Analysis of the Behavior of Low-Noise Asphalt Mixtures with Modified Binders under Sinusoidal Loading

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Abstract: The paper presents the results of tests of the stiffness modulus according to the 4PB-PR method of low-noise asphalt mixtures with the addition of rubber granulate (RG). Mixtures of this type are characterized by an increased air void content (about 10–25%). This causes a rapid bitumen oxidation, which results in oxidative hardening, contributing to a faster deterioration of the properties of the mixtures. This means that binders of appropriate quality should be used in the process of producing asphalt mixtures, which will provide the mixtures with sufficiently high technical properties. The tested asphalt mixtures are differentiated according to the type of bitumen modifiers: styrene–butadiene–styrene copolymer (SBS) and crumb rubber (CR). The article presents the tests results of the stiffness modulus using the 4PB-PR method. This test has a high correlation with regard to “in situ” tests. The research proved that each of the modifiers used increased the stiffness modulus of low-noise asphalt mixtures. Replacing the mineral aggregate with 30% RG leads to a tenfold decrease in the stiffness modulus. In the entire range of analyzed temperatures, mixtures with the use of modifiers show higher values of the elastic component of the stiffness modulus, as evidenced by lower values of the phase angle.

Keywords: low-noise pavement; stiffness modules; rubber granulate; modified bitumen; crumb rubber

1. Introduction

The 20th century was characterized by the rapid development of road traffic [1]. During this period, road pavements built in Poland, due to the type of structure and the materials used, did not fully reduce the noise that was increasing all the time. This phenomenon attracted the attention of many researchers and contributed to the creation of low-noise asphalt pavements. Such pavements include, among others: BBTM (French for Beton Bitumineux Tres Mince), SDA (Semi-Dense Asphalt), PA (Porous Asphalt), noise reduced stone mastic asphalt SMA LA (German for Lärm Arm), PERS (Poroelastic Road Surface) [2]. Research has shown that the use of such mixtures for the wearing course of road pavements allows the reduction of noise to 10–12 dB [3,4]. Asphalt mixtures from this group are characterized by air void content in the range of 15–25%. Many studies [5,6] have shown that higher air void content contributes to the formation of carbonyl groups in the binder, resulting in oxidative hardening, which causes faster pavement degradation. Therefore, to produce “quiet” mixtures, it is required to properly select bitumen binders with high technical parameters, particularly with the increased resistance to long-term (in-service) aging [7].

The quality of the raw material used in the distillation process of the crude oil has a huge impact on the properties of road bitumen, which was used in the production of asphalt mixture. Unfortunately, in recent years there has been a trend to refine light crude oil (increasing fuel profit), which has reduced the distillation residue from 20% to 10% or less. For this reason, the quality of industrially produced bitumen does not meet the requirements for use in “quiet” pavements, which has been confirmed by investigations...
carried out by many scientific centers [8–10]. Therefore, in order to improve the performance properties of neat binders, various types of modifiers are often used. This group includes: chemical modifiers, polymers, hydrocarbons, nanomaterials, fillers, and oxidants. The best-known types of the modifiers from these groups are: styrene–butadiene–styrene copolymer (SBS), crumb rubber (CR) derived from scrap tires, or the more and more often used composite of these two-SBS/CR modifiers [11–13].

CR obtained from scrap tires was first used in the 1960s by engineer Charles McDonald. It is a well-known additive to bitumen binders. The process of bitumen modification with CR is a complex process and depends on many factors, such as mixing time and temperature, number of rotations during mixing, method of grinding rubber and its particle size, method of adding, chemical composition of binder, and rubber [14,15]. In the modification process at the temperature of 180 °C, the rubber partially undergoes devulcanization and swelling, which are caused by the absorption of light aromatic structures contained in the binder [16]. According to the analyses described in [17–20], rubber-asphalt binder improves properties of asphalt mixtures, such as rutting resistance, freezing-thawing resistance, aging resistance, low temperature cracking, and fatigue resistance.

SBS copolymer is the most commonly used modifier for bitumen binders. It began to be used on a large scale as bitumen modifier in the 1970s of the 20th century [21]. SBS copolymer, when added to bitumen, changes its chemical properties: an interaction begins between the bitumen and the polystyrene and polybutadiene blocks. Interactions between polybutadiene blocks are carried out by π-electrons of positively charged groups of bitumen, and they are much stronger than interactions between polystyrene blocks, which interact with electron-rich groups through aromatic protons [22]. The effect of this interaction is hardening of bitumen binder, thanks to which it is possible to lower the breaking point, decrease the rate of penetration, extend the viscoelastic range, improve fatigue life and rutting resistance, reduce the temperature sensitivity, and increase the stiffness of asphalt mixtures [23–26].

Recently, composites have been increasingly used in place of single bitumen additive. One of them is the polymer-rubber-asphalt binder SBS/CR. Due to the simultaneous modification, such a composite is able to eliminate the disadvantages and strengthen the advantages characteristic of a single modifier, e.g., only SBS or only CR [27]. In the case of the SBS/CR composite, the storage stability of binder in the high temperature range, its aging resistance and low temperature cracking resistance were improved [28,29].

It is necessary in the design process to properly select the technical parameters of asphalt mixtures in order to construct durable, safe, and characterized-by-low-maintenance-costs road pavements [30]. One of the most important characteristics of asphalt mixtures is the stiffness modulus. It mainly determines the structural durability of road pavements. It allows one to predict the “behavior” of asphalt mixtures in road surface construction under the traffic, particularly at the place of tire/pavement contact [31,32]. The stiffness modulus of asphalt mixtures is a key parameter used in the design process of the fatigue life of road pavements (low temperature cracking and rutting resistance) in terms of mechanical and empirical analyses. Low values of the stiffness modulus at low test frequencies testify to poor pavement resistance to permanent deformation, while its high values at higher frequencies negatively affect the low-temperature performance at winter conditions [33]. The higher values of the stiffness modulus make it possible to reduce the tensile stresses that arise at the bottom of the asphalt layer (the criterion of cracking of asphalt layers) and to reduce the compressive stresses on the upper asphalt layer [34]. It is known that the tensile stresses at the bottom of the layer are almost twice as high as the compressive stresses at the top of the layer [35]. There are several methods for determining the value of the stiffness modulus of asphalt mixture, e.g., indirect tensile modulus test (IDT), uniaxial compressive test (UC) or four point bending with prismatic samples (4PB-PR). The research on the stiffness modulus of asphalt mixtures proved that the 4PB-PR method allows one to simulate the loading conditions of mixtures similar to the real pavement working conditions [36].
However, the influence of rubber granulate (RG) on changes in stiffness modulus by the 4PB-PR method of “quiet” mixtures has not yet been investigated, which is an important aspect in the design of this type of pavement.

The aim of the research presented in this paper is to analyze the effect of the type of modification of bitumen binders with SBS polymer and CR and the addition of RG (1/4 mm fraction) on the change of technical parameters (stiffness modulus and phase angle) in the four-point bending study with prismatic samples 4PB-PR of low-noise asphalt mixtures.

Chapter 2 presents the characteristics and properties of the materials used for the designed asphalt mixtures (PA8, SMA8 and SMA8 LA) and mineral-rubber-asphalt mixtures SMA8 LA (10% RG), SMA8 LA (20% RG), SMA8 LA (30% RG). The grain size distribution (percentage of material passing through the sieve), binder content, air void content, and density of mixtures are given. The basics and principles of determining the stiffness modulus and phase angle according to the four-point bending with prismatic samples (4PB-PR) are also discussed.

Chapter 3 presents and discusses the results of tests of stiffness modulus 4PB-PR for conventional asphalt mixtures and results of tests of stiffness modulus for asphalt mixtures with the addition of RG, change of the phase angle $\Phi$ at variable temperature and frequency for conventional asphalt mixtures and change of the phase angle $\Phi$ at variable temperature and frequency for asphalt mixtures with the addition of RG. A discussion of the results in comparison with the findings of other researchers presented in the literature is also provided.

### 2. Materials and Methods

#### 2.1. Bitumen Binders

Four types of bitumen binders were used for the tests:
- Bitumen 50/70 (reference);
- Bitumen 50/70 modified with copolymer SBS (5%) (SBSM-5);
- Bitumen 50/70 modified with CR (10%) (CRM-10);
- Bitumen 50/70 modified with a combination of copolymer SBS (2%) and CR (10%) (SBSM-2 + CRM-10).

The technical properties of the modified binders before and after the RTFOT (rolling thin film oven test) technological aging process are presented in Table 1. Detailed test results of bitumen binders and aggregates used for asphalt mixtures are described in publications [37,38].

