

Deformation characteristics of asphalt mixtures

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Abstract. Asphalt pavement is among the most widespread road surfaces. For their design, assessment, and service life, it is necessary to evaluate the deformation characteristics of asphalt mixtures, which include the complex modulus of rigidity. Two-point (2PB-TR) and four-point (4PB-PR) flexural tests are used to determine these. The scientific paper focuses on the evaluation of the complex modulus as a function of varying temperature and frequency. The results of the study indicated that both methods provide significant information on the behaviour of asphalt mixtures under different loading conditions. Four-point bending may be more sensitive to changes in deformation properties than two-point bending. This finding is of fundamental importance when analysing the influence of different factors on the mechanical properties of asphalt mixtures. Measurements were performed at temperatures of 0°C, 10°C and 20°C and frequencies of 1 Hz, 5 Hz, 10 Hz, 15 Hz and 20 Hz. Validation of the different measurement methods was carried out on the comparison asphalt mix AC 11 O PMB 45/80-75.

1 Introduction

Roads have played a strategic role in the distant past. Road construction has undergone a great evolution and roads have gradually been improved. Nowadays, most roadways are made of asphalt mixtures [1]. For the best possible mix design, laboratory tests are carried out in labo, where deformation characteristics, among other properties, are determined. The focus of this technical paper is on the complex modulus of rigidity. The results are based on laboratory measurements in accordance with STN standards [2]. Experimental measurements were carried out using 2PB and 4PB. It is these two different measurement methodologies that are credited for the comprehensive evaluation of the selected mixture. Similar issues have already been addressed by many authors [3-5]. Previous experimental measurements and research show that the deformation characteristics serve as a prediction of the behavior of the mixture embedded in the pavement. Their verification can be carried out by several methods. The paper is focused on the comparison of the results of the 2PB and 4PB auxiliary values. The intercept of the values and the common mean deviation were sought. The contribution lies in the appropriate selection of the chosen measurement procedure based on different criteria.

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2 Asphalt pavements

The structural layers (base and wearing course) of the asphalt pavement are made of asphalt mixtures. The correct selection of materials, their thickness and finish are important in the design of the pavement [6]. Several factors influence the designing of pavements:

- traffic congestion-conditions of the engineering and geological subsoil,
- bearing capacity of the subsoil,
- climatic conditions-properties of the materials,
- use of the materials (with a preference for reuse-life cycle of the construction work (input costs and costs of restoration and maintenance),
- environment and its protection.

3 Asphalt mixtures

Asphalt mixtures are defined according to the European Standards as a mixture of aggregates having a continuous or discontinuous grain line. The mixture is bonded together using an asphalt binder. The binder consists in most cases of an asphalt emulsion, in some cases of asphalt only or modified asphalt. When modified, the properties of the asphalt are modified by additives and admixtures. The improvement of the characteristics focuses on influencing the elasticity, adjusting the rheological properties, but also on better adhesion of the asphalt binder to the aggregate and so on [7]. The modified PMB binder is used in scientific experiments. The composition of the asphalt mix, which is made up of asphalt, aggregate and air gaps, is shown in Fig. 1. Each part of the asphalt mixture affects the overall volume and gap properties of the mixture. The individual constituent representation and their quality affect the overall behaviour of the mix and its deformation characteristics [8]. Composition of asphalt mixtures shows Fig. 1.

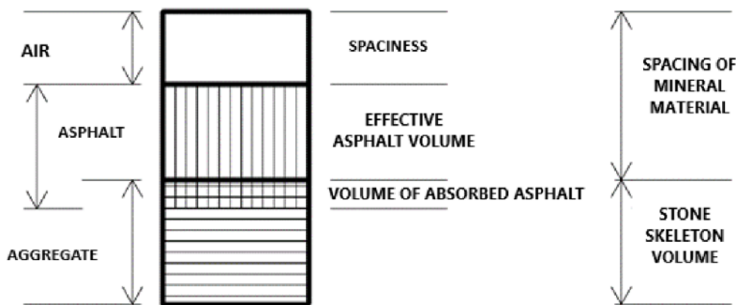


Fig. 1 Composition of asphalt mixtures [8].

