Geomechanics and Engineering, *Vol. 13, No. 5 (2017) 793-807*
DOI: https://doi.org/10.12989/gae.2017.13.5.793

Regularities for temperature variation in subgrade of highway

Bagdat B. Teltayev* and Elena A. Suppes

Kazakhstan Highway Research Institute, 2A, Nurpeissov St., Almaty City, 050061, Republic of Kazakhstan

(Received June 14, 2016, Revised March 27, 2017, Accepted May 13, 2017)

Abstract. Regularities of temperature variation were determined in points of subgrade of the highway. Measurement of temperature was performed by special sensors, based on the effect of thermal resistance. Regular measurements of temperature were performed for two sections of the highway with asphalt concrete and cement concrete pavements for continuous period from November 2010 to March 2016. Multi-year experimental data, which we obtained, allowed establishing of peculiarities for temperature variation in points of subgrade in time and temperature distribution in the depth for annual cycle. Characteristics were determined for winter period-depth, duration and freezing rate, duration and defreezing rate for pavement and subgrade of the highway.

Keywords: highway; subgrade; sensor; temperature; temperature gradient; freezing; defreezing

1. Introduction

Pavement structure and subgrade are the main elements of the highway from the point of view for provision of strength and durability. Since during impact of mechanical forces from vehicles and natural and climatic factors they work jointly as the unique mechanical and physical system, they are considered jointly during designing of highways (Huang 2004, Papagiannakis and Masad 2008, Yoder and Witczak 1975, NCHRP 2004, Alawi and Helal 2014).

Temperature influences greatly on state, and therefore, on physical and mechanical properties of subgrade soil. Thus, the freezing procedure starts in wet soil when the temperatures are lower than the freezing temperature, which is accompanied by transition of pure water from liquid aggregate condition into solid one (ice) with phase transition heat emission. As it is known, deformability, strength and thermal physical characteristics of frozen soils differ greatly from unfrozen soils (Liu 2002). Tan *et al.* (2011), Ye *et al.* (2012), Song *et al.* (2007) and Vaitkus *et al.* (2014) devoted their works to the analysis of peculiarities for temperature variation in subgrade in seasonal frozen soils. Ye *et al.* (2012) developed a moisture-thermal coupling model and determined temperature distribution in subgrade and depth of freezing with the help of it. Song *et al.* (2007) used finite element method for analysis of temperature distribution in subgrade and evaluated stresses, occurred in subgrade during its freezing and defreezing. Tan *et al.* (2011) obtained experimentally that temperature varied in time under cosine law in subgrade and the heat was transferred non-linearly in the depth. In the work (Vaitkus *et al.* 2014) the results of

*Corresponding author, Professor, E-mail: bagdatbt@yahoo.com

http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

experimental research for temperature distribution in subgrade of the trial highway section showed that moisture variation was connected with temperature variation, and the least moisture occurred when the temperature was minimal.

Temperature gradient shows the direction of heat flow and causes the effect of thermal diffusion (moisture transfer with availability of temperature difference). For example, it was obtained experimentally in the work Xu *et al*. (2013) that formation of water concentration gradient in subgrade soil was based, mainly, on temperature gradient.

Highway specialists of the beginning of the last century understood the importance of temperature impact in subgrade on pavement state. Thus, as the short message of Wiley read (1919) they believed in the Illinois University, that concrete highway cracking phenomenon can be explained by limits and rates of temperature variation in pavement and subgrade, and investigations were started. Preliminary results showed that extreme temperatures delay greatly in comparison with the air.

Tan and Hu (2010) obtained experimentally that water transfer in soil under impact of temperature gradient takes a long time. There was no obvious water transfer in the tested samples during first days. It became obvious only after expiring of five days.

Essential role of temperature gradient in water transfer in the frozen soil was evaluated experimentally in the work of Mao *et al.* (2014).

The paper (Izvolt and Hodas 2014) mentions the practical importance of zero isotherm during construction of subgrade for railway and it is investigated experimentally by testing stand and numerical simulation.

They calculated temperature values in New Hampshire State (Vincent *et al.* 1999) for the surface of highway subgrade under computer program in each month of the year and they obtained resilient modulus values for subgrade soils at those temperatures in the laboratory.

The works (Hossian *et al.* 2000, Long *et al.* 1997) show existence of reliable correlation relationship between temperature and subgrade modulus.

Some results of investigation for temperature variation in pavement and subgrade of highways were published in the works (Teltaeyev 2011, 2013a, b, Teltaeyev and Aitbayev 2015a, b, Teltaeyev *et al.* 2015).

This work determines regularities of temperature variation in highway subgrade based on analysis of multi-year experimental data (from November 2010 to March 2016).

2. Experimental section and sensors

2.1 Experimental highway section

The sections with asphalt concrete (km 76+30) and cement concrete (km 19+750) pavements of “Astana-Burabai” highway were selected for performance of long-term monitoring for temperature and moisture variation in pavement structure layers and points of subgrade of the highway in climatic conditions of northern region of Kazakhstan in November 2010. Fig. 1 shows general view of experimental highway section with asphalt concrete pavement. Highway sections have 6 lanes with the width of 3.75 m each. It is allowable for car to move with the speed of 140 kph, and for trucks with the speed of 110 kph along this highway. Reconstruction of the highway was completed in November of 2009.

