8 The most common method to prevent the aforementioned damage to paved surfaces is the
9 replacement of traditional bitumens with polymer-modified bitumens, which changes the
10 interfacial properties of the primary bituminous material (Błażejowski & Styk, 2004). The aim of
11 bitumen modification is to improve the useful properties of the mixtures of mineral aggregates,
12 and to extend the expected service life of paved surfaces - asphalts. This requires better
13 pavement resilience to permanent deformation, cracking, aging, fatigue and the impact of
14 external factors. Methods based on increasing the angle of internal friction in the mixture of
15 bitumen and mineral aggregates, i.e. increasing the content of crushed grains and grit, and on
16 optimizing the binder content and binder consistency do not ensure all the required properties,
17 particularly in the case of increasing road traffic (Piłat & Radziszewski, 2007).
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32 Polymer-modified bitumens used for paving contain a specified amount of modifier in the
33 form of polymer which was introduced into the bitumen via dedicated technological processes
34 (Błażejowski & Styk, 2004; Piłat & Radziszewski, 2007). The modification process is based on
35 crosslinked modifiers at the phase boundary. The final product has properties which improve
36 pavement resilience to rutting and cracking. Polymer-modified bitumens are mainly used for
37 paving roads exposed to high volume traffic of heavy vehicles, bridges, roundabouts and
38 intersections.
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48 Application of polymer-modified bitumens increased the need for reliable quality control
49 procedures determining the content of modifiers in bitumens. This has become one of many tasks
50 of modern analytical chemistry dealing with the composition of complex mixtures.
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3 is the method of choice to determine low-volatility and non-volatile mixture components. The
4 application of liquid chromatography is particularly recommended for determining the group-
5 type composition of bitumens (Gudebska, 1999). Liquid chromatography can also be used for the
6 determination of bitumen modifiers in asphalts.
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12 So far, a procedure using Fourier transform infrared spectroscopy (FTIR) for determining the
13 content of styrene-butadiene-styrene (SBS), styrene-butadiene rubber (SBR) and styrene-
14 butadiene (SB) copolymers in modified bitumens has been developed (AASHTO T302-05,
15 2007). FTIR spectroscopy is well-known technique utilized widely in asphalt technology. It can
16 be used to determine the presence and approximate content of polymers in an asphalt binder
17 (Diefenderfer, 2006), to evaluate oxidation levels in bitumens and polymer-modified bitumens
18 (Yut & Zofka, 2011). The FTIR allows for comparison of different types of bituminous samples
19 (Zhang, Wang, Wu, Sun & Wang, 2009; Wu, Zeng, Ou, Yu, Lu & Xu, 2010; Izquierdo, Navarro,
20 Martínez-Boza & Gallegos, 2012). It can be also helpful while explaining interactions occurring
21 between the polymer modifier and bitumen (Ramalinga Chandra Sekar, Mahendran, Vasudevan
22 & Velkennedy, 2015) and while investigating the aging resistance characteristics of polymer-
23 modified bitumens (Ouyang, Wang, Yong Zhang & Yinxi Zhang, 2006; Nivitha, Prasad &
24 Krishnan, 2015). Size exclusion chromatography (GPC/SEC) has also been applied for similar
25 analyses (Peramanu & Pruden, 1999). This is due to the fact that polymers with high molecular
26 weights are used as bitumen modifiers. Furthermore, GPC/SEC is a technique commonly used in
27 many aspects of bitumen analytics (Doh, Amirkhani & Kim, 2008; K.W. Kim, K. Kim, Doh,
28 & Amirkhani, 2006). Thin layer chromatography coupled with flame ionization detection
29 (TLC-FID) also seems to be useful for determining the modifier content. However, its major
30 application is determination of the group composition (Paliukaitė, Vaitkus & Zofka, 2014;
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3 Kamiński, Gudebska, Górecki & Kartanowicz, 2003; Ecker, 2001; Masson, Price & Collins,
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6 2001) – a so-called SARA (Saturates, Aromatics, Resins, Asphaltenes).
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8 In the current Polish standard PN EN 14023, describing the classification rules for polymer-
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10 modified bitumens, the determination of modifier content is not required (PN EN 14023, 2009).
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12 Modified bitumens are on average 20 to 25% more expensive than traditional bitumens. Because
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14 of that, adulteration of modified bitumens by lowering the required content of modifiers is quite
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16 probable. Lack of monitoring of the amount of modifier used in paved surfaces makes tampering
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18 even more likely. Liquid chromatography, especially SEC, could be used for the determination
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20 of modifier content in bitumens. It should be noted, however, that for some purposes only highly
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22 selective and highly orthogonal separation systems can provide a satisfactory separation of the
23
24 analytes allowing their quantitative analysis (Boczkaj, Jaszczółt, Przyjazny & Kamiński, 2013;
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26 Gilgenast, Boczkaj, Przyjazny & Kamiński, 2011).
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31 In the light of the above facts, the development of the procedure for determining modifiers in
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33 bitumens is very important. In addition, the information about the actual amount of ground
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35 polymer added is important from the point of view of quality control. The basic principle of
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37 quality control concerning addition of modifiers is based on fluorescence microscopy. However,
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39 this technique only allows assessment of the technology, but does not allow determining the
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41 content of modifier added.
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45 In contrast, this work provides the procedure for the determination of the content of modifier,
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47 but does provide any information on whether the modifier occurs in a granular form.
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49 Nevertheless, the methodology presented in this paper can be used in quality control laboratories
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51 as well as in process analytics, as a tool for the control of modifier content in road pavements.
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3 The results and conclusions of these investigations should also contribute to the identification of
4 adulterated modified bitumens.
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7 8 **2. Materials and methods**

9 10 **2.1. Materials**

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12 The standards used: polystyrene (1,260,000 Da, 120,000 Da, 30,300 Da, 2,450 Da) and
13 benzene were purchased from Merck (Germany), SBS (styrene-butadiene-styrene) and SB
14 (styrene-butadiene) – both from Polish manufacturer. The eluents/solvents used in the
15 investigations – dichloromethane, methanol and toluene (POCH, Poland) were analytically pure
16 and tetrahydrofuran (Merck, Germany) was of HPLC grade. The chromatographic columns
17 employed during the experiments were: two 250 x 7 mm LiChrogel PS1 (5 μm) columns
18 (Merck, Germany) and two 250 x 7 mm LiChrogel PSMix columns (Merck, Germany). The
19 PTFE disc filters (0.45 μm) were purchased from Merck (Germany).
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32 **2.2. Apparatus**

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34 A Merck–Hitachi (Darmstadt, Germany) gradient liquid chromatograph equipped with an L-
35 7100 four-channel pump, a 7450A UV-Vis diode array detector, a RID 7490 refractive index
36 detector, a 7350 thermostat with a 7350i cooling system, a Rheodyne model RH-7725i injector
37 with a 20- μL sample loop, a V7226 six-port two-position backflush valve (Knauer, Berlin,
38 Germany) to switch the flow direction of the mobile phase, were used in the present work.
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47 A FTIR NICOLET 8700 (Thermo Electron Corporation) spectrometer with Specac Golden
48 Gate ATR accessory; an analytical balance (RADWAG Poland); an XL ultrasonic bath, a 2020
49 Sonificator® Misonix (USA) and a rotary evaporator Heidolph (Germany) were used.
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54 An Iatroscan (Iatron Labs, Japan) TLC-FID analyzer equipped with Chromarod-S III rods was
55 also used. Additional equipment included: an automated sample dispenser SES 3200/IS-01, a
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3 TLC rods dryer model TK-8, an analogue-to-digital converter and software for data processing
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5 (Elkor, Poland).
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8 **2.3 Samples**

