TEMPERATURE CORRECTION OF DEFLECTIONS AND BACKCALCULATED ELASTICITY MODULI DETERMINED FROM FALLING WEIGHT DEFLECTOMETER MEASUREMENTS ON ASPHALT PAVEMENTS

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Resume

The evaluation of the bearing capacity of asphalt pavements is usually performed by analysing the deflections measured by a Falling Weight Deflectometer (FWD). The deflection changes with the pavement temperature. In evaluation is necessary to consider the thermal gradient of pavement and perform the temperature correction. The article contains an analysis of effects of the pavement temperature on FWD results on the long-term monitored sections. The temperature correction was performed on measured deflections or back-calculated elasticity moduli. The moduli recalculated to the temperature of 20 °C according to both procedures were similar. Comparison of moduli determined by recalculation to moduli back-calculated from the deflection bowls measured at the temperature of 20 °C, has proven smaller differences for the moduli determined from the deflection bowl corrected to the temperature of 20 °C.

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1 Introduction

Asphalt layers of flexible pavements contain a bituminous binder that is sensitive to temperature changes occurring in a pavement due to air temperature changes. In [1] it is stated that the temperature of asphalt layers not only changes within the year, but within a single day, as well, when changes of temperature gradients occur in asphalt layers. A change in the stiffness of a bituminous binder used in asphalt mixtures causes a change in their stiffness. Therefore, a deflection measured in one place in a different time will have different values. This has to be considered in diagnostics and evaluation of asphalt pavement bearing capacity. The necessity of temperature correction has already been clearly proven in numerous scientific publications, e. g. [2-11].

Due to the fact that the temperature gradient in a pavement can be high (particularly during the sunny summer days), some requirements, limiting measurements in relation to pavement temperature, can be found. According to [12], the temperature of pavement during the measurement has to be in the range of 0 - 30 °C. The temperature of pavement is characterized by the average temperature of asphalt layers, which is considered as the temperature in a certain depth under the pavement surface, e. g. 40 mm [1-12] or 50 mm [10]. As the average temperature of asphalt layers should be determined at every diagnostic point, a non-destructive method, based on the surface temperature of pavement and temperature gradients during the day, is optimum for its determination. According to [13], the average temperature of asphalt layers can be determined from the surface temperature of asphalt pavement and the temperature difference between the surface temperature and the average temperature of asphalt layers. Other ways of predicting temperature in asphalt pavement, based on the pavement surface temperature, can be found e. g. in [14] or [15].

Two approaches of temperature correction can be used in the evaluation process of data from an FWD device. The first is the temperature corrections of deflections, which are subsequently used for back-calculation of elasticity moduli. Possible approaches, used for the temperature correction of deflections, are presented e. g. in [6, 10]. An important finding, regarding the temperature correction of deflections, is that the effect of temperature decreases with growing distance from the load axis and can be neglected at a certain distance. According to [10], the effect of temperature on deflections can be neglected at a distance longer than 600 mm from the load axis d. Different impact of temperature on deflections at various distances from the load axis was also proven in [6].

***Table 1** Composition of tested pavements*

Section	Thickness of layer (mm)			
	Asphalt	Base	Subbase	Total
1	190	200	200	590
2	100	400	0	500
3	110	200	200	510
4	350	450	0	800
5	70	450	0	520
6	180	400	0	580
7	250	200	400	850
8	140	400	0	540
9	120	300	0	420
10	90	300	0	390

The other option is the back-calculation of elasticity moduli for a specific temperature occurring during the measurement and temperature correction of the back-calculated moduli. Various reference temperatures are used worldwide depending on the next use (calculation of residual life, design of overlay thickness, etc.) and relates to used method. The value of 20 °C [4], or potentially 25 °C [5], is frequently used as a reference temperature. Equation published in [6] allows to select own reference temperature (e. g. 20 °C, 25 °C). The method of the elasticity moduli temperature correction is described in numerous publications, e. g. [4, 7-8, 11]. An extensive overview of models for the temperature correction of the asphalt layers elasticity moduli by different authors is shown in [2].