**Table 1. Technical properties of modified binders.**

| Indexes          | Units of Measurement | 50/70  | SBSM-5 | CRM-10 | SBSM-2 + CRM-10 |
|------------------|----------------------|--------|--------|--------|-----------------|
| Penetration:     |                      |        |        |        |                 |
| $5\,^\circ C$    | 0.1 mm               | 11.4/8.4 | 8.7/6.1 | 8.7/6.8 | 7.7/5.6         |
| $15\,^\circ C$   |                      | 32.8/20.3 | 20.6/16.2 | 19.5/14.1 | 16.2/13.1       |
| $25\,^\circ C$   |                      | 58.3/44.3 | 40.2/30.1 | 40.0/27.8 | 30.6/24.8       |
| Softening Point  | $^\circ C$           | 50.8/56.3 | 78.6/77.8 | 60.6/68.2 | 70.7/77.8       |
| Fraass Breaking Point | $^\circ C$    | $-14.7/-12.9$ | $-19.3/-17.3$ | $-16.1/-15.5$ | $-17.9/-16.5$   |
| Dynamic Viscosity|                     |        |        |        |                 |
| $90\,^\circ C$   | Pa·s                 | 11.3/19.3 | 224.4/258.7 | 83.6/265.4 | 292.2/574.1     |
| $110\,^\circ C$  |                      | 2.2/3.6 | 25.1/27.7 | 13.4/39.3 | 43.7/74.9       |
| $135\,^\circ C$  |                      | 0.5/0.7 | 2.5/3.6 | 2.1/4.8 | 5.4/8.8         |
2.2. Used Additives for Binders and Asphalt Mixtures

Modified binders were obtained in the “wet process”. Kraton D1192 which is a linear triblock polymer with 30% styrene content by mass, was used for the preparation of polymer bitumen. Information on the basic chemical properties of the SBS copolymer is presented in Table 2. The rubber-asphalt binder was prepared on the basis of CR with a grain size of 0/0.8 mm. The grain size analysis of the CR is presented in Table 3.

Table 2. Chemical properties of the SBS triblock polymer.

| Chemical Properties          | Value |
|------------------------------|-------|
| Styrene content (% m)        | 30    |
| Molecular weight (kg/mol)    | 151   |
| Bulk density (kg/dm$^3$)     | 0.4   |
| Specific gravity             | 0.94  |

Table 3. Grain size distribution of CR 0/0.8 mm.

| Sieve Size (mm) | Percent Passing (%) |
|-----------------|---------------------|
| 1               | 100                 |
| 0.71            | 88.5                |
| 0.60            | 73.5                |
| 0.50            | 38.3                |
| 0.43            | 11.5                |
| 0.25            | 2.3                 |
| 0.13            | 0                   |

In the mixtures with increased flexibility, part of the aggregate in the “dry process” was replaced with RG with a grain size of 1/4 mm. The sieve analysis of the granulate is presented in Table 4.

Table 4. Sieve analysis of RG 1/4 mm.

| Sieve Size (mm) | Percent Passing (%) |
|-----------------|---------------------|
| 4               | 99.0                |
| 3               | 86.0                |
| 2               | 53.0                |
| 1               | 30.0                |
| 0.7             | 3.0                 |
| 0.5             | 0                   |

Bitumen with a penetration of 50/70 was used for the production of modified binders. Bitumen was heated to a temperature of 180 °C. A measured amount of modifier (5% SBS copolymer or 10% CR, or 2% SBS copolymer and 10% CR) was gradually added to the bitumen and mixed for 1 h at a constant speed of 700 rpm [39]. Then, using the RTFOT device, the binder was subjected to the test simulating the process of technological aging according to [40].

Before being added to the mix, RG was preheated, which caused a swelling effect and a “slight” devulcanization of the rubber to allow the binder to bond with the rubber more effectively. In mineral-rubber-asphalt mixtures, part of the mineral aggregate was replaced with RG in the amount of 10%, 20%, and 30% in relation to the mixture volume in order to improve their flexibility.

2.3. Designed Low-Noise Asphalt Mixtures

The following asphalt mixtures and low-noise mineral-rubber-asphalt mixtures were used for laboratory tests: porous asphalt (PA8), stone mastic asphalt (SMA8), stone mastic asphalt reducing tire/road noise (SMA8 LA), and stone mastic asphalt reducing tire/road
noise with 10% (SMA8 LA [10% RG]), 20% (SMA8 LA [20% RG]), and 30% (SMA8 LA [30% RG]). The mixtures were prepared in a laboratory mixer which set up a 3-dimensional counter-rotating mixing process with an eccentric rotary agitator. Before compacting, the mixtures were spread into a thin layer and for 2 h subjected to thermostating in a dryer at the temperature of 145 ± 5 °C with the reference binder and at 155 ± 5 °C for the modified binder. Such a procedure made it possible to bring the mixture preparation process closer to the conditions in an asphalt plant and is required by the standard [41]. The samples for 4PB-PR tests were prepared according to [42] in a slab roller compactor with the dimensions of the plates 300 mm × 400 mm × 80 mm. Then, rectangular beams with dimensions of 50 mm × 63 mm × 400 mm were cut from these plates.

The binder content, air void content, grain size composition, and density of the designed asphalt mixtures are presented in Table 5 and Figure 1.

Table 5. Grain size distribution (percentage of material passing through the sieve), binder content, air void content, and density of mixtures.

| Sieve (mm) | Type of Mixture | PA8 | SMA8 | SMA8 LA | SMA8 LA (10% RG) | SMA8 LA (20% RG) | SMA8 LA (30% RG) |
|------------|-----------------|-----|------|---------|-----------------|-----------------|-----------------|
| 11.2       |                 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 8          |                 | 91.2  | 94.6  | 92.4  | 92.8  | 93.4  | 93.9  |
| 5.6        |                 | 16.2  | 48    | 27.9  | 31.2  | 37.2  | 42.0  |
| 4          |                 | 9.3   | 38.5  | 20.5  | 25.3  | 31.4  | 36.4  |
| 2          |                 | 7.7   | 25.5  | 15.6  | 18.6  | 19.3  | 19.9  |
| 1          |                 | 7.1   | 20.2  | 13.0  | 14.8  | 14.6  | 14.5  |
| 0.5        |                 | 6.6   | 17.0  | 11.2  | 12.2  | 12.1  | 12.0  |
| 0.25       |                 | 6.2   | 14.5  | 9.9   | 10.2  | 10.1  | 10.0  |
| 0.125      |                 | 5.9   | 12.7  | 8.8   | 8.8   | 8.7   | 8.6   |
| 0.063      |                 | 3.9   | 9.5   | 6.3   | 6.3   | 6.3   | 6.2   |
| <0.063     |                 | 3.9   | 9.5   | 6.3   | 6.3   | 6.3   | 6.2   |
| Air voids (%) |            | 23.8 | 2.89  | 10.56 | 11.64 | 11.99 | 15.0  |
| Binder content (%) |        | 6.3   | 6.8   | 6.8   | 8.0   | 10.0  | 12.0  |
| Maximum density (kg/m³) |    | 2.574 | 2.449 | 2.528 | 2.314 | 2.067 | 1.949 |
| Bulk density (kg/m³) |          | 1.954 | 2.378 | 2.261 | 2.045 | 1.819 | 1.651 |

Figure 1. The particle size distribution of tested mixtures [39].

Particle size distribution of tested mixtures (Figure 1) indicate that the tested mixtures are characterized by discontinuous grain size. The presented curves show that the PA8 mixture contains the most air voids, and the SMA8 mixture has the least air voids. When
comparing SMA8 LA mixtures, it was concluded that increasing the addition of rubber granulate approximates the grain size curves of SMA8 LA mixtures with granulate to the SMA8 mixture. This is an advantageous solution due to the noisiness of the pavement as the air void content in such mixtures increases compared to SMA8 LA.

2.4. Stiffness Modulus and Phase Angle According to the Four Point Bending with Prismatic Samples (4PB-PR)

The stiffness of asphalt mixtures has a significant impact on the stress level generated in the structural layers of the road surface by traffic loads and temperature changes during operation. These stresses determine the resistance to fatigue and cracking of the pavement. The stiffness modules by the four-point bending method were tested according to [43]. The loads applied to the sample were cyclic and sinusoidal, which is typical in real conditions. The thermostatic time at the test temperature was 1 h. According to [43], the samples were rotated 90° along the longitudinal compaction axis in the slab. The stiffness modulus was determined at the 100th load cycle. Due to the fact that asphalt mixture is a typical visco-elastic material, its mechanical properties largely depend on the test temperature and frequency. Therefore, it was decided to perform tests in a wide temperature range: 5 °C, 15 °C, 25 °C and at the following frequencies: 0.5 Hz, 1.0 Hz, 5.0 Hz, 10 Hz, 20 Hz.

The value of the stiffness modulus is defined as the absolute value of the complex modulus, $|E^*|$, determined from the dependency between the stress and the deformation at time $t$. Characteristic for viscoelastic materials is the shift of the stress curve in relation to the deformation curve by the value of the phase angle, $\Phi$ (Figure 2).

![Figure 2. Stress and strain as a function of time.](image)

Perfectly elastic bodies are characterized by a phase angle, $\Phi = 0^\circ$. In viscous bodies, the phase angle fluctuates around $90^\circ$. For visco-elastic bodies, the angle value ranges from $0^\circ$ to $90^\circ$.