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11 Unmodified bitumens: 35/50, 160/220 and modified bitumens: 25/55-60, 45/80-55 (from
12 international supplier of bitumens) were examined. In addition, samples of asphalt from streets
13 paved at different times (year: 2006, 2007, 2008) were investigated. The latter samples were
14 taken from various streets in Gdansk, Poland (see Fig. 1), namely:
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21 ➤ modified bitumen samples were taken from: Marynarki Polskiej Street (year 2006),
22 Grunwaldzka Street (year 2007) and Cienista Street (year 2008);
- 23
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25 ➤ unmodified bitumen samples – from: Spacerowa Street (year 2006), Źródłana Street
26 (year 2007) and Kampinoska Street (year 2008).
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30 **2.4 Procedure**

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32 **2.4.1. Sample preparation**

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34 **a) Road pavement samples**

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39 Six samples of modified and unmodified bitumens were collected in the Gdansk area at
40 different time points during the road construction. Samples (3-5 grams) were taken from the
41 depth of 1 cm (sample width ca. 1 cm).
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47 **b) Bitumen solutions**

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51 The size-reduced samples (approximately 2.5 g) of collected road pavements were transferred
52 into pre-weighed 10-mL vials and subjected to ultrasound-assisted extraction with an organic
53 solvent - dichloromethane (DCM) for 10 minutes. The extraction was then continued until the
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3 mineral aggregates turned clean and bitumen was visibly dissolved. The undissolved material
4 was vacuum filtered onto 90 mm disc filters which were subsequently washed a couple of times
5 with dichloromethane. The filtrates were transferred into pre-weighed 100-mL round-bottom
6 flasks and evaporated to dryness in a rotary evaporator at 40 °C. Finally, the flasks were dried in
7 a laboratory dryer for 30 min at 120 °C and the obtained samples (of known mass) were
8 dissolved in THF for GPC/SEC.
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10 11 12 13 14 15 16 17 18 **2.4.2 Infrared Spectroscopy (FT-IR)**

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20 Spectral analysis was performed by using the attenuated total reflectance (ATR) technique
21 according to the modified procedure described in standard AASHTO T 302-05 (2007). Total
22 reflectance is achieved by directing a beam of infrared radiation onto the side of a diamond
23 optical element that constitutes the main part of a Golden Gate accessory. Samples in a solid
24 state were placed on the surface of a crystal (diamond). Spectra were recorded at a 4cm⁻¹
25 resolution by averaging 32 measurements in the range from 4000 cm⁻¹ to 500 cm⁻¹. The
26 maximum absorbance for bitumen should be at ca. 1375 cm⁻¹, while the peak having a maximum
27 at 975 cm⁻¹ indicates the presence of SB or SBS.
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43 Two PS-MIX (250×7 mm, d_p = 5µm) and two PS-1 (250×7 mm, d_p = 5µm) columns with
44 tetrahydrofuran as the mobile phase, and a refractive index and a UV-DAD detectors connected
45 in series were used in this study. All samples were separated at 20 °C. The mobile phase flow
46 rate was 1 mL/min and the injection volume was 20 µL. The solutions were filtered through
47 0.45-µm PTFE membrane filters. For the determination of molecular mass, calibration curves
48 were prepared by using molecular mass standards with known masses (1,260,000 Da, 120,000
49 Da, 30,300 Da, 2,450 Da, benzene). To determine the modifiers in bitumens, calibration curves
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3 were prepared by using solutions of bitumens in THF at 50 mg/mL with the following modifier
4 concentrations: 1% SBS, 3% SBS, 5% SBS, 7% SBS. An analogous series of solutions was
5 prepared using bitumens modified with SB.
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10 **2.4.4 Thin Layer Chromatography Coupled with Flame Ionization Detection (TLC-FID)**

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12 Separation of bitumens was performed according to a modified procedure published previously
13 (Gudebska, 1999). During bitumen separation, an optimization procedure was carried out – the
14 flow rates of hydrogen and air were changed prior to analysis of each of the ten chromarods –
15 and the optimum flow rates for hydrogen (150 mL min^{-1}) and for air (1.8 L min^{-1}) were selected.
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23 Chromarods were activated by passing them through a TLC-FID analyzer using a hydrogen
24 flame just before sample application. Activated rods were spotted with $1 \mu\text{L}$ of sample solution
25 containing: $10 \text{ mg asphalt mL}^{-1}$ dichloromethane and 1 mg SBS mL^{-1} dichloromethane, using a 2 -
26 μL microsyringe. After application of spots, the rods were dried for 2 minutes in an oven at 70°C
27 and placed for 10 minutes in a desiccator. Next, the rod holder carrying the chromarods was
28 placed in a TLC chamber containing the solvent – a mixture of dichloromethane: methanol 95:5
29 (v/v). Elution was carried out to a height of 2.5 cm. The rod holder was put in an oven at 70°C
30 for 2 minutes and then placed in a desiccator for 10 minutes, and after that – for 10 minutes in a
31 TLC chamber containing toluene where the chromarods were developed up to a height of 6 cm.
32 Next, the rod holder was transferred to an oven for 2 minutes, then to a desiccator for 10
33 minutes, and finally it was placed in the TLC chamber containing hexane for 5 min where the
34 elution was carried out to a height of 10 cm.
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51 Detection was carried out by the FID detector with digital acquisition of the detector signal.
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54 **2.4.5 Determination of SB and SBS**

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3 Analytical conditions were optimized using solutions of road bitumen having concentrations of
4 0.05 g/mL and of modifiers of 0.005 g/mL in tetrahydrofuran (for GPC analysis). Next, the
5 samples were prepared according to the procedure described in „Sample preparation FT-IR and
6 GPC/SEC”.

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12 The limit of quantitation (LOQ) was taken as the concentration corresponding to the signal five
13 times as great as the noise corrected for the recovery. The LOQ values (the lowest concentration
14 of modifier that could be determined using the developed procedure) for SBS and SB were
15 0.46% and 0.38%, respectively. The determination of polymer content in bitumens was carried
16 out by the external standard method. Four-point calibration curves were prepared using solutions
17 of modified bitumens with known modifier concentrations in a typical range of 1-7%. Each
18 determination was repeated five times. The peak area of modifiers in real samples was
19 determined using a so-called “drop” integration method and the same method was applied for the
20 preparation of the calibration curve. Drop method is based on drawing a perpendicular line to the
21 baseline from the “valley” between the chromatographic peaks which are not separated.

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In case of calibration curve preparation, the applied “drop” method enabled to obtain
satisfactory values of determination coefficient (R^2) within the “practical” range of
concentrations presented in the paper. It confirms the correctness of determinations performed
with the use of the calibration curve.

2.4.6 Quality control, quality assurance

Statistical studies were carried out using Microsoft Excel Data Analysis ToolPak. The
following parameters were calculated: the arithmetic mean, standard deviation (SD), relative
standard deviation (RSD), limit of repeatability and parameters describing the regression, i.e. the

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3 value of the slope and correlation coefficients. The results are reported as the mean value from at
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5 least five independent measurements, in which the difference did not exceed 5%.
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8 **3. Results and discussion**

9 10 **3.1 Infrared spectroscopy (FT-IR)**

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12 Attenuated total reflection (ATR) infrared spectroscopy was used to perform spectral analysis
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14 of the samples (see Fig.2).
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17 Spectral analysis confirmed the presence of alkyl groups as evidenced by the C-H stretching
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19 vibrations in the $3000\text{--}2850\text{ cm}^{-1}$ region. No bands were detected for the wavenumber values
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21 greater than 3000 cm^{-1} . Inspection of the $1760\text{--}1665\text{ cm}^{-1}$ range (carbonyl band position)
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23 revealed no evidence for the presence of carboxylic, ester, aldehyde, amide and ketone groups.
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27 The following characteristic bands were observed:
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- 29 ✓ C-H stretching from $3000\text{ to }2850\text{ cm}^{-1}$,
- 30 ✓ C-H bending or scissoring from $1470\text{ to }1450\text{ cm}^{-1}$,
- 31 ✓ C-H rocking from $1370\text{ to }1350\text{ cm}^{-1}$.