Pavement structure of the section with asphalt concrete (Fig. 2) consists of the following layers:

Fig. 1 General view of section with asphalt concrete pavement (km 76+30) of “Astana-Burabai” highway

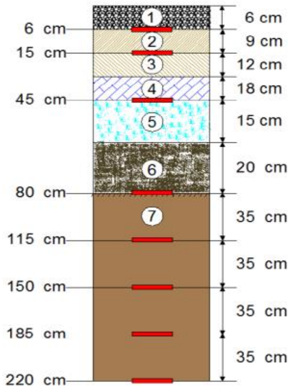

Fig. 2 Scheme for location of sensors in pavement structure and subgrade for section with asphalt concrete pavement of “Astana-Burabai” highway: 1…6- numbers of pavement layers, 7-subgrade, -temperature and moisture sensors

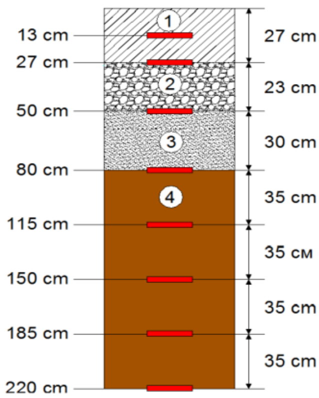

Fig. 3 Scheme for location of sensors in pavement structure and subgrade for section with cement concrete pavement of “Astana-Burabai” highway: 1…3-numbers of pavement layers,4subgrade, -temperature and moisture sensors

1-stone mastic asphalt concrete, 6 cm; 2-dense asphalt concrete, 9 cm; 3-crushed stone treated with bitumen, 12 4-crushed stone and sand mix treated with cement (7%), 18 cm; 5-crushed stone and sand mix, 15 cm; 6-sand, 20 cm. Subgrade is constructed from heavy sandy clay loam: moisture in the plastic limit W_P=18.7%; moisture in the liquid limit W_T =34.8%. Pavement structure for the section with cement concrete (Fig. 3) consists of the following layers: 1-cement concrete pavement, 27 cm; 2-crushed stone, 23 cm; 3-crushed stone and sand mix treated with ash, 30 cm. Subgrade of this section is constructed from light dusty clay loam: moisture in the plastic limit W_P=15.0%; moisture in the liquid limit W_T=25.4%.

Underground water is deep (lower than 3.0 m).

2.2 Sensors

Company “Interpribor” (Chelyabinsk, Russia) produced temperature and moisture sensors on

Fig. 4 One set of temperature and moisture sensors

Fig. 5 Installation of sensor into pavement structure

Fig. 6 Measurement (land) system for set of temperature and moisture sensors

the order of Kazakhstan Highway Research Institute (KazdorNII). Each sensor, produced in the form of metal capsule, contains element for measurement of temperature based on the effect of thermal resistance and element for measurement of moisture through diamagnetic permeability. Such design concept allows performing simultaneously the measurement of temperature and moisture in points of pavement and subgrade.

Fig. 4 shows general view of one set of sensors visually.

Temperature elements of sensors were calibrated by the producer and moisture elements were calibrated in the laboratory of KazdorNII. Calibration of sensors was performed with the use of soils, selected from the areas of their installation.

Installation of sensors into pavement and subgrade layers of the highway (Fig. 5) was performed by the specialists of KazdorNII during the first decade of November 2010. Measurement ends of the sensors were put on the surface of the highway and collected in measurement chamber of land system of the set (Fig. 6).

Temperature and moisture measurements are performed regularly in points of pavement and subgrade since the moment of installation of the set of sensors up to the present moment.

Each set had 8 temperature and moisture sensors, 3 of which were installed in pavement layers, and 5 of them were installed into subgrade of the highway.

The depth for their installation, calculated from pavement surface, were equal to: for the sections with asphalt concrete-6, 15, 45, 80, 115, 150, 185, 220 cm and for the section with cement concrete-13, 27, 50, 80, 115, 150, 185, 220 cm. Complete procedure for installation of sensors was performed in the following consecutive sequence:

1. The well was developed with diameter of 16 cm and depth 220 cm from the pavement surface by machine drilling.
2. Soil was carefully removed from the well, then it was stored in separate portions in row, and measures were taken for observance of its initial moisture content without change.
3. Sensor, installation of which was provided in the depth of 220 cm, was laid on the bottom of the well.
4. Portion of soil was excavated from subgrade in the depth of 220 cm and filled above the sensor.
5. Soil was compacted physically up to the designed level.

All other sensors were installed by similar way. Portions of soil, excavated from the well, were filled in reversed order and compacted up to the designed level.

