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Classification of Surface Temperature for the Flexible Pavement Design

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Abstract. Surface temperature significantly affects the asphalt layers modulus and entire pavement structure response to vehicles traffic loading. Because of the rheological properties of bitumen binders, the asphalt performs similarly to temperature-susceptible visco-elastic materials. The historical temperature data of local regions is necessary to design sustainable pavement structures. Likewise, the layers' material mechanical properties determined at specific temperatures is essential for proper design too. This paper presents an analysis of pavement surface temperature classification results. Data analysis covers temperature data from the Road Weather Information Stations from the past ten years. An analysis of various temperature profile forecast methods is presented, followed by a review of recent research on the impact of temperature and cause of failure. Particular emphasis is laid on sorting the qualitative temperature data. The complete linkage clustering method had been used for establishing the most similar pairs for classification. Accordingly, the territory of Lithuania was divided into three main regions with different pavement temperature distributions for each temperature interval. Temperature classification along these lines enables pavement responses to be estimated over the pavement design life.

Keywords: cold climate, flexible pavement, pavement temperature, temperature profile.

Conference topic: Roads and railways.

Introduction

Premature distresses and failures of pavement are caused by an unsuitable design, construction or maintenance activities. The engineering mistakes are related to insufficient or incomplete initial data evaluation. Data pertaining to the local climate, traffic load, and layers' materials and subgrade properties are essential for pavement design. Pavement performs differently in hot, warm, and cold climates, and hence the environmental effects determine pavement design solutions. Pavement environment can be defined as a set of physical properties related to climatic factors in a specific geological and geomorphological situation (Dore, Zubeck 2009). The climate factors that are of importance are as follows (Dave *et al.* 2013; Minhoto *et al.* 2008; Žiliūtė *et al.* 2016): air and surface temperatures, freezing and thawing indices, representative temperature for asphalt mixtures, thermal properties of soils and pavement materials, frost and thaw depths, frost heave, thaw settlements and stresses and strains at critical pavement locations. Simonsen and Isacsson (1999) found that during winter pavement bearing capacity may increase by up to 15%, return to its original state in the summer, and that during autumn and spring, under the influence of rain and thaw, the subgrade bearing capacity is reduced from 15% to 70%.

Surface temperature significantly affects asphalt layer modulus and causes whole pavement response to traffic load. Because of the rheological properties of bitumen binders, the asphalt concrete behaves similarly to temperature-susceptible visco-elastic materials (Alkasawneh *et al.* 2007). Asphalt mixture response viscoelastic behaviour at high temperatures and elastic (brittle) at low temperatures. The modulus of asphalt mixtures depends on bitumen quantity and type of mixture of texture, filler materials, additives and also on void volume and varies with temperature and loading. Information on surface and pavement temperatures is needed for pavement deflection analysis, bitumen binder selection, condition settings for performance tests, and forecast pavement resistance to low-temperature cracking, fatigue and rutting.

This paper analyse surface and pavement temperature and discusses its application to flexible pavement design pavement design procedure. The objectives of this study are to classify historical temperature data of pavement and determine temperature intervals and its distribution intended to apply for flexible pavement design, test conditions determination, and forecast of the pavement performance.

Literature review of temperature influence on pavement

Since the late 1960's many researchers have investigated temperature influence, propagation and prognoses to the flexible pavement (Barber 1957; Lukanen *et al*. 1998; Solaimanian, Bolzan 1993). However, continual changes in the climatic and environmental situation cause difficulties in the evaluation, analysis and prediction (Wistuba, Walther 2013; Mills *et al.* 2007). Europe climate is classified into four main regions: temperate (with cool summers and mild winters), extreme (hot summers and cold winters), cold, and hot (COST 333 1999). Mills *et al*. (2007) analysed the impact of climate change on pavement performance and found that increasing severity of rutting and plastic deformation of asphalt pavement is directly related to rising air temperature. By the information shown below and historical data presented by Žiliūtė *et al.* (2016), Lithuania can be taken as an extreme climatic region, where surface temperature can rise to 51 °C during the hot period and drop to –22 °C (see Fig. 1). Juknevičiūtė-Žilinskienė (2010) investigated the impact of climate on Lithuania's road network and analysed frost depth, wind speed, freezing/thawing cycles. Vaitkus *et al.* (2016) proposed an improved methodology for the design of frost-resistant pavement that was based on data for the period 2012–2014 from 26 Road Weather Stations (RWS), statistical analysis and best practice of other countries.