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36 Bands in the $1300\text{--}900\text{ cm}^{-1}$ region, which is called the fingerprint region, originated from
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38 skeletal vibrations and formed a complex picture. In general, it is difficult to interpret bands in
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40 this particular region. However, each organic compound has its unique pattern, the so-called
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42 fingerprint, which can be used for its identification by comparing the compound's fingerprint
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44 with the fingerprint of the selected standard reference material (AASHTO T302-05, 2007). In the
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46 case of reference standards such as SBS and SB, the characteristic region occurs at 965 cm^{-1} and
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48 697 cm^{-1} , respectively. The SBS band is split, while no such feature occurs in the case of SB
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50 (Fig. 3). The polymers in the analyzed samples could not be positively identified because their
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52 content was too low and the absorption bands were blurred.
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3 The contents of modifiers were determined from a calibration curve (Fig. 4 prepared on the
4 basis of data listed in Table 1) for the characteristic regions ($R^2=0.9998$; absorbance =
5 $f(\text{concentration of modifier}): (A1/A2) = 0.031c + 0.0286$).
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10 The concentrations of modifiers determined in all the examined samples are listed in Table 2.
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12 13 **3.2 Size exclusion chromatography (GPC/SEC)** 14

15 Examples of chromatograms of selected bitumens (including those from road pavement) are
16 shown in Figures 5 and 6, while Figure 7 presents chromatograms of the mixtures containing
17 polystyrenes and the analyzed modifiers.
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22 The chromatograms of modified bitumens reveal an additional peak compared to the
23 chromatograms of unmodified bitumens. The peak is attributed to the presence of a modifier
24 (Fig. 5a) and has a lower retention due to the high molecular weight of the compound (Fig. 7).
25 The obtained molecular weight of ca. 550 kDa is not the true molecular weight of the analyzed
26 polymer, but its relative molecular weight with respect to the molecular weight of polystyrene.
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34 The GPC/SEC molecular weight distribution calibration curve ($\log M = f(V_e)$) presented in
35 Fig. 8 (blue curve) was prepared on the basis of Fig. 7a. The five points (blue dots in Fig. 8)
36 indicated on the calibration curve refer to the obtained values of $\log M = f(V_e)$ of
37 polystyrenes of masses: 1,260,000, 120,000, 30,300, 2,450 Da and to acetone (58 Da). The
38 average molecular weights for the modifier and bitumens were calculated from the equation: \log
39 $M = -0.4656V_e + 13.31$. Using the GPC/SEC chromatograms in Fig. 5-7, it was possible to
40 indicate on the calibration curve the ranges of elution volume characteristic of the modifier
41 (purple line) and bitumen (black lines). Since the chromatographic peaks for bitumen (Fig. 5, 6)
42 are not typical because they split into two fractions, there are two black lines in Fig. 8. It is likely
43 that the first fraction (counting from right to left) represents bitumen sample components with
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3 lower molecular weights, while the second is the result of oxidation and polymerization process
4 and contains sample components with higher molecular weights. It was not possible to present
5 separately the V_e ranges for two types of the examined modifiers (SBS and SB) due to their
6 similar molecular weights. Therefore, size exclusion chromatography is not an appropriate
7 technique to distinguish these two modifiers.
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11 A calibration curve (Fig. 9 prepared on the basis of data listed in Table 3) used for the
12 determination of modifier concentration was constructed based on the GPC/SEC measurements
13 made for four 35/50 bitumen solutions with increasing polymer contents, namely, 1, 3, 5 and 7%
14 ($R^2=0.9844$, peak area = f(concentration of modifier): $A = 149295c + 201.45$). The obtained
15 results, including descriptive statistics, are presented in Table 4. A comparison of
16 chromatograms of unmodified and modified asphalts, both “unused” samples (obtained from the
17 manufacturer) and samples collected from the roads reveals that the analytical signal in the range
18 of the expected value of the modifier retention time was obtained only in the case of modified
19 bitumen samples. According to the obtained results, both steps, *i.e.*, sample preparation
20 procedure and chromatographic analysis, proved to be optimal for the intended use of the
21 methodology presented in this study. In this way, the ability of GPC/SEC to distinguish modified
22 road bitumens from unmodified ones was confirmed. The procedure developed in this work is
23 particularly important in quality control measurements of modified bitumens as well as in
24 comparative and arbitration analysis whenever there is a suspicion that the amount of modifier
25 added to bitumen was lowered by the manufacturer or when there is a suspicion that the
26 delivered material does not meet the specifications concerning the modifier content. Moreover,
27 the procedure described here is also applicable to the assessment of aging of road asphalts and
28 their degradation during usage.
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3 As was the case of ATR infrared spectroscopy measurements, sample 1 again displayed a
4 lowered content of modifier when assayed by GPC/SEC. A comparison of the results obtained
5 by FTIR and GPC/SEC shown in Tables 2 and 4 reveals that the differences between the two
6 procedures for the average modifier content in each of the investigated bitumens are within the
7 repeatability of the FTIR method. Consequently, the developed GPC/SEC procedure is a viable
8 alternative to FTIR while offering an improved precision of the determinations as indicated by
9 substantially lower relative standard deviation values.
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20 **3.3 Thin layer chromatography coupled with flame ionization detection (TLC-FID)**

21 Table 5 summarizes the differences in group composition content resulting from the presence
22 of the modifier. For unmodified bitumen 35/50, it can be noticed that the most abundant group
23 are aromatic compounds (49.99%), followed by resins (21.58 %) and saturated compounds
24 (21.27 %). In contrast, modified bitumen 25/55-60 shows significant differences in the group
25 composition, caused by the presence of the modifier.
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35 The TLC-FID technique is not useful for the determination of asphalt modifiers; however, it
36 allows determining the group composition of bitumens. Comparing the results of each fraction
37 content for both types of bitumen one can observe a decrease in aromatic compounds content and
38 an increase in resin content in a modified bitumen sample (Table 5). These changes result from
39 the polymer presence, because SBS – due to the presence of aromatic rings in polystyrene and
40 the double bonds in polybutadiene – has a greater affinity to aromatic and resin fractions.
41 Differences in group-type composition after bitumen modification may result from the
42 conversion of bitumen constituents. SBS probably binds aromatic molecules in a molecular
43 network, causing an increase in their weight and, therefore, shifting them to the resin fraction
44 region.
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3 The polymer applied at a high concentration on the chromatods was not separated and
4 remained at the start along with some part of the asphaltene fraction. Another attempt with a
5 lower concentration of a polymer sample showed the presence of the signal which had the
6 highest intensity in the range of aromatic fractions. At a high concentration (greater than 30 mg
7 ml⁻¹) of the polymer there is a problem of polymer solubility. The mobile phase used for
8 chromatogram development is a mixture of dichloromethane-methanol 95/5 (v/v) and the
9 polymer is insoluble in methanol. Consequently, the presence of methanol causes SBS stoppage
10 at the start. This limitation is only theoretical due to a relatively low concentration of the
11 modifier in commercial bitumens.
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24 **4. Conclusions**