The stiffness modulus consists of the real ($E_1$) and the imaginary ($E_2$) component:

$$|E^*| = \sqrt{E_1^2 + E_2^2},$$

(1)

The real component is determined according to the Equation (2):

$$E_1 = \gamma \cdot \left( \frac{F}{z} \cdot \cos(\Phi) + 10^{-6} \cdot \mu \cdot \omega^2 \right),$$

(2)

where:

- $\gamma$—shape coefficient (1/m);
- $F$—vertical force (kN);
- $z$—specimen deflection (m);
- $\Phi$—phase angle (deg);
- $\mu$—mass coefficient (kg);
- $\omega$—angular frequency (rad/s).

The imaginary component is calculated according to the Dependency (3):

$$E_2 = \gamma \cdot \frac{F}{z} \cdot \sin(\Phi),$$

(3)
The mass and shape coefficients are calculated according to the Formulas (4)–(7):

\[
\gamma = \frac{L^2}{B \cdot H^2} \left( 0.75 - \frac{A^2}{L^2} \right),
\]

\[
\mu = R\{x\} \cdot \left( \frac{M}{\pi^4} + \frac{m}{R(A)} \right),
\]

\[
R\{x\} = \frac{12L}{A} \left( \frac{1}{3L^2 - 3L^2 - \frac{A^2}{L^2}} \right),
\]

\[
A = \frac{L - l}{A},
\]

where:

- \(L\) — distance between outer supports (m);
- \(B\) — sample width (m);
- \(H\) — sample height (m);
- \(M\) — sample mass (kg);
- \(m\) — mass of the moving parts of the device (kg);
- \(l\) — distance between places of sample loading (m);
- \(A\) — distance between the outer clamp and the next inner clamp (m);
- \(x\) — position of the probe for measuring beam deformation (m).

Phase angle is defined as the phase difference between stress and strain and is determined by Equation (8):

\[
\Phi = (B_e - B_l) \cdot \frac{180}{\pi},
\]

where:

- \(B_e\) — phase angle of the approximate function of the strain value (rad);
- \(B_l\) — phase angle of the approximate function of the stress value (rad).

3. Results and Discussion

3.1. Stiffness Modulus 4PB-PR

The results of testing the stiffness modulus with the 4PB-PR method at different frequencies at temperatures 5 °C, 15 °C, and 25 °C are shown in Tables 6 and 7, while the change of the stiffness modulus values as a function of temperature at 10 Hz is shown in Figure 3.

Table 6. Results of tests of stiffness modulus 4PB-PR for conventional asphalt mixtures.
Table 6. Cont.

| Type of Mixture | Type of Binder | Temperature (°C) | Frequency (Hz) |
|-----------------|----------------|-----------------|----------------|
|                 |                | 0.5  | 1  | 5  | 10 | 20 |
| PA8             | 50/70          | 5    | 2372 | 2798 | 3872 | 4325 | 4587 |
|                 |                | 15   | 1037 | 1274 | 1923 | 2247 | 2542 |
|                 |                | 25   | 533  | 603  | 915  | 1096 | 1155 |
|                 | SBSM-5         | 5    | 2124 | 2444 | 3232 | 3535 | 3737 |
|                 |                | 15   | 1136 | 1284 | 1860 | 2128 | 2271 |
|                 |                | 25   | 540  | 664  | 962  | 1094 | 1214 |
|                 | CRM-10         | 5    | 2297 | 2654 | 3541 | 3875 | 4081 |
|                 |                | 15   | 1140 | 1370 | 2009 | 2302 | 2450 |
|                 |                | 25   | 570  | 653  | 988  | 1086 | 1142 |
|                 | SBSM-2 + CRM-10| 5    | 2529 | 2926 | 3577 | 4135 | 4521 |
|                 |                | 15   | 1255 | 1486 | 2145 | 2407 | 2521 |
|                 |                | 25   | 584  | 702  | 1044 | 1230 | 1358 |
| SMA8 LA         | 50/70          | 5    | 3963 | 4709 | 6550 | 7286 | 8055 |
|                 |                | 15   | 1616 | 2025 | 3281 | 3961 | 4478 |
|                 |                | 25   | 668  | 821  | 1415 | 1806 | 2113 |
|                 | SBSM-5         | 5    | 5862 | 6618 | 8482 | 9309 | 9916 |
|                 |                | 15   | 2673 | 3199 | 4642 | 5371 | 6145 |
|                 |                | 25   | 1181 | 1434 | 2310 | 2764 | 3016 |
|                 | CRM-10         | 5    | 5472 | 6253 | 8128 | 8931 | 9680 |
|                 |                | 15   | 2385 | 2911 | 4366 | 5028 | 5746 |
|                 |                | 25   | 1001 | 1254 | 2088 | 2560 | 3059 |
|                 | SBSM-2 + CRM-10| 5    | 6481 | 7004 | 8794 | 9531 | 10,057 |
|                 |                | 15   | 3141 | 3699 | 5238 | 5993 | 6547 |
|                 |                | 25   | 1323 | 1665 | 2593 | 3118 | 3437 |

The results of the 4PB-PR stiffness modulus tests presented in this study confirm the previous research results described in publications [44–48]. The SBS copolymer consists of three-dimensional styrene-butadiene-styrene chains, in which the rigid styrene domains are dispersed in a flexible butadiene matrix that serves as a continuous phase. When SBS is added to bitumen, the styrene blocks, through physical connections, can form three-dimensional networks that enable elastomers to give binders higher stiffness. When crumb rubber is added to the binder, it causes physical swelling and chemical degradation (devulcanization and depolymerization). Maltenes (light fractions of bitumen) are absorbed by rubber networks. This process is the main phenomenon that causes the swelling of crumb rubber (three–five times its original volume). In addition, a “gel” structure is formed at the bitumen/rubber interface. At this stage, effective stiffening of the binder takes place, which consequently affects the value of stiffness modulus of asphalt mixtures.

Due to the fact that asphalt mixtures are materials with visco-elastic properties, their technical features should be presented as a function of temperature change. The stiffness modulus of asphalt mixtures significantly decreases with increasing test temperature. This phenomenon results in a reduction in load-bearing capacity and load-carrying capability. Inverse changes are observed when the test temperature is decreased: the value of stiffness modulus begins to increase rapidly. This indicates that there is an increase in thermal stresses in the visco-elastic material. When the thermal stress value exceeds the tensile strength of the material, the initiation of low-temperature cracking occurs.
Table 7. Results of tests of stiffness modulus 4PB-PR for asphalt mixtures with the addition of RG.

| Type of Mixture | Type of Binder | Temperature (°C) | Frequency (Hz) |
|-----------------|----------------|------------------|----------------|
|                 |                | 0.5  | 1    | 5    | 10   | 20   |

SMA8 LA (10% RG)

|                  |                | 5    | 10   | 20   |
| SMA8 LA (10% RG) | 50/70          | 5    | 2432 | 2908 | 3920 | 4298 | 4491 |
|                  |                | 15   | 1052 | 1272 | 1908 | 2233 | 2539 |
|                  |                | 25   | 487  | 571  | 917  | 1084 | 1318 |
| SBSM-5           |                | 5    | 3226 | 3631 | 4596 | 4992 | 5311 |
|                  |                | 15   | 1606 | 1869 | 2604 | 2938 | 3267 |
|                  |                | 25   | 782  | 934  | 1402 | 1619 | 1644 |
| CRM-10           |                | 5    | 2354 | 2771 | 3638 | 3962 | 4157 |
|                  |                | 15   | 1042 | 1285 | 1908 | 2233 | 2538 |
|                  |                | 25   | 512  | 629  | 950  | 1121 | 1301 |
| SBSM-2 + CRM-10  |                | 5    | 2715 | 3098 | 3939 | 4349 | 4627 |
|                  |                | 15   | 1233 | 1477 | 2106 | 2346 | 2605 |
|                  |                | 25   | 567  | 691  | 1026 | 1211 | 1446 |

SMA8 LA (20% RG)

|                  |                | 5    | 1199 | 1376 | 1783 | 1939 | 2069 |
|                  |                | 15   | 621  | 722  | 994  | 1091 | 1233 |
|                  |                | 25   | 424  | 487  | 630  | 672  | 724  |
| SBSM-5           |                | 5    | 1188 | 1341 | 1692 | 1819 | 1970 |
|                  |                | 15   | 708  | 762  | 985  | 1046 | 1110 |
|                  |                | 25   | 393  | 423  | 595  | 644  | 725  |
| CRM-10           |                | 5    | 943  | 1082 | 1398 | 1442 | 1638 |
|                  |                | 15   | 512  | 567  | 778  | 843  | 945  |
|                  |                | 25   | 306  | 359  | 481  | 571  | 652  |
| SBSM-2 + CRM-10  |                | 5    | 1010 | 1191 | 1467 | 1574 | 1823 |
|                  |                | 15   | 569  | 652  | 891  | 973  | 1044 |
|                  |                | 25   | 379  | 423  | 537  | 611  | 712  |

SMA8 LA (30% RG)

|                  |                | 5    | 544  | 620  | 800  | 875  | 980  |
|                  |                | 15   | 324  | 363  | 477  | 527  | 573  |
|                  |                | 25   | 251  | 277  | 328  | 360  | 417  |
| SBSM-5           |                | 5    | 596  | 679  | 853  | 971  | 1097 |
|                  |                | 15   | 357  | 397  | 505  | 554  | 616  |
|                  |                | 25   | 258  | 287  | 346  | 375  | 419  |
| CRM-10           |                | 5    | 556  | 614  | 742  | 857  | 951  |
|                  |                | 15   | 351  | 378  | 479  | 514  | 579  |
|                  |                | 25   | 274  | 300  | 363  | 398  | 461  |
| SBSM-2 + CRM-10  |                | 5    | 543  | 619  | 765  | 883  | 964  |
|                  |                | 15   | 331  | 362  | 474  | 535  | 586  |
|                  |                | 25   | 261  | 291  | 357  | 387  | 429  |

When analyzing the results presented in Tables 6 and 7, it should be clearly stated that the stiffness modulus depends on many factors: type of mixture, type of binder used, amount of RG, test temperature, and frequency.