For the chosen experiment, AC 11 O PMB 45/80-75 mixture was used. The asphalt mixture was taken directly from the construction site and subsequently processed to produce the test samples.

4 Deformation characteristics of asphalt mixtures

The theoretical basis of the scientific experiment is based on the determination of the deformation characteristics of road materials [3]. These parameters are influenced by the force effects generated by traffic loads, but are mainly affected by temperature changes, which are manifested by cyclic changes in the structural parts of the road [4]. It is true that the deformation of different materials, despite the same simulated load, is very different. The

magnitude of the deformation is influenced by the deformation characteristics on which the calculation of the stresses is based. The most important are:

- modulus of deformation,
- modulus of elasticity,
- complex modulus (stiffness and elasticity),
- Poisson's number.

The deformation characteristics depend on several factors such as temperature, humidity, time of load application, type of material, etc. The ways in which the deformation characteristics can be investigated are based on EN 13108-20, which specifies the type of loading, temperature, frequency, or duration of loading. Fig. 2 shows Tests to determine the stiffness of asphalt mixtures.

LOAD TYPE	TEMPERATURE	FREQUENCY / LOADING TIME
2 PB - TR	15 °C	10 Hz
2 PB - TR	30 °C	10 Hz
2 PB - PR	15 °C	10 Hz
3 PB - PR	15 °C	10 Hz
4 PB - PR	20 °C	8 Hz
4 PB - PR	10 °C	10 Hz
DTC - CY	15 °C	10 Hz
DT - CY / DT - PR	15 °C	0,02 s
4 PB - PR	10 °C	8 Hz
4 PB - PR	15 °C	8 Hz
4 PB - PR	20 °C	8 Hz
CIT - CY	10 °C	10 Hz
CIT - CY	20 °C	0,1 Hz

Fig. 2 Tests to determine the stiffness of asphalt mixtures [9].

4.1 Complex stiffness modulus

In terms of rheological properties, the complex modulus of rigidity is crucial for asphalt mixtures. During the measurement of the complex modulus, harmonic alternating and short-term loading of the specimens is carried out. The complex modulus establishes a relationship between the transformation and the stresses that are generated over time (t). A sinusoidal waveform is produced in cases where the material is perfectly elastic [10]. The effect of the stresses gives rise to the resulting deformation. The transformation is displaced in time relative to the stress by a phase angle [5]. The magnitude of the transformation, as well as the value of the phase angle, varies with the frequency and temperature at which the test is carried out. The relationship between voltage and transformation is further specified by the complex modulus of elasticity (E). The complex modulus of rigidity shall be measured experimentally on specimens in accordance with the prescribed standard. The test samples are loaded with a harmonic force. The tests are carried out at different temperatures, and proper tempering with sufficient time intervals is necessary when the temperatures change. The correct procedure for tempering the test sample is to cool or heat the whole sample to the required temperature. For each temperature, the frequency is also varied. The relationship between stress σ and the transformation ε is valid.

$$E = \frac{\sigma}{\varepsilon}$$

E- complex stiffness module [MPa]
σ- tension [MPa]

(1)

ϵ - maximum deformation [-]

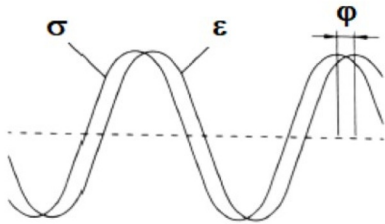


Fig. 3 Voltage dependence and transformation, with the displacement expressing the phase angle [11].