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26 The concept of using infrared spectroscopy for determining the content of polymer modifiers
27 in road bitumens is valid, as supported by the published literature. Such polymer modifiers as
28 styrene-butadiene-rubber (SBR), styrene-butadiene-styrene (SBS) and styrene-butadiene (SB)
29 are characterized by the specific band regions at 965cm⁻¹ and 697 cm⁻¹. The SBS band at 965
30 cm⁻¹ is split in contrast with the SB modifier. A positive identification of individual polymers in
31 the analyzed samples of paving bitumens was not possible due to low analyte content and the
32 significantly blurred bands.
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43 The studies revealed that infrared spectroscopy should be appended with the size exclusion
44 chromatography, as the latter results in repeatable measurements with smaller errors.
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48 The developed procedure for the determination of polymer modifiers in paving bitumens by
49 size exclusion chromatography requires the use of four columns connected in series, i.e. two PS1
50 columns and two PS Mix columns packed with a styrene-divinylbenzene copolymer, and
51 tetrahydrofuran as the eluent. This procedure allows the separation of modifiers from other
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3 bitumen components, as well as the determination of modifier content. However, size exclusion
4 chromatography does not allow simultaneous identification of SBS and SB modifiers present in
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6 the same sample because the difference between the molecular weights of these polymers is too
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8 small.
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12 In addition, the studies carried out using thin layer chromatography coupled with flame
13 ionization detection have demonstrated that this technique is useful for determining the
14 composition of modified bitumens. Modified bitumens contain more so-called resins and less
15 aromatic compounds than unmodified bitumens. This is due to structural changes in aromatic
16 hydrocarbons interacting with polymer molecules. The TLC-FID technique does not allow the
17 determination of the modifier content in bitumen samples because the modifier is eluted in the
18 range of aromatic compounds and resins. Furthermore, the application of the procedure described
19 in Polish standard PN EN 129161 (2008) using NP-HPLC also did not allow the measurement of
20 the polymer content. In this case, the failure was caused by poor solubility of polymer modifiers
21 in the eluent used. The developed procedures also allow determining the modifier content in road
22 bitumens already used for road paving, as well as the rate of degradation of the modifier during
23 its use.
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41 This paper describes the methodological basis for the determination of modifiers content in
42 bitumen samples collected from the roads. It is the first work allowing to perform such
43 determination using gel permeation/size exclusion chromatography (GPC/SEC). The developed
44 methodology will be used for monitoring the changes of modifier concentration in bitumens
45 during road pavement aging, as well as, for comparative studies of modified bitumen supplied by
46 different manufacturers. The results of this research will be the subject of subsequent papers.
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58
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References

AASHTO T302-05. (2007). Standard Method of Test for Polymer Content of Polymer-Modified Emulsified Asphalt Residue and Asphalt Binders.

Airey, G.D. (2004). Styrene butadiene styrene polymer modification of road bitumens. *Journal of Materials Science*, 39, 951–959.

Błażejowski, K. & Styk, S. (2004). *Technologia warstw asfaltowych* [Technology of asphalts]. Warszawa: Wydawnictwo Komunikacji i Łączności (in Polish).

Boczka, G., Jaszczolt, M., Przyjazny, A. & Kamiński, M. (2013). Application of normal phase high performance liquid chromatography followed by gas chromatography for analytics of diesel fuel additives, *Analytical and Bioanalytical Chemistry*, 405, 6095–103.

Diefenderfer, S. (2006). Detection of Polymer Modifiers in Asphalt Binder. Final report no. FHWA/VTRC 06-R18, Virginia Transportation Research Council in Cooperation with the U.S. Department of Transportation, available at: http://www.virginiadot.org/vtrc/main/online_reports/pdf/06-r18.pdf

Doh, Y. S., Amirkhanian, S. N. & Kim, K. W. (2008). Analysis of unbalanced binder oxidation level in recycled asphalt mixture using GPC. *Construction and Building Materials*, 22(6), 1253–1260.

Ecker, A. (2001). The application of IATROSCAN-technique for analysis of bitumen. *Petroleum and Coal*, 43(1), 51–53.

Fernandes, M.R.S., Forte, M.M.C. & Leite, L.F.M. (2008). Rheological Evaluation of Polymer-Modified Asphalt Binders. *Materials Research*, 11(3), 381–386.

1
2
3 Gilgenast, E., Boczkaj, G., Przyjazny, A. & Kamiński M. (2011). Sample preparation
4
5 procedure for the determination of polycyclic aromatic hydrocarbons in petroleum
6
7 vacuum residue and bitumen, *Analytical and Bioanalytical Chemistry*, 401, 1059-69.
8
9

10 Gudebska, J. (1999). *Chromatografia cieczowa w oznaczaniu składu grupowego olejów*
11
12 *bazowych i asfaltów drogowych* [Base oil and road bitumens group-type composition
13
14 studies by means of liquid chromatography]. PhD thesis, Gdańsk University of
15
16 Technology, Gdańsk (in Polish).
17
18
19

20 Izquierdo, M.A., Navarro, F.J., Martínez-Boza, F.J. & Gallegos, C. (2012). Bituminous
21
22 polyurethane foams for building applications: Influence of bitumen hardness.
23
24 *Construction and Building Materials*, 30, 706–713.
25
26

27 Kamiński, M., Gudebska, J., Górecki, T. & Kartanowicz, R. (2003). Optimized conditions for
28
29 hydrocarbon group type analysis of base oils by thin-layer chromatography–flame
30
31 ionisation detection. *Journal of Chromatography A*, 991, 255–266.
32
33
34

35 Kim, K.W., Kim, K., Doh, Y.S. & Amirkhanian, S.N. (2006). Estimation of RAP's binder
36
37 viscosity using GPC without binder recovery. *Journal of Materials in Civil Engineering*,
38
39 *18(4)*, abstract.
40
41

42 Lamontagne, J., Dumas, P., Mouillet, V. & Kister, J. (2001). Comparison by Fourier
43
44 transform infrared (FTIR) spectroscopy of different ageing techniques: application to
45
46 road bitumens. *Fuel*, 80, 483–8.
47
48

49 Loeber, L., Muller, G., Morel, J. & Sutton, O. (1998). Bitumen in colloid science: a chemical,
50
51 structural and rheological approach. *Fuel*, 77, 1443–50.
52
53

54 Lu, X. & Isacson, U. (1998). Chemical and rheological evaluation of ageing properties of
55
56 SBS polymer modified bitumens. *Fuel*, 77, 961–72.
57
58
59
60

- 1
2
3 Masson, J-F., Price, T. & Collins, P. (2001). Dynamics of Bitumen Fractions by Thin-Layer
4
5 Chromatography/Flame Ionization Detection. *Energy & Fuels*, 15, 955–960.
6
7
- 8 Nivitha, M.R., Prasad, E. & Krishnan, J.M. (2015). Ageing in modified bitumen using FTIR
9
10 spectroscopy. *International Journal of Pavement Engineering*, first page preview,
11
12 <http://dx.doi.org/10.1080/10298436.2015.1007230>
13
14
- 15 Ouyang, Ch., Wang, S., Zhang, Yong & Zhang, Yinxi (2006). Improving the aging resistance
16
17 of styrenebutadieneestyrene tri-block copolymer modified asphalt by addition of
18
19 antioxidants. *Polymer Degradation and Stability*, 91, 795–804.
20
21
22
- 23 Paliukaitė, M., Vaitkus A. & Zofka, A. (2014). Evaluation of bitumen fractional composition
24
25 depending on the crude oil type and production technology. *The 9th International*
26
27 *Conference Environmental Engineering. Selected Papers, Article number:*
28
29 *enviro.2014.162.*
30
31
- 32 Peramanu, S. & Pruden, B.B. (1999). *Industrial & Engineering Chemistry Research*, 38,
33
34 3121–3122.
35
36
- 37 Piłat, J. & Radziszewski, P. (2007). *Nawierzchnie asfaltowe* [Asphalt surfaces]. Warszawa:
38
39 Wydawnictwo Komunikacji i Łączności (in Polish).
40
41
42
- 43 PN-EN 12916. (2008). *Przetwory naftowe. Oznaczanie grup węglowodorów aromatycznych w*
44
45 *średnich destylatach. Metoda wysokosprawnej chromatografii cieczowej z detektorem*
46
47 *współczynnika załamania światła* [Petroleum products. Determination of aromatic
48
49 hydrocarbon types in middle distillates. High performance liquid chromatography method
50
51 with refractive index detection] (in Polish).
52
53
54
55
56
57
58
59
60

1
2
3 PN-EN 14023. (2009). *Asfalty i lepiszcza asfaltowe, Zasady klasyfikacji asfaltów*
4
5 *modyfikowanych polimerami* [Bitumen and bituminous binders. Specification Framework
6
7 for polimer modified bitumens] (in Polish).
8
9

10 Polacco, G., Biondi, D., Stastna, J., Vlachovicova Z. & Zanzotto, L. (2004). Effect of SBS on
11
12 Rheological Properties of Different Base Asphalts. *Macromolecular Symposia*, 218, 333–
13
14 342.
15
16

