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RESEARCH ARTICLE

Calculation of the equivalent temperature of pavement structures

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Abstract

Due to the difficulties of the description of temperature variation, rating of asphalt pavement structures respecting fatigue is made on equivalent temperature. In general, equivalent temperature is calculated according to average and weighted air temperature. It is proven, based on processing numerous data provided by the temperature detectors laid in the pavement structures as well as determination of the partial fatigue values, which the present method used to calculate the equivalent temperature results in data losses. Furthermore, it is proven, that pavement structure temperature based on air temperature can be determined only to limited extent. Knowledge of temperature distribution of the pavement structure provides the possibility of more accurate design.

Keywords

Equivalent temperature · pavement structure design

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1 Introduction

Stresses and deformations of the asphalt pavements greatly depend on the pavement structure temperature. The pavement structure engineers tried to summarize this temperature dependence in an easily manageable index. The issue of temperature dependence of asphalt pavements was of special importance and interest in countries covering large area and more climatic regions. These countries applied uniform technical regulations for different road sections, even if exposed to different climatic conditions.

It was also important to determine the temperature of the pavement structure based on air temperature. The air temperature values are registered by relatively densely established weather stations, whereas metering the pavement structure temperature coincides with problems of establishment and data recording.

According to the practice applied in Hungary, our calculations were based on full depth asphalt pavement and asphalt pavement on 150 mm thick hydraulically bonded subbase, in C, D, E and K traffic loading classes (Table 1), considering three-layer-structure types (2). The three-layer-structure types are derived form the combination of K-22/F and mK-20/NM base course mixture as well as AB-11/F, mZMA-12 wearing course mixture.

A separate database has been set up for each traffic loading classes and for each pavement structure types. Databases consist of 7300 pavement structure models what means generation and calculation of $2 \times 3 \times 4 \times 7300 = 175\,200$ pavement structure models. Pavement structure models were set up based on stiffness tests implemented in laboratory conditions and high frequency temperature metering on site.

2 Relation between temperature data and stress

In the course of model creation, data groups must have been ordered to each type of pavement structures. Data groups consist of coherent data in time as follows:

- air temperature;
- temperature of each pavement structure at the load centre;
- stiffness modulus of each pavement structure layer;

Tab. 1. Pavement thickness according to the load classes

load class		C	D	E	K
number of load repetitions (Mio. ESAL)		0.3-1.0	1.0-3.0	3.0-10.0	10.0-30.0
full depth asphalt pavement structure	asphalt thickness (cm)	18	21	24	27
	subbase (cm)	–	–	–	–
asphalt pavement structure on hydraulically bonded subbase	asphalt thickness (cm)	13	17	20	24
	subbase (cm)	15	15	15	15

Tab. 2. Pavement structure types for modelling

type	I.	II.	III.
wearing course	AC 11 (AB-11/F)	AC 11 (AB-11/F)	SMA-11(nZMA-11)
base course	AC-22 (K22/F)	AC-22, HMA (mK22/NM)	AC-22, HMA (mK22/NM)
base course	AC-22 (K22/F)	AC-22 (K22/F)	AC-22 (K22/F)

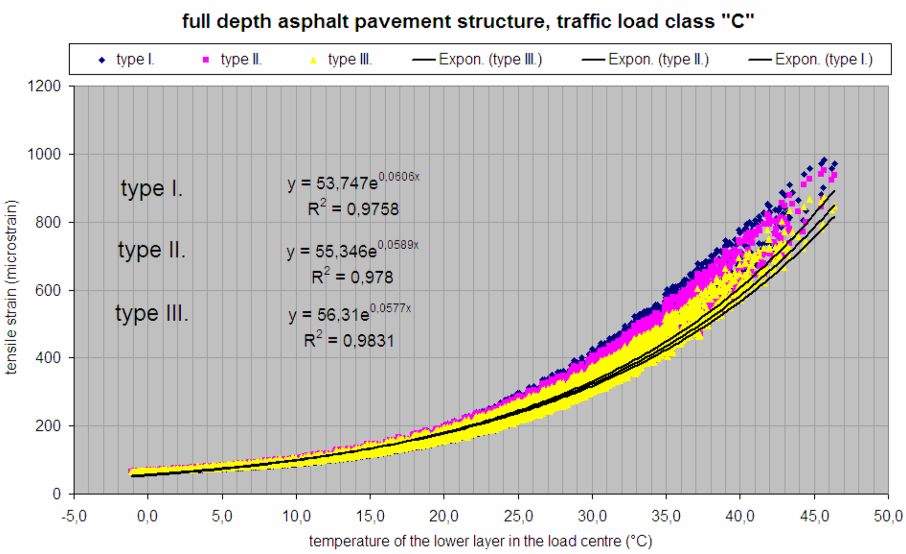


Fig. 1. Relation between temperature of the centre of the lower layer and tensile strain