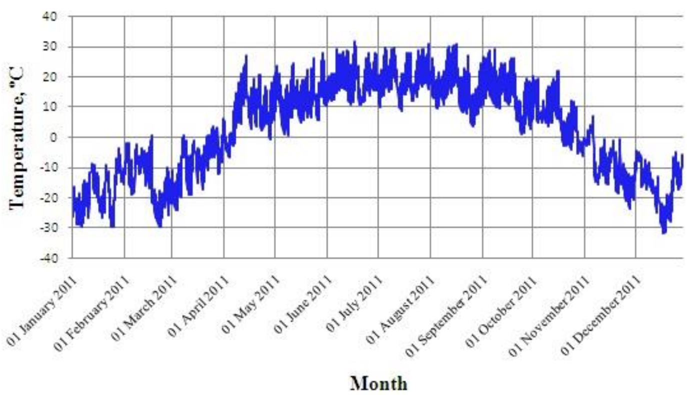

Fig. 7 Graph for air temperature variation in Astana city in 2011

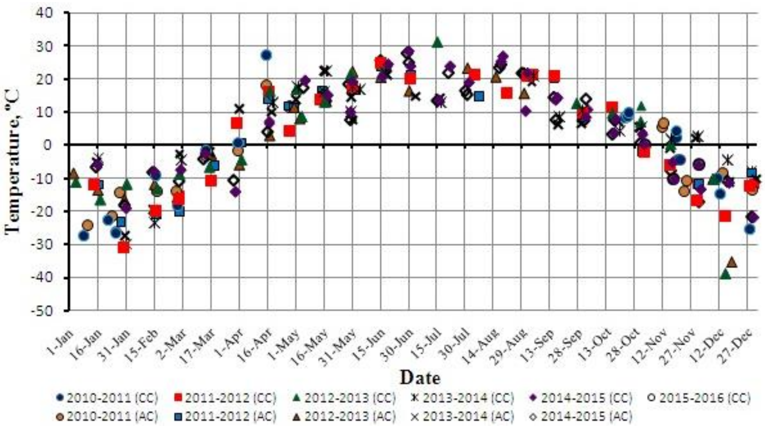

Fig. 8 Air temperature values on experimental sections of “Astana-Burabai” highway: CC-cement concrete and AC-asphalt concrete

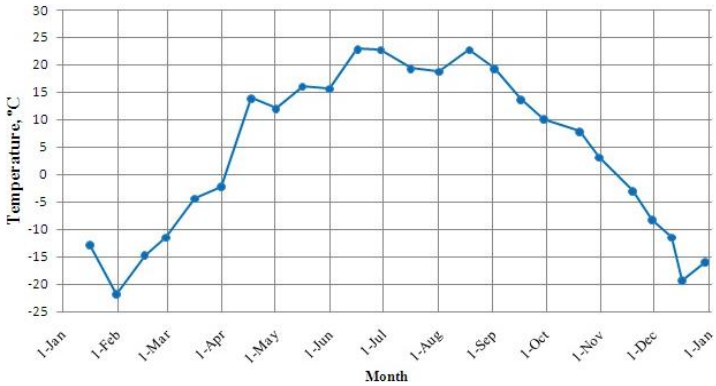

Fig. 9 Mean half-monthly air temperature values in experimental sections of “Astana-Burabai” highway

3. Air temperature

Analysis and comparison of perennial data regarding air temperature and temperature in points of subgrade of the highway showed that behavior of temperature in points of subgrade, located in different depths, and mean monthly air temperature are the same. Fig. 7 as an example shows graph of air temperature variation in Astana city in 2011. As it is seen, air temperature varies during annual cycle from +32.0℃ in summer (June) to -32.0℃ in winter (December). Maximum and minimum temperatures in summer can account for +32.0℃ and +4.0℃ respectively, and 0℃ and -32.0℃ respectively in winter. Air temperature variation during wide range of annual cycle and seasons of the year causes temperature variation in points of subgrade of the highway, especially in the upper part of subgrade.

Fig. 8 shows values of air temperature, measured in selected experimental sections, for the period from November 2010 to March 2016. It is seen that despite of availability of some discrepancy, air temperature values of experimental sections, measured for various years (for 5 successive years), they have similar variation behavior. Fig. 9 shows the graph of mean half-monthly air temperature values, constructed according to data of Fig. 8. The last graph will be useful during analysis of temperature in points of subgrade.

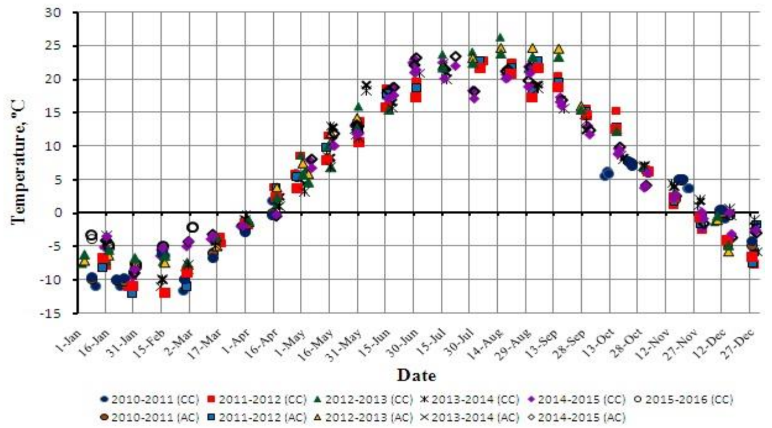

Fig. 10 Temperature values in the depth of 80 cm (surface of subgrade)