17 Ramalinga Chandra Sekar, A., Mahendran, M., Vasudevan, R. & Velkennedy, R. (2015).
18
19 Polymer modified bitumen prepared using abs polymer characterization and application in
20
21 flexible pavement. *ARPJ Journal of Engineering and Applied Sciences*, 10(8), 1819–
22
23 6608.
24
25
26

27 Roberts F.L. et al. (1996). *Hot Mix Asphalt Materials, Mixture Design and Construction*,
28
29 second ed., National Center for Asphalt Technology (NCAT).
30
31

32 Ruan, Y., Davison, R.R. & Glover, C.J. (2003). The effect of long-term oxidation on the
33
34 rheological properties of polymer modified asphalts, *Fuel*, 82, 1763–73.
35
36
37

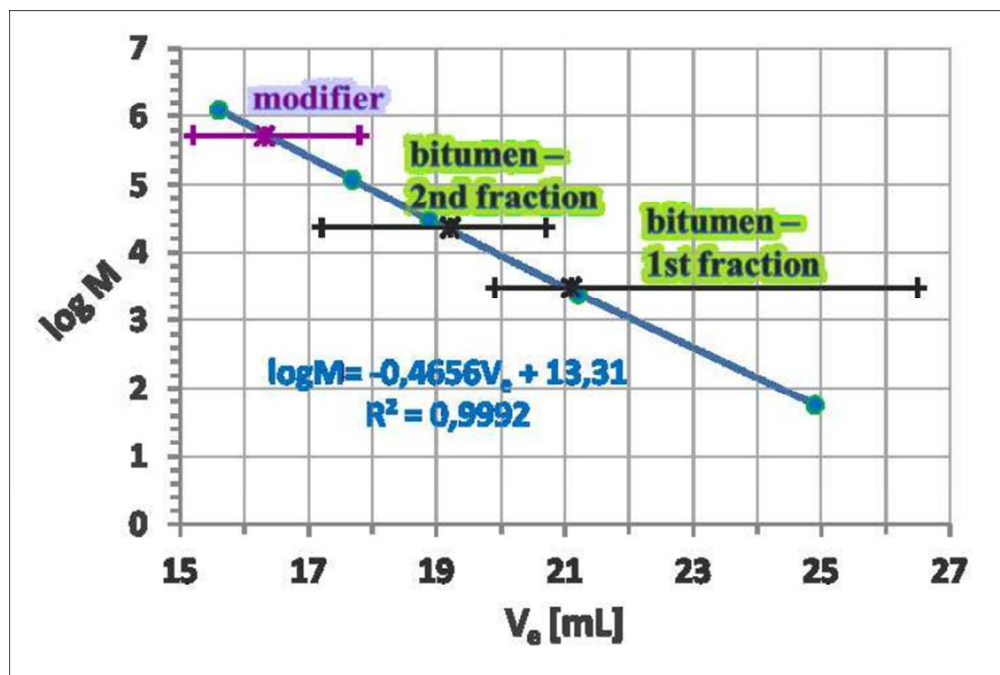
38 Wang, L., Razaqpur, G., Xing Y. & Chen G. (2015). Microstructure and rheological
39
40 properties of aged and unaged polymer-modified asphalt binders. *Road Materials and*
41
42 *Pavement Design*, 16(3), 592–607.
43
44

45 Wu, G., Zeng, S., Ou, E., Yu, P., Lu, Y. & Xu, W. (2010). Photoinitiator grafted styrene–
46
47 butadiene–styrene triblock copolymer. *Materials Science & Engineering C*, 30, 1030–
48
49 1037.
50
51

52 Yut, I. & Zofka, A. (2011). Attenuated total reflection (ATR) Fourier transform infrared (FT-
53
54 IR) spectroscopy of oxidized polymer-modified bitumens. *Applied Spectroscopy* 65:7,
55
56 abstract. doi: 10.1366/10-06217.
57
58
59
60

1
2
3 Zhang, J., Wang, J., Wu, Y., Sun, W. & Wang, Y. (2009). Thermal Behaviour and Improved
4
5 Properties of SBR and SBR/Natural Bitumen Modified Bitumens. *Iranian Polymer*
6
7 *Journal*, 18(6), 465-478.
8
9

10 Zhang, H., Jia, X., Yu, J. & Xue L. (2013). Effect of expanded vermiculite on microstructures
11
12 and aging properties of styrene-butadiene-styrene copolymer modified bitumen.
13
14 *Construction and Building Materials*, 40, 224-230.
15
16
17
18
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21
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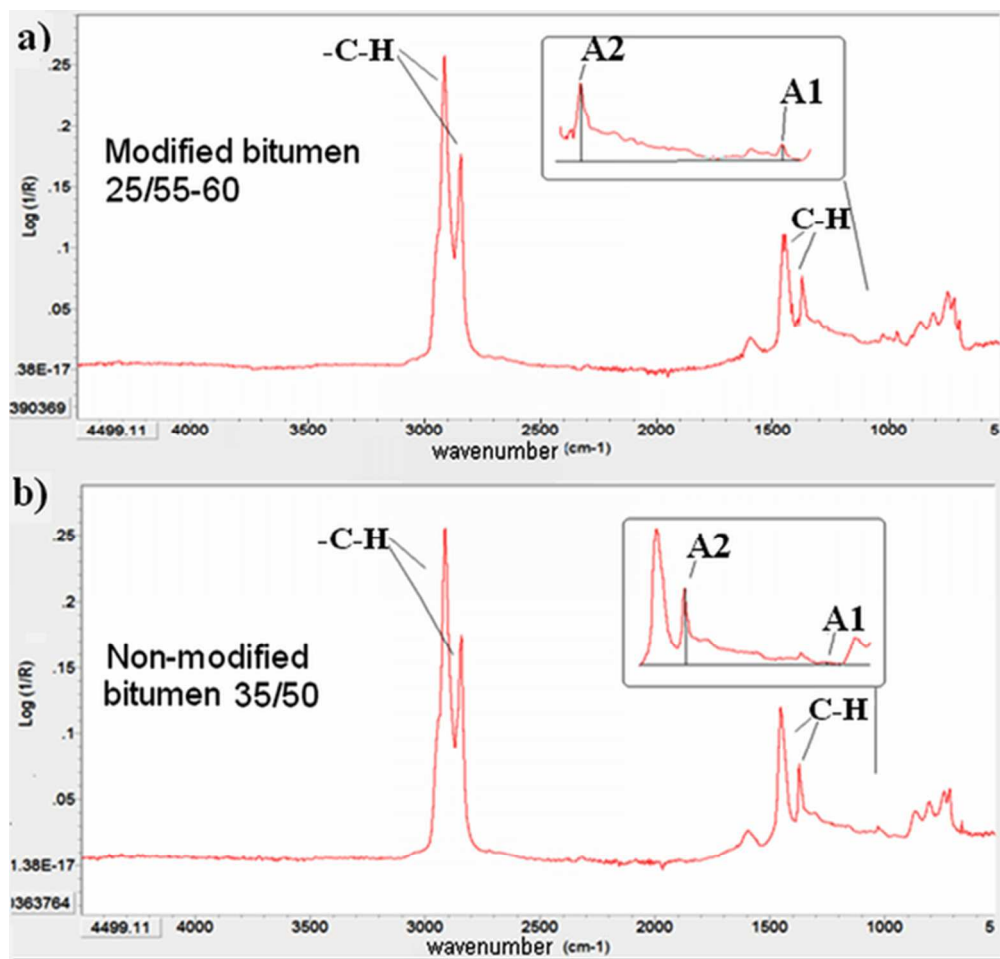