The widest range of temperature variation is determined at the pavement surface, while at deeper levels temperature variation decreases and becomes uniform (Alkasawneh *et al.* 2007; Ongel, Harvey 2004; Myers *et al.* 1998; Wang, Al-Qadi 2010; Žiliūtė *et al.* 2016). The surface temperature gradient may be up to 5 °C/cm, and the temperature may change up to 40 °C/h (Herb *et al.* 2009). The severe cooling rate results in thermal cracking (Apeagyei *et al.* 2008). Other factors are the effect of temperature variation on asphalt modulus as well as the stress and strain distribution (Nunn, Smith 1997) in every pavement layer. Additional temperature variation analysis in Road of Experimental Pavement Section (REPS) (No. 18) is presented in Figure 2.

Although thermal cracking is related mainly to low temperatures and freezing severity, permanent deformations and rutting are also issues in cold temperature countries. During the season of high temperatures (when the mean daily temperature is >20 °C) flexible pavement bearing capacity decreases 3 to 4 times (Alkasawneh *et al.* 2007) and causes structural and plastic deformation (Vaitkus *et al.* 2014). The road authorities of countries in cold temperature regions prefer select asphalt mixtures with softer bitumen binders to prevent pavement from thermal cracking. This, however, leads to the appearance of permanent deformations. Pavement thermal gradient is greater during the cold season and depends on pavement thickness (Herb *et al.* 2009).

The extreme temperatures, negative or positive, heavy precipitation and excessive moisture content, greater than average frost depth and intense freezing/cooling cycles severely shorten the performance and lifetime of standard designed pavement (Meyer *et al.* 2010; Meyer, Wiegel 2011). Engineers have to base their design decisions on an assessment of relevant properties of materials and layer thicknesses, which will provide pavement performance under extreme environmental conditions.

Temperature variation within the pavement structure is usually characterized by the temperate profile and is affected by the pavement surface temperature which varies continuously during the entire year (Alkasawneh *et al.* 2007). From annual pavement temperature recordings at different depths of structure (Fig. 1) it can be seen that temperature in the subgrade has sinusoidal function trend. However, the temperature in the upper layers and on the surface is highly variable. This unstable temperature variation is caused by solar radiation, thermal properties of materials, convection, and precipitation intensity. Analysis of temperature recordings from REPS showed that surface temperature difference measured at 15 min intervals can be more than 3.5 °C. The highest daily temperature fluctuation is at the surface and at a depth of 2−3 cm (Minhoto *et al.* 2008), but temperature changes in the subgrade are not significantly different during the day.

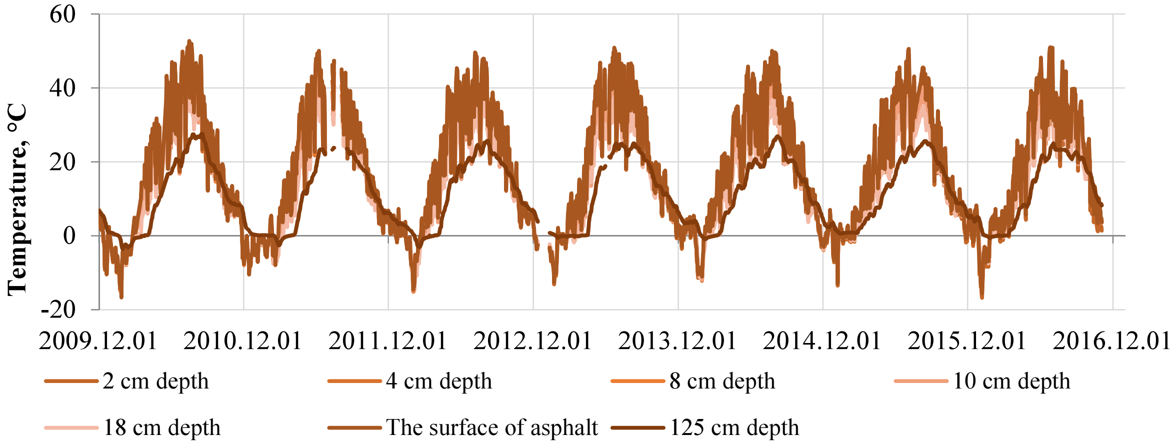


Fig. 1. Recorded temperature variation during 2009−2016 (Source: Žiliūtė *et al.* 2016)