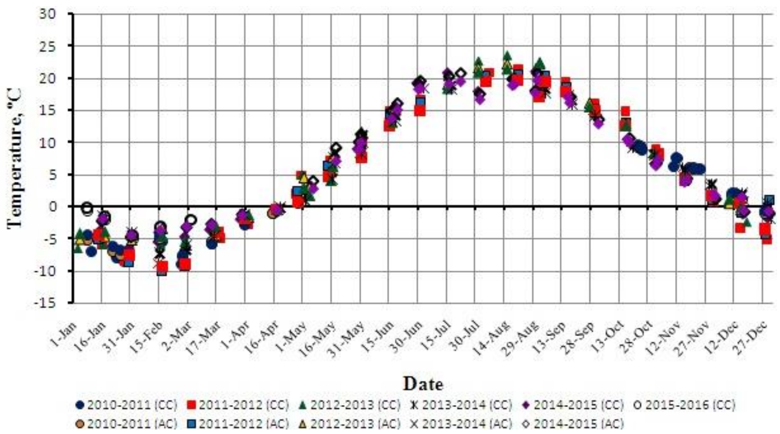

Fig. 11 Temperature values in the depth of 115 cm

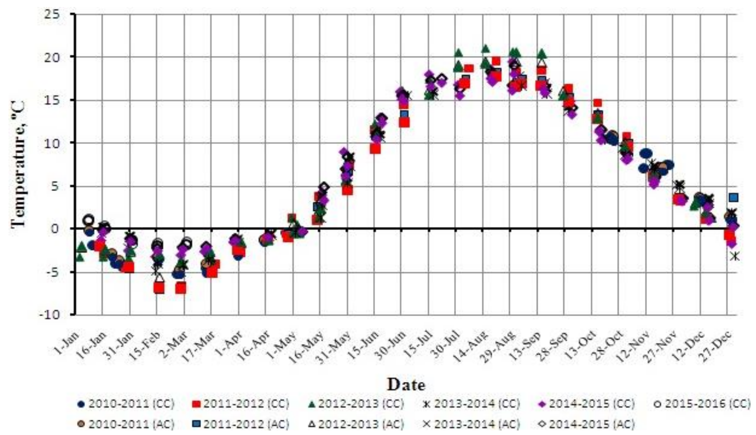

Fig. 12 Temperature values in the depth of 150 cm

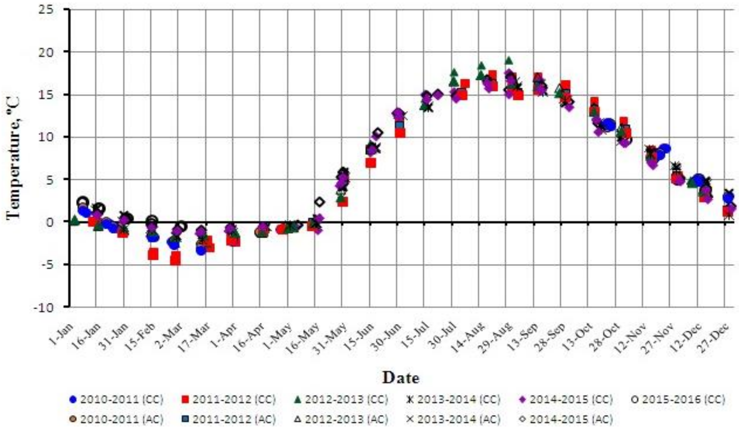

Fig. 13 Temperature values in the depth of 185 cm

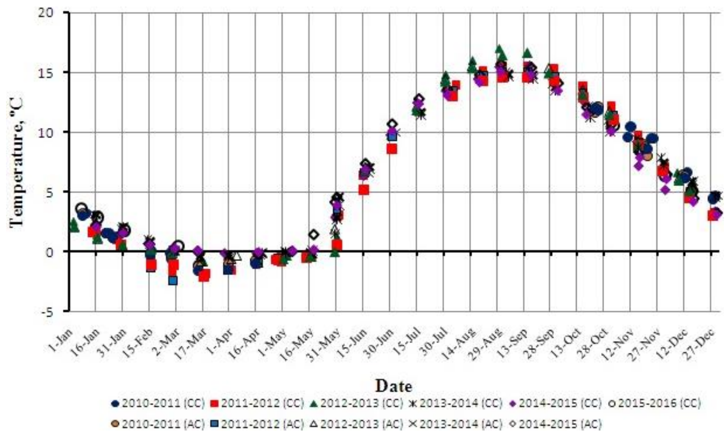

Fig. 14 Temperature values in the depth of 220 cm

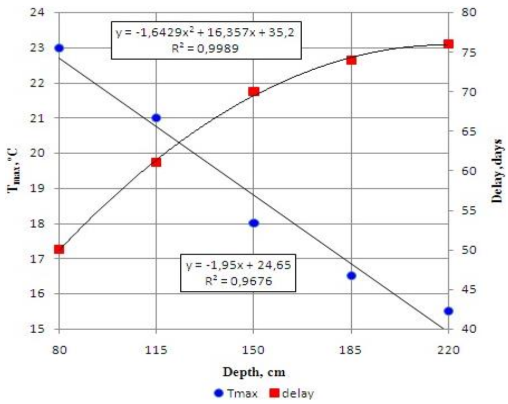

Fig. 15 Dependencies of maximum temperature and delay time of maximum temperature on the depth

4. Temperature in subgrade

Figs. 10-14 show temperature values in points of subgrade, located in various depths, they were measured in experimental sections for the period from November 2010 to March 2016. It should be noted that temperature variation has harmonicity for all designated depths of subgrade for annual cycle, and discrepancy of temperature values, measured for various years, is considerably less in comparison with air temperature, i.e., one can say that statistic homogeneity of perennial temperature values increases with the depth increase.

