REQUIREMENTS FOR BITUMINOUS BINDERS RESULTING FROM CLIMATIC CONDITIONS IN SLOVAKIA

JOZEF KOMAČKA
Department of Road Engineering, University of Žilina, Slovak Republic
komacka@fstav.utc.sk

ABSTRACT

Air temperature represents one of the most important climatic factors influencing the service efficiency and serviceability of asphalt pavements. The effect of climatic factors in the regions of Slovakia has not been taken into account in the stage of selection of binder into asphalts. The research in this field was conducted and representative air temperatures were determined for the summer and winter season. Results have shown that there are differences in air temperatures among regions of Slovakia. Differences are higher during the winter season than in the summer. The representative values of air temperature for the summer and winter seasons were used to calculate temperatures of wearing, binder and upper base course during summer days. Physical principle of the solar radiation and thermal propagation through the pavement was used for this aim. Then these values were used for determination of requirements on bitumen properties to minimize rutting and cracking of asphalt pavements. Finally, requirements for softening point, breaking point, and range of penetration were determined for each of asphalt layer of pavement taking into account maximum temperature for the summer season and minimum temperature for the winter season in these layers. Various combinations of softening point, breaking point and penetration are necessary to cover the variability of climatic conditions in Slovakia and thermal regime of asphalt layers.

1. INTRODUCTION

Design of structure of flexible pavement has to take into account climatic conditions. In Slovak design method it is respected in computational part of evaluation process. Three basic periods of the year are used (relative duration and representative temperature is determined for each of them) and stresses in a pavement structure are calculated for values of deformation characteristics of asphalt layers (Young modulus, Poisson ratio etc.) recommended for these periods. As for selection of components of asphalts, especially bitumen, influence of climatic conditions was expressed only in the form of recommendation to use some type of bitumen in so called „warmer regions“ (according to average temperature of the air). Taking into account thermal regime of pavement structure, this recommendation did not respect extremum of temperature during the summer or winter when pavement layers are exposed to high or low air temperature.

The research was focused on an analysis of maximal daily air temperatures during the summer and winter and determination of representative values of air temperature for these seasons. The representative values were used for calculation of temperature in asphalt layers. Requirements on softening and breaking point were proposed on the basis of temperatures calculated for individual pavement layers and the range of penetration was determined from a chosen range of penetration index.

2. REPRESENTATIVE TEMPERATURE OF AIR

Database of hourly temperatures from 20 Slovak automatic meteorological stations (which cover whole territory of Slovak road network) was used for evaluation. Values for the period between April and September were included into the "summer" season and the time interval November – March was taken for the "winter" season.

Average maximum air temperatures for 3-days, 5-days and 7-days period were calculated from maximal daily temperatures for each of meteorological stations for each year. Maximal yearly values were used to calculate the average maximum air temperature (Figure 1) and standard deviation for each of meteorological stations.

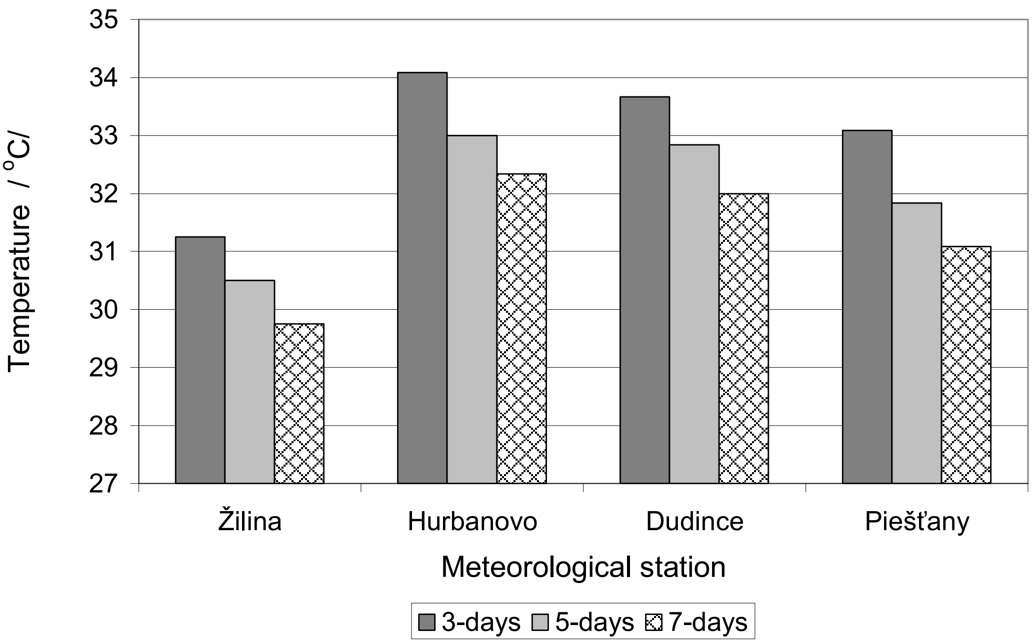

Figure 1 - Summer average maximum air temperatures at some of meteorological stations

As it can be seen from Figure 1, the average values for the summer season decrease from 3-days to 7-days average (it means a colder day(s) always occurs in hot summer period) but differences are not very high. Nevertheless, 3-day average was used in all following calculations.