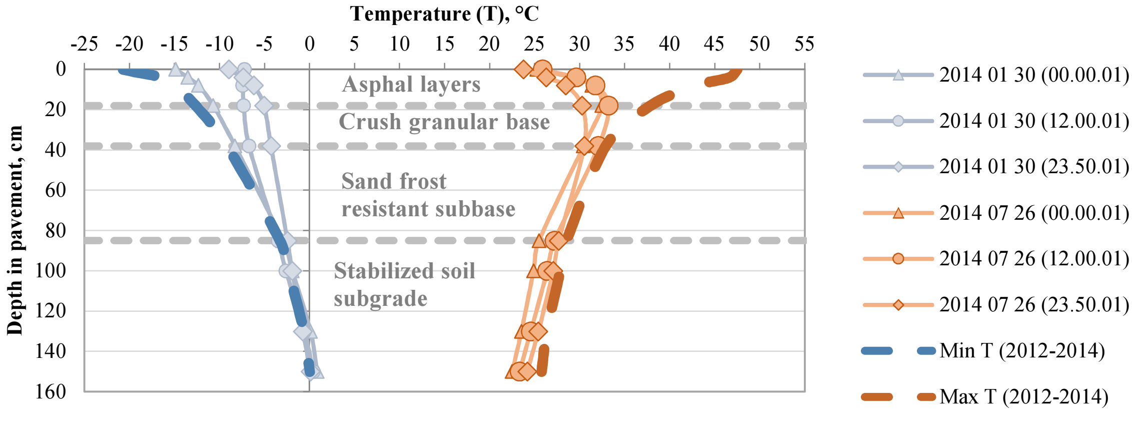


Fig. 2. Measured temperature profiles in REPS (No. 18)

Figure 1 shows that the temperature in the asphalt layers is irregular and varies considerably in a short time. However, the temperature at the top of the subgrade changes slightly and repeats daily average seasonal temperature changes.

Temperature variation in pavement structure can be calculated using empirical and statistical analysis methods. Traditional temperature variation is calculated as temperature profiles based on historical data (Barber 1957; Lukanen *et al.* 1998; Solaimanian, Bolzan 1993; Straub *et al.* 1968) or heat balance equations (Domaschuk *et al.* 1964; Christison, Anderson 1972; Straub *et al.* 1968). Graczyk *et al*. (2014) presented a new concept of analytical solution for heat propagation into pavement based on variations of external temperature and heat flux. Herb *et al*. (2009) simulated the one-directional finite difference heat transfer model and calibrated it with temperature data from MnROAD pavement structures. The temperature variation modelling into pavement structure was considered accepting that the temperature in the structure changes (increases or downward) only in the vertical direction (Herb *et al*. 2006).

The reliability of temperature variation within pavement structure depends on the accuracy of the data and the number of observations. Therefore, it is necessary to have historical data, covering at least a decade, on air temperature (°C), relative humidity (%), wind speed (m/s) and solar radiation (W/m^2) recordings. Some researchers have stated that during the dry season the data can be recorded every hour, but have recommended in wet and cold seasons temperature recordings should be set every 10−15 min. The predictions of surface temperature variation within pavement structure is inseparable from the specific heat capacity of materials of pavement layers (the amount of heat needed for 1 kg of material temperature increase of 1 °C), and the thermal conductivity (the amount of heat transmitted per unit time of one square metre area) (Herb *et al*. 2006).

Temperature variation in the pavement structure was modelled for each layer, subdividing thickness into smaller sublayers. Commonly, the asphalt wearing and binder layers of the pavement structure are divided into 1−2 cm thick sublayers, and asphalt base layer into 5 cm thick sublayers (Herb *et al.* 2006). The modulus and Poisson ratio is set for each sublayer corresponding to the forecasted temperature at the middle of the sublayer.