4.2 Two-point bending test- 2PB

The name two-point bending (2PB) indicates that the test samples are stressed at two points (in the indentation and at the free end). The principle of the test is to determine the stiffness of the asphalt mixture. The measurement is made by harmonic sinusoidal loading, which stresses the test samples at short intervals. The result of the experiments is a prediction of how the mix will behave in the structural layers of the road. For this experiment, the 2PB-TR method was chosen, which tests trapezoid-shaped samples. The measuring equipment is located at the University of Žilina, Faculty of Civil Engineering, in the Road Laboratory. The result of the test is the value of the complex modulus of rigidity E^* [12]. To perform the experiment, it is necessary to create test specimens that meet the required shape and dimensional parameters. The specimens are made from asphalt mixtures, compacted in a mold. After disassembly of the mold, the slab is cut in accordance with the required dimensions. A water-cooled circular saw is used for cutting. A sample of the trapezoid shape is shown in Fig.4.

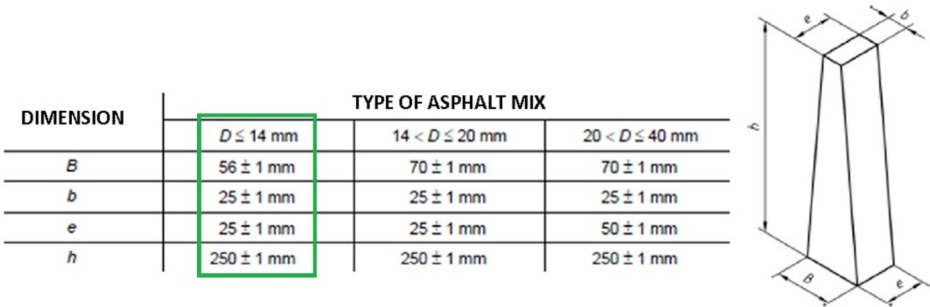


Fig. 4 Dimensions of the trapezoid shape sample for 2PB-TR [13].

The anchor plates are mounted on the cut and measured test samples to the required dimensions using a mounting template and glued with a special two-component adhesive designed for tear-off tests.

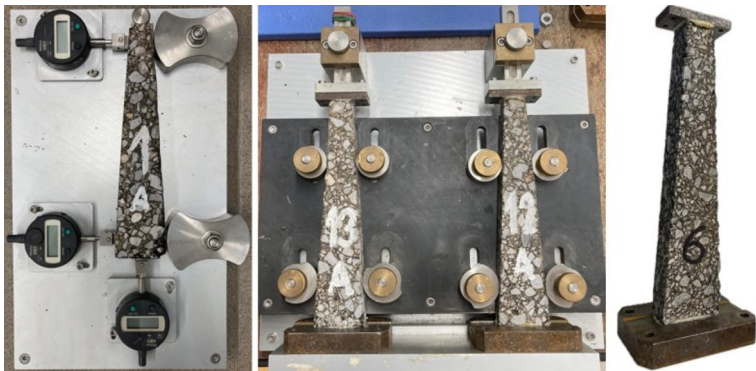


Fig. 5 Procedure for measuring and bonding anchor plates.

In Fig. 5, from the left side to the left, the measuring template and the sample sticking template, which are part of the COOPER CRT-2PT-FET measuring device, are shown. The right part of the picture shows the test body with the anchor plates)



Fig. 6 COOPER CRT-2PT-FET (on the left the whole device, on the right a detail of the inside of the device and mounted samples).

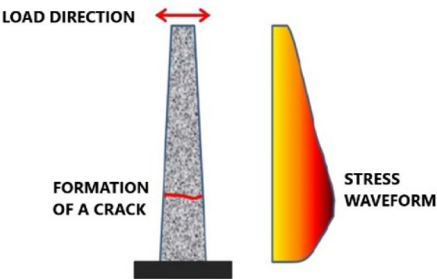


Fig.7 Test principle and stress waveform 2PB-TR [12].