As for winter season, average minimum air temperatures for the individual stations were calculated using the same procedure as for summer season but only one-day minimum air temperature was used for calculation.

Finally representative temperatures of air for summer and winter conditions were calculated for different levels of reliability taking into account average air temperatures (minimum and maximum) and standard deviations.

Results showed there are temperature differences across Slovakia. It can be stated that the territory is relatively homogenous during the summer period because average temperatures at most of the meteorological stations are in narrow range of 3 °C and only some parts of the territory differ more (see Table 1). Moreover, the relatively low values of standard deviations indicate regular repeating of high temperatures in each year. The situation is a little bit different for winter conditions. The territory is not so homogenous

(Figure 2), differences of average temperatures are higher and according to standard deviations, there is an evident variety of very cold and warm winter seasons. The analysis of data also showed that one part of southern Slovakia is colder than some parts in the middle of Slovakia.

Table 1 - Air temperature characteristics for the hottest and coldest area

Area	Summer season			Winter season		
	Period	Average	Stand. dev.	Period	Average	Stand. dev.
Hottest	3-day 5-day 7-day	34,1 °C 33,0 °C 32,3 °C	1,3 °C 1,7 °C 1,7 °C	One-day	- 12,0 °C	3,7 °C
Coldest	3-day 5-day 7-day	26,6 °C 26,0 °C 25,2 °C	1,1 °C 1,3 °C 1,3 °C	One-day	- 20,6 °C	4,6 °C

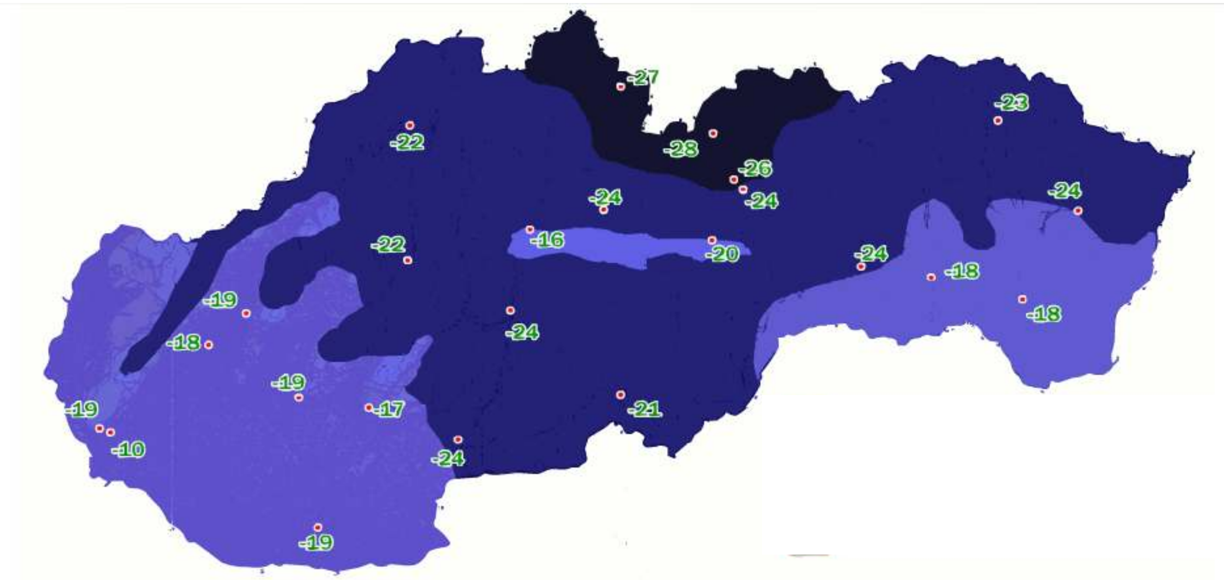

Figure 2 – Temperatures areas according to minimal temperatures distribution

3. TEMPERATURE OF PAVEMENT LAYERS

3.1. Summer season

Temperature on pavement surface depends mainly on solar radiation, heat transfer and energy balance. The following equation published in [1] was used to calculate temperature on pavement surface.

$$422\alpha\tau_{\alpha}^{1/\cos z}\cdot\cos z+\varepsilon_a\sigma T_a^4-h_c\left(T_s-T_a\right)-\frac{k}{d}\left(T_s-T_d\right)-\varepsilon\sigma T_s^4=0 \quad (1)$$

where: α - surface absorptivity to the solar radiation
τ_a - transmission coefficient for unit air mass
z - angle between the zenith and direction of the sun`s rays