Pavement design procedure in Germany has simplified the temperature variation in determining the assessment of temperature change in temperature intervals (FGSV 2009). According to this regulation, pavement surface temperature ranges from –15 to +50 °C. The surface temperature range is subdivided into 13 intervals of 5 °C. With regard to the statistical distribution of temperature intervals determined at pavement surface territory was divided into 4 zones. Zoning was performed after the temperature data over a 15 to 25-year period. On the basis of the pavement surface temperature distribution, the temperature calculated at any depth of pavement. The temperature gradient (change) function of an asphalt layer under different conditions can be estimated on the basis the of Speth 1985 and Hess 1998 formula (1):

$$y = b\ln\left(0.01x+1\right)+T, \quad (1)$$

y – temperature at depth x, °C; x – depth in pavement structure, mm; T – temperature of pavement surface, °C; b – empirically determined coefficient, see Table 1.

Table 1. Empirically determined coefficient b (FGSV 2009)

Surface temperature, °C	<–10	<–5	< 0	< 5	< 10	< 15	< 20	< 25	< 30	< 35	< 40	< 45	> 45
Coefficient b	6.5	4.5	2.5	0.7	0.1	0.3	0.4	–1.6	–4.0	–6.2	–8.5	–10.5	–12.0

Analysis of temperature data

During the day, pavement temperature varies very in response to extraneous factors such as shade, shelter, cloud and road de-icing. Therefore, data that were used for the purpose of analysis were collected from those stations where the temperature was measured across all the pavement structure, recording the temperature at the pavement surface and at 7cm depths. The raw data represent 149 stations of the road weather information system (RWIS)and cover the period 2005 to 2015, totalling over 20 million observations (Fig. 3).

The primary data analysis showed that, owing to technical problems when the sensors did not work or when the wrong values were recorded, in some stations many outliers in the raw data were observed – in some moments temperature values went beyond the possible temperature variation range or were significantly different from the temperatures recorded in the same moment measured at different depths. Therefore, these outliers were eliminated from further analysis according to these criteria: Temperature came out of range (–40; 60), and the difference between the same moment surface temperature and temperature at 7cm depth was higher than 15 °C. After applying the data eligibility criteria, 50 RWIS stations, or about 30% of data (~ 6 million observations), remained suitable for further analysis. However, some of the 50 stations were installed only in the middle of 2014 (No. 306, 308, 310, 361, 362, 363, 367, 383, 402, 406, 410, 412, 413, 414, 415, 1004, 1166, 1201 1214), and, therefore, because of the short period of observation these stations were not included in further analysis as well. The final data set encompasses data from 29 stations (a total of 5.56 million observations). RWIS stations used in the statistical analysis are presented in Figure 7. Pavement temperature variation per year measured in 7 cm depth are presented in Figure 4. Descriptive statistics for observed temperature are presented in Table 2. Pavement surface temperature variations per month (2005−2015) are presented in Figure 5.