As the two mentioned approaches can lead to different outputs, the aim of the presented study was to investigate differences in the back-calculated moduli recalculated to the reference temperature of 20 °C using both approaches.

2 Experimental sections and methodology

The effect of temperature on measured deflections and back-calculated elasticity moduli was investigated on 10 testing sections with different composition of asphalt pavement structures (Table 1). Three points with the interval of 1 m were selected for repeated testing in each section.

Deflections were generated and registered by the deflectometer FWD RODOS. Twenty cycles were performed at each testing point. Each cycle was executed at different temperature and consisted of three drops with the load force of 50 kN.

Temperature of air and pavement on surface, in the depth of 30 - 40 mm and 70 - 90 mm was registered during the measurements in the vicinity of the tested point. The total temperature range was 1-35 °C.

The modulus of elasticity of individual pavement layers was determined by back-calculation using the computer program PADAL.

3 Temperature correction of backcalculated elasticity moduli

This approach uses the elasticity moduli calculated for a specific temperature occurring during the measurements. These are corrected (recalculated) to a “reference” temperature.

The plot of temperature against elasticity moduli back-calculated directly from a measured deflection bowl and determination of the regression curve was the first step in determination of the temperature effect on asphalt layers elasticity moduli. The example in Figure 1 shows the back-calculated elasticity moduli derived from all the repeated measurements at three points of the section 5 that were performed at different times and temperatures. The coefficient of determination is high and the temperature effect on back-calculated modulus is evident.

The temperature correction coefficients of each section, intended for the recalculation of the back-calculated elasticity moduli to the reference temperature of 20 °C, were derived from the regression curve using the formula:

$$c_E = E_{20}/E_T, \tag{1}$$

where:
c_E = temperature correction coefficient for modulus of elasticity [-],
E_{20} = elasticity modulus of asphalt layers at the temperature of 20 °C calculated from the regression curve [MPa],
E_T = elasticity modulus of asphalt layers at the temperature T calculated from the regression curve [MPa].

The set of curves, representing the calculated temperature correction coefficients (Figure 2) was used for determination of a general formula:

$$c_E = e^{-0{,}0387 \cdot (20 - T)}. \tag{2}$$

Using this, the recalculation of elasticity modulus to the reference temperature of 20 °C was determined in the form:

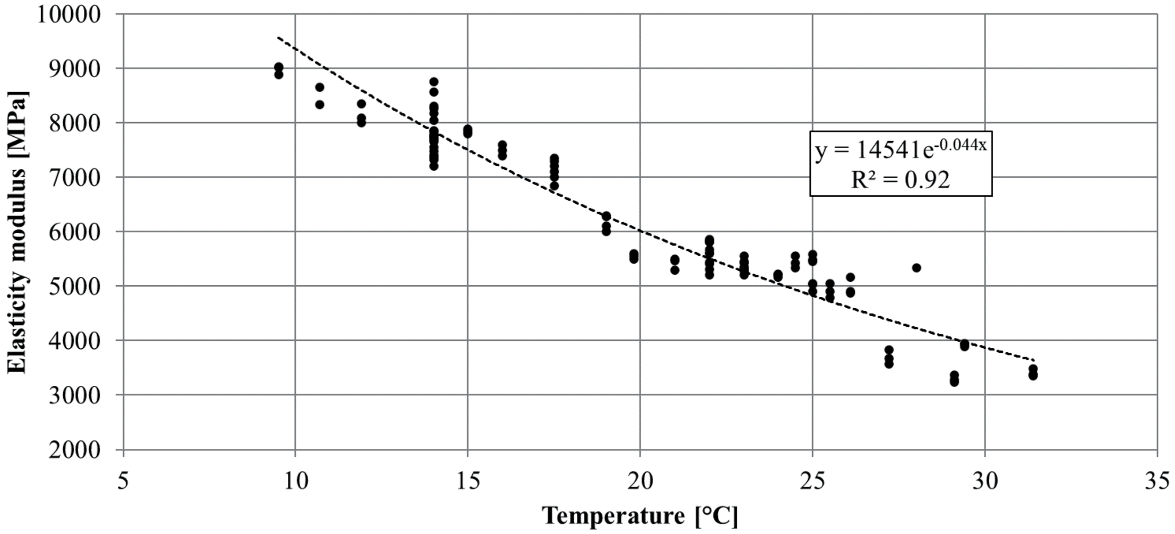

Figure 1 *Variation of the asphalt layers elasticity moduli with temperature (section 5)*