ε_a - 0.49 .($10^{-0,074.\rho}$)
ρ - vapour pressure varying between 1 and 10 mm of mercury
σ - Stefan-Boltzman constant = 5.68 . 10^{-8} [$W.m^{-2}. K^{-4}$]
T_a - air temperature [K]
T_s - surface temperature [K]
h_c - average convective heat transfer coefficient of surface [$W.m^{-2}.C^{-1}$]
k - thermal conductivity [$W.m^{-1}.C^{-1}$]
d - depth below the surface [m]
T_d - temperature at depth d [K]
ε - emissivity

Apparently a lot of thermal parameters influence calculated temperature. An analysis carried out in [3] showed that the most important is the surface coefficient of heat transfer h_c that depends mainly on wind velocity. For this reason, temperature on pavement surface was calculated for two cases: average summer value of wind speed specific for each of the meteorological stations (range from 2,1 $m.s^{-1}$ to 4,9 $m.s^{-1}$) and wind velocity of 0,9 $m.s^{-1}$ (second level of Beaufort scale - capful) that was deemed as the representative value for hot summer days. Calculated temperatures were (according to chosen reliability of air temperature and locality) in the range from 52 ^oC to 66 ^oC for the average summer value of wind speed and in the range from 60 ^oC to 72 ^oC for the wind velocity of 0,9 $m.s^{-1}$ (Figure 3). It means that the difference caused by wind velocity is about 6 ^oC – 12 ^oC and by locality of weather station it is about 12 ^oC. These differences are not negligible if type of binder has to be determined.

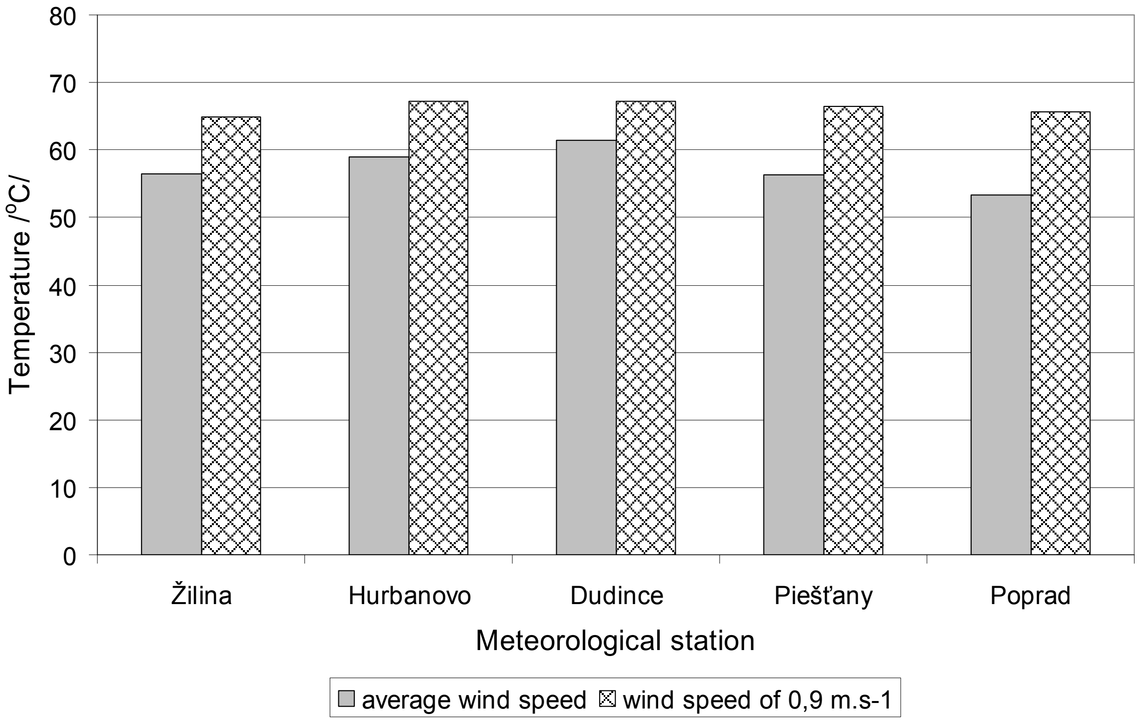

Figure 3 – Temperatures on pavement surface at some of meteorological stations (95 % level of reliability)

Temperature of asphalt layers below pavement surface was calculated using thermal diffusion theory. According to Fourier`s law, the thermal diffusion and the changes of heat flow can be described by equations published in [4]

$$q(x,t) = -\lambda \cdot \frac{\partial T(x,t)}{\partial x} \tag{2}$$

$$\frac{\partial q(x,t)}{\partial x} = -\rho \cdot c \frac{\partial T(x,t)}{\partial t} \tag{3}$$

The final equation resulting from the formulas (2) and (3) is then

$$\frac{\partial T(x,t)}{\partial t} = \frac{\lambda}{\rho \cdot c} \cdot \frac{\partial^2 T(x,t)}{\partial x^2} \tag{4}$$

where: *q(x,t)* - density of heat flow at the point x and time t [$W.m^{-2}$]
λ - thermal conductivity coefficient [$W.m^{-1}.K^{-1}$]
T(x,t) - temperature at the point x and time t [K]
ρ - bulk density of the material [$kg.m^{-3}$]
c - thermal capacity of the material [$J.kg^{-1}.K^{-1}$]

Various computing methods can be used to solve equation (4) but we used the methodology of final differences published in [5]. This procedure offers the possibility to calculate temperature of pavement at depth *d* when thermal characteristics of layers above level *d* and temperature changes in pavement layers are known.