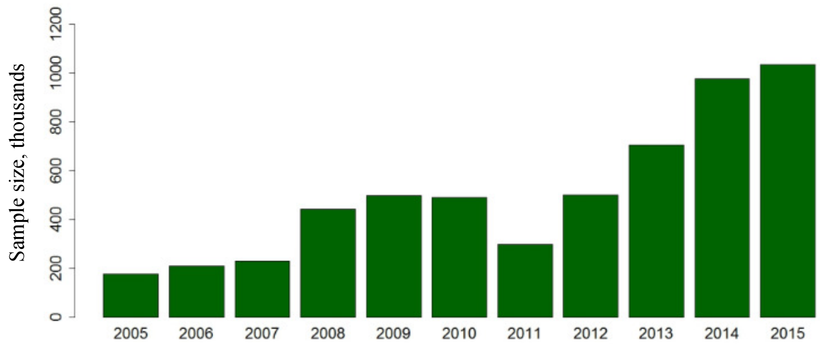


Fig. 3. Number of observations used for statistical analysis

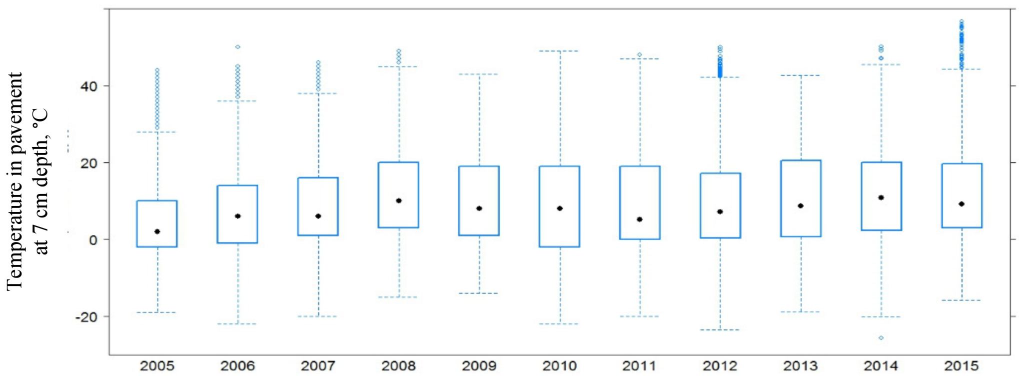


Fig. 4. Pavement temperature variation per year measured at 7cm depth

Table 2. Descriptive statistics for observed temperature

Month		Pavement surface temperature (and temperature in 7 cm depth) , °C					
		First quantile	Third quantile	Minimum	Maximum	Median	Average
January	01	–7.0 (–6.2)	0.5 (0.4)	–27.0 (–25.6)	15.0 (20.8)	–2.0 (–1.8)	–3.5 (–3.0)
February	02	–4.6 (–4.0)	1.0 (0.9)	–28.2 (–23.4)	14.7 (16.0)	–1.0 (–1.0)	–2.1 (–1.9)
March	03	–0.4 (0)	6.3 (5.9)	–20.0 (–19.0)	29.7 (25.9)	3.0 (3.0)	3.2 (2.9)
April	04	5.8 (6.73)	16.1 (14.8)	–9.7 (–6.0)	50.0 (50.0)	10.0 (10.0)	11.6 (10.9)
May	05	13.0 (14.0)	24.4 (22.8)	–2.0 (–1.0)	53.0 (50.0)	17.4 (18.0)	19.3 (18.9)

End of Table 2

Month		Pavement surface temperature (and temperature in 7 cm depth) , °C					
		First quantile	Third quantile	Minimum	Maximum	Median	Average
June	06	16.9 (18.8)	28.6 (27.0)	5.8 (6.0)	54.9 (50.0)	21.0 (22.0)	23.1 (23.0)
July	07	19.4 (21.7)	31.0 (29.7)	7.0 (6.4)	55.9 (56.5)	23.9 (25.0)	25.7 (25.9)
August	08	18.0 (20.0)	28.5 (27.6)	4.0 (–2.0)	53.5 (50.0)	22.0 (23.4)	23.8 (24.1)
September	09	12.4 (14.0)	19.8 (19.6)	0 (–5.0)	50.0 (50.0)	15.2 (16.4)	16.5 (16.9)
October	10	5.0 (6.0)	11.0 (11.05)	–8.6 (–7.0)	50.0 (50.0)	8.0 (8.6)	8.1 (8.6)
November	11	2.0 (2.4)	6.4 (6.6)	–17.0 (–18.8)	15.8 (24.7)	4.4 (5.0)	3.9 (4.4)
December	12	–3.0 (–2.5)	2.4 (2.6)	–26.0 (–18.1)	16.1 (22.5)	0 (0.3)	–0.6 (–0.1)

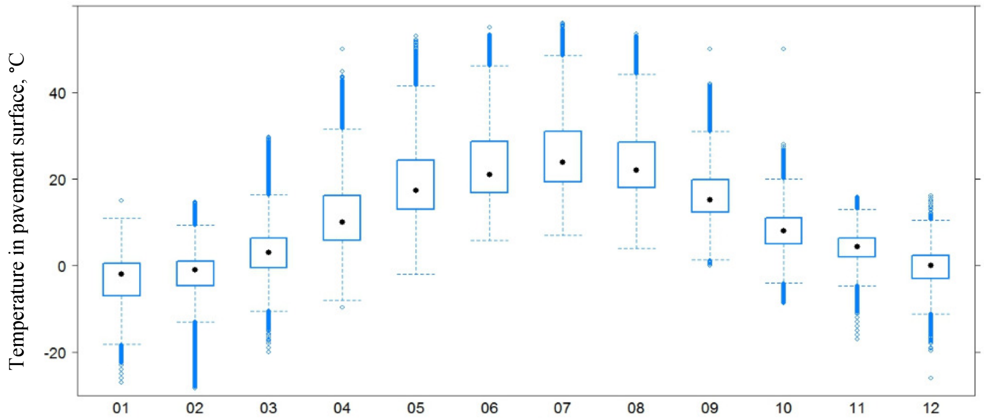


Fig. 5. Pavement surface temperature variation per month (2005–2015)