Fig. 15 shows dependencies of maximum temperature for annual cycle T_{max} and its delay in relation to maximum value of mean air temperature in points of subgrade from the depth. It turned out that maximum temperature decreases linearly with the depth, and delay time increases nonlinearly. Maximum temperature is 23℃ on the surface of subgrade and 15.5℃ in the depth of 220 cm. Delay time in these points is equal to 50 and 76 days respectively, i.e., temperature will reach maximum value in the depth of 220 cm only 26 days later (about one month) after the surface of subgrade will have maximum temperature. The least negative temperature also depends linearly on the depth: its absolute value decreases with the depth increase (Fig. 16).

Minimum negative temperature, equal to -12.5℃, was obtained on the surface of subgrade on January 31st.

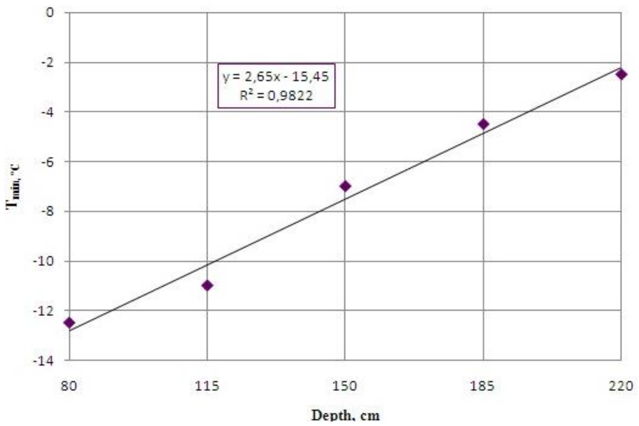

Fig. 16 Dependence of the least negative temperature in the points of subgrade on the depth

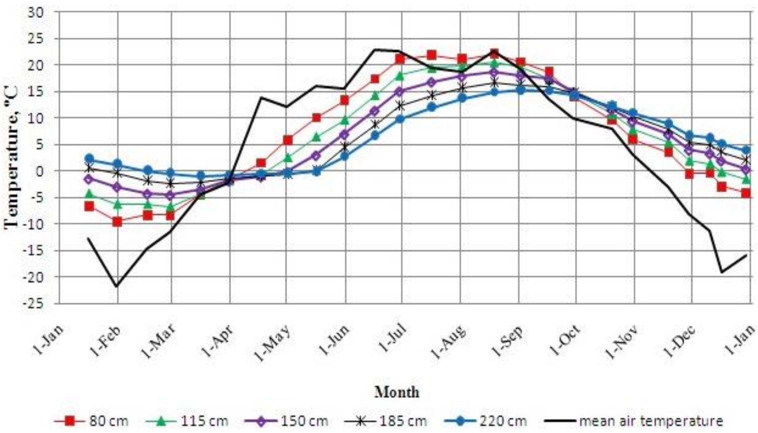

Fig. 17 Mean multi-year temperature in points of subgrade and mean multi-year half-monthly air temperature

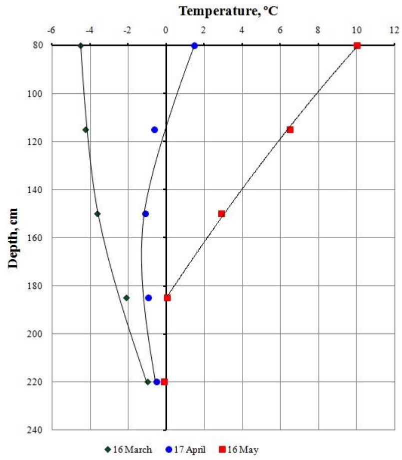

Fig. 18 Mean multi-year temperature in points of subgrade and mean multi-year half-monthly air temperature

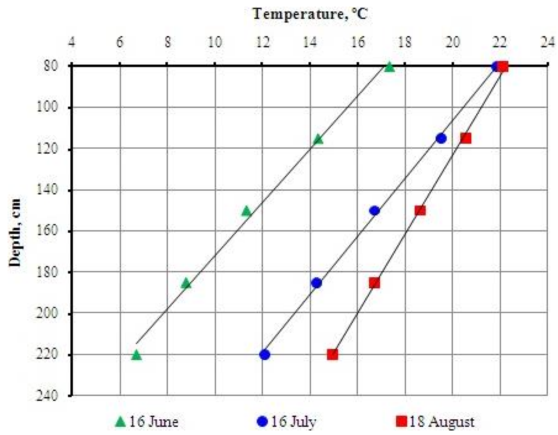

Fig. 19 Distribution of temperature in the depth of subgrade in the months of June, July and August