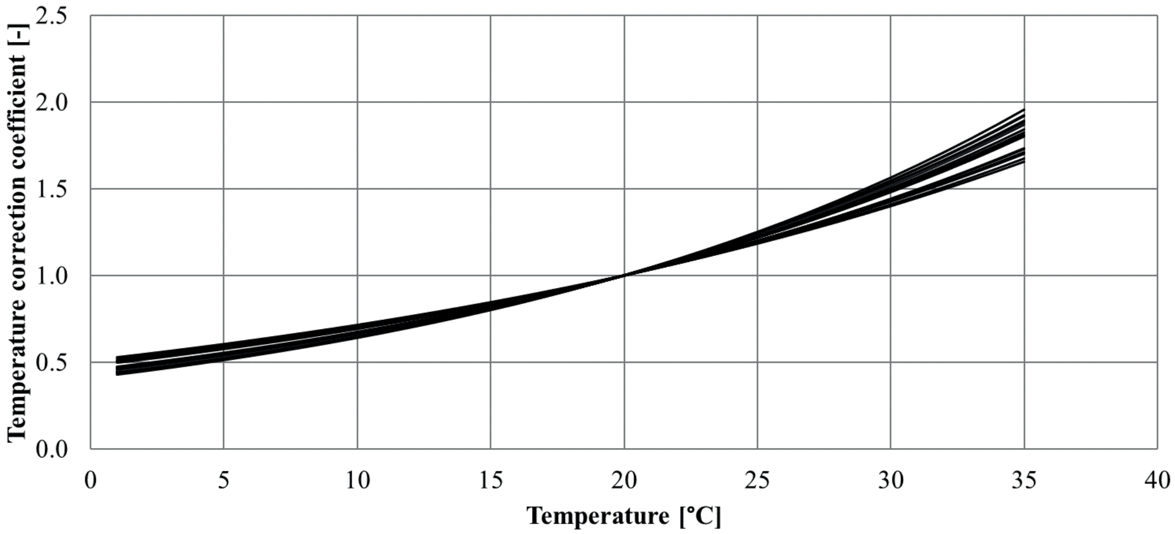

Figure 2 *Calculated temperature correction coefficients*

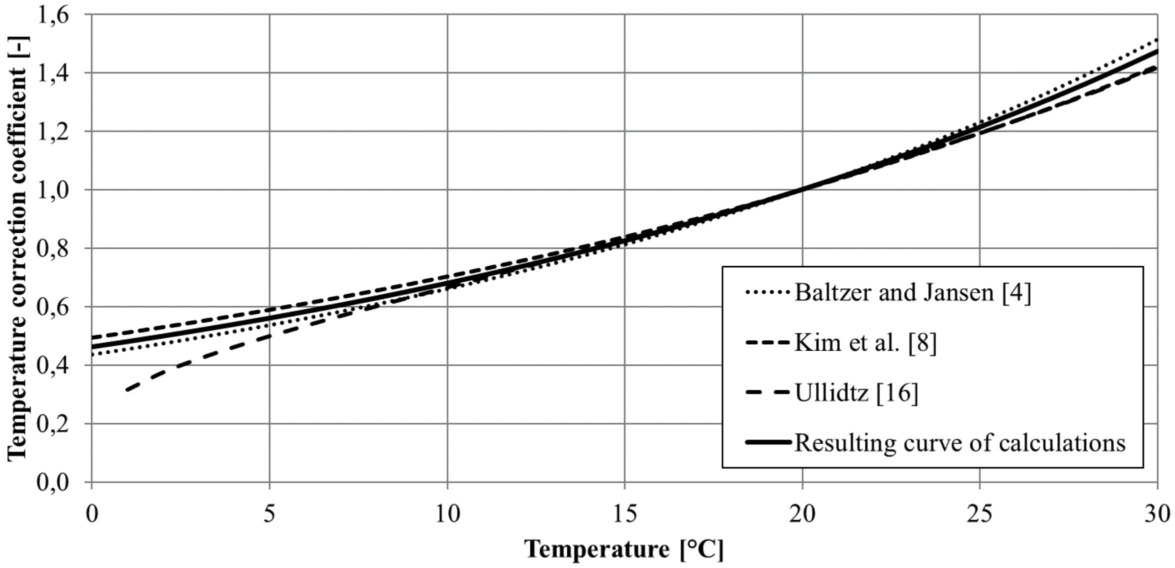

Figure 3 *Comparison of determined correction to results of other authors*

$$E_{20,cor} = E_T \cdot e^{-0.0387 \cdot (20-T)}, \quad (3)$$

where:
$E_{20,cor}$ = elasticity modulus of asphalt layers corrected to the reference temperature of 20 °C [MPa],
E_T = back-calculated elasticity modulus of asphalt layers for the test temperature T [MPa],
T = test temperature of asphalt layers in the depth of 40 mm [°C].

The determined temperature correction coefficients of elasticity modulus of asphalt layers are similar to previously published results [4, 8, 16] (see Figure 3).

4 Temperature correction of measured deflections

The direct correction of deflections is another option how to consider the effect of temperature. To do this, correction coefficients must be known. Therefore, the deflections measured at the position of sensors were plotted against the test temperature and a regression curve was derived (Figure 4). The example in Figure 4 that shows deflections from repeated measurements at the same point(s) at different times and temperature conditions, confirms the linear dependency for all the distances of sensors and variability of the temperature effect. The change in deflection due to the temperature variation is the most significant in the case of the central deflection (the distance of 0 mm from the load axis) and gradually decrease for the more distant sensors.

The temperature correction coefficients for each sensor to the reference temperature of 20 °C were derived from the regression curve using the formula:

$$c_d = d_{20}/d_T, \quad (4)$$

where:
c_d = temperature correction coefficient for deflections [-],

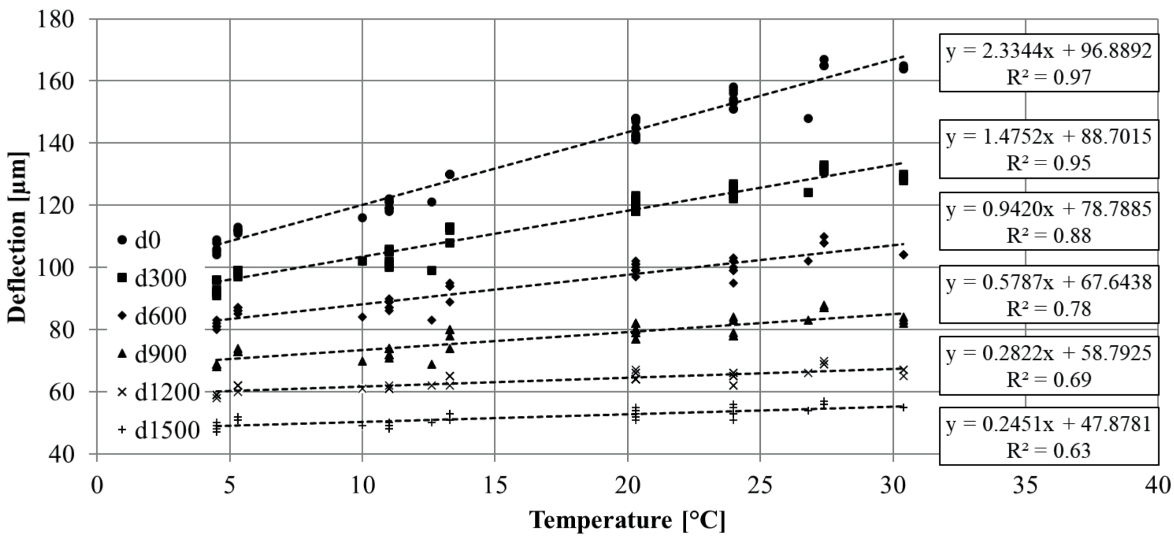

Figure 4 *Change of deflections with temperature (section 5)*

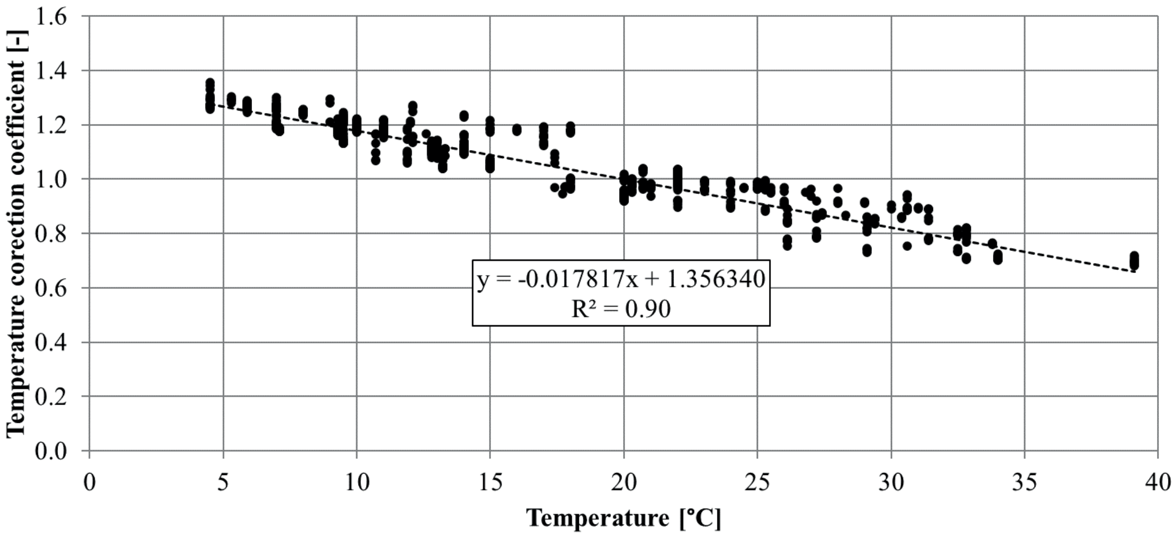

Figure 5 *Regression curve of the temperature correction coefficient deflection d_0 (in the load axis)*

d_{20} = deflection at the temperature of 20 °C calculated from the regression curve [μm],
d_T = deflection at the temperature T calculated from the regression curve [μm].

Subsequently, all of correction coefficients, calculated for a given sensor from the measurements on all of test sections, were grouped together and the final regression curve was derived (Figure 5). This procedure was applied for all the sensors and the regression curves according to distance of a sensor from the load axis given by Equations (5) - (10).

$$c_{d,0} = -0.017817 \cdot T + 1.35634 (R^2 = 0.90), \quad (5)$$

$$c_{d,300} = -0.012116 \cdot T + 1.24232 (R^2 = 0.82), \quad (6)$$

$$c_{d,600} = -0.007555 \cdot T + 1.15110 (R^2 = 0.64), \quad (7)$$

$$c_{d,900} = -0.0003958 \cdot T + 1.07916 (R^2 = 0.36), \quad (8)$$

$$c_{d,1200} = -0.002838 \cdot T + 1.05676 (R^2 = 0.24), \quad (9)$$

$$c_{d,1500} = -0.000631 \cdot T + 1.01262 (R^2 = 0.03), \quad (10)$$

where:
$c_{d,i}$ = deflection correction coefficient to the reference temperature of 20 °C at a distance i from loading axis [-].