The measured data is then processed for assessment, evaluation, and comparison with each other. The following tables show the average values of the complex stiffness moduli of the test samples. From the values, it is possible to see the influence of temperature and frequency on the magnitude of the complex modulus of stiffness of the mixture. In practice, this means that the effect of high pavement temperatures combined with slower truck travel

(associated with braking, turnouts, and direction changes) results in the smallest complex modulus of stiffness. It is due to these factors that permanent deformations in the form of transverse and longitudinal irregularities are generated in the roadways. The evaluation of mixtures under laboratory conditions based on their deformation characteristics serves as a tool to predict and eliminate as much as possible the occurrence of deformations on the real mixture embedded in the pavement. The deformation characteristic parameters predict the durability of the mixture loaded with traffic.

Tab.1 Complex stiffness module 2PB-TR [MPa] for the mixture AC11 O+PMB.

Asphalt mixture	frequency [Hz]	temperature				
		0 °C	10°C	15°C	20°C	27°C
AC 11 O	1	6 996	3 247	2 063	1 312	566
	5	8 774	4 839	3 408	2 331	1 205
	10	9 546	5 486	3 980	2 775	1 459
	15	9 722	5 820	4 261	3 045	1 651
	20	10 134	6 165	4 553	3 290	1 848

The table shows the measured values of the complex stiffness moduli while varying the temperature and frequency. From the measured data, we can conclude that the largest values of complex stiffness moduli are at the combination of maximum frequency (20Hz) and minimum temperature (0°C). On the other hand, at minimum frequency (1Hz) and maximum temperature (27°C), the complex modulus is the smallest. The gradual saturation of the color to orange indicates a decrease in the complex modulus of rigidity. On the other hand, the saturation of green indicates an increase in the value of the complex modulus of rigidity.

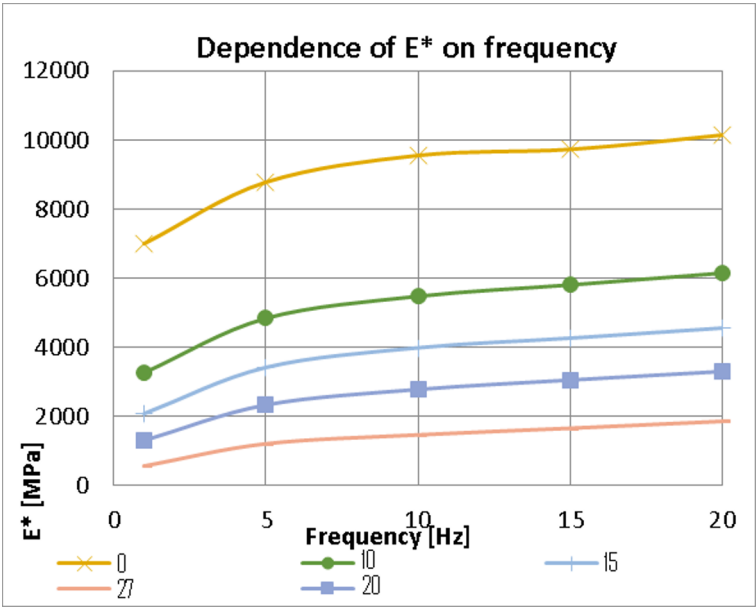


Fig. 8 Complex modulus versus frequency 2PB.