Necessary inputs for calculation) were obtained from field measurements at experimental field test sections (Figure 4). Position of thermometers in asphalt layers are given in the Table 2.

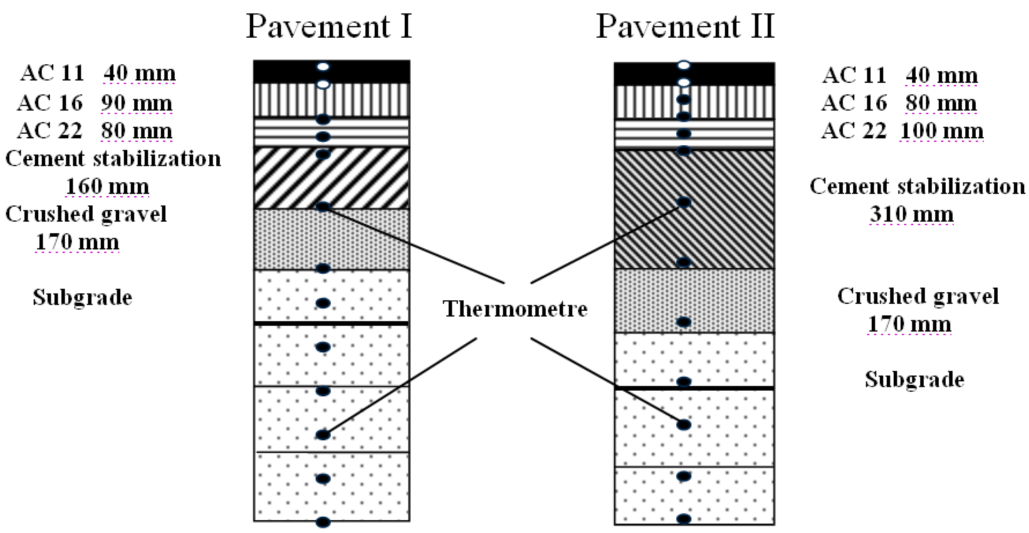

Figure 4 - Cross section of pavements at the test section

Characteristic course of temperature changes in asphalt layers of pavement during hot summer day in Slovakia is shown on Figure 5. As can be seen it is possible very easy to determine time intervals of maximal temperatures at wearing, binder and base course and time shift among them and temperature differences at various depths of asphalts layers.

Table 2 - Positions of thermometers

Pavement I		Pavement II	
Thermometer	Depth below the	Thermometer	Depth below the

number	pavement surface	number	pavement surface
I/13	5 mm	II/13	5 mm
I/12	40 mm	II/12	40 mm
I/11	130 mm	II/11	80 mm
I/10	180 mm	II/10	120 mm
I/9	210 mm	II/9	170 mm
		II/8	220 mm