As it was found out, the correction of deflections at sensors with spacing more than 900 mm from the load axis has marginal effect, the final equations for correction of deflections to the reference temperature of 20 °C were derived only for e deflections d_0 - d_{900}. They were set in the form:

$$d_{0,20,cor} = d_{0,T} \cdot (1 + 0.017817 \cdot (20 - T)), \quad (11)$$

$$d_{300,20,cor} = d_{300,T} \cdot (1 + 0.012116 \cdot (20 - T)), \quad (12)$$

$$d_{600,20,cor} = d_{600,T} \cdot (1 + 0.007555 \cdot (20 - T)), \quad (13)$$

$$d_{900,20,cor} = d_{900,T} \cdot (1 + 0.003958 \cdot (20 - T)), \quad (14)$$

where:
$d_{i,20,cor}$ = deflection at a distance i from the load axis corrected to the reference temperature of 20 °C [μm],
$d_{i,T}$ = deflection measured at temperature T at a distance i from the load axis [μm],
T = average temperature of asphalt layers in the depth of 40 mm [°C].

All the measured deflection bowls were subsequently corrected according to the derived equations. Then, example of the temperature correction of the deflection bowls to the reference temperature of 20 °C, is shown in Figure 6.

The corrected deflection bowls were used in the next step as an input for the back-calculation of elasticity modulus of pavement layers.

5 Comparison of the back-calculated moduli resulting from different approaches

This stage included statistical processing of moduli of elasticity determined by the back-calculation from the original (non-corrected) deflection bowls and subsequently corrected to the temperature of 20 °C and moduli of elasticity determined by the back-calculation from deflection bowls corrected to the temperature of 20 °C before performing the back-calculation. In the ideal case the elasticity moduli determined by both approaches should reach the same values.

The average elasticity moduli of asphalt layers, determined according to the presented approaches on all the tested sections, are shown in Figure 7. Three groups of moduli can be observed, which are located around the moduli of elasticity of 4500, 5500 and 7000 MPa. The elasticity moduli in each of the groups, determined by both approaches (Figure 8), differ slightly at the sections 1 - 7 and for these sections can be concluded that the used approach does not significantly affect the value of elasticity modulus recalculated to the reference temperature of 20 °C. More significant deviations can be observed for sections 8-10 with the higher moduli determined by recalculation of the modulus determined from an original deflection bowl.

The previous findings regarding the differences between the elasticity moduli of asphalt layers that are resulting from two used approaches, lead to a question,

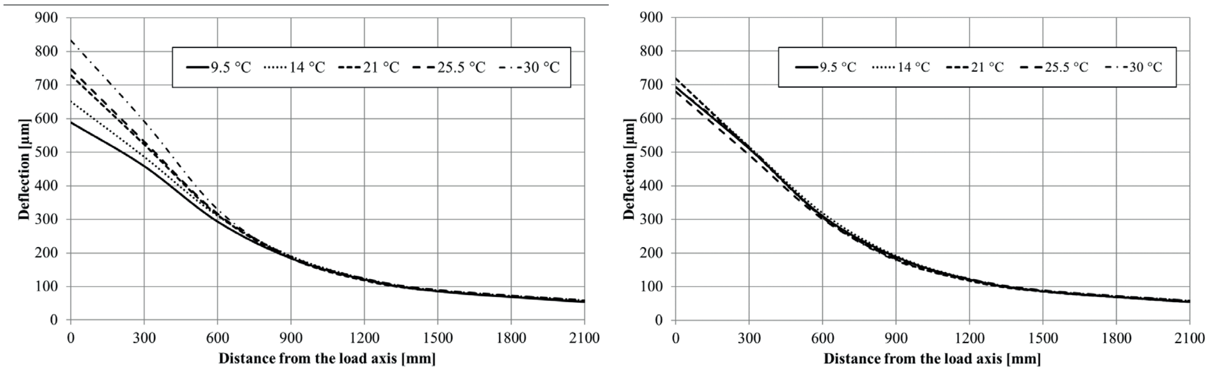

Figure 6 *Deflection bowls measured at different temperatures (left) and corrected to the reference temperature of 20 °C; (right) section 5, point 1*

