Equivalent temperature for design of airport pavements using mechanistic-empirical methods

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Abstract

V príspevku je prezentovaná metóda zavedenia ekvivalentnej teploty pri navrhovaní asfaltových letiskových vozoviek. Uvádzajú sa metódy výpočtu podľa Shell method, francúzskej metódy aj Asphalt Institute. Ako príklad sa uvádza výpočet ekvivalentnej teploty pre letisko Gdansk. Ukázalo sa, že metódu výpočtu ekvivalentnej teploty, ktorá sa používa pri navrhovaní vozoviek všeobecne, možno použiť aj pri navrhovaní letiskových vozoviek.

1. Introduction

Temperature has big impact on the behaviour of the different pavement types. In case of asphalt pavements temperature affects the mechanical characteristics of the pavement. Cyclical variations of temperature cause shrinkage cracks in materials treated with hydraulic binders. Also, thermal gradients cause strains in the concrete slabs of rigid pavements. In the practice of design of bituminous pavements, calculations in most cases are carried out with consideration of an equivelent constant temperature. The behaviour of asphalt layers in terms of deformation and fatique depends on temperature, stress levels and damage of the pavement. According to French practice [1] structural design is carried out for the constant temperature, referred to as the equivalent temperature θ_{eq}. This temperature is at such level, that the cumulative damage in the pavement over a year, for a given temperature distribution, is equal to the damage that the pavement would undergo with the same traffic but for the constant temperature θ_{eq}. The equivalent temperature is determined by applying Miner's law. Accodding to the Shell procedure [2, 3] the equivalent temperature can be also called as „effective temperature". The effective stress generated in the 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 can be performed according to equation (1):

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

where:

N_{eff} - effective cycle number (the effective design life) in effective single temperature applied for the design according to Miner's hypothesis,

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

n - number of temperature gradients.

The objective of the analysis was to determine the equivalent temperature for the asphalt pavement of taxiway of the Gdansk Lech Walesa Airport with the use of mechanistic-empirical methods. The designed asphalt pavement consists following layers: 5 cm thick wearing course with AC11S asphalt concrete, 10 cm thick binder course with AC22W asphalt concrete, 14 cm thick asphalt concrete base course, 20 cm thick crushed aggregate subbase and 26 cm of capping layer. The total thickness of bituminous layers is 29 cm. The ambient temperature data were collected for the following 20 years long period:from 1994 to 2013.

2. Calculating methods of equivalent temperature

2.1. Shell method

Analysis of equivalent temperature for design of asphalt pavement of taxiway of the Gdansk Airport according to the Shell procedure [2] consisted following steps:

1. Determination of the mean monthly air temperature (MMAT) for each month during 20 years period: from 1994 to 2013.
2. For each MMAT value the „weighting factor" was derived from figure 1.

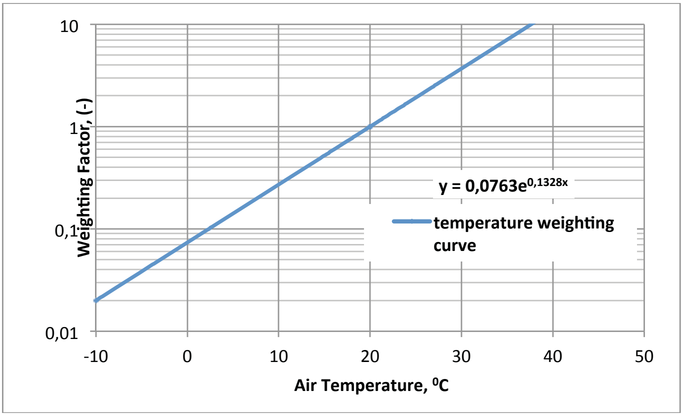

Figure 1. Temperature weighting curve, according to Shell method [2]

3. Calculation of the annual average weighting factor for analyzed location.
4. Determination of the equivalent temperature values (effective Mean Annual Air Temperature MAAT) on the basis of annual average weighting factor.

2.2. The French method

In the French method [1, 7] calculations of the equivalent temperature were conducted according to the following equation (2):

$$\sum_i \frac{n_i(\theta_i)}{N_i(\theta_i)} = \frac{\sum_i n_i(\theta_i)}{N(\theta_{eq})} \qquad (2)$$

where:

θ_i - temperature distribution during a year,

$N_i(\theta_i)$ - number of loadings causing failure due to fatigue for the level of strain $\varepsilon(\theta_i)$,

$\varepsilon(\theta_i)$ - tensile strain in the pavement under the standard axle,

$n_i(\theta_i)$ - number of temperature θ_i gradients,
θ_{eq} - equivalent temperature.