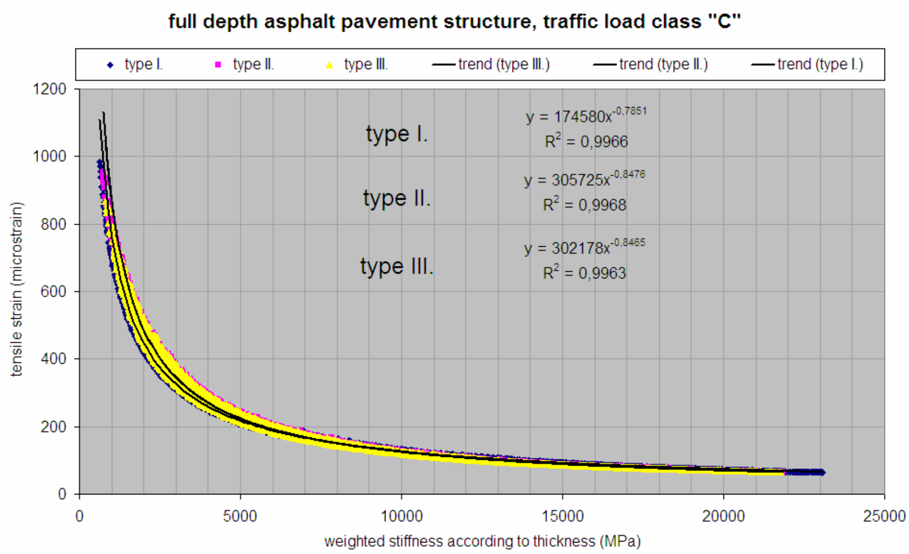


Fig. 2. Relation between equivalent stiffness modulus weighted according to thickness and tensile strain

- pavement structure equivalent stiffness modulus weighed according to thickness;
- relative tensile strain at the bottom of the asphalt layers of the pavement structure;

Based on numerous coherent data groups, regression relations between the different variables are as follows:

- an exponential relation of close correlation (R^2 >0,99) exists between temperature of the centre of the lower layer and tensile strain on the underside of the asphalt layer (Fig. 1);

Fig. 3. Relation between air temperature data and calculated tensile strain

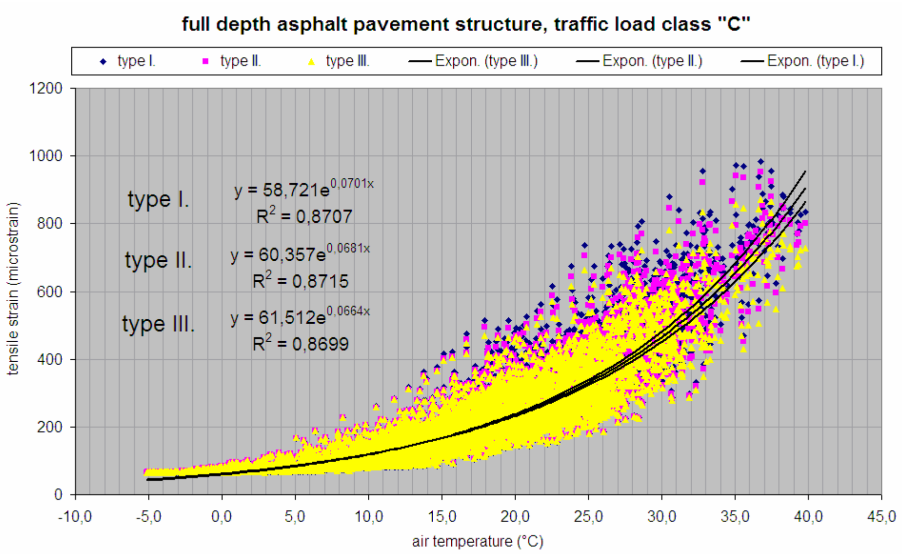
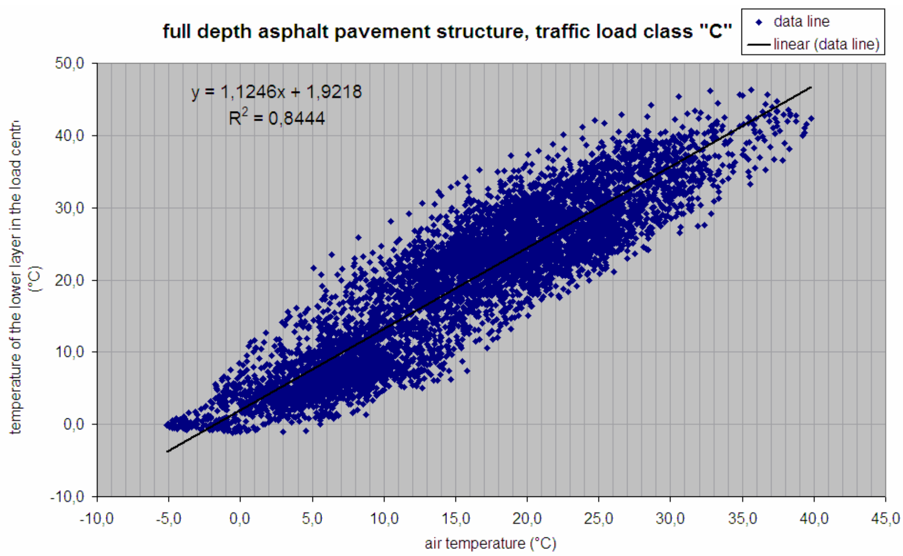