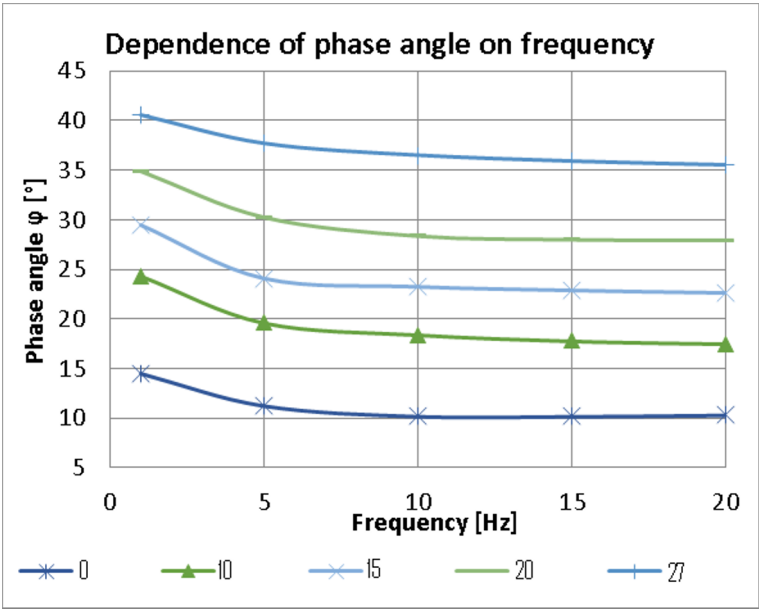


Fig. 9 Phase angle versus frequency 2PB.

4.3 Four-point bend test 4PB

The name four-point bending (4PB) refers to the way the test is performed, where the specimen is stressed in four areas by bending. The test body is fixed symmetrically. The test procedure and method shall be in accordance with EN 12 697-26. The measurement shall be carried out at different temperatures: 0°C, 10°C and 20°C, selecting the following frequencies for each temperature: 0.1Hz, 1.0Hz, 2.0Hz, 3.0Hz, 5.0Hz, 8.0Hz, 10.0Hz, 15.0Hz, 20.0Hz, 30.0Hz and 50.0Hz. The test waveform is created by applying a sinusoidal force to achieve an amplitude of 50 microstrain [10]. The dynamic modulus values are used to characterize the viscoelasticity of asphalt mixtures. 4PB serves as a mechanical empirical method that has applications in pavement design and composition. The dynamic modulus takes into account the loading rate while varying the temperature. It simulates the loading of an asphalt mixture under laboratory conditions in the design phase. Isothermal curves are constructed from the measured values.

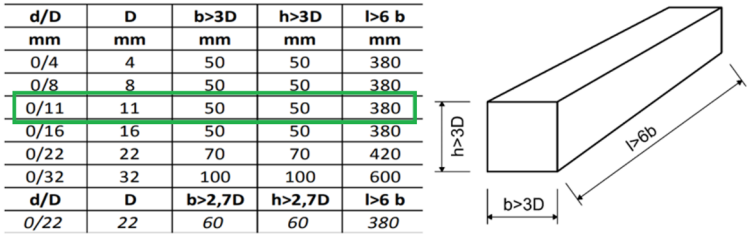


Fig. 10 Dimensions of the trapezoid shape sample for 4PB-PR [13].

The measurement of the stiffness of the dynamic modulus is carried out on test bodies in the shape of a regular tetrahedral prism. In the case of the experiment with the comparison mixture AC11, the dimensions were 50x50mm with a length of 400mm in accordance with STN EN 12697-24. It is valid that the width and height of the test body shall be at least three times the largest grain of the aggregate mixture. The specimens are cut from the slab, then

their current dimensions are measured and weighed. It is important to temper the specimens to the required temperature before the actual measurement, but the specimens must not be tempered for more than 6 h because of possible aging and deformation. In Fig. 11, the test bodies in the measuring device are shown. The experimental measurement of 4PB-PR was realized thanks to cooperation with the Faculty of Civil Engineering of the ČVUT in Prague [5, 10].