After calculating the elementary damage $1/N(\theta_{eq})$, equivalent temperature θ_{eq} was obtained from the curve giving the variation in damage according to temperature distribution θ_i.

The calculation of the equivalent temperature according to the French method was performed using the following procedure:

1. Determination of the mean monthly air temperature (MMAT) distribution and mean monthly pavement temperature (MMPT) in 5°C intervals.Determination of the stiffness modulus of asphalt base course for each temperature interval.
2. Calculation of horizontal strain at the bottom of asphalt layers at certain temperature (at certainstiffness modulus of asphalt mixture).
3. Adaptation according to the literature [4] that the value of strain ε_6 in millionth load cycle (assumed for temperature to +10°C) $\varepsilon_6 = 115x10^{-6}$. Other ε_6 strain values for other temperatures were estimated due to the lack of laboratory results. In addition the laboratory fatigue test method and shape of samples that are typicaly used in France are different from those used in Poland.
4. Calculation of the weighted average fatigue damage based on pavement temperature distribution and unit of fatigue damage in each temperature interval.
5. Determination of the equivalent temperature based on the calculated average fatigue damage according to a particular function of the temperature and fatigue damage.

2.3. Method with the use of Asphalt Institute fatique criteria

Determination of the equivalent temperature with use of Asphalt Institute fatigue criteria [4, 8] included the following steps:

1. Determination of mean monthly air temperature (MMAT) based on the temperature data from meteorological station located at the Gdansk Airport.
2. Calculation of the mean monthly pavement temperature according to the equation (3) developed originally by Witczak (1972):

$$MMPT = MMAT \cdot \left[1 + \frac{1}{z+4}\right] - \frac{34}{(z+4)} + 6 \quad (3)$$

where:

MMPT - mean monthly pavement temperature, (°F),
MMAT - mean monthly air temperature, (°F),
z - depth below the pavement surface, (inch).

3. Calculation of fatigue life with the use of the fatigue cracks criteria and structural deformation of the analyzed flexible asphalt pavement. It was calculated for the temperature range from -20°C to +30°C with 5°C intervals. Stiffness moduli of asphalt mixes were determined using the program Shell-BANDS. To simplify the calculation the wheel load was assumed to 50 kN as the value typically use during road pavements design. Frequency of traffic at the airport was assumed as uniform flow during entire year. Calculation of fatigue life during entire year was performed using the following equation (4):

$$N_{year} = \frac{100}{\left(\frac{\%\,traffic1}{N1}+\frac{\%traffic2}{N2}+\cdots+\frac{\%\,traffic12}{N12}\right)} \tag{4}$$

where:

N_{year} - fatigue life of asphalt pavement during entire year,
$\%\ traffic_1$ - percentage of traffic in January (the 1st month),
$\%\ traffic_2$ - the same but in February (the 2nd month),
$\%\ traffic_{12}$ - the same but in December (the 12th month),
$N_1, N_2 \ldots N_{12}$ - fatigue life calculated in each month.

4. On the basis of fatique curve determined for each mean monthly temperature one annual equivalent temperature was assigned as a value in which fatigue life is equal to a value obtained from different temperatures.

3. Analysis of temperature data

Temperature data which were required for the calculation of equivalent temperature were obtained from database server NCDC (National Climatic Data Center) [5], that consists data from station No. 121500 which is located directly at the Gdansk Airport. Figure 2 shows monthly variation of the mean monthly air temperature during each year frorm 1994 to 2013. The mean values and maximum and minimum air temperatures recorded for each month for the coldest year 1996 were shown in Figure 3. The temperature measurement results for the hottest year 2007 are presented in Figure 4.

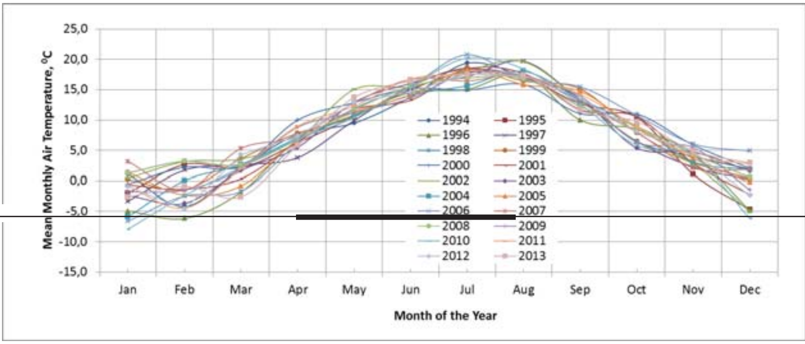

Figure 2. Mean monthly air temperature variations for the period of last 20 years (1994-2013) measured at the Gdansk Airport