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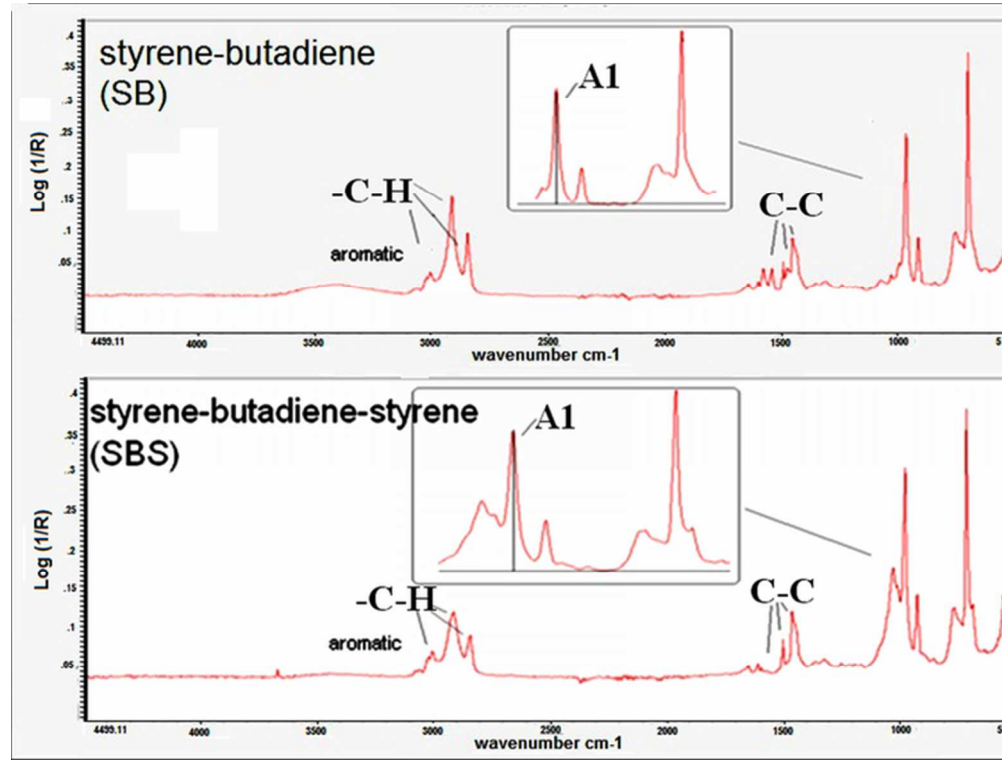
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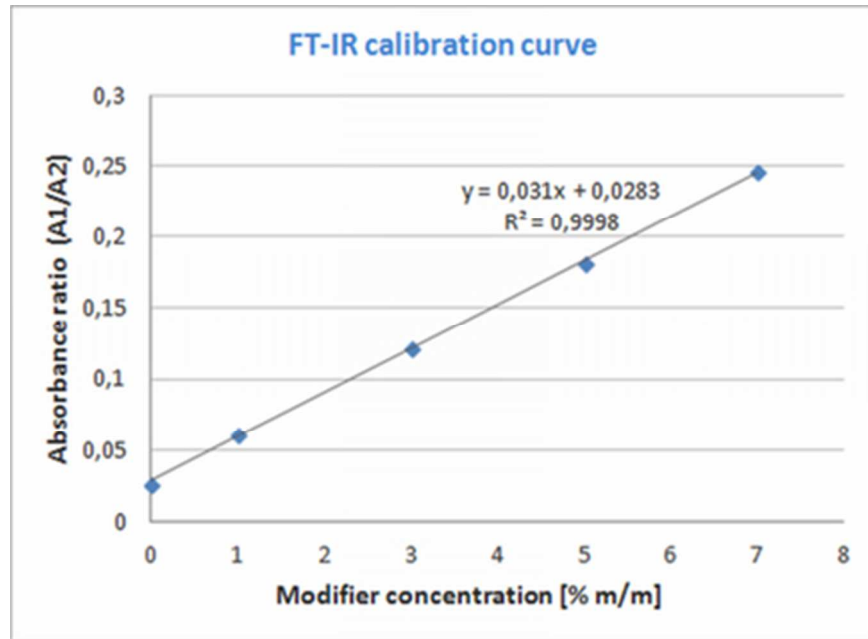
Map of Gdansk with sampling sites of modified and unmodified bitumens marked.
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ATR IR spectra with a resolution of 4 cm⁻¹ in the range 4000–500 cm⁻¹ of: a) modified bitumen 25/55-60
b) unmodified bitumen 35/50.
27x26mm (600 x 600 DPI)



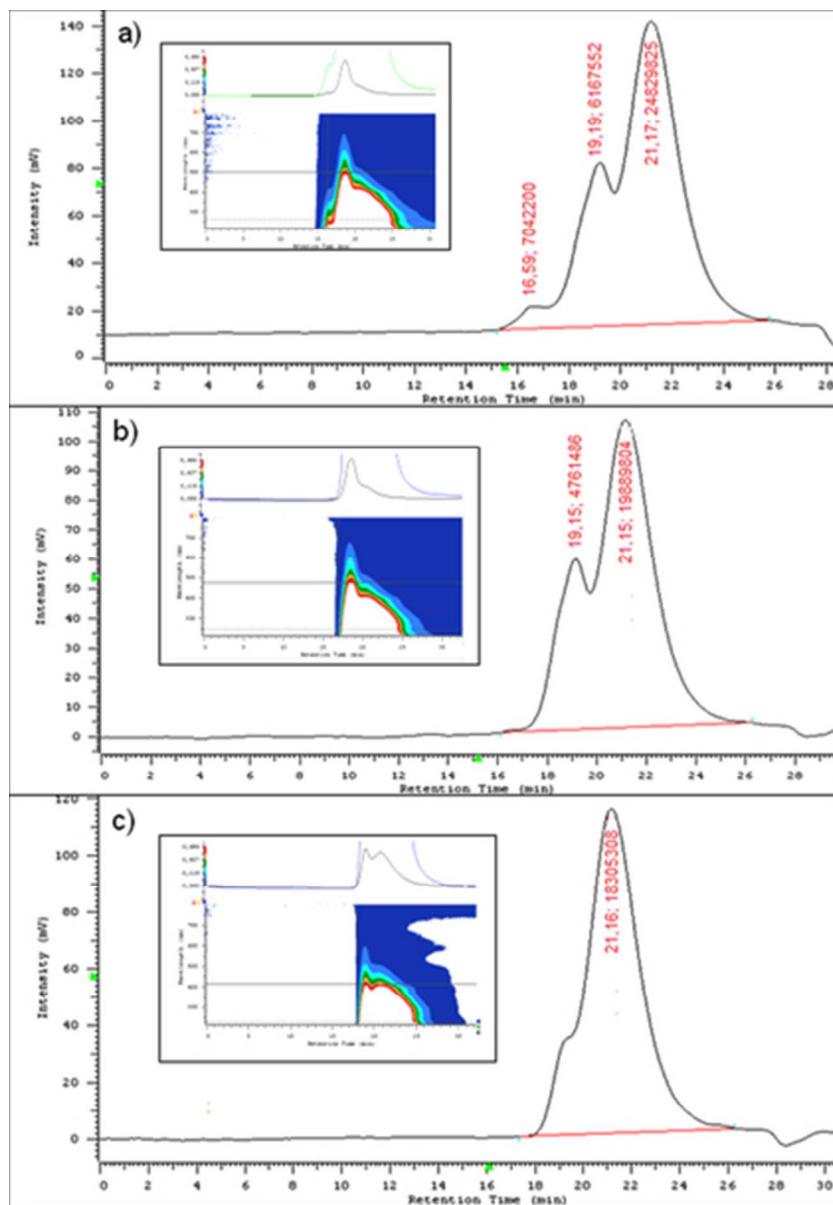
ATR IR spectra with a resolution of 4 cm^{-1} in the range 4000–500 cm^{-1} of SB and SBS modifiers.
30x23mm (600 x 600 DPI)