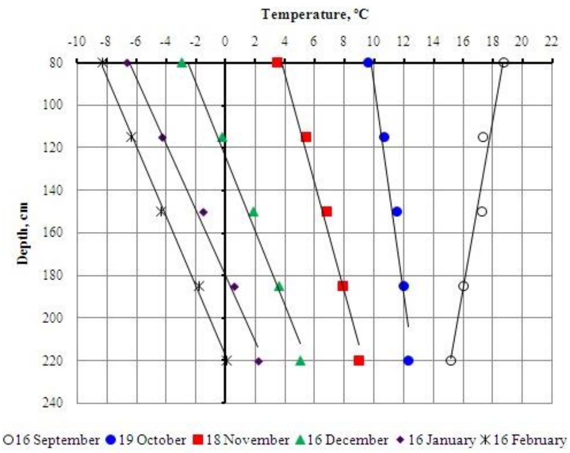

Fig. 20 Distribution of temperature in the depth of subgrade in the months of September, October, November, December, January and February in the months of June, July and August

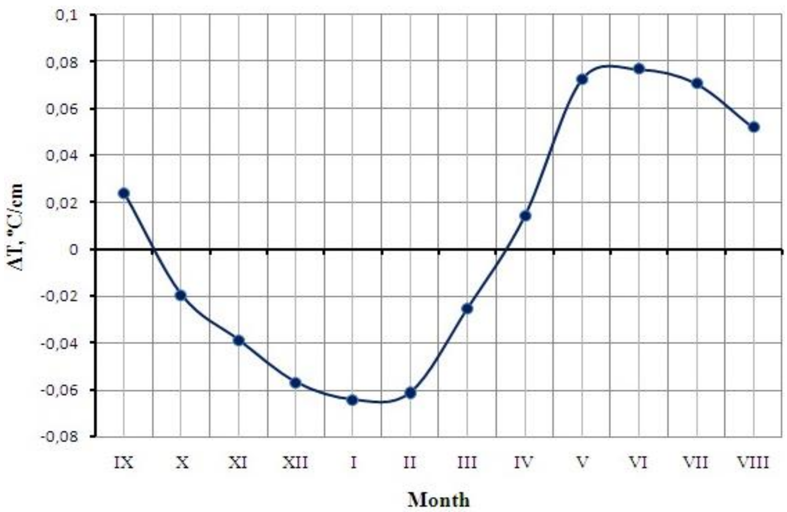

Fig. 21 Variation of temperature gradient in subgrade

Fig. 17 shows graphs of mean values for temperature in points of subgrade, constructed under data of Figs. 10-14. Fig. 17 also shows mean perennial half-monthly values of air temperature. It is seen from Fig. 17 that there is time moment in spring (tentatively in the beginning of April), when temperature is the same and equal to -1…-2℃ in points of subgrade (to the depth of 220 cm), and there is time moment in autumn (tentatively the end of September), when temperature is the same and equal to +14…+15ºC (to the depth of 220 cm). Temperature in subgrade decreases with the depth increase between determined time moments tentatively for 6 months, and temperature increases with the depth increase for other 6 months. It can be also seen in Figs. 18-20, which show the graphs of temperature distribution in the depth of subgrade during various months of the year. It should be also mentioned that the temperature is distributed linearly in the depth of subgrade in practice, except for March, April, May months, i.e., gradient temperature has constant values. Air temperature increases with coming of spring. Mean daily temperature of March passes over 0℃ to positive temperatures, and pavement and subgrade start to defreeze gradually from top to bottom. The rate of temperature increase is higher in the upper part of subgrade, than in its bottom part, which provides non-linear temperature distribution in the depth of subgrade during this transition period. Temperature gradient of these months can be characterized by its mean values in the depth.

Fig. 21 shows the graph of temperature gradient variation in subgrade during annual cycle. It was found that temperature gradient varies during annual cycle under harmonic law similar to temperature in points of subgrade. This graph has two points with zero temperature gradient, i.e., when temperature has the same values for the whole depth of subgrade. They correspond to the values of the end of September and beginning of April, and we mentioned them above during analysis of the graphs in Fig. 17. Maximum values of temperature gradient in summer (in June) and in winter (in January) are equal to 7.7℃/m and 6.4℃/m, respectively.

Information regarding temperature gradient is important during analysis of heat and moisture transfer in subgrade and pavement of the highway. First, temperature gradient shows the direction of heat flow, and you can use it for calculation of heat quantity. Second, it causes the effect of thermal diffusion, i.e., transfer of moisture with availability of temperature gradient.

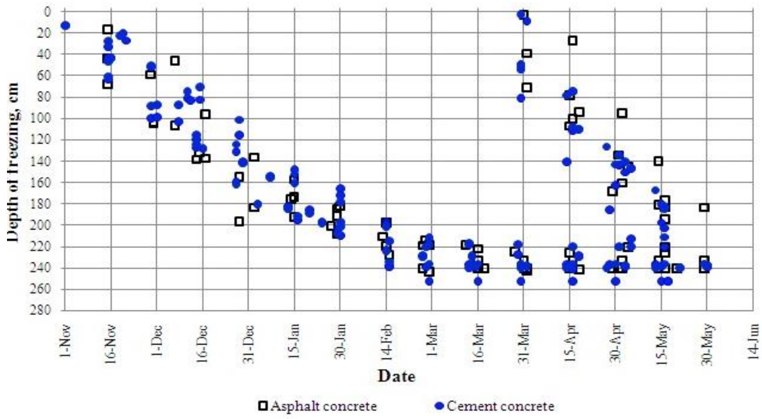

Fig. 22 Values for depth of freezing and defreezing in pavement structure and subgrade (2010-2016)