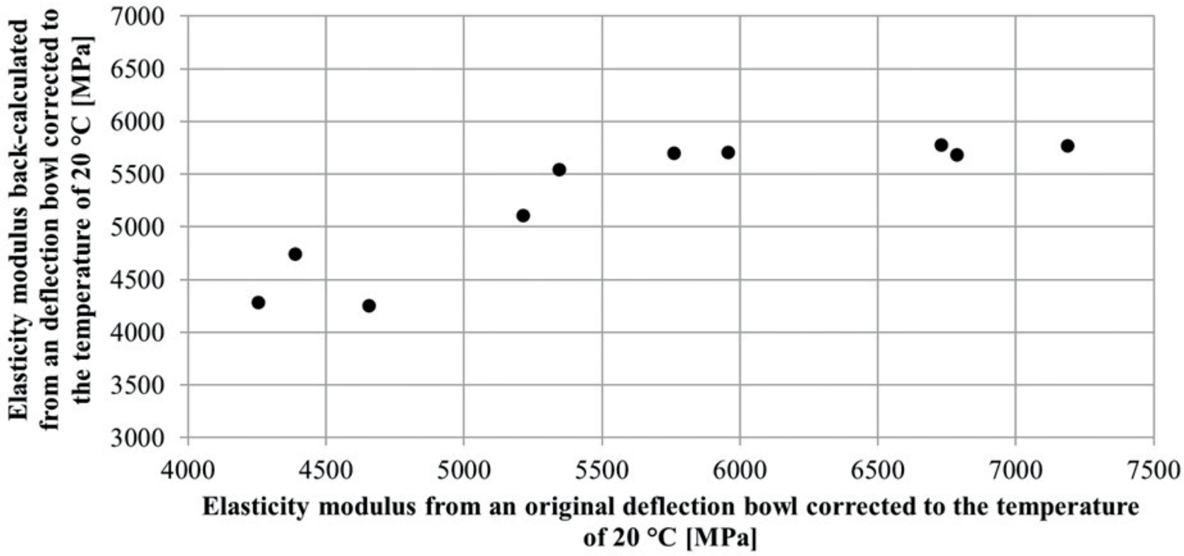

Figure 7 *Average elasticity moduli of asphalt layers on tested sections*

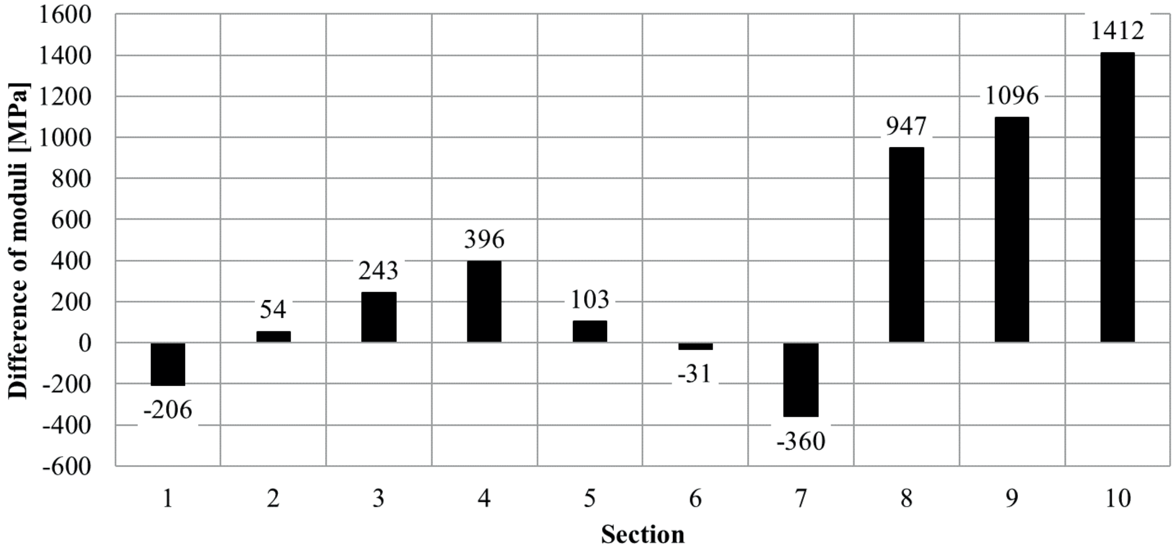

Figure 8 *Differences in elasticity moduli of asphalt layers due to different approaches used for their determination*