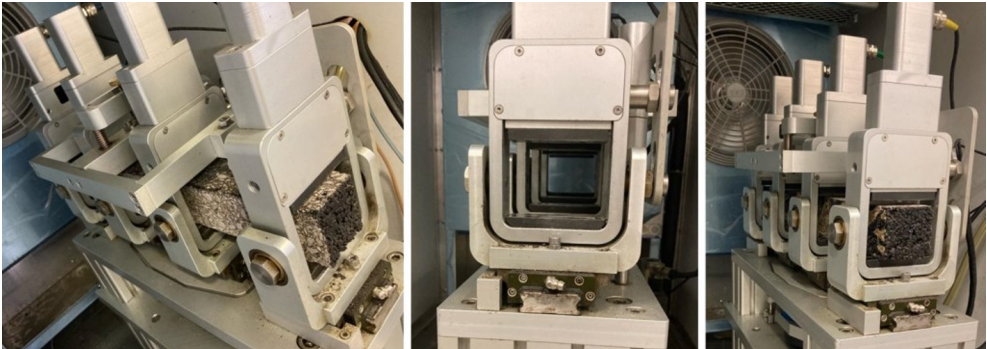


Fig. 11 Test samples of the measuring device at the ČVUT in Prague 4PB-PR.

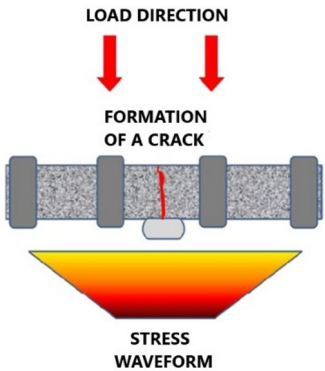


Fig. 12 Test principle and stress waveform 4PB-PR [12].

The experimentally measured values of the complex stiffness moduli of 4PB-PR have been tabulated in the following table. The data are based on the diameters of the measured test-samples where the temperature and loading frequency were varied [12].

Tab.2 Complex stiffness modulus 4PB-PR [MPa] for the mixture AC11 O+PMB.

Asphalt mixture	frequency [Hz]	temperature		
		0 °C	10°C	20°C
AC 11 O	0.10	3 132	1 439	703
	1.00	5 822	2 955	1 526
	2.00	6 652	3 503	1 833
	3.00	7 167	3 878	2 046
	5.00	7 758	4 362	2 369
	8.00	8 300	4 823	2 693
	10.00	8 565	5 051	2 858
	15.00	8 946	5 463	3 184
	20.00	9 213	5 639	3 419
	30.00	9 692	6 240	3 999
	50.00	9 711	6 512	4 408

From Table 2, the frequency-temperature relationship is also valid for 4PB-PR, which influences the values of the complex modulus of rigidity of asphalt mixtures. For the combination of the highest temperature (20°C) and the lowest frequency (0.1Hz), the complex modulus of stiffness is the lowest. Otherwise, for the condition of lowest temperature (0°C) and highest frequency (50 Hz), the value of the complex modulus of rigidity is the highest. In practice, this means that during the winter period the pavement is less susceptible to permanent deformation. Similarly to 2PB, for 4PB the orange color indicates a reduced complex modulus of rigidity and the green color symbolizes the highest values.

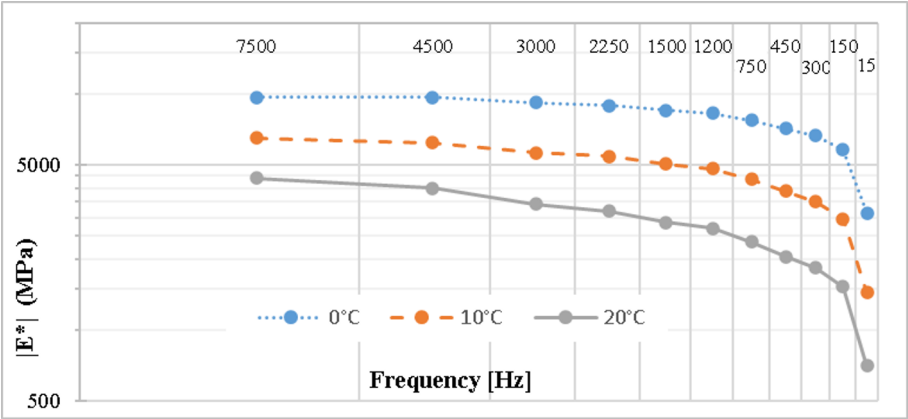


Fig. 13 Complex modulus versus temperature and frequency 4PB.