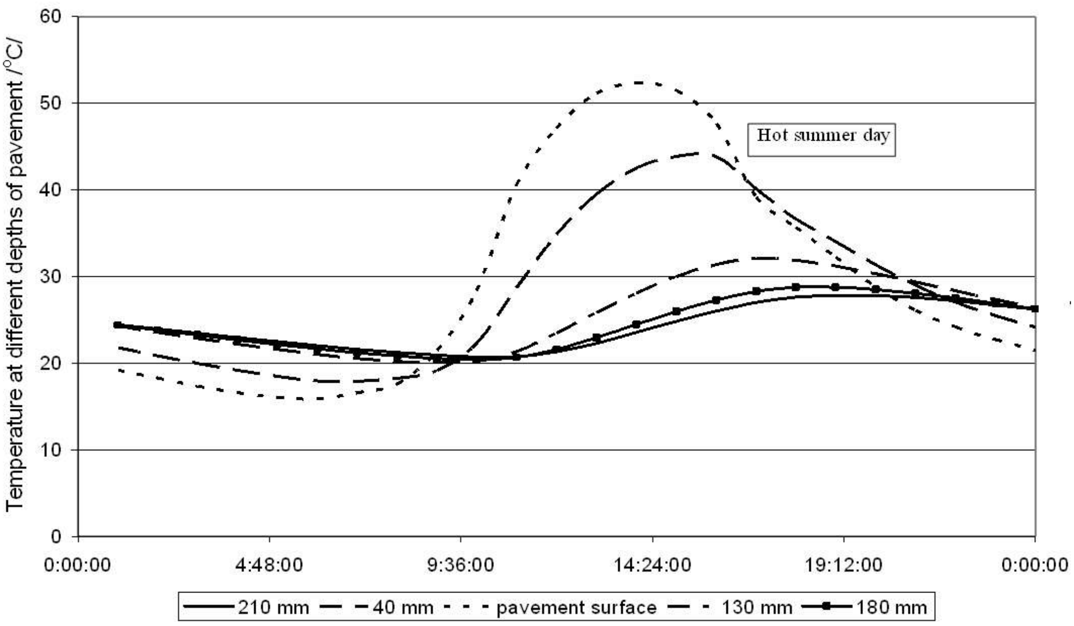

Figure 5 - Example of the temperature changes in the asphalt pavement layers

These data were used to calculate maximal temperature at the top of binder and base course (depth of 40 mm and 130 mm respectively) according to [5]. Calculated temperatures were in very good correlation with values measured in the test pavements (Figure 6) and validated accuracy of theoretical solution and the possibility to calculate the temperature of pavement at any depth of asphalt layers. Consequently the method of final differences was used for calculation of temperatures at depth above for all summer representative temperatures of air for each of meteorological stations. Range of temperatures is given in Table 3.

Temperatures at depth of 20 mm below pavement surface were calculated for the comparison to temperatures determined according to procedure above. Following equation published in [6] were used

$$T_{20mm} = \left(T_{air} - 0{,}00618 \cdot Lat^2 + 0{,}2289 \cdot Lat + 42{,}2\right) \cdot 0{,}9545 - 17{,}78 \quad (5)$$

where: T_{air} - seven-day average maximum temperature [°C]
Lat - geographical latitude of the meteorological station in degrees

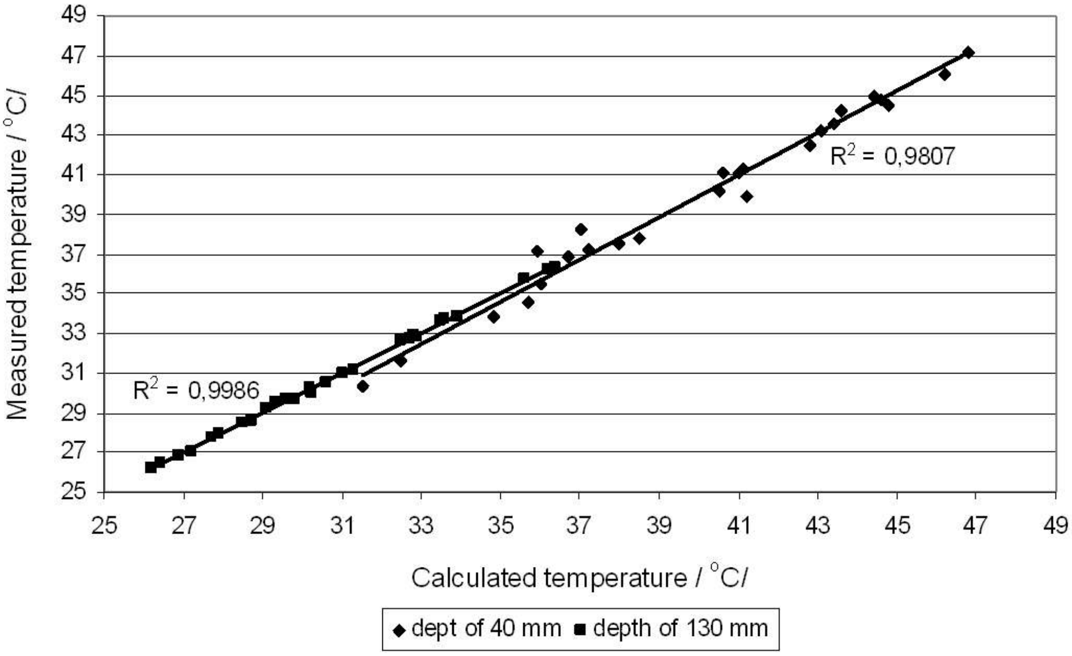

Figure 6 - Comparison of calculated and measured temperatures

Range of latitudes for Slovakia is narrow (approx. from 47°50´ to 49°50´) and it means average maximum temperature has main influence on temperature at depth of 20 mm. Some of results are in Figure 7. As can be seen the difference of temperatures between the coldest part (Donovaly, Telgárt) and the hottest (Hurbanovo) is about 7 °C and it corresponds to differences in air temperatures that are done in Table 1 for summer season.