Considering the type of mixture, the highest values of the stiffness modulus were obtained at 5 °C at the frequency of 20 Hz for the mixture SMA8 with SBSM-2 + CRM-10 and CRM-10 binder (15,423 MPa and 14,978 MPa, respectively). On the other hand, the lowest values of modulus under the same test conditions were obtained for the mixture SMA8 LA (30% RG) with bitumen CRM-10 and SBSM-2 + CRM-10 (951 MPa and 964 MPa, respectively). It is a tenfold decrease in the value of the modulus in relation to the SMA8 LA mixture without the addition of RG (CRM-10–9680 MPa, SBSM-2 + CRM-10–10,057 MPa). It is worth emphasizing that the addition of another 10% of RG to the SMA8 LA mixture causes a decrease in the modulus value by approximately 50% in practically the entire range of analyzed temperatures.
Figure 3. Change of 4PB-PR stiffness modulus values as a function of temperature at 10 Hz for mixtures: (a) SMA8, (b) PA8, (c) SMA8 LA, (d) SMA8 LA (10% RG), (e) SMA8 LA (20% RG), (f) SMA8 LA (30% RG).
The lowest (favorable) temperature sensitivity (e.g., at the frequency of 10 Hz) in the group of mixtures without the addition of RG achieved the mixtures with SBSM-5 and SBSM-2 + CRM-10 binder (Figure 3). On the other hand, the highest (unfavorable) temperature sensitivity was shown by the mixtures with the reference bitumen 50/70. In mixtures where part of the aggregate was replaced with RG, the lowest sensitivity to temperature changes was found in the mixtures SMA8 LA (10% RG) with bitumen SBSM-5, SMA8 LA (20% RG) with SBSM-2 + CRM-10 binder, and SMA8 LA (30% RG) with CRM-10 binder. However, the most sensitive to temperature are the mixtures of SMA8 LA (10% RG and 20% RG) with bitumen 50/70 and SMA8 LA (30% RG) with the SBSM-5 binder.

Testing the stiffness modulus at variable frequencies of load application in the range from 0.5 Hz to 20 Hz allows for predicting the behavior of asphalt mixtures at variable vehicle speeds. The conducted tests proved that the temperature and the amount of RG have a significant influence on the change of the range of modulus values obtained at different load frequencies. The lowest discrepancies were obtained at 5 °C for mixtures without RG, the highest—at 25 °C for mixtures with 30% RG. This proves that at 5 °C the phase angle is much lower (higher stiffness of asphalt mixtures) than at 25 °C (Table 7).

Low values of the stiffness modulus of mixtures with the addition of rubber granulate allow us to conclude that they will be able to transfer and withstand higher tensile stresses, thus allowing us to decrease the low-temperature cracking.

The second degree polynomial was used to describe the changes in the stiffness modulus values:

\[
Z = a_0 + a_1X_1 + a_2X_1^2 + a_3X_2 + a_4X_2^2 + a_5X_3 + a_6X_3^2 + a_7X_4 + a_8X_4^2 + a_9X_1X_2 + a_{10}X_1X_3 + a_{11}X_1X_4 + a_{12}X_2X_3 + a_{13}X_2X_4 + a_{14}X_3X_4
\]  
(9)

where:

- \( Z \) — analyzed mixture parameter (stiffness modulus 4PB-PR);
- \( a_0 - a_{14} \) — regression coefficients;
- \( X_1 \) — type of mixture;
- \( X_2 \) — type of binder;
- \( X_3 \) — temperature (°C);
- \( X_4 \) — frequency (Hz).

The statistical analysis of the obtained results was started with the significance test using the ANOVA analysis of variance (STATISTICA software). The results of this analysis are presented in Table 8.

**Table 8.** Assessment of the significance of influence of temperature, type of mixture, type of modifier and frequency on changes in the stiffness modulus using the ANOVA test.

| Effect                  | Variable: [Material] (MPa); \( R^2 = 0.7665; \) \( R^2\) adj = 0.7571; Error MS = 2,313,330 |
|-------------------------|-------------------------------------------------------------------------------------------------|
|                         | SS | MS | F          | p      |
| (1) Type of Mixture (L) | 1.041 \times 10^8 | 1.041 \times 10^6 | 450.204 | <0.05 |
| Type of Mixture (Q)    | 4.099 \times 10^7 | 4.099 \times 10^5 | 17.719  | <0.05 |
| (2) Type of Binder (L) | 1.850 \times 10^7 | 1.850 \times 10^5 | 7.998   | <0.05 |
| Type of Binder (Q)     | 9.433 \times 10^5 | 9.433 \times 10^3 | 0.408   | 0.524 |
| (3) Temperature (L)    | 6.266 \times 10^8 | 6.266 \times 10^6 | 270.847 | <0.05 |
| Temperature (Q)        | 1.375 \times 10^7 | 1.375 \times 10^5 | 5.944   | <0.05 |
| (4) Frequency (L)      | 1.130 \times 10^8 | 1.130 \times 10^6 | 48.859  | <0.05 |
| Frequency (Q)          | 2.775 \times 10^7 | 2.775 \times 10^5 | 11.997  | <0.05 |
| 1L-2L                  | 2.636 \times 10^7 | 2.636 \times 10^5 | 11.393  | <0.05 |
| 1L-3L                  | 3.204 \times 10^8 | 3.204 \times 10^6 | 138.517 | <0.05 |
Table 8. Cont.

| Effect          | Variable: 4PB-PR (MPa); $R^2 = 0.7665$; $R^2$ adj = 0.7571; Error MS = 2,313,330 |
|-----------------|------------------------------------------------------------------------------------------|
|                 | SS       | MS       | F   | $p$          |
| 1L-4L           | $6.271 \times 10^7$ | $6.271 \times 10^7$ | 27.108 | <0.05        |
| 2L-3L           | $9.426 \times 10^5$ | $9.426 \times 10^5$ | 0.407  | 0.524        |
| 2L-4L           | $2.192 \times 10^4$ | $2.192 \times 10^4$ | 0.009  | 0.923        |
| 3L-4L           | $1.100 \times 10^2$ | $1.100 \times 10^2$ | 4.753  | <0.05        |
| Error           | $7.981 \times 10^8$ | $2.313 \times 10^6$ |        |              |
| Total SS        | $3.419 \times 10^9$ |                      |        |              |

Where: Q—quadratic; L—linear.

Based on the analysis of the parameters, it can be clearly stated that the temperature, type of mixture and binder, and frequency are important factors affecting the stiffness modulus, because the $p$-value is lower than the assumed significance level $\alpha = 0.05$ ($p$-Value < 0.05). Analyzing the square term referring to the type of binder (Type of Binder (Q)) and the factor describing the interaction of the binder type and frequency (2L-4L), no significant influence was found on the values of the stiffness modulus determinations. The values describing the parameters of the regression model are summarized in Table 9.

Table 9. Parameters of model describing the dependence of the stiffness modulus on temperature, frequency, type of mixture, and modifier.

| Effect          | Variable: 4PB-PR (MPa); $R^2 = 0.7665$; $R^2$ adj = 0.7571; Error MS = 2,313,330 |
|-----------------|------------------------------------------------------------------------------------------|
|                 | Regression Coefficients | Std. Error | t(345) | $p$-Value | $-95\%$ Conf. Lmt | $+95\%$ Conf. Lmt |
| Intercept       | $-361,542$ | 1,030,245 | −0.351 | 0.726     | −2,387,895 | 1,664,810 |
| (1) Type of Mixture (L) | $-16,414$ | 8141 | −2.016 | <0.05 | −32,425 | −403 |
| Type of Mixture (Q) | 135 | 32 | 4.209 | <0.05 | 72 | 198 |
| (2) Type of Binder (L) | 26,015 | 17,042 | 1.526 | 0.128 | −7505 | 59,535 |
| Type of Binder (Q) | −51 | 80 | −0.639 | 0.524 | −209 | 106 |
| (3) Temperature (L) | −6973 | 1093 | −6.379 | <0.05 | −9123 | −4823 |
| Temperature (Q) | 4 | 2 | 2.438 | <0.05 | 1 | 7 |
| (4) Frequency (L) | 3822 | 1238 | 3.088 | <0.05 | 1387 | 6256 |
| Frequency (Q) | −7 | 2 | −3.464 | <0.05 | −11 | −3 |
| 1L-2L           | −142 | 42 | −3.375 | <0.05 | −224 | −59 |
| 1L-3L           | 68 | 6 | 11.769 | <0.05 | 56 | 79 |
| 1L-4L           | −34 | 7 | −5.207 | <0.05 | −47 | −21 |
| 2L-3L           | −6 | 9 | −0.638 | 0.524 | −23 | 12 |
| 2L-4L           | 1 | 10 | 0.097 | 0.923 | −19 | 21 |
| 3L-4L           | −3 | 1 | −2.180 | <0.05 | −6 | −0 |

Where: Q—quadratic; L—linear.