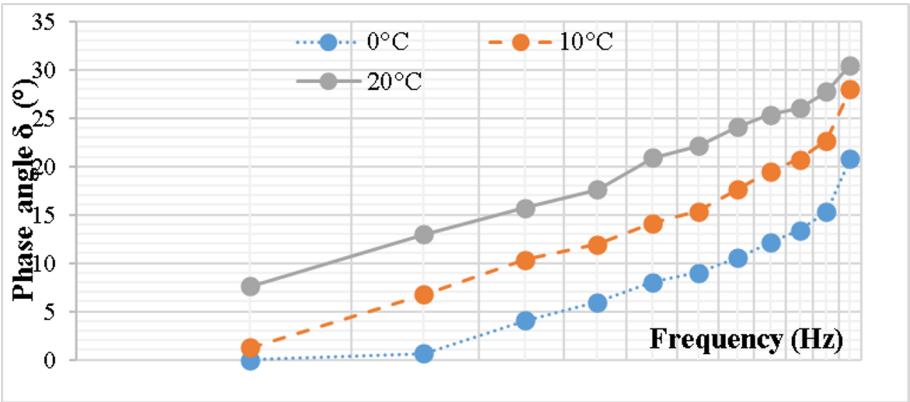


Fig. 14 Phase angle versus frequency 4PB.

5 Peer review of results

The values of the complex stiffness moduli experimentally measured using the two methods, 2PB-TR and 4PB-PR, were then compared. Only data with common penetration (same frequency and temperature) were compared. The processing of the measured results is presented in the following table, where the percentage differences of the values for 2PB and 4PB are shown in the right part. The average difference of the measured values was 8.3% as shown in Tab 3.

Tab.3 Comparison of measured results 4PB-PR and 2PB-TR.

frek. [Hz]	2PB			4PB			mutal deviation between 4PB a 2PB		
	0 °C	10°C	20°C	0 °C	10°C	20°C			
1.00	6 996	3 247	1 312	5 822	2 955	1 526	16.8%	9.0%	14.1%
5.00	8 774	4 839	2 331	7 758	4 362	2 369	11.6%	9.9%	1.6%
10.00	9 546	5 486	2 775	8 565	5 051	2 858	10.3%	7.9%	2.9%
15.00	9 722	5 820	3 045	8 946	5 463	3 184	8.0%	6.1%	4.4%
20.00	10 134	6 165	3 290	9 213	5 639	3 419	9.1%	8.5%	3.8%
average deviation							8.3%		

6 Conclusion

In this study, the deformation characteristics of asphalt mixtures were investigated in detail using the 2PB-TR and 4PB-PR methods. The results showed that both methods provide important information on the behaviour of asphalt mixtures under different loading conditions. Four-point bending may be more sensitive (investigated at multiple frequencies) to changes in deformation properties than two-point bending, which may be important when analysing the influence of various factors on the mechanical properties of asphalt mixtures. The increased sensitivity of the 4PB lies in the larger range of measured frequencies. The evaluation was carried out on one AC11 O PMB 45/80-75 mixture.. Based on our findings, we recommend the use of a combination of both methods in the evaluation of the deformation

properties of asphalt mixtures. The variety of investigation procedures produces comprehensive information about the behaviour under realistic loading conditions. The technical article highlights the methods for evaluating the deformation characteristics. For a more detailed investigation, further studies are necessary, which should focus on optimizing the testing methods and on identifying correlations between the results obtained by different methods of scientific experiments.

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