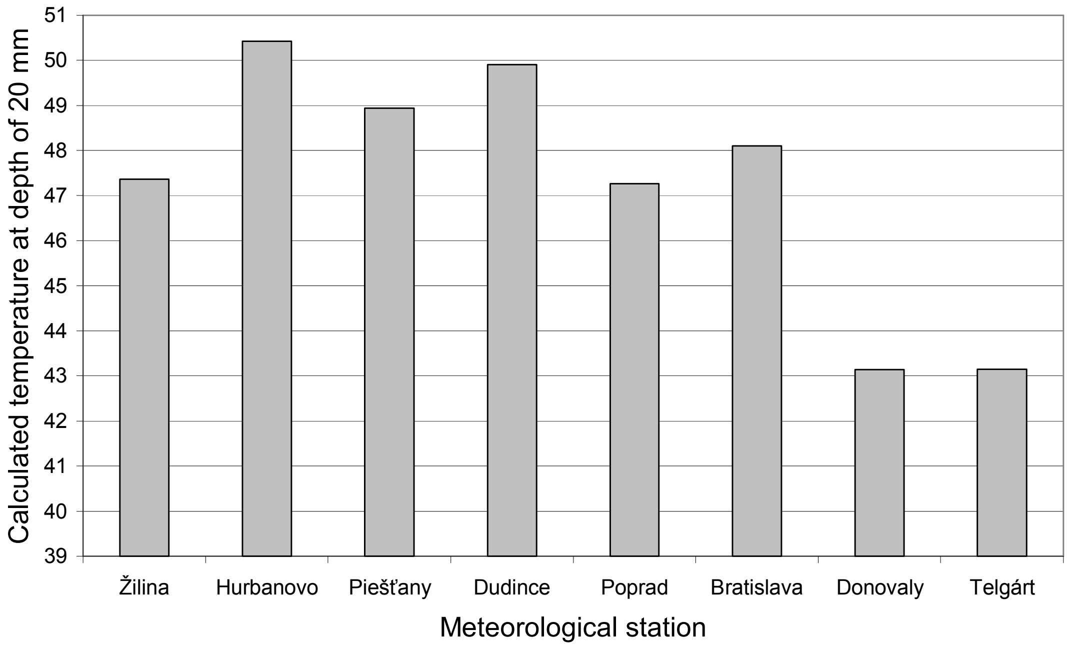

Figure 7 - Example of calculated temperatures at depth of 20 mm below pavement surface

3.2. Winter season

Temperature on surface of pavement was calculated using the following equation published in [6]

$$T_{\min} = 0{,}859 \cdot T_{air} + 1{,}7 \qquad (6)$$

where: $T_{\min}$ - minimum temperature on the surface of pavement [^{o}C]
T_{air} - minimum yearly air temperature for a chosen level of reliability [^{o}C]

Calculated values and temperatures measured at the test section correlated very well (Figure 8) and confirmed the validity of the used equation for Slovak conditions.

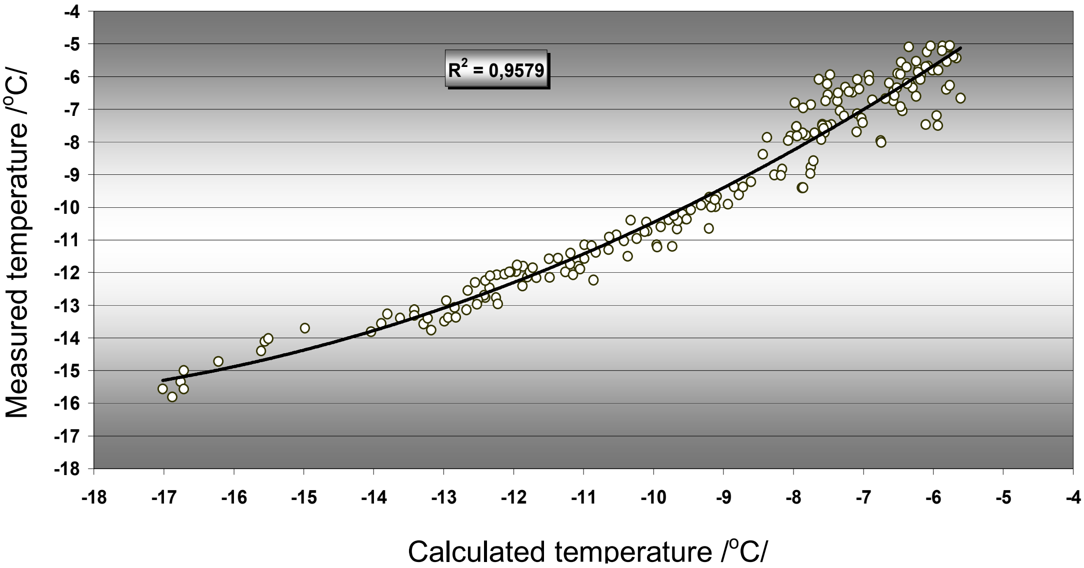

Figure 8 – Comparison calculated and measured temperatures on the top of pavement during winter conditions [3]

Field measurements at the test section were used to determine the temperature in asphalt layers of pavement. The main general conclusions resulting from the analysis of temperature changes in asphalt layers during winter days are the following:

- temperature of asphalt layers decreases during the night and the values are lowest early in the morning;
- the lowest temperature is at the top of pavement and the highest at the bottom of asphalt layers;
- temperature difference of the two levels in asphalt layers is constant during decreasing temperature;
- time shift of minimum temperatures at the top of pavement and bottom of asphalt layers is shorter than time shift for maximum daily temperatures.