On the basis of the analysis, it was observed that the value of the corrected determination coefficient was $R^2$ adj = 76%, which proves the correct adoption of the model.

The developed model of changes in the stiffness modulus can be presented using the following Relationship (10):

$$4PB-PR = -361,542 - 16,414 \cdot TM + 135 \cdot TM^2 + 26,015 \cdot TB - 51 \cdot TB^2 - 6973 \cdot Temp$$
$$+ 4 \cdot Temp^2 + 3822 \cdot F - 7 \cdot F^2 - 142 \cdot TM \cdot TB + 68 \cdot TM \cdot Temp - 34 \cdot TM \cdot F$$
$$- 6 \cdot TB \cdot Temp + 1 \cdot TB \cdot F - 3 \cdot Temp \cdot F$$

(10)

where:

- TM—type of mixture: SMA8 = 105, PA8 = 106, SMA8 LA = 107, SMA8 LA (10% RG) = 108, SMA8 LA (20% RG) = 109, SMA8 LA (30% RG) = 110;
- TB—type of binder: 50/70 = 101, SBSM-5 = 102, CRM-10 = 103, SBSM-2 + CRM-10 = 104;
Temp—test temperature; 
F—frequency.

The obtained regression model (Equation (10)) allows us to predict with good precision (about 76%) the stiffness modulus of the analyzed mixtures with SBS and crumb rubber modified binder (Figure 3).

The graphical interpretation of the 4PB-PR stiffness modulus change as a function of the type of mixture and binder is shown in Figure 4a, as a function of the binder type and temperature 4(b), and as a function of the binder type and frequency 4(c).

![Figure 4](image)

**Figure 4.** The dependence of the stiffness modulus 4 PB-PR: (a) as a function of the type of mixture and binder, (b) as a function of the type of binder and temperature, (c) as a function of the type of binder and frequency.

3.2. Phase Angle Φ

The changes in the phase angle Φ for the individual mixtures at different temperatures and frequencies are presented in Tables 10 and 11. A graphical interpretation of the change in phase angle, as a function of frequency at temperature 15 °C is shown in Figure 5.
Table 10. Change of the phase angle $\Phi$ at variable temperature and frequency for conventional asphalt mixtures.

| Type of Mixture | Type of Binder | Temperature (°C) | Frequency (Hz) |
|-----------------|----------------|-----------------|----------------|
|                 |                | 0.5  | 1   | 5   | 10  | 20  |
| SMA8            | 50/70          | 5    | 20  | 18  | 15  | 13  | 12  |
|                 |                | 15   | 33  | 30  | 25  | 23  | 21  |
|                 |                | 25   | 43  | 40  | 36  | 36  | 34  |
|                 | SBSM-5         | 5    | 16  | 14  | 11  | 10  | 10  |
|                 |                | 15   | 25  | 22  | 19  | 18  | 16  |
|                 |                | 25   | 34  | 33  | 29  | 27  | 26  |
| SMA8            | CRM-10         | 5    | 16  | 14  | 11  | 10  | 9   |
|                 |                | 15   | 27  | 22  | 19  | 17  | 15  |
|                 |                | 25   | 39  | 37  | 32  | 30  | 28  |
|                 | SBSM-2 + CRM-10| 5    | 14  | 12  | 10  | 9   | 8   |
|                 |                | 15   | 24  | 21  | 17  | 16  | 14  |
|                 |                | 25   | 33  | 31  | 28  | 25  | 24  |
| PA8             | 50/70          | 5    | 24  | 22  | 18  | 17  | 16  |
|                 |                | 15   | 35  | 33  | 29  | 28  | 27  |
|                 |                | 25   | 43  | 41  | 39  | 37  | 34  |
|                 | SBSM-5         | 5    | 21  | 20  | 17  | 16  | 15  |
|                 |                | 15   | 31  | 29  | 25  | 24  | 23  |
|                 |                | 25   | 39  | 38  | 35  | 33  | 30  |
|                 | CRM-10         | 5    | 22  | 20  | 17  | 16  | 14  |
|                 |                | 15   | 32  | 30  | 25  | 24  | 23  |
|                 |                | 25   | 39  | 38  | 36  | 34  | 33  |
|                 | SBSM-2 + CRM-10| 5    | 20  | 19  | 16  | 15  | 14  |
|                 |                | 15   | 30  | 29  | 24  | 23  | 22  |
|                 |                | 25   | 42  | 37  | 34  | 33  | 32  |
| SMA8 LA         | 50/70          | 5    | 23  | 20  | 17  | 16  | 14  |
|                 |                | 15   | 35  | 33  | 27  | 25  | 24  |
|                 |                | 25   | 44  | 42  | 39  | 38  | 37  |
|                 | SBSM-5         | 5    | 17  | 15  | 13  | 12  | 11  |
|                 |                | 15   | 28  | 25  | 21  | 20  | 19  |
|                 |                | 25   | 38  | 35  | 32  | 30  | 29  |
|                 | CRM-10         | 5    | 19  | 16  | 13  | 13  | 11  |
|                 |                | 15   | 31  | 28  | 23  | 21  | 20  |
|                 |                | 25   | 40  | 40  | 34  | 32  | 31  |
|                 | SBSM-2 + CRM-10| 5    | 16  | 14  | 12  | 11  | 10  |
|                 |                | 15   | 26  | 23  | 20  | 18  | 17  |
|                 |                | 25   | 35  | 34  | 30  | 28  | 27  |

In the literature, there are few studies of the stiffness modulus tested using the 4PB-PR method. In addition, the authors of these publications hardly analyze the very important parameter, which is the phase angle, $\Phi$. According to [49,50], the phase angle, $\Phi$, mainly defines the viscoelastic properties of asphalt mixtures. It reflects the proportion of viscous and elastic parts in the asphalt mixtures. A lower value of the phase angle, $\Phi$, indicates that elastic properties predominate in the mixture. In the case of mixtures with the base bitumen, the phase angle in the low-frequency area remained almost constant, and then gradually decreased with increasing frequency. A similar relationship was also observed in asphalt mixtures with modified binders, but the values of the phase angle, $\Phi$, are lower in relation to mixtures with base bitumen, which is confirmed by the test results (Figure 5). This proves that asphalt mixtures with modified binders are more rigid (the elastic phase
dominates), while the mixtures with a conventional binder are more flexible (lower content of the elastic phase).

Table 11. Change of the phase angle $\Phi$ at variable temperature and frequency for asphalt mixtures with the addition of RG.

| Type of Mixture | Type of Binder | Temperature ($^\circ$C) | Frequency (Hz) | 0.5 | 1  | 5  | 10 | 20 |
|----------------|----------------|-------------------------|----------------|-----|----|----|----|----|
|                |                | 5                       | 15             | 5   | 33 | 32 | 28 | 25 | 25 |
| SMA8 LA (10% RG) | SBSM-5         | 5                       | 15             | 5   | 27 | 25 | 21 | 18 | 17 |
|                |                | 5                       | 25             | 5   | 34 | 33 | 29 | 26 | 24 |
|                |                | 15                      | 15             | 5   | 32 | 31 | 27 | 24 | 24 |
|                |                | 15                      | 25             | 5   | 43 | 40 | 37 | 36 | 34 |
|                | CRM-10         | 5                       | 5              | 21 | 20 | 17 | 16 | 15 |
|                |                | 15                      | 15             | 5   | 32 | 31 | 27 | 24 | 24 |
|                |                | 25                      | 25             | 5   | 43 | 40 | 37 | 36 | 34 |
|                | SBSM-2 + CRM-10 | 5                       | 5              | 19 | 18 | 15 | 14 | 13 |
|                |                | 15                      | 15             | 5   | 28 | 28 | 23 | 21 | 20 |
|                |                | 15                      | 25             | 5   | 43 | 40 | 36 | 34 | 31 |
| SMA8 LA (20% RG) | SBSM-5         | 5                       | 5              | 20 | 19 | 16 | 15 | 15 |
|                |                | 15                      | 15             | 5   | 31 | 28 | 26 | 23 | 20 |
|                |                | 15                      | 25             | 5   | 42 | 37 | 34 | 33 | 31 |
|                | CRM-10         | 5                       | 5              | 24 | 21 | 18 | 16 | 13 |
|                |                | 15                      | 15             | 5   | 34 | 29 | 28 | 27 | 25 |
|                |                | 25                      | 15             | 5   | 41 | 39 | 38 | 37 | 35 |
|                | SBSM-2 + CRM-10 | 5                       | 5              | 23 | 19 | 18 | 16 | 12 |
|                |                | 15                      | 15             | 5   | 30 | 28 | 25 | 24 | 21 |
|                |                | 15                      | 25             | 5   | 42 | 37 | 36 | 35 | 32 |
| SMA8 LA (30% RG) | SBSM-5         | 5                       | 5              | 29 | 28 | 26 | 24 | 23 |
|                |                | 15                      | 15             | 5   | 41 | 37 | 35 | 32 | 30 |
|                |                | 25                      | 25             | 5   | 52 | 45 | 39 | 37 | 35 |
|                | SBSM-5         | 5                       | 5              | 25 | 21 | 20 | 16 | 15 |
|                |                | 15                      | 15             | 5   | 35 | 33 | 29 | 28 | 24 |
|                |                | 25                      | 25             | 5   | 42 | 42 | 38 | 36 | 32 |
|                | CRM-10         | 5                       | 5              | 25 | 23 | 21 | 19 | 19 |
|                |                | 15                      | 15             | 5   | 33 | 32 | 29 | 28 | 22 |
|                |                | 25                      | 15             | 5   | 45 | 42 | 39 | 35 | 35 |
|                | SBSM-2 + CRM-10 | 5                       | 5              | 25 | 22 | 20 | 20 | 20 |
|                |                | 15                      | 15             | 5   | 34 | 32 | 30 | 28 | 24 |
|                |                | 15                      | 25             | 5   | 43 | 42 | 38 | 36 | 35 |