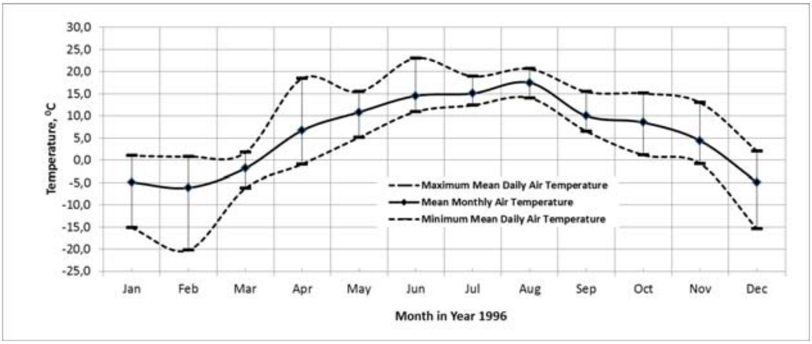

Figure 3. Mean monthly temperature with maximum and minimum air temperature in the Gdansk Airport area in the coldest year 1996 (period 1994-2013)

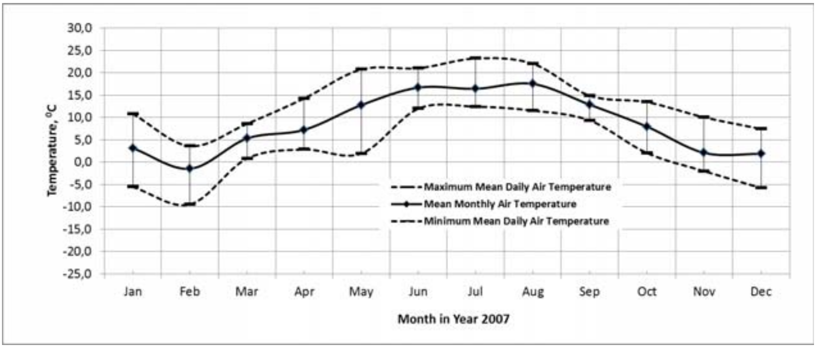

Figure 4. Mean monthly temperature with maximum and minimum air temperature in the Gdansk Airport area in the hottest year 2007 (period 1994-2013)

It was proven that temperature in the Gdansk Airport area can vary significantly, especially during winter months of the year. For example, in February 1996 difference between minimum and maximum values of mean daily air temperature was over 20°C.

4. Results and analysis

The results of calculation of equivalent temperature according to Shell method were presented in table 1.

Table 1. The results of calculation of equivalent temperature according to Shell method

Month	MMAT 1994-2013	Weight factor W-F	Annual mean value of W-F	Annual equivalent temperature
	°C	(-)	(-)	°C
Jan	-1,6	0,06	0,31	10,6
Feb	-0,6	0,07		
Mar	1,9	0,10		
Apr	6,9	0,19		
May	11,5	0,35		
Jun	15,0	0,56		
Jul	17,7	0,80		
Aug	17,4	0,77		
Sep	13,0	0,43		
Oct	8,2	0,23		
Nov	3,8	0,13		
Dec	-0,5	0,07		

The Shell method calculations have shown that in the Gdansk Airport area annual equivalent temperature that can be used for airport pavement design is equal to 11°C (rounded to 1,0°C).

In the French method of calculation of equivalent temperature, the annual mean distribution of pavement temperature in the depth of h/3 of asphalt layers (10 cm) is given in table 2.

Table 2. Annual mean distribution of pavement temperature

Temperature, °C	-20	-15	-10	-5	0	5	10	15	20	25	30
Duration in year, %	0,3	0,7	2,4	6,0	14,7	17,1	15,2	17,4	17,0	8,2	1,0

The stiffness moduli of asphalt base course $E(\theta_i)$ were calculated with the use of Shell-BISAR program. It was assumed that bitumen content in asphalt mixture V_B is 9,5% v/v and voids content V_a is 7% v/v. To simplify the calculation the wheel load was assumed to 50 kN as the value typically use during road pavements design.

The elementary damage was calculated according to French fatique law from the equation (5):

$$d(\theta_i)=\left(\frac{\varepsilon_6(\theta_i)}{\varepsilon(\theta_i)}\right)^{\frac{1}{b}}\cdot 10^{-6} \qquad (5)$$

where:

$d(\theta_i)$ – elementary damage at the temperature θ,
$\varepsilon_6(\theta_i)$ – strain after 10^6 cycles,
$\varepsilon(\theta_i)$ – tensile strain at the bottom of asphalt layers,
b – slope of fatigue curve (b = -0,2)

The results of calculation of elementary damage were presented in table 3.