The temperature differences between the top of pavement and various depths of pavement were determined using the conclusions above and field measurements. Then temperatures at depth of 40 mm and 130 mm were calculated for all winter representative temperatures of air for each of meteorological stations. Range of temperatures is given in Table 3.

4. REQUIREMENTS FOR PROPERTIES OF BINDER

The main aim for the selection was to maximize rutting resistance and minimaliization of frost cracks generation. From this point of view penetration grading system was chosen. Although it is empirical nature nevertheless it can be used as an indicator of susceptibility of asphalt binder to rutting or cracking. Because the procedure was not focused on determination of the ideal bitumen for best mix performance the Superpave Performance Graded Asphalt Binder Specifications System was not used.

Requirements concerning softening point, breaking point, and penetration of binder were determined in relation to temperatures at the top of asphalt layers. Two temperatures were taken into account in the case of wearing course. The first was temperature at the top of pavement calculated according to equation (1) and second was temperature at the depth of 20 mm resulting form equation (2). It was stated the temperature calculated according to [6] was relatively low (lower than temperature calculated at the depth of 40 mm using thermal diffusion theory) and did not correspond to temperatures measured at experimental field test sections. Using of it could lead to underestimation of requirements on binders into wearing course for hot periods of year (relatively low value of Penetration Grade according to Superpave Performance Graded Asphalt Binder Specifications). That situation was presented in [10] for climatic conditions in Czech Republic that are similar to Slovakia. The penetration grades determined according to SUPERPAVE methodology had to be changed and shifted up to come to properties of binders that have been required for long time (mainly from resistance to rutting point of view).

Therefore temperatures calculated at depths corresponding to the top of wearing, binder and upper base course according to equation (1) and thermal diffusion theory were used for determination of requirements. This means that the temperature on surface of pavement was used for wearing course, the temperature at depth of 40 mm was used for binder course, and the temperature at depth of 130 mm was used for upper base course. The last two depths respect the average thickness of a wearing and binder course used in Slovakia. The range of temperatures used for the asphalt layers that covers the whole territory of Slovakia is given in Table 3.

Table 3 - Range of temperatures for specification of parameters of binder

Asphalt layer	Summer season *	Winter season
Wearing course	from 62 ^{o}C to 68 ^{o}C	from -12 ^{o}C to -20 ^{o}C
Binder course	from 51 ^{o}C to 56 ^{o}C	from -10 ^{o}C to -17 ^{o}C
Upper base course	from 39 ^{o}C to 43 ^{o}C	from -9 ^{o}C to -13 ^{o}C
* valid for wind velocity of 0,9 $m.s^{-1}$		

Required values of softening point and breaking point of bitumen for a pavement layer were determined in relation to the maximum temperature for the summer season and the minimum temperature for the winter season. The range of penetration was calculated from the equation that was used for calculation of penetration index. Three values of penetration were calculated for the penetration index equal to 0, 1 and 2.

Two problems came to light after the calculations. The first one: low values of penetration for the wearing course (less than 30 x 0,1 mm), and second: high values of penetration for the upper base course (more than 130 x 0,1 mm). In the case of wearing course it is not suitable to use hard bitumen in cold regions (formation of frost cracks). Therefore, higher values of penetration were selected but the choice was limited so that the value of penetration index was about 3. As for the upper base course, the choice of higher value of softening point (higher than it would be necessary in relation to the temperature in the layer) led to acceptable range of penetration (regardless of penetration index).

When calculated values were compared to the classification of binders according to [8] and [9] it was stated that only polymer modified binders met the requirements concerning combinations of softening point and penetration. Any bitumen does not exist in categories determined in European standards for the combination of softening point, penetration and breaking point. Therefore a preference of rutting resistance (traffic safety) could be used for selection of bitumen.

Debatable question is if the penetration grading system can be used for modified bitumens. When the viscosity grading system is used for comparison of unmodified and modified bitumens it can be found in [11] that linear relationship between the viscosity and conventional testing (softening point and penetration) exists for modified bitumens too when testing according to ASTM D-2493. As for values, the viscosity derived form softening point is higher then from the DSR test. It was stated that shear rate is considered to be a significant factor affecting the differences and relatively strong correlation between the shift and penetration/softening point was observed. Taking into account these findings it can be assumed that values of the softening point and penetration are sufficient for the selection of bitumen from rutting resistance and frost cracks generation point of view.

The review of requirements for parameters of binders is shown in Table 4. It reflects the variability of climatic conditions in Slovakia. As it can be seen, the most of the combinations are for the wearing course. It is a logical consequence of temperature distribution in pavement and decreasing of temperature differences from the top to the bottom of asphalt layers. If these requirements are compared to Superpave Performance Graded Asphalt Binder Specifications it can correspond to PG 64-16, PG 70-10, PG 70-16 and PG 70-22 for wearing courses, PG 52-10 and PG 52-16 for binder courses. The requirements for parameters of binders for upper base courses do not harmonize with any category of PG. Categories of bitumen according to European standards respecting the requirenents on softening point and penetration range are in the last column.