When analyzing the obtained results of the phase angle, $\Phi$, on the basis of the stiffness modulus tests using the 4PB-PR method presented in Tables 10 and 11 and in Figure 5; it should be stated that the type of binder, temperature, and frequency show a significant influence on the change of the phase angle, $\Phi$. Mixtures with modified binders show higher values of the elastic component of the stiffness modulus (lower phase angle, $\Phi$) in the entire range of tested temperatures and frequencies of loading. This fact proves that these mixtures are more resistant to accumulation and deformation in pavements compared to mixtures with conventional binders. For example, when analyzing the values of the phase angle, $\Phi$, in the mixtures without the addition of RG at a temperature of 15 $^\circ$C (Figure 5),
it is clearly visible that the best elastic properties were obtained by all the mixtures with modified binder SBSM-2 + CRM-10 (the smallest value of the phase angle, $\Phi$). No such obvious difference can be observed in mixtures with the addition of RG. This proves that in these mixtures, the value of the phase angle, $\Phi$, is mainly determined by the “elasticity” of RG.

Figure 5. Phase angle, $\Phi$, change at 15 °C at variable frequencies for the mixtures: (a) SMA8, (b) PA8, (c) SMA8 LA, (d) SMA8 LA (10% RG), (e) SMA8 LA (20% RG), (f) SMA8 LA (30% RG).
The type of mixture does not significantly affect the value of the phase angle, $\Phi$, in the low frequency range of 0.5 Hz, 1 Hz, 5 Hz and temperatures of 5 °C and 15 °C (Table 9). The greatest changes were observed only for the SMA8 LA (30% RG). On the other hand, the type of modified binder and the amount of RG additives have a significant impact.

Changes in this parameter at higher frequency ranges (10 Hz and 20 Hz) and test temperatures (25 °C) are significantly influenced by the type of binder, the amount of RG addition and the type of mixture.

The comprehensive description of the dependence of the phase angle, $\Phi$, of asphalt mixtures with modified binder was made using the second degree polynomial:

$$
Z = a_0 + a_1 X_1 + a_2 X_1^2 + a_3 X_2 + a_4 X_2^2 + a_5 X_3 + a_6 X_3^2 + a_7 X_4 + a_8 X_4^2
+ a_9 X_1 X_2 + a_{10} X_1 X_3 + a_{11} X_1 X_4 + a_{12} X_2 X_3 + a_{13} X_2 X_4
+ a_{14} X_3 X_4
$$

(11)

where:

- $Z$—analyzed mixture parameter (phase angle, $\Phi$);
- $a_0 - a_{14}$—regression coefficients;
- $X_1$—type of mixture;
- $X_2$—type of binder;
- $X_3$—temperature (°C);
- $X_4$—frequency (Hz).

The first stage of model evaluation was to perform the significance test using ANOVA. The results of this analysis are presented in Table 12.

Table 12. Assessment of the significance of the influence of temperature, frequency, type of mixture, and binder on changes in the phase angle using ANOVA analysis.

| Effect                      | SS       | MS       | F         | p         |
|-----------------------------|----------|----------|-----------|-----------|
| (1) Type of Mixture (L)     | 1863.588 | 1863.588 | 273.099   | <0.05     |
| Type of Mixture (Q)         | 40.357   | 40.357   | 5.914     | <0.05     |
| (2) Type of Binder (L)      | 712.693  | 712.693  | 104.441   | <0.05     |
| Type of Binder (Q)          | 288.011  | 288.011  | 42.206    | <0.05     |
| (3) Temperature (L)         | 20,944.945 | 20,944.945 | 3069.368 | <0.05     |
| Temperature (Q)             | 17.735   | 17.735   | 2.599     | 0.108     |
| (4) Frequency (L)           | 2190.877 | 2190.877 | 321.061   | <0.05     |
| Frequency (Q)               | 513.714  | 513.714  | 75.282    | <0.05     |
| 1L.2L                       | 53.505   | 53.505   | 7.841     | <0.05     |
| 1L.3L                       | 10.937   | 10.937   | 1.603     | 0.206     |
| 1L.4L                       | 2.502    | 2.502    | 0.367     | 0.545     |
| 2L.3L                       | 12.607   | 12.607   | 1.848     | 0.175     |
| 2L.4L                       | 0.261    | 0.261    | 0.038     | 0.845     |
| 3L.4L                       | 44.807   | 44.807   | 6.566     | <0.05     |
| Error                       | 2354.233 | 6.824    |           |           |
| Total SS                    | 30,701.556 |         |           |           |

Where: Q—quadratic; L—linear.

The comprehensive statistical analysis of the parameters listed in Table 12 allows us to unequivocally state that the type of mixture and binder, temperature, and frequency are important factors affecting the phase angle, $\Phi$, because the $p$-value related to them is lower than the assumed significance level $\alpha = 0.05$. This relationship is not only observed with the square expression describing the influence of temperature. The existence of interactions between the type of mixture and the temperature, which affects the analyzed parameter ($p$-value less than $\alpha = 0.05$), is of significant importance.
The developed regression model of the dependence of the phase angle, Φ, in terms of the type of mixture and binder, temperature, and frequency are summarized in Table 13.

Table 13. Parameters of the applied model of the dependence of the phase angle, Φ, on temperature, frequency, type of mixture, and binder.

| Effect                        | Regression Coefficients | Std. Error | t (345) | p-Value | -95% Conf. Lmt | +95% Conf. Lmt |
|-------------------------------|-------------------------|------------|---------|---------|----------------|----------------|
| Intercept                     | 13,119.572              | 1769.445   | 7.415   | <0.05   | 9639.314       | 16,599.829     |
| (1) Type of Mixture (L)       | −47.956                 | 13.981     | −3.430  | <0.05   | −75.455        | −20.457        |
| Type of Mixture (Q)           | 0.134                   | 0.055      | 2.432   | <0.05   | 0.026          | 0.243          |
| (2) Type of Binder (L)        | −206.074                | 29.270     | −7.040  | <0.05   | −263.645       | −148.503       |
| Type of Binder (Q)            | 0.894                   | 0.138      | 6.497   | <0.05   | 0.624          | 1.165          |
| (3) Temperature (L)           | 4.300                   | 1.877      | 2.290   | <0.05   | 0.607          | 7.992          |
| Temperature (Q)               | 0.005                   | 0.003      | 1.612   | 0.108   | −0.001         | 0.010          |
| (4) Frequency (L)             | −0.536                  | 2.126      | −0.252  | 0.801   | −4.717         | 3.645          |
| Frequency (Q)                 | 0.030                   | 0.003      | 8.677   | <0.05   | 0.023          | 0.037          |
| 1L-2L                         | 0.202                   | 0.072      | 2.800   | <0.05   | 0.060          | 0.344          |
| 1L-3L                         | −0.012                  | 0.010      | −1.266  | 0.206   | −0.032         | 0.007          |
| 1L-4L                         | −0.007                  | 0.011      | −0.605  | 0.545   | −0.029         | 0.015          |
| 2L-3L                         | −0.020                  | 0.015      | −1.359  | 0.175   | −0.050         | 0.009          |
| 2L-4L                         | 0.003                   | 0.017      | 0.195   | 0.845   | −0.030         | 0.037          |
| 3L-4L                         | −0.006                  | 0.002      | −2.562  | <0.05   | −0.011         | −0.001         |

Where: Q—quadratic; L—linear.