Table 3. Results of calculation of elementary damage according fo French method

Temperature θ_i [°C]	Duration in year $n_i(\theta_i)/\Sigma n_i(\theta_i)$ [%]	Stiffness modulus of asphalt base course $E(\theta_i)$ [MPa]	Tensile strain at the bottom of asphalt layers $\varepsilon(\theta_i)$ [μstrain]	Strain after 10^6 cycles $\varepsilon_6(\theta_i)$ [μstrain]	Elementary damage $d(\theta_i)$ [-]
-20	0,3%	31000	20	71	0,00161
-15	0,7%	29000	21	73	0,00181
-10	2,4%	26400	22	77	0,00213
-5	6,0%	22600	26	83	0,00279
0	14,7%	18600	30	91	0,00389
5	17,1%	14800	36	102	0,00568
10	15,2%	11700	44	115	0,00829
15	17,4%	9310	53	129	0,01185
20	17,0%	6540	70	154	0,02001
25	8,2%	4330	97	189	0,03510
30	1,0%	2710	137	239	0,06128

The elementary damage for equivalent temperature $1/N(\theta_{eq})$ was calculated from the equation (6):

$$\frac{1}{N(\theta_{eq})} = \sum_i \frac{n_i(\theta_i)}{\sum_i n_i(\theta_i)} d(\theta_i) \qquad (6)$$

where:

$1/N(\theta_{eq})$ – elementary damage for equivalent temperature,
$n_i(\theta_i)$ – number of temperature θ_i gradients,
$d(\theta_i)$ – elemetary damage in temperature θ_i.

The value of equivalent temperature according to calculations made with use of the French procedure is 15°C.

The results of calculation of asphalt mixture stiffness moduli according to method with use of the Asphalt Institute fatigue criteria were presented in table 4.

Table 4. The results of calculation of asphalt mixture stiffness moduli

Temperature, °C	Stiffness modulus of bitumen, MPa		Stiffness modulus of asphalt mixture, MPa		
	35/50	50/70	Wearing course AC11S 50/70	Binder course AC22W 35/50	Base course AC22P 35/50
-20	1630	1620	30700	31000	31500
-15	1310	1280	28400	28900	29400
-10	1020	965	25700	26700	27200
-5	733	701	21900	22800	23400
0	501	457	17700	19000	19600
+5	310	285	14000	15100	15600
+10	190	169	10800	11900	12400
+15	116	89,9	7750	9400	9840
+20	64,8	44,8	4760	6610	7030
+25	33,3	20,7	2770	4290	4670
+30	15,8	9,16	1570	2640	2960

For the subbase course made of unbound crushed aggregate it was assumed that the value of modulus of elasticity is 400 MPa and the Poisson ratio is equal to 0,3. Figure 5 presents the resulting fatique curve from the calculations.

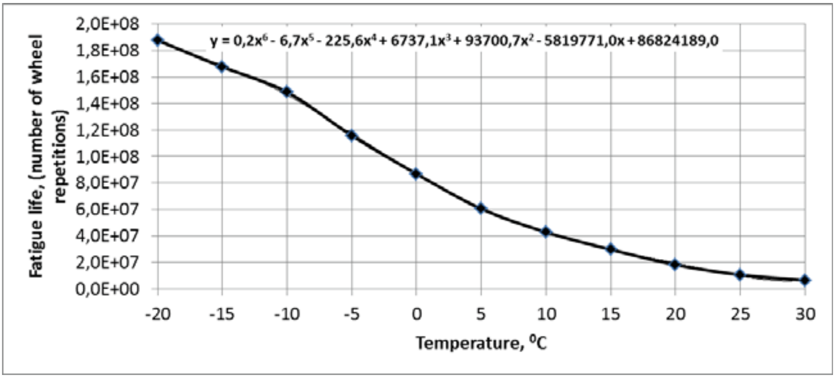

Figure 5. The resulting fatigue curve from the calculations

The annual equivalent temperature value calculated with the use of Asphalt Institute fatigue criteria for the Gdansk Airport area is equal to 14°C (rounded to 1,0°C).

5. Conclusions

1. The equivalent temperature is very important issue in design process of airport pavements using mechanistic-empirical methods. It was shown that obtained values can vary between 11°C for Shell method through 14°C for Asphalt Institute and 15°C for French method of calculations.
2. It was found that the value of equivalent temperature mostly depends on the method of calculation and the collected air temperature data. It is very important to collect temperature data from meteorological stations located in the area of designed pavement.
3. It was also shown that methods of calculation of equivalent temperature that are usually used in the design process of road pavements can be also implemented in design process of airport pavements. The implementation process should take into account the differences in design between road and airport pavements, for example the fatigue criteria and traffic evaluation and type of axle load.

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