Classification methods

The main task of clustering analysis was to determine the various regions that had a similar temperature distribution in Lithuanian territory. For this purpose, the observed temperature distribution (histogram) from each station was described by the same number of partial intervals (from –15 °C to 45 °C, at every 5 °C) and observed frequencies (percentage distribution) of analysed temperature in each of them. For the grouped data of surface temperature and temperature at 7 cm depth, hierarchical cluster analysis was used to identify similar groups of RWIS stations according to the observed temperature distribution (histogram) in each of them. The clustering methods result on the selected criteria of "similarities". The analysis was done with several hierarchical clustering cases, from which the experts assessed the most logical option. The Euclidean distance between groups, complete linkage (nearest neighbor) method was selected (Čekanavičius, Murauskas 2009). The results are displayed in a dendogram (Fig. 6), which shows that according to the temperature of pavement surface and temperature at 7 cm depth, three main stations groups, representing three regions of the territory of Lithuania, could be identified. Classification of Lithuanian territory based on surface and pavement temperature analysis is depicted in Figure 8. A histogram of the percentages of the average temperature range for the main regions is presented in Figure 9.

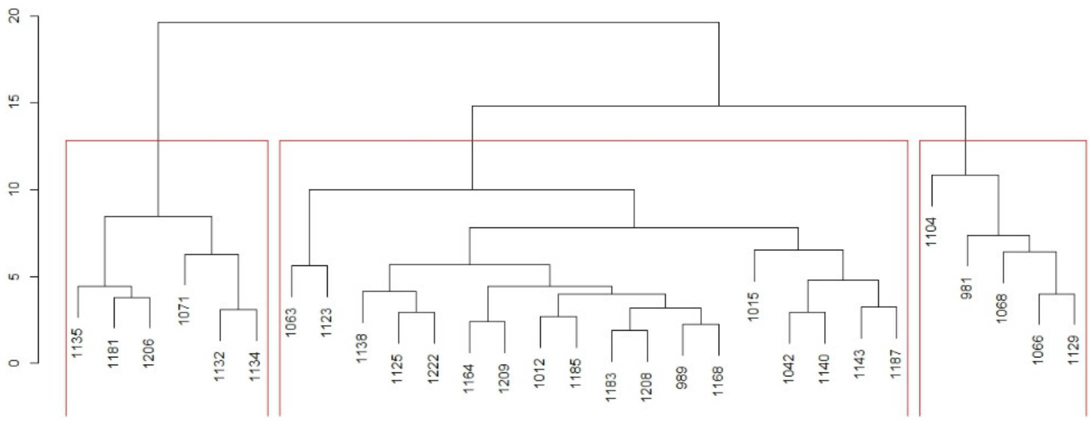


Fig. 6. Dendogram of complete linkage clustering of RWS

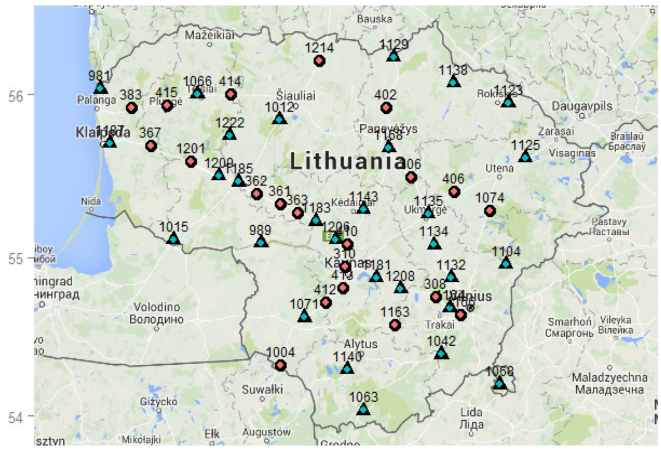


Fig. 7. Road weather stations names and distribution in Lithuania (marked round symbol was eliminated from analysis)