Based on the analysis, it can be concluded that the value of the corrected determination coefficient equals $R^2_{\text{adj}} = 92\%$, which proves the correct adoption of the model.

The developed model of the analyzed change in the phase angle, Φ, can be presented using the Equation (12):

$$
\Phi = 13,119.572 - 47.956 \cdot \text{TM} + 0.134 \cdot \text{TM}^2 - 206.074 \cdot \text{TB} + 0.894 \cdot \text{TB}^2 + 4.300 \cdot \text{Temp} + 0.005 \cdot \text{Temp}^2 - 0.536 \cdot \text{F} + 0.030 \cdot \text{F}^2 - 0.012 \cdot \text{TM} \cdot \text{Temp} - 0.007 \cdot \text{TM} \cdot \text{F} - 0.020 \cdot \text{TB} \cdot \text{Temp} - 0.003 \cdot \text{TB} \cdot \text{F} - 0.006 \cdot \text{Temp} \cdot \text{F}
$$

(12)

where:

- TM—type of mixture: SMA8 = 105, PA8 = 106, SMA8 LA = 107, SMA8 LA (10% RG) = 108, SMA8 LA (20% RG) = 109, SMA8 LA (30% RG) = 110;
- TB—type of binder: 50/70 = 101, SBSM-5 = 102, CRM-10 = 103, SBSM-2 + CRM-10 = 104;
- Temp—test temperature;
- F—frequency.

The obtained regression model (Equation (12)) allows to predict with very good precision (about 92%) the stiffness modulus of the analyzed mixtures with SBS and crumb rubber modified binder (Figure 5).

The graphic interpretation of the change of the phase angle as a function of the type of mixture and binder is shown in Figure 6a, as a function of the type of binder and temperature in Figure 6b, and as a function of the type of binder and frequency in Figure 6c.
4. Conclusions

Based on the analysis of technical parameters obtained in the four-point bending test with prismatic samples of stone mastic mixtures SMA8, stone mastic asphalt reducing tire/road noise SMA8 LA and porous asphalt PA8 with SBS copolymer-modified binders, crumb rubber modified binders, and binders simultaneously modified with SBS and crumb rubber, the following conclusions were made:

1. The type of modifier has a significant impact on the stiffness modulus of all analyzed asphalt mixtures, increasing its values in the entire range of analyzed temperatures from 5 °C to 25 °C. The highest values of the stiffness modulus were obtained at 5 °C and at the frequency of 20 Hz for the mixture of SMA8 with the binder SBSM-2 + CRM-10 and CRM-10 (15,423 MPa and 14,978 MPa). On the other hand, the lowest values of modulus under the same test conditions were obtained by the mixture SMA8 LA (30% RG), with bitumen CRM-10 and SBSM-2 + CRM-10 (951 MPa and 964 MPa, respectively).

2. The addition of rubber granulate significantly lowers the stiffness modulus. It was found that the addition of 30% rubber granulate reduces the value of the stiffness modulus tenfold. For example: SMA8 LA mixture with bitumen CRM-10 and SBSM-2 + CRM-10 (stiffness modulus-9680 MPa and 10,057 MPa, respectively), SMA8 LA (30% RG) (stiffness modulus-951 MPa and 964 MPa).
3. Replacing the mineral aggregate by another 10% rubber granulate in the SMA8 LA mixture causes a decrease in the stiffness modulus by about 50% in the entire range of analyzed temperatures.

4. Mixtures SMA8, PA8, SMA8 LA with the reference bitumen 50/70 had the highest (unfavorable) temperature sensitivity. The highest temperature sensitivity in mixtures, in which part of the aggregate was replaced with rubber granulate, was achieved by the mixtures SMA8 LA (10% RG and 20% RG) with asphalt 50/70 and SMA8 LA (30% RG) with the SBSM-5 binder. The SMA8 LA (10% RG) mixture with bitumen SBSM-5, SMA8 LA (20% RG) mixture with SBSM-2 + CRM-10 binder and SMA8 LA (30% RG) with CRM-10 binder showed the lowest sensitivity to temperature changes.

5. The type of binder, the temperature, and the frequency show a significant influence on the change of the phase angle, \( \Phi \).

6. Mixtures with the use of modified binders show higher values of the elastic component of the stiffness modulus (lower phase angle, \( \Phi \)) in the entire range of tested temperatures and frequency of loading. This fact proves the greater resistance of these mixtures to accumulation and deformation in a pavement compared to mixtures with conventional binders.

7. According to the analysis of the obtained test results, the optimal solution from a practical point of view is to use a binder simultaneously modified with 2% of SBS and 10% of crumb rubber for the production of low-noise asphalt mixtures. Mixtures SMA8 LA with the addition of 10% of rubber granulate are a good solution for applications in a climate where the average annual temperature is between 5–10 °C.

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References

1. Mikhailenko, P.; Piao, Z.; Kakar, M.R.; Bueno, M.; Athari, S.; Pieren, R.; Heutschi, K.; Poulikakos, L. Low-Noise Pavement Technologies and Evaluation Techniques: A Literature Review. Int. J. Pavement Eng. 2020, 23, 1911–1934. [CrossRef]

2. Ling, S.; Yu, F.; Sun, D.; Sun, G.; Xu, L. A Comprehensive Review of Tire-Pavement Noise: Generation Mechanism, Measurement Methods, and Quiet Asphalt Pavement. J. Clean. Prod. 2021, 287, 125056. [CrossRef]

3. Gardziejczyk, W.; Jaskula, P.; Ejsmont, J.A.; Motylewicz, M.; Stienss, M.; Mioduszewski, P.; Jawadzki, M. Investigation of Acoustic Properties of Poroelastic Asphalt Mixtures in Laboratory and Field Conditions. Materials 2021, 14, 2649. [CrossRef] [PubMed]

4. Gardziejczyk, W. The Effect of Time on Acoustic Durability of Low Noise Pavements—The Case Studies in Poland. Transp. Res. Part Transp. Environ. 2016, 44, 93–104. [CrossRef]

5. Caro, S.; Diaz, A.; Rojas, D.; Nuñez, H. A Micromechanical Model to Evaluate the Impact of Air Void Content and Connectivity in the Oxidation of Asphalt Mixtures. Constr. Build. Mater. 2014, 61, 181–190. [CrossRef]

6. Aliha, M.R.M.; Fazaeli, H.; Aghajani, S.; Moghadas Nejad, F. Effect of Temperature and Air Void on Mixed Mode Fracture Toughness of Modified Asphalt Mixtures. Constr. Build. Mater. 2015, 95, 545–555. [CrossRef]