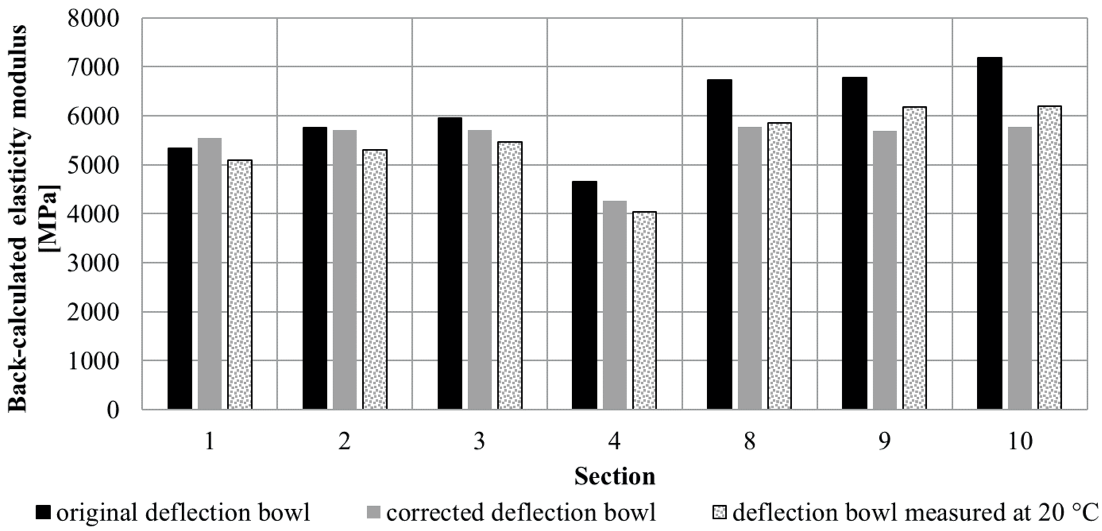

Figure 9 *Elasticity moduli of asphalt layers recalculated to temperature of 20 °C and determined from measurements at temperature of 20 °C*

which of approaches is more accurate. As both approaches recalculate moduli of deflection from a test temperature T to the reference temperature of 20 °C, the comparison of average recalculated moduli to values back-calculated from the deflection bowl measured exactly at 20 °C can be a useful information. Unfortunately, measurements at 20 °C were performed only on some of the test sections. Nevertheless, it is clear from Figure 9 that in most cases the moduli back-calculated from the corrected deflection bowl are closer to the values calculated directly for the test temperature of 20 °C.

6 Conclusions

The presented research confirmed known effect of temperature of asphalt pavement on measured deflections and back-calculated elasticity moduli.

Temperature correction of back-calculated moduli or measured deflections to the reference temperature of 20 °C was performed using temperature correction coefficient derived from regression curves.

Temperature correction coefficients applied on a measured deflection bowl were determined only for the sensors with spacing up to 900 mm from the load axis, since it was found out that the temperature has marginal effect on deflections measured by more distanced sensors.

The comparison of elasticity moduli of asphalt layers determined for the reference temperature of 20 °C according to two applied approaches (the correction of moduli back-calculated from an original (non-corrected) deflection bowl vs the correction of measured deflection bowl to the reference temperature of 20 °C and the subsequent back-calculation of moduli) has proven similarity of moduli for majority of the tested sections. On the remaining sections, the moduli back-calculated from an original deflection bowl were higher. When the corrected moduli, or those determined from the corrected deflection bowl, were compared to moduli back-calculated from the deflection bowls measured at the temperature of 20 °C smaller differences were recorded for the moduli determined from the deflection bowl corrected to the reference temperature of 20 °C.

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