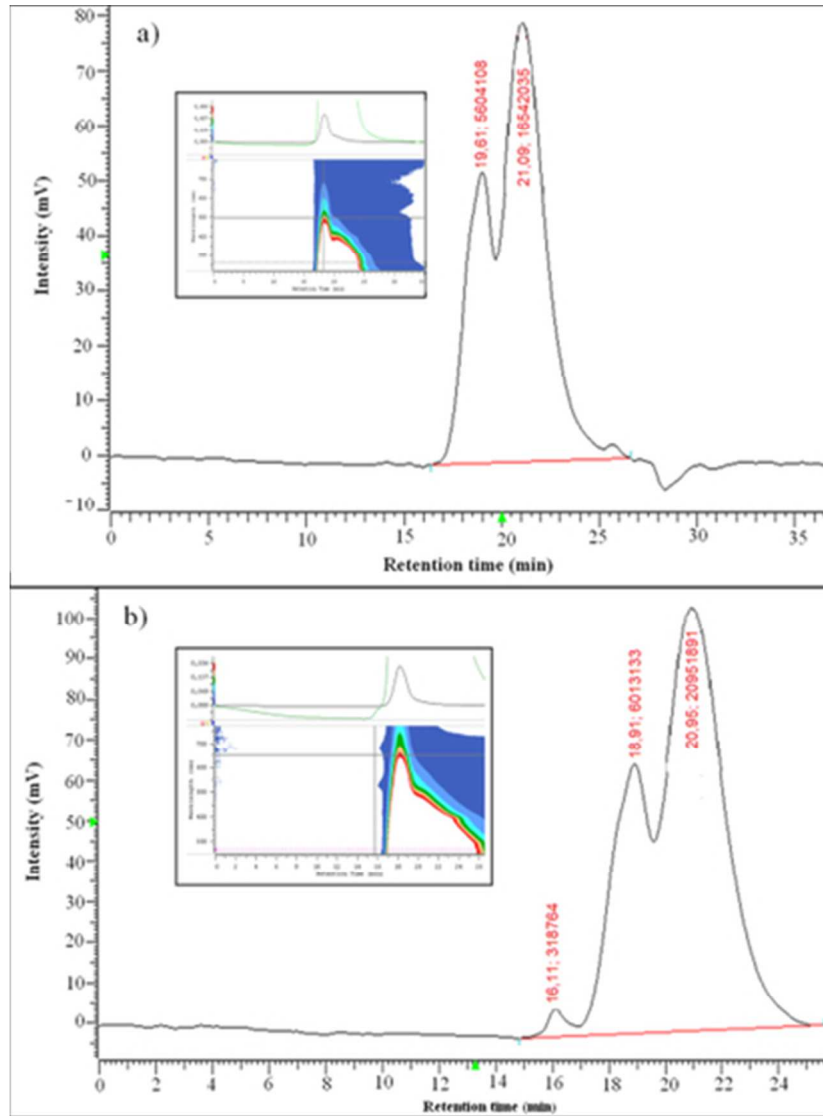
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Calibration curve for FT-IR. Variable x stands for modifier concentration (in % m/m), variable y – for absorbance ratio.

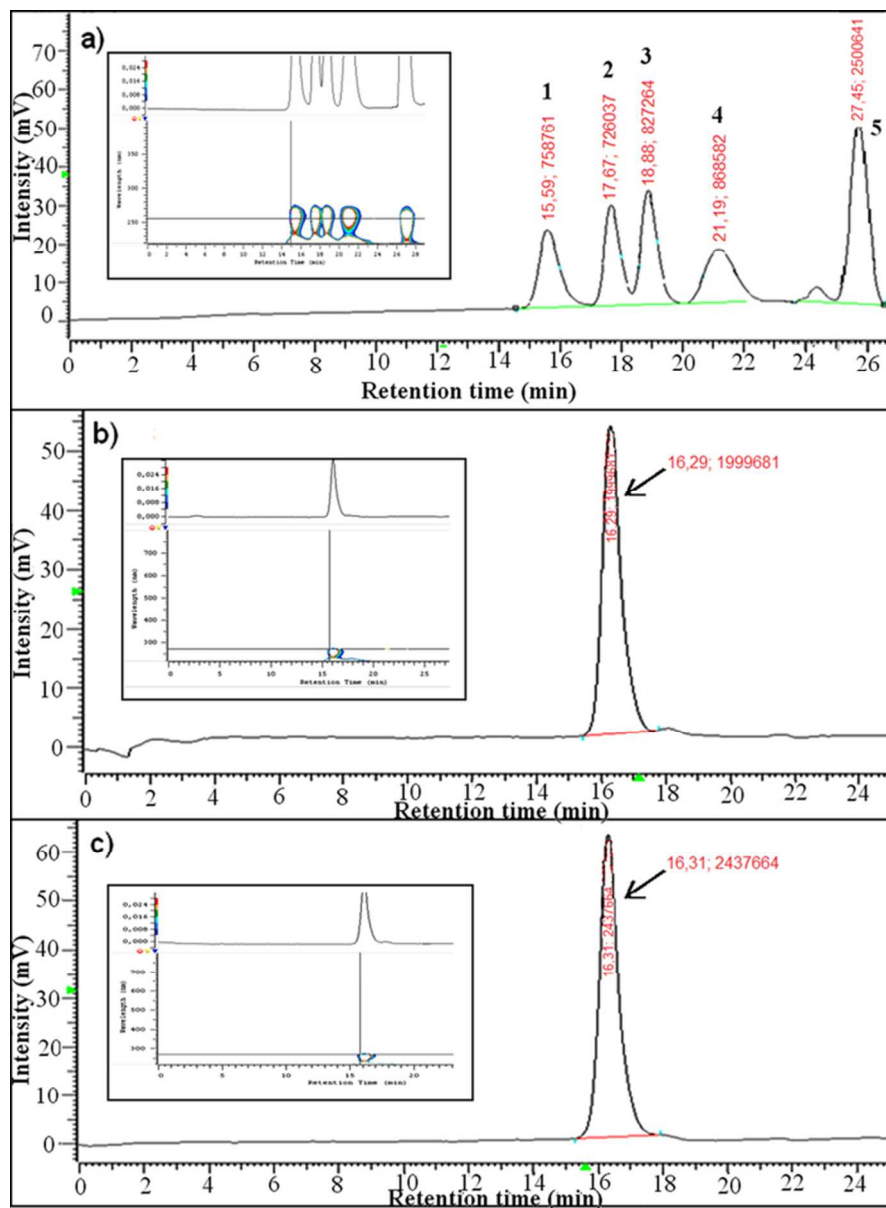
18x13mm (600 x 600 DPI)



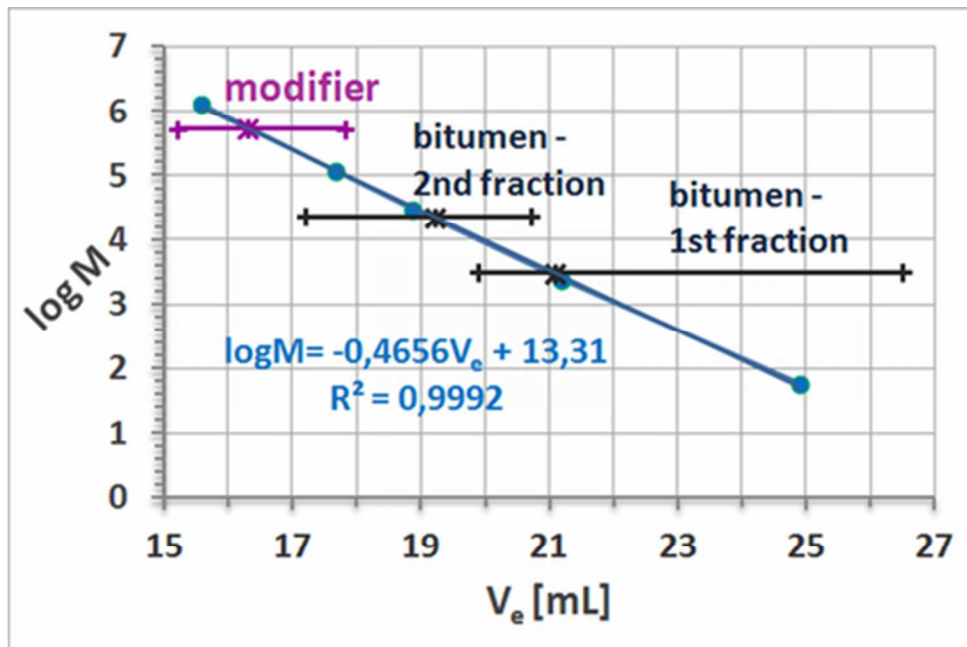
GPC/SEC chromatograms of bitumens. Columns: 2xPS1+2xPS MIX, eluent: tetrahydrofuran 1mL min⁻¹, injection volume 20 μ L, temperature 20 $^{\circ}$ C, a - modified bitumen 25/55-60 (50 mg mL⁻¹); b - unmodified bitumen 35/50 (50 mg mL⁻¹); c - unmodified bitumen 160/220 (50 mg mL⁻¹).
19x25mm (600 x 600 DPI)