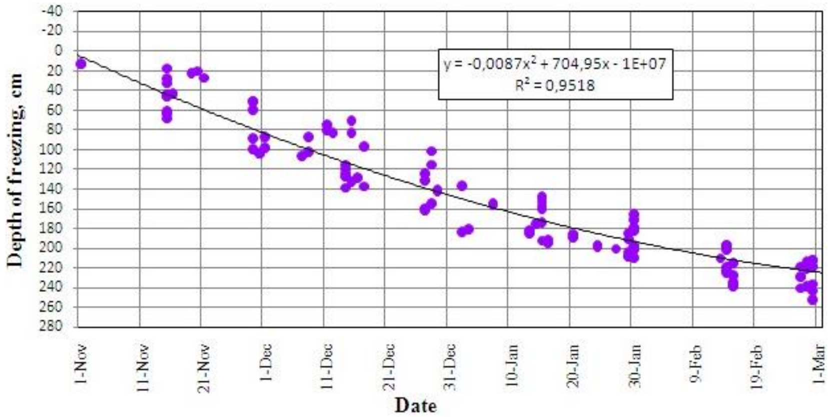

Fig. 23 Graph of freezing in pavement structure and subgrade (2010-2016)

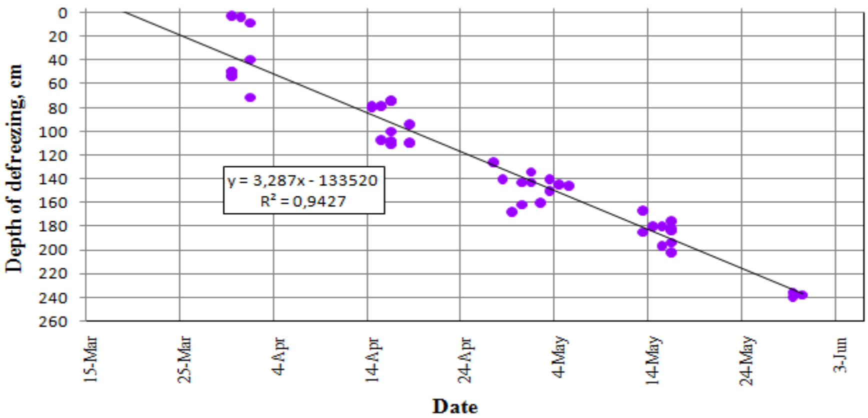

Fig. 24 Graph of defreezing in pavement structure and subgrade (2010-2016)

5. Freezing depth

Freezing depth is one of the important characteristics of highways during winter season. This indicator is considered during designing of pavement structure in Kazakhstan. The more the depth of freezing is, the more severe the design requirements are for pavement structure and soil of subgrade. Fig. 22 shows the values for depth of freezing during cold season in pavement structure and subgrade.

The figure shows clearly that the whole process of freezing and defreezing can be divided into three significant periods. Freezing of pavement structure and subgrade occurs during the first period with decreasing rate (Fig. 23). Permanent freezing of pavement starts tentatively on 30th October. Initial freezing rate is 2.5 cm/day. Depth of freezing increases for this period under parabolic curve, and freezing rate decreases under linear dependence. Freezing depth reaches its biggest value in the end of this period-tentatively on 1st March. Mean rate value during the first period and its mean duration are 1.25 cm/day and 120 days respectively. The second period (average duration 92 days from 1st March to 31st May) is characterized by permanent freezing depth, maximum value of which is 253 cm. Defreezing of pavement and subgrade occurs from top to bottom during the third period, which starts from 20th March and lasts until 31st May (Fig. 24).

Average duration for the period of defreezing is equal to 72 days. The process of defreezing during this period occurs with permanent rate, which is equal to 3.51 cm/day. As it is seen, average defreezing rate is 2.81 times more than the average freezing rate. Pavement and top part of subgrade are frozen for 130-140 days at average during the course of the year.

6. Conclusions

(1) Difference in pavement structures (cement concrete or asphalt concrete pavement, pavement layers from various materials) does not have essential impact on distribution and temperature variation in points of subgrade.

(2) Temperature variation has harmonicity in points of subgrade during annual cycle. Statistical homogeneity of temperature values, measured during various years, increases with the depth increase.

(3) Annual maximum air temperature is 32℃ in the considered climatic conditions, and it is equal to 23℃ and 15.5℃ on the surface of subgrade and in the depth of 220 cm respectively. Annual maximum temperature in points of subgrade decreases with the depth increase. Annual maximum temperature in points of subgrade delays in time in relation to annual maximum air temperature. Time delay increases with the depth increase under parabolic dependence. So, time delay accounts for 50 and 76 days on the surface of subgrade and in the depth 220 cm respectively.

(4) Annual minimum air temperature is equal to -32℃, and it is equal to -12.5℃ and -2.5℃ on the surface of subgrade and in the depth of 220 cm respectively. Absolute value of annual minimum air temperature in points of subgrade increases with the depth increase.