Table 4 - Requirements for binder parameters in relation to climatic conditions in Slovakia

Asphalt layer	Softening point	Penetration [x 0,1 mm]	Breaking point	Proposed bitumen according to EN 14023 and EN 12591
Wearing course	min. 65 ^{o}C	40 - 70	min. -15 ^{o}C	PmB 45-80
	min. 70 ^{o}C	35 - 50	min. -10 ^{o}C	PmB 25-55
			min. -15 ^{o}C	
			min. -19 ^{o}C	
Binder course	min. 55 ^{o}C	50 -70	min. -10 ^{o}C	PmB 45-80
		70 - 100	min. -15 ^{o}C	PmB 65-105
Upper base course	min. 50 ^{o}C	90 - 140	min. - 9 ^{o}C	PmB 75-130
			min. -12 ^{o}C	
	min. 45 ^{o}C	70 - 100	min. - 9 ^{o}C	PmB 65-105 PG 70/100
			min. -12 ^{o}C	

5. CONCLUSIONS

The analysis of air temperature showed that temperature differences among regions are higher during the winter season than in the summer. It was also found out that a part of Southern Slovakia is colder than some parts in the middle of Slovakia.

Experimental measurements of temperatures in pavements in the test section were in accordance to calculated values and confirmed validity of published formulas for Slovak conditions. The calculated temperatures on the top of pavement ranged from 62 ^{o}C to 68 ^{o}C for the summer season and wind velocity of 0,9 m.s^{-1}, and from -12 ^{o}C to -20 ^{o}C for the winter season. The temperature difference between the top of pavement and the bottom of binder course (130 mm bellow pavement surface) was about 24 ^{o}C for maximum temperatures during the summer season and about 5 ^{o}C for minimum temperatures during the winter season.

Required values of softening point and breaking point of bitumen for the wearing course, binder course, and upper base course were determined in relation to the maximum temperature for the summer season and the minimum temperature for the winter season. The temperature on the surface of pavement was used for wearing course, temperature at depth of 40 mm was used for binder course, and temperature at depth of 130 mm was used for upper base course. The range of penetration was calculated for the penetration index equal to 0, 1 and 2. The calculated range of penetration for the wearing course was low (less than 30 x 0,1 mm) and higher values were selected to minimise formation of frost cracks. Higher values of softening point were chosen to obtain acceptable range of penetration (calculated penetrations were more than 130 x 0,1 mm) in the case of the upper base course.

Various combinations of softening point, breaking point and penetration are necessary to cover the variability of climatic conditions in Slovakia and thermal regime of asphalt layers. Any category determined in European standards for paving grade bitumens and modified bitumens does not cover the requirements for all three parameters and a preference of rutting resistance (traffic safety) could be used for selection of bitumen. According to requirements it is necessary to use the different binders for the same asphalt layer in various regions of Slovakia and binders used for the wearing course, the binder course and the upper base course should have different parameters too.

REFERENCES

1. Solaimanian, M., Kennedy, T., W. (1993). Predicting maximum pavement surface temperature using maximum air temperature and hourly solar radiation. Transportation Research Record 1417, pp. 1-11, TRB.
2. Hermansson, A. (2000). Simulation model for calculating pavement temperatures including Maximum Temperature. Transportation Research Record 1699, paper No. 00-0131, pp. 134-141, TRB.
3. Hroncová, L. (2008). Influence of climatic parameters on quality of pavement structure. PhD thesis. University of Zilina, Zilina. (in Slovak)
4. Čorej, J., Čelko, J., Trojanová, M. (1994). Water and thermal regime of pavements and rail subgrade. VŠDS Žilina, Žilina. (in Slovak)
5. Čelko, J. (1992). Modelling and regulation of thermal regime of flexible pavements. PhD thesis. VŠDS Žilina, Žilina. (in Slovak)
6. Superpave Performance Graded Asphalt Binder Specification and Testing. Superpave Series No. 1 (SP-1). Asphalt Institute, 2003, ISBN 9781934154168
7. Superpave Mix Design. Superpave Series No. 2 (SP-2). Asphalt Institute, 2001, ISBN 9781934154175
8. EN 12591:2009 Bitumen and bituminous binders. Specifications for paving grade bitumens

9. EN 14023:2005 Bitumen and bituminous binders. Framework specification for polymer modified bitumens
10. Mondschein, P., Valentin, J.: Principles of temperature map generation for Czech Republic. In Influence of climatic conditions on road construction. Bratislava, KONGRES management s.r.o 2008. pp.58-63. ISBN 978-80-89275-13-7
11. Mirza, M.W. – Rizvi, M. – Abbas, Z. 2011. Conventional versus Superpave asphalt binder characterization. *5th International conference „Bituminous mixtures and pavements*“. *Volume I* [CD ROM]. Thessaloniki: prof. A.F. Nikolaides, Jún 2011. ISBN 978-960-99922-0-6, p. 521-529.