Fig. 4. Relation between the temperature of the lower layer centre and the air temperature



- a power relation of close correlation ($R^2 > 0{,}99$) exists between equivalent stiffness modulus weighted according to thickness and tensile strain on the underside of the asphalt layer (Fig. 2);
- based on analysis of coherent air temperature data and calculated asphalt strain data, exponential function of relatively close correlation ($R^2 > 0{,}84$) can be determined (Fig. 3);
- linear relation of relatively weak correlation ($R^2 > 0{,}80$) can be determined between the temperature of the lower layer centre and the air temperature (Fig. 4).

The relations depend upon the thickness of the pavement structure (traffic loading class) and the type of layer structure. The figures demonstrate the pavement structure load class C. Due to dimension barriers the figures can be shown neither for other traffic loading classes nor for asphalt pavement on hydraulically bonded subbase. R^2 however, refers to all pavement structures.

3 The real definition of equivalent temperature

Design at equivalent temperature is the realistic demand of engineers dealing with design of pavement structure, since the vertical distribution of the temperature of the pavement structure is important "only" indirectly during the design of the pavement structure [1].

Though the behaviour of the asphalt pavement structure depends on temperature, its design is performed at equivalent temperature. The researchers used Miner's hypothesis for the definition of equivalent temperature, where the effective stress generated in a pavement structure characterized by a single temperature model corresponds to the stresses calculated on the basis of models set up in accordance with various temperature values. Calculation must be performed according to Eq. 1.

$$N_{eff} = \frac{1}{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{N_i}\right)} \quad (1)$$

where

N_{eff} is the effective cycle number applied for the design according to Miner's hypothesis;

N_i actual allowed cycle number calculated on the basis of various temperatures;

Applying the basic equation for fatigue used for the calculation of partial fatigue values the tensile strain ε_{eff} belonging