7. Porto, M.; Angelico, R.; Caputo, P.; Abe, A.A.; Teltayev, B.; Rossi, C.O. The Structure of Bitumen: Conceptual Models and Experimental Evidences. Materials 2022, 15, 905. [CrossRef]
8. Abdulrahman, S.; Hainin, M.R.; Mohd Satar, M.K.I.; Hassan, N.A.; Al Saffar, Z.H. Review on the Potentials of Natural Rubber in Bitumen Modification. *JOP Conf. Ser. Earth Environ. Sci.* 2020, 476, 012067. [CrossRef]  
9. Subhy, A.; Lo Presti, D.; Ainey, G. An Investigation on Using Pre-Treated Tyre Rubber as a Replacement of Synthetic Polymers for Bitumen Modification. *Road Mater. Pavement Des.* 2015, 16, 245–264. [CrossRef]  
10. Apostolidis, P.; Liu, X.; Erkens, S.; Scarpas, A. Evaluation of Epoxy Modification in Bitumen. *Constr. Build. Mater.* 2019, 208, 361–368. [CrossRef]  
11. Porto, M.; Caputo, P.; Loise, V.; Eskandar, S.; Teltayev, B.; Oliviero Rossi, C. Bitumen and bitumen modification: A review on latest advances. *Appl. Sci.* 2019, 9, 742. [CrossRef]  
12. Wang, T.; Xiao, F.; Zhu, X.; Huang, B.; Wang, J.; Amirkhanian, S. Energy Consumption and Environmental Impact of Rubberized Asphalt Pavement. *J. Clean. Prod.* 2018, 180, 139–158. [CrossRef]  
13. Mieczkowski, P.; Budzinski, B. Evaluation of The Modification Efficiency of Bituminous Binders with SBS Polymer Based on Changes in Strain Energy in the Ductility Test. *IOP Conf. Ser. Mater. Sci. Eng.* 2019, 603, 042013. [CrossRef]  
14. Loderer, C.; Partl, M.N.; Poulikakos, L.D. Effect of Crumb Rubber Production Technology on Performance of Modified Bitumen. *Constr. Mater. 2018*, 191, 1159–1171. [CrossRef]  
15. Nejad, F.M.; Aghajani, P.; Modarres, A.; Firoozifar, H. Investigating the Properties of Crumb Rubber Modified Bitumen Using Classic and SHRP Testing Methods. *Constr. Mater. 2012*, 26, 481–489. [CrossRef]  
16. Wang, H.; Liu, X.; Apostolidis, P.; Erkens, S.; Scarpas, T. Numerical Investigation of Rubber Swelling in Bitumen. *Constr. Mater.* 2019, 214, 506–515. [CrossRef]  
17. Mashaan, N.S.; Ali, A.H.; Karim, M.R.; Abdelaziz, M. An Overview of Crumb Rubber Modified Asphalt. *Int. J. Phys. Sci.* 2012, 7, 166–170. [CrossRef]  
18. Khan, N.; Nafees, A.; Hussain, A.; Zaidi, G.; Osama, M.; Ghaffar, S. Exploring the Properties of Recycled Tyre Rubber for Flexible Asphalt Pavement. *J. Basic Appl. Sci.* 2017, 13, 335–339. [CrossRef]  
19. Abdelmagid, A.A.A.; Pei Feng, C. Evaluating the Effect of Rice-Husk Ash and Crumb-Rubber Powder on the High-Temperature Performance of Asphalt Binder. *J. Mater. Civ. Eng.* 2019, 31, 04019296. [CrossRef]  
20. Wang, H.; Liu, X.; Apostolidis, P.; Erkens, S.; Scarpas, A. Effect of Laboratory Aging on Chemistry and Rheology of Crumb Rubber Modified Bitumen. *Mater. Struct.* 2020, 53, 26. [CrossRef]  
21. Zhu, J.; Birgisson, B.; Kringos, N. Polymer Modification of Bitumen: Advances and Challenges. *Eur. Polym. J.* 2014, 54, 18–38. [CrossRef]  
22. Kaya Ozdemir, D.; Topal, A.; McNally, T. Relationship between Microstructure and Phase Morphology of SBS Modified Bitumen with Processing Parameters Studied Using Atomic Force Microscopy. *Constr. Mater. 2021*, 268, 121061. [CrossRef]  
23. Saboo, N.; Kumar, P. Performance Characterization of Polymer Modified Asphalt Binders and Mixes. *Adv. Civ. Eng.* 2016, 2016, 1–12. [CrossRef]  
24. Al-Hadidy, A.I.; Yi-qiu, T. Effect of Styrene-Butadiene-Styrene on the Properties of Asphalt and Stone-Matrix-Asphalt Mixture. *J. Mater. Civ. Eng.* 2011, 23, 504–510. [CrossRef]  
25. Behnood, A.; Olek, J. Rheological Properties of Asphalt Binders Modified with Styrene-Butadiene-Styrene (SBS), Ground Tire Rubber (GTR), or Polyphosphoric Acid (PPA). *Constr. Mater. 2017*, 151, 464–478. [CrossRef]  
26. Hassanpour-Kasanagh, S.; Ahmedzade, P.; Fainleib, A.M.; Behnood, A. Rheological Properties of Asphalt Binders Modified with Recycled Materials: A Comparison with Styrene-Butadiene-Styrene (SBS). *Constr. Mater. 2020*, 230, 117047. [CrossRef]  
27. Zhou, J.; Chen, X.; Xu, G.; Fu, Q. Evaluation of Low Temperature Performance for SBS/CR Compound Modified Asphalt Binders Based on Fractional Viscoelastic Model. *Constr. Mater. 2019*, 214, 326–336. [CrossRef]  
28. Ye, Y.; Xu, G.; Lou, L.; Chen, X.; Cai, D.; Shi, Y. Evolution of Rheological Behaviors of Styrene-Butadiene-Styrene/Crumb Rubber Composite Modified Bitumen after Different Long-Term Aging Processes. *Materials 2019*, 12, 2345. [CrossRef]  
29. Xiang, L.; Cheng, J.; Kang, S. Thermal Oxidative Aging Mechanism of Crumb Rubber/SBS Composite Modified Asphalt. *Constr. Mater. 2015*, 75, 169–175. [CrossRef]  
30. Hasheminejad, N.; Vuye, C.; Margaritis, A.; Van den bergh, W.; Dirckx, J.; Vanlanduit, S. Identification of the Viscoelastic Properties of an Asphalt Mixture Using a Scanning Laser Doppler Vibrometer. *Mater. Struct.* 2020, 53, 131. [CrossRef]  
31. Sówik, M.; Bartkowiak, M. Calculation of Measurement Uncertainty for Stiffness Modulus of Asphalt Mixture. *J. Civ. Eng. Archit.* 2015, 9, 1325–1333. [CrossRef]  
32. Poulikakos, L.D.; Hofko, B. A Critical Assessment of Stiffness Modulus and Fatigue Performance of Plant Produced Asphalt Concrete Samples Using Various Test Methods. *Road Mater. Pavement Des.* 2020, 22, 2661–2673. [CrossRef]  
33. Hou, H.; Wang, T.; Wu, S.; Xue, Y.; Tan, R.; Chen, J.; Zhou, M. Investigation on the Pavement Performance of Asphalt Mixture Based on Predicted Dynamic Modulus. *Constr. Mater. 2016*, 106, 11–17. [CrossRef]  
34. Lee, H.J.; Lee, J.H.; Park, H.M. Performance Evaluation of High Modulus Asphalt Mixtures for Long Life Asphalt Pavements. *Constr. Mater. 2007*, 21, 1079–1087. [CrossRef]  
35. Cheng, H.; Liu, L.; Sun, L.; Li, Y.; Hu, Y. Comparative Analysis of Strain-Pulse-Based Loading Frequencies for Three Types of Asphalt Pavements via Field Tests with Moving Truck Axle Loading. *Constr. Mater. 2020*, 247, 118519. [CrossRef]  
36. Cheng, H.; Wang, Y.; Liu, L.; Sun, L. Effects of Using Different Dynamic Moduli on Predicted Asphalt Pavement Responses in Mechanistic Pavement Design. *Road Mater. Pavement Des.* 2021, 23, 1860–1876. [CrossRef]
37. Pakholak, R.; Plewa, A.; Gardziejczyk, W. Influence of Type of Modified Binder on Stiffness and Rutting Resistance of Low-Noise Asphalt Mixtures. *Materials* 2021, 14, 2884. [CrossRef]
38. Pakholak, R.; Plewa, A.; Hatalski, R. Evaluation of Selected Technical Properties of Bitumen Binders Modified with SBS Copolymer and Crumb Rubber. *Struct. Environ.* 2020, 12, 12–19. [CrossRef]
39. Gardziejczyk, W.; Plewa, A.; Pakholak, R. Effect of Addition of Rubber Granulate and Type of Modified Binder on the Viscoelastic Properties of Stone Mastic Asphalt Reducing Tire/Road Noise (SMA LA). *Materials* 2020, 13, 3446. [CrossRef]
40. European Standard: EN 12607-1; 2014 Bitumen and Bituminous Binders-Determination of the Resistance to Hardening under Influence of Heat and Air-Part 1: RTFOT Method. European Standard: Brussel, Belgium, 2014. Available online: https://www.sis.se/api/document/preview/104363/ (accessed on 9 June 2022).
41. AASHTO R 30; Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA). AASHTO: Washington, DC, USA, 2022. Available online: https://global.ihs.com/doc_detail.cfm?document_name=AASHTO%20R%2030&item_s_key=00488905 (accessed on 9 June 2022).
42. European Standard: EN 12697-33; 2019 Bituminous Mixtures-Test Method-Part 33: Specimen Prepared by Roller Compactor. European Standard: Brussel, Belgium, 2019. Available online: https://www.sis.se/api/document/preview/80010375/ (accessed on 9 June 2022).
43. European Standard: 12697-26; 2018 Bituminous Mixtures-Test Methods-Part 26: Stiffness. European Standard: Brussel, Belgium, 2018. Available online: https://www.sis.se/api/document/preview/80004874/ (accessed on 9 June 2022).
44. Di Mino, G.; Di Liberto, C.M. Experimental Survey on Dry Asphalt Rubber Concrete for Sub-Ballast Layers. *J. Civ. Eng. Archit.* 2012, 6, 1615–1626.
45. Skotnicki, L.; Koba, H.; Szydlo, A. Rubber Modified Stone Matrix Asphalts. In Proceedings of the Asphalt Rubber 2012 Conference, Munich, Germany, 23–26 October 2012; Jorge, B., Sousa, Eds.; pp. 253–265.
46. Moreno-Navarro, F.; Sol-Sánchez, M.; Rubio-Gámez, M.C.; Segarra-Martínez, M. The Use of Additives for the Improvement of the Mechanical Behavior of High Modulus Asphalt Mixes. *Constr. Build. Mater.* 2014, 70, 65–70. [CrossRef]
47. Ghasemi, M.; Marandi, S.M. Performance Improvement of a Crumb Rubber Modified Bitumen Using Recycled Glass Powder. *J. Zhejiang Univ. Sci. A* 2013, 14, 805–814. [CrossRef]
48. Zhang, J.; Huang, W.; Hao, G.; Yan, C.; Lv, Q.; Cai, Q. Evaluation of Open-Grade Friction Course (OGFC) Mixtures with High Content SBS Polymer Modified Asphalt. *Constr. Build. Mater.* 2021, 270, 121374. [CrossRef]