GPC/SEC chromatograms of bitumens. Columns 2xPS1+2xPS MIX, eluent: tetrahydrofuran 1mL min⁻¹, injection volume 20 μ L, temperature 20 $^{\circ}$ C, a - unmodified bitumen from Kampinoska Street from year 2008 (50 mg mL⁻¹); b - modified bitumen from Cienista Street from year 2008 (50 mg mL⁻¹). 17x23mm (600 x 600 DPI)

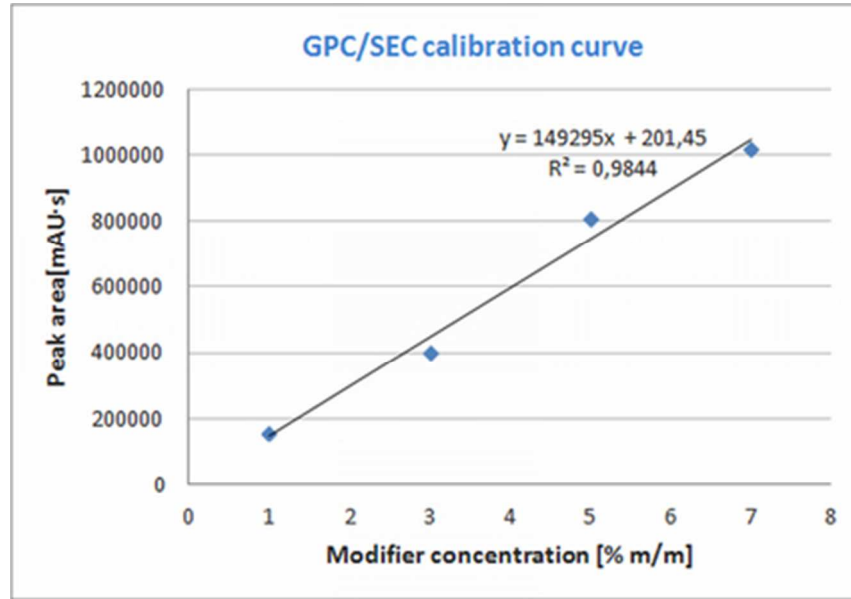


GPC/SEC chromatograms of polystyrenes and analyzed modifiers. Columns: 2xPS1+2xPS MIX, eluent: tetrahydrofuran 1mL min⁻¹, injection volume 20 μ L, temperature 20 OC; a-mixture of standards (where 1-4 are polystyrenes of masses: 1-1,260,000, 2-120,000, 3-30,300, 4-2,450, 5-acetone, 6-benzene) (5mg mL⁻¹); b-SBS (5 mg mL⁻¹); c-SB (5.3 mg mL⁻¹).
29x40mm (600 x 600 DPI)



GPC/SEC calibration curve ($\log M = f(V_e)$; blue) for polystyrenes of masses: 1,260,000, 120,000, 30,300, 2,450 and acetone. The relevant ranges of V_e values obtained for bitumen (black, 1st and 2nd fraction, where the 1st one refers to fraction of lower molecular mass, and 2nd - to higher molecular mass; explained in text), as well as for bitumen modifier (purple) are depicted in the graph.

20x13mm (600 x 600 DPI)



27 Calibration curve for GPC/SEC. Variable x stands for modifier concentration [% m/m], variable y – for peak
28 area [mAU·s].
29 18x12mm (600 x 600 DPI)

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4 **Figure captions**
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10 **Figure 1.** Map of Gdansk with sampling sites of modified and unmodified bitumens marked.
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17 bitumen 25/55-60 b) unmodified bitumen 35/50.
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43 25/55-60 (50 mg mL^{-1}); b – unmodified bitumen 35/50 (50 mg mL^{-1}); c – unmodified bitumen
44 160/220 (50 mg mL^{-1}).
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55 **Figure 6.** GPC/SEC chromatograms of bitumens. Columns 2xPS1+2xPS MIX, eluent:
56 tetrahydrofuran 1 mL min^{-1} , injection volume $20\text{ }\mu\text{L}$, temperature $20\text{ }^{\circ}\text{C}$, a – unmodified bitumen
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3 from Kampinoska Street from year 2008 (50 mg mL^{-1}); b – modified bitumen from Cienista
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5 Street from year 2008 (50 mg mL^{-1}).
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13 2xPS1+2xPS MIX, eluent: tetrahydrofuran 1 mL min^{-1} , injection volume $20 \mu\text{L}$, temperature 20
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15 $^{\circ}\text{C}$; a–mixture of standards (where 1–4 are polystyrenes of masses: 1–1,260,000, 2–120,000, 3–
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17 30,300, 4–2,450, 5–acetone, 6–benzene) (5 mg mL^{-1}); b–SBS (5 mg mL^{-1}); c–SB (5.3 mg mL^{-1}).
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25 **Figure 8.** GPC/SEC calibration curve ($\log M = f(V_e)$; blue) for polystyrenes
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27 of masses: 1,260,000, 120,000, 30,300, 2,450 and acetone. The relevant ranges of V_e values
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29 obtained for bitumen (black, 1st and 2nd fraction, where the 1st one refers to fraction of lower
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33 modifier (purple) are depicted in the graph.
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41 **Figure 9.** Calibration curve for GPC/SEC. Variable x stands for modifier concentration [%
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43 m/m], variable y – for peak area [mAU·s].
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List of tables

Table 1. Actual data used for calibration curve preparation in case of FT-IR.

modifier concentration [% m/m]	0,0	1,0	3,0	5,0	7,0
absorbance ratio (A1/A2)*	0.027	0.061	0.122	0.182	0.246

* where A1 is characteristic absorbance for polymer modifier (965cm^{-1}), and A2 is characteristic absorbance for bitumen (1375cm^{-1})

Table 2. Concentration of modifiers in bitumens and statistical parameters for FT-IR technique.

Parameters	modified bitumen 25/55-60	modified bitumen 45/80-55	1 (2008)	2 (2007)	3 (2006)
Modifier concentration [%m/m]	4.52	3.51	2.24	3.32	3.36
Standard deviation	0.25	0.25	0.13	0.80	0.57
Relative standard deviation	0.05	0.07	0.06	0.24	0.17

Table 3. Actual data used for calibration curve preparation in case of GPC/SEC.

modifier concentration [% m/m]	1,0	3,0	5,0	7,0
peak area [mAU·s]*	158199	402767	811214	1017353

* the peak area are averages for triplicate analysis

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Table 4. Concentration of modifiers in bitumens and statistical parameters for GPC/SEC technique.

Parameters	modified bitumen 25/55-60	modified bitumen 45/80-55	1 (2008)	2 (2007)	3 (2006)
Modifier concentration [%m/m]	4.41	3.16	2.11	3.28	3.57
Standard deviation	0.24	0.13	0.06	0.24	0.06
Relative standard deviation	0.05	0.04	0.03	0.07	0.01

Table 5. Group composition of unmodified and modified bitumens.

Bitumen	Saturated compounds [%]	Aromatic compounds [%]	Resins [%]	Asphaltenes [%]
Unmodified bitumen 35/50	21.27	49.99	21.58	7.16
Modified bitumen 25/55-60	16.22	36.15	38.97	8.67