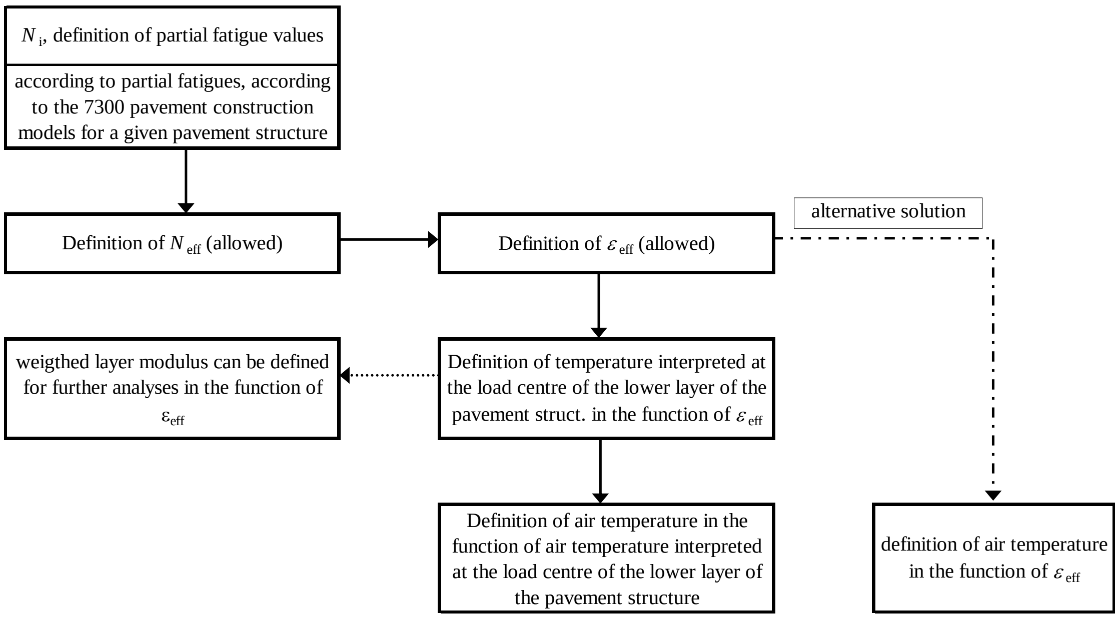


Fig. 5. Algorithm for calculating the equivalent temperature in case of detailed pavement structure

to the value of N_{eff} can be defined. The inaccuracies due to averaging in the calculations are characterized by the fact that even Claessen and his partners did not find an effective modulus value (except for thin pavement structures and values on lower temperature than 10˚C) where they would have ended up with the same effective planning period in their calculations, which they had calculated with the application of the cumulated fatigue law. Thus the effective (equivalent) modulus value can be applied in case of pavement structures thicker than 200 mm and values on higher temperature than 10 ˚C, but the value of the planning lifetime must be corrected with a factor between 1 and 2 [2].

The content of Fig. 5 demonstrates an algorithm we have elaborated, on the basis of which – using the figures displayed in Fig. 5 – the air temperature value can be defined besides which the same tensile strain value is received as in case of detailed pavement structure models. Using the algorithm the stresses will not have to be calculated on the basis of the detailed pavement structure models with the help of the SHELL – BISAR program; the correlations obtained from the calculations of correlation can be used.

The effective air temperature value has been calculated according to the 7300 pavement structure models on one hand, and on the basis of the average air temperature of 12 months applying the algorithm of Fig. 5 on the other. We performed our calculations in case of the whole pavement structure and for the pavement structures defined for every traffic load category. The pavement structure models were defined in a way that the temperature of the pavement structure had to be equal to the pavement structure temperature defined from the average monthly temperature on the basis of the Shell correlation in its full thickness [5].

When the allowed tensile strains were defined during the calculations, it was taken into consideration that allowed tensile strain increases at higher temperature [4] . The results are summarized in Table 3 that the equivalent temperature became higher solely due to the more detailed set up of pavement structure models. The reason for that is the fact that extreme temperature data could also be taken into consideration due to better and more detailed description of temperature change.

Tab. 3. The equivalent temperature calculated in different ways

model	traffic load class	ε_{eff}	temperature of pavement structure [˚C]	air temperature [˚C]
according to 7300 pavement structure models	C	293	-	23.0
	D	230	–	23.0
	E	185	–	23.0
	K	150	–	23.0
			average	23.0
according to 12 pavement structure models	C	151	24.3	18.5
	D	120	24.4	18.6
	E	98	24.5	18.7
	K	81	24.5	18.7
			average	18.6

The extent of the deviation and the absolute value of equivalent temperature are obviously influenced by the model applied for the fatigue of the asphalt mix. The equivalent temperature value is not influenced by the thickness of the pavement structure; more or less the same temperature values were received in case of both detailed (7300 pavement structures) and restricted (12 pavement structures) modelling with the application of similar fatigue model.