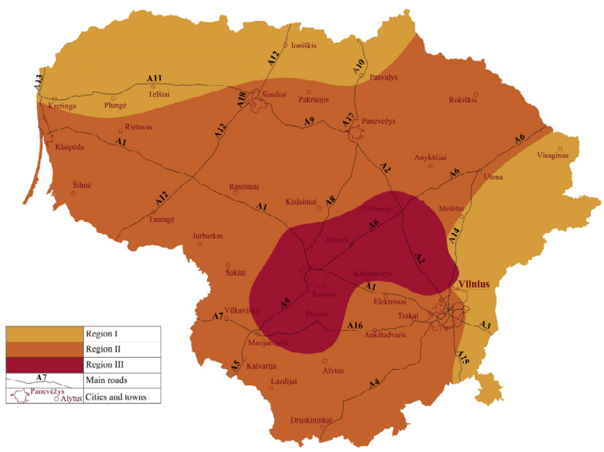
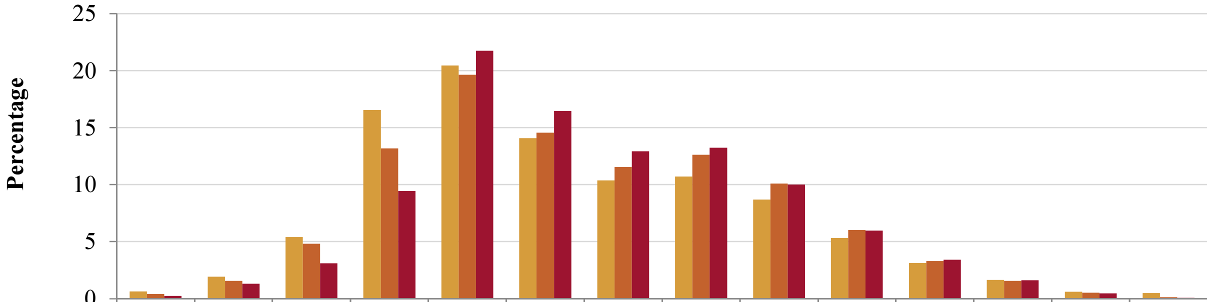


Fig. 8. Classification of Lithuania based on surface and pavement temperature analysis



	(-t;-15)	(-15;-10]	(-10;-5]	(-5;0]	(0;5]	(5;10]	(10;15]	(15;20]	(20;25]	(25;30]	(30;35]	(35;40]	(40;45]	(45;t)
	-17.5°C	-12.5°C	-7.5°C	-2.5°C	2.5°C	7.5°C	12.5°C	17.5°C	22.5°C	27.5°C	32.5°C	37.5°C	42.5°C	47.5°C
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
Region I	0,63	1,92	5,41	16,56	20,44	14,07	10,37	10,70	8,70	5,33	3,12	1,64	0,60	0,50
Region II	0,40	1,57	4,80	13,19	19,65	14,57	11,55	12,63	10,10	6,02	3,30	1,57	0,53	0,12
Region III	0,24	1,30	3,10	9,44	21,74	16,47	12,92	13,24	10,01	5,95	3,42	1,63	0,48	0,06

Fig. 9. Histogram of the percentages of the average temperature range for the main regions

Conclusions

The following are the major conclusions of the paper:

1. The temperature measurements on the pavement surface and at 7cm depth from 29 stations through the period 2005–2015 showed relatively small differences. However, observation of the average temperature on the surface, 10.07 °C, and at 7cm depth, 10.19 °C, shows accumulation of heat.
2. The lowest recorded temperature on the pavement surface was −28.20 °C in 2012, while at 7 cm depth it was −23.4 °C. The highest measured temperature reached 55.90 °C on the surface and 56.53 °C at 7 cm depth in 2015. The average annual temperature data analysis for the 10-year period showed that the pavement temperature ranged from 4.86 °C (2005) to 11.34 °C (2008). The high temperature levels may be attributable to global warming.
3. Statistical analysis of measured and sorted asphalt pavement structure temperatures and the application of the complete linkage clustering method led to the division of the territory of Lithuania into three regions. In each region 14 temperature ranges (classes), each of 5 °C, from −15 °C to +45 °C were determined. This approach will encourage the use of the advanced pavement design procedure for long-lasting pavement structures.

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