(5) There is time moment in spring (beginning of April), when temperature is the same and equal to -1…-2℃ in points of subgrade, and there is time moment in autumn (end of September), when the temperature is +14…+15ºC. Temperature in points of subgrade decreases with the depth increase during warm season (from the beginning of April to the end of September), and the temperature increases with the depth increase during cold season (from the end of September to the beginning of April. Temperature is distributed linearly in subgrade except for spring months March, April and May. Mean temperature gradient varies quasi harmonically during annual cycle. Its maximum value (in June) and minimum value (in January) are equal to 7.7℃/m and 6.4℃/m, respectively.

(6) Permanent freezing of pavement of the considered region starts on October 30 or so. Mean rate and maximum depth of freezing are 1.25 cm/day and 253 cm respectively. Process of defreezing for pavement and subgrade starts from March 20 with constant rate of 3.51 cm/day. Pavement and subgrade are frozen approximately for 130-140 days in the course of the year. Duration of defreezing for the highway from top to bottom is approximately 72 days.

Acknowledgments

This research is supported by the Road Committee of the Ministry for Investments and Development of the Republic of Kazakhstan (Agreement No. 36 dated July 21, 2016).

References

Alawi, M.H. and Helal, M.M. (2014), "A mathematical model for the distribution of heat through pavement layers in Makkah roads", *J. King Saud U. Eng. Sci*., **26**(1), 41-48.

Hossian, M., Romanoschi, S. and Gisi, A. (2000), "Seasonal and spatial variation of subgrade response", *Proceedings of the Sessions of Geo-Denver 2000*, Denver, Colorado, U.S.A., August.

Izvolt, L. and Hodas, S. (2014), "Software support for Temperature regime modeling of railway track construction", *Logist*., **4**, 2861-2871.

Liu, W., He, P. and Zhang, Z. (2002), "A calculation method of thermal conductivity of soils", *J. Glaciol. Geocry*., **24**(6), 770-773.

Long, B., Hossian, M. and Gisi, A. (1997), "Seasonal variation of backcalculated subgrade moduli", *Transport. Res. Rec*., **1577**, 70-80.

Mao, X., Miller, C. Xou, Z., Khandker, A. and Xiao, X. (2014), "Experimental study of soil water migration in freezing process", *Geotech. Test. J*., **37**(3), 1-11.

NCHRP (2004), *Project 1-37 A, Guide for Mechanistic Empirical Design of New and Rehabilitated Pavement Structures*, Final Report, Transportation Research Board of the National Academies, Washington, U.S.A.

Song, M., Xie, Z., Zheng, H. and Zhang, W. (2007), "Numerical simulation for temperature field of subgrade on seasonal frozen area", *Proceedings of the International Conference on Transportation Engineering*, Chengdu, China, July.

Tan, Y. and Hu, X. (2010), "Experimental study on moisture transmission of compacted laterite soil under temperature effect", *Proceedings of the International Symposium on Multi-field Coupling Theory of Rock and Soil Media and Its Applications*, Chengdu, China, October.

Tan, Y.Q., Xu, H.N., Zhou, C.X. and Chen, F.C. (2011), "Temperature distribution characteristics of subgrade in seasonally frozen regions", *J. Harbin Inst. Technol*., **43**(8), 98-102.

Teltayev, B.B. (2011), "Regularities of water and thermal regime of the highway Astana-Burabay", *Bull. Kazakhst. Highw. Res*., **3-4**, 36-54.

Teltayev, B. (2013a), "Road subgrade temperature and moisture variations", *Proceedings of the 5th International Geotechnical Symposium Geotechnical Engineering for Disaster Preventions and Redaction, Environmentally Sustainable Development*, Incheon, Korea, May.

Teltayev, B. (2013b), "Water and temperature regime of the highway Astana-Burabay", *Road Tech*., 26-34.

Teltayev, B. and Aitbayev, K. (2015a), "Modeling of temperature field in flexible pavement", *Ind. Geotech. J*., **45**(4), 371-377.

Teltayev, B. and Aitbayev, K. (2015b), "Modeling of transient temperature distribution in multilayer asphalt pavement", *Geomech. Eng*., **8**(2), 133-152.

Teltayev, B.B., Suppes, E.A. and Baibatyrov, A.I. (2015), "Characteristics of highway subgrade frost penetration in regions of the Kazakhstan", *Proceedings of the 15th Asian Regional Conference on Soil Mechanics and Geotechnical engineering*, Fukuoka, Japan, November.

Vaitkus, A., Cygas, D., Laurinavicius, A., Vorobjovas, V. and Ziliute, L. (2014), "Long term monitoring of performance characteristics of the pavement test track", *Proceedings of the Transport Research Arena 5th Conference on Transport Solutions from Research to Deployment*, Paris, France, April.

Vincent, C.J., John, J.B., Glen, D.D. and Charles, E.S. (1999), *Resilient Modulus for New Hampshire Subgrade Soils for Use in Mechanistic AASHTO Design*, US Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, U.S.A.

Wiley, C.C. (1919), "Comparison of road-subgrade and air temperatures", *Month. Weath. Rev.*, **47**(11), 802.

Xu, J., Niu, F., Niu, Y. and Hou, Z. (2013), "Analysis on the moisture migration of subgrade soil under effect of temperature gradient", *J. Chongqing U.*, **4**, 24.

Ye, Z.Q., Mao, X.S. and Ye, M. (2012), "Moisture-thermal coupling model for the temperature calculation of the permafrost subgrade", *Appl. Mech. Mater.*, **204**, 1580-1585.

CC