Using the average monthly air temperature values we calculated the weighted average temperature (w-MMAT) with the

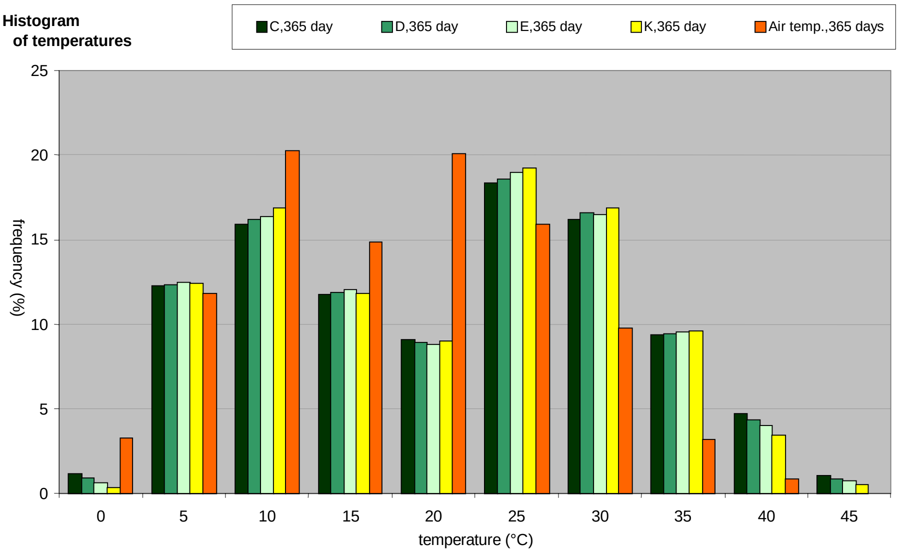


Fig. 6. Relative distribution of the temperature related to the load centre of the lower layers, full depth asphalt pavement structure, one year

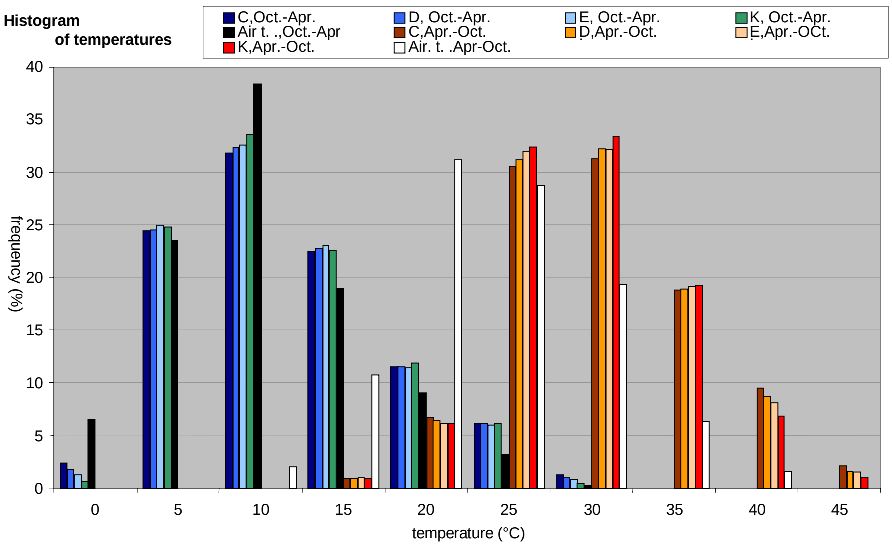


Fig. 7. Relative distribution of the temperature related to the load centre of the lower layers, full depth asphalt pavement structure, two seasons

help of SPDM 3.0. (Shell Pavement Design Method) program, of which the value happened to be 17,7 ˚C using the air temperature data applied in our calculations. This value is closer to the value that we have calculated using the restricted (12) pavement structure models.

With the results obtained by the application of the method presented in this study we pointed to the fact that equivalent temperature can be defined on the basis of air temperature, however

- its value will be higher than the values applied so far;
- in accordance with that the weight numbers of the air temperature values must be defined in a way that the values for the summer months must be included in the calculations with higher weight;

The temperature dependent fatigue characteristics of the asphalt can strongly influence this value both relatively and absolutely in the course of calculations.

4 Distribution of temperatures measured in the lower layers of the pavement structure

In order to understand temperature values that actually occur in the pavement structure we examined the distribution of temperatures measured at the load centre of the lower layer of the full depth asphalt type pavement structures associated with various traffic load classes. The data were supplied by the temperature detectors laid in the pavement structure (as mentioned earlier). The data of the same temperature detector were used for the previously presented calculations as well. The device for temperature detection is a BSS-03 type soil sampler placed in the pavement structure. The device measures the temperature in the following depths from the surface of the pavement: 0 cm; −2 cm; −7 cm; −14 cm; −29 cm;−49 cm. The internal resolution of the temperature detectors is 0,0625˚C whereas the output is of 0,1˚C accuracy. In addition to the air temperature values the measuring station located in the pavement structure recorded the temperature of the pavement structure in every 10 minutes, as a result of which 144 records in 24 hours and 52560 records in 365 days were logged.

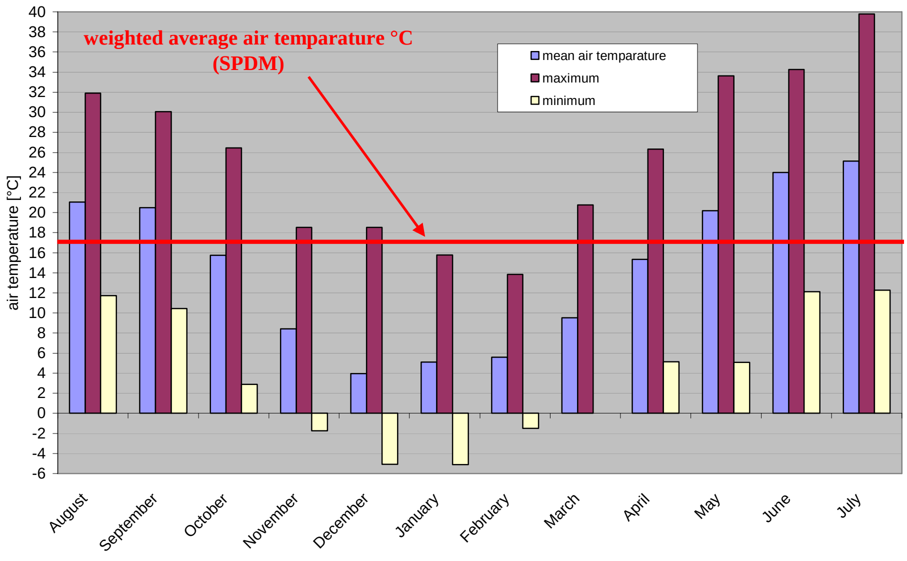


Fig. 8. Mean, maximum and minimum air temperature in one year period

The diaphragm gap was set to a fine value of 5˚C temperature difference regarding the 52560 data. The results are summarized by the chart in Fig. 6. The diagram displays the frequency of the distribution of temperatures related to the load centre of the lower layers of the given pavement structure in the percentage of all the measurement results related to the given pavement structure. Since evaluation refers to 365 days, it cannot be filtered off what kind of temperature frequencies occur in the various pavement structures between 1 April and 1 October (a period significant regarding temperature). Consequently we performed separate analysis of the frequency of air temperature values and temperature values related to the load centre of the lower layer for the periods between 1 April and 1 October as well as 1 October and 1 April. The results are summarized by the chart in Fig. 7.

It can be ascertained that in case of pavement structures of identical type extremely low and high temperatures occur more frequently in the lower traffic load category (thinner pavement structures) than in the higher traffic load category (thicker pavement structures).

5 Conclusions

During our calculations of demonstrating the importance of continuous change of temperature in the pavement structure we used the results of measurements that were actually performed. During the calculations we used the temperature measurement results of an entire year and the dynamic modulus of the asphalt mix defined on the basis of laboratory tests for setting up detailed pavement structure models. During our calculations – using the definition of equivalent temperature according to Fig. 5 – we indicated the following:

- the real equivalent temperature is higher than the value can be specified from the weighted average air temperatures;
- the specification of equivalent temperature from the simple averaging of air temperature results loss of data in terms of designing even if it is corrected with weighting;
- if correction is performed with weighting, summer months must be taken into consideration with higher weight than months during winter, spring or autumn;
- weighting is not necessary in case of using detailed pavement structure calculation because the equivalent temperature can be specified with the algorithm presented in Fig. 5 with the use of long-term air temperature measurements, however the relatively weak correlation between air temperature and tensile strain may reduce the accuracy of the definition.
- the equivalent design temperature derived from air temperature in general underestimates the importance of high temperatures, however it may be corrected with the adequate selection of a shift factor.

For the sake of demonstration we summarized the air temperature averages applied in our calculations in the chart of Fig. 8 indicating the highest and lowest air temperature values measured in